

# Economic evaluation of a remote microgrid system for an Omani island

R. Ahshan, N. Hosseinzadeh, A. H. Al-Badi

*College of Engineering, Dept. of Electrical & Computer Engineering, Sultan Qaboos University, Oman*

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## Abstract

An effective solution for power generation in an isolated area is to establish microgrids using locally available clean energy sources. The establishment of a microgrid can enhance the integration of renewable power, resiliency, reliability, and efficiency. This paper evaluates the technical viability of developing a microgrid system that includes a mix of renewable and conventional energy along with suitable energy storage facilities for application in an Omani island. Models of different renewable energy systems are presented to evaluate their energy production. Economic indices, such as the net present cost (NPC) and levelized cost of energy (LCOE) are utilized to analyze the economic performance of the proposed microgrid system. Five different microgrid scenarios are designed, and their economic, operational, and environmental performance are evaluated and compared. Two system architectures, namely, microgrid utilizing a mix of renewable energy sources and renewable-conventional energy mix microgrid, are proposed. The HOMER Pro Microgrid software is utilized in this study to size, simulate, and optimize the microgrids. The NPC and the LCOE for a renewable-only mix (wind-PV-BS) microgrid are 108.3 million US dollars (USD) and 0.189 USD/kWh, while for a renewable-conventional energy mix (wind-diesel-PV-BS) microgrid with energy storage they are 63.6 million USD and 0.108 USD/kWh, respectively. A wind-diesel-PV-BS microgrid achieves a lower NPC and LCOE than the diesel-only, wind-diesel-BS, or PV-diesel-BS microgrid systems. A thermal load controller is introduced to the microgrid models to verify the impact of excess electricity and to better utilize the microgrid capacity. The outcomes of the sensitivity analysis indicate that a microgrid using a renewable-only mix will become cost competitive if the increasing trend in the price of diesel and the decreasing trend in the cost of renewable technologies persist.

*Keywords: Remote microgrid, renewable energy, economic evaluation, optimization, sensitivity analysis*

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## 1. Introduction

The rapidly declining reserves, volatile market prices, and environmental impacts of fossil fuel resources are the major reasons to increase the utilization of renewable energy sources. However, the stochastic variation in renewable power generation and the high cost of electricity production using renewable resources are the two major issues impeding the deployment of renewable energy systems [1]. Therefore, utilization of a mix of these renewable resources and conventional energy systems has led to the concept of the microgrid system. In addition, microgrids with suitable storage systems can enhance the feasibility of integrating a high proportion of renewable power, improve efficiency, increase reliability and resiliency, and reduce the cost of energy [2].

The microgrid is an emerging technology involving the interconnection of multiple diverse generation units, storage devices, and loads that is capable of operating locally as a single controllable system with or without the presence of a utility grid [3]. Microgrids without utility grid connections or far from the utility grid are known as isolated or remote microgrids. Remote microgrids are developed for and operated in communities such as islands, and in rural and urban areas of a country [4]. Diesel power generation systems are commonly used to meet the electricity demands of these remote communities; these systems

produce a large amount of pollutant emissions and require expensive fuel. It is reported that globally, about 1.18 billion people live in detached areas with almost no supply of electricity, and that these areas often have good renewable energy resources [5]. Remote microgrids can reduce pollutant emissions, reduce dependency on high-cost diesel fuel, and improve the quality of human life in isolated areas. Therefore, remote microgrids that combine renewable and conventional power generation would be an appropriate solution for remote communities. However, proper technology and feasibility studies must be carried out in this area.

A number of investigations into the feasibility of developing microgrids for remote communities are found in the recent literature [4, 6-8, 10-17]. In these studies, the levelized cost of energy (LCOE), renewable energy fraction (REF), and net present cost (NPC) are used as performance metrics to evaluate off-grid microgrid systems. Designing an optimal remote microgrid system can be difficult, since the design analysis involves multiple variables such as the availability of resources and technologies, and consideration of various possible component capacities, etc. The HOMER software developed by the U.S. National Renewable Energy Laboratory (NREL) is utilized in these studies to ease the design process [9]. HOMER is an optimization tool that evaluates different possible system architectures under various uncertainties and compares them based on their LCOE, NPC, and REF. As reported by Abdilahi et al. [8], the feasibility of a hybrid system for an urban residential load in Somalia was studied. This study utilized NASA satellite data for wind and solar resources as the inputs for HOMER. The NPC-based results showed that the hybrid system design was 1.5 times less expensive than the diesel-based generation system. HOMER-based optimal design and comparative analysis of microgrids was performed in [4]. When evaluated based on NPC and LCOE, a diesel-renewable mix isolated microgrid outperformed a diesel-only or a renewable-only microgrid system. A feasibility study of an island microgrid is presented in [10], where the optimal system was selected based on the NPC and LCOE. The authors in [11] performed a feasibility study of a micro-hydro and photovoltaic microgrid system using HOMER as an optimization tool. It was shown that the micro-hydro based microgrid could meet the load demand at a low LCOE and reduce CO<sub>2</sub> emissions substantially. A feasibility study of an off-grid solar- and wind-dependent microgrid in Ethiopia is presented in [12]. Satellite data were used as inputs for the HOMER optimization tool in this study, and the LCOE was utilized to assess the economic feasibility of the system. The authors of [13] also studied a microgrid system that included hydro-PV-wind-diesel generators along with batteries for a different rural site in Ethiopia. A feasibility study of an isolated renewable-source-dependent microgrid for a rural area in Iran was conducted in [14]. This analysis showed that a PV-battery system has a low NPC and a lower excess electricity fraction than a wind-battery or wind-PV-battery system. The feasibility analysis of a diesel-wind-battery and wind-PV-diesel-battery hybrid microgrid for Binalood, Iran is presented in [15]. An isolated hybrid renewable energy system for rural area applications in Pakistan is presented in [16]. Three different strategies are investigated and their economical aspects are examined. The models are developed and optimized in HOMER platform. Feasibility study of a hybrid system consisting of PV, diesel, and battery for rural area application in Iraq is presented in [17]. The optimization and sensitivity analysis was carried out using HOMER software by considering the multi-year input variations.

The feasibility analysis of a wind-PV-battery based microgrid for application in a Mediterranean island community was performed using HOMER [18]. The results of this study suggested two feasible microgrid systems for this community based on the lowest NPC and LCOE. Bhandari et al. [19] proposed a PV-wind-hydro-based off-grid hybrid power system to electrify villages in Nepal. An economic assessment and feasibility analysis of a wind-PV-battery system for application in an isolated island were studied in [20]. The study results based on the NPC and LCOE showed that a wind-PV-battery based hybrid system was feasible and economically viable for this island. The optimal sizing of a PV-wind-biomass hybrid microgrid for rural townships was examined, and the results showed that the proposed system was economically viable and able to meet the demands of the existing load [21]. The economic analysis and sizing of a PV-wind-battery based hybrid system for Hormoz Island in Iran is presented in [22]. It was shown that the PV-wind-battery based system can meet the load demand without any energy

shortage and can save the cost required for the grid expansion.

An isolated community located on Masirah Island in the Sultanate of Oman is considered in this study. This location has many characteristics that make it attractive for the evaluation, testing, and development of a microgrid system. It is a remote isolated community, is attractive for tourism, operates diesel-based power generation, and has an excellent availability of renewable resources such as wind and solar. This location has one of the highest annual average wind speeds (5.54 m/s at 10 m height) in the Sultanate of Oman [23], and the annual average solar irradiance in this location is 6.38 kWh/m<sup>2</sup>/day [24]. This research is part of the national vision and aim of obtaining minimum 10% of energy requirements from renewable-based power generation in the Sultanate of Oman by 2025 [23]. Four studies have recently been conducted to design a hybrid power system for Masirah Island. The study reported in [25] found that wind-diesel-based generation could reduce the energy cost by 48% compared to the diesel-only system, however, the solar resource available on the island was not included in the study. The feasibility of a hybrid power system for Masirah Island was evaluated in [24]. It was found that a PV-wind-diesel-based energy system could produce lower-cost energy compared to wind-diesel or solar-diesel-only systems. However, this investigation was restricted to a renewable energy fraction of 25% or less, while the authors in [26] indicate the possibility of developing an energy system using 100% renewable sources. The possibility of using renewable energy sources in a hybrid system for this island was also presented in [27]. The study showed that a wind-solar-diesel-dependent system would be a viable option, as this system had the lowest NPC and COE. However, this study lacked a sensitivity analysis for the proposed hybrid system, which is an important aspect of investigating renewable-source-based energy systems, as indicated in [28]. Sensitivity analyses reveal the impact of uncertainties such as wind speed, solar insolation, future diesel prices, the cost of technologies, and the lifetime of the storage unit variations on a hybrid system design. Without this analysis, the ideal size of the components in a hybrid system with variations in the aforementioned variables will remain unknown to designers, developers, and policy makers. Therefore, detailed sensitivity analysis in conjunction with optimization represents a better approach to examine the feasibility of renewable energy microgrid systems. A fourth study was carried out to assess the techno-economic performance of a hybrid power system for Masirah Island [29]; however, sensitivity analysis was not carried out in this fourth study. Thus, the system component sizes may vary due to the uncertainties described above. This will result in a different system cost, and hence a different NPC, operation and maintenance cost, and LCOE.

Briefly, the feasibility of hybrid energy systems has been examined for various locations worldwide, including Masirah Island, which has unique attributes that make it interesting for research into microgrids. The feasibility investigations in these studies have mainly focused on techno-economic viability, and the nature and dimension of the key technologies (wind, diesel, and PV) included in the hybrid systems varied. However, a microgrid design method and performance evaluation that consider fluctuations in the resource availability with hourly sampled data, changes in the diesel fuel price, reduction in the cost of technologies, and variations in the energy storage lifetime have not been comprehensively studied. Moreover, while a few investigations have been carried out to explicitly study the feasibility of a hybrid power system for Masirah Island, none of these investigations concurrently examined the possible addition of suitable storage systems to minimize the excess electricity produced by the optimal system. Therefore, the objectives of this investigation are the following:

- To design an optimal, most economical, and robust microgrid system that could be utilized as a remote microgrid for the communities on Masirah Island using meteorological data sampled hourly over one year. This data reflects the expected weather conditions over a long period.
- To maximize the use of excess electricity produced by the renewable sources using the thermal load to better utilize the microgrid capacity and hence maximize the system efficiency.
- To examine the expected performance of the designed microgrids while considering the effect of uncertainties in resource availability, future diesel prices, the cost of technologies, and the lifetime of the energy storage such as battery, and hence to pinpoint the variable that has the greatest impact on establishing a microgrid system for the selected island.

## 2. Methodology

In this study, an integrated approach that combines energy and economic models is utilized to assess the performance of the possible microgrid configurations. The energy models determine the energy output of PV systems, wind turbines, diesel generators, and battery systems so that the load demand of a microgrid can be met, while the economic models calculate the NPC and LCOE for the possible microgrid configurations to rank them based on lowest NPC so that the most economically viable system can be identified. The details of each model are presented in the following subsections.

### 2.1 Energy model

#### 2.1.1. Wind system

Wind turbine power curves provide the turbine output power for a range of wind speeds (cut-in to cut-out). The manufacturer develops such power curves experimentally, taking into account losses related to the wind turbine system. Therefore, the power curve versus wind speed was utilized as a model to determine the output power of a wind turbine. A large wind turbine, Enercon E-44/900 kW, was considered in this study. The technical information and power curve specifications of this turbine were obtained from [30].

#### 2.1.2. PV system

The model of the PV system to determine its energy output for each hour given in [7] was used in this study. The PV module (model: CS6U-340M) developed by Canadian Solar Co. was utilized in this study. Moreover, the technical specifications and associated parameter values were obtained from [7, 31]. The model of the PV module takes into account a de-rating factor to include the consequences of temperature variation and dust accumulation on the modules.

#### 2.1.3. Diesel system

The diesel system model is composed of the fuel curve and the efficiency curve models. The fuel curve models the amount of fuel utilized by the generator to produce electricity in a given time step. The efficiency curve describes the generator efficiency, which is calculated by the ratio of the electrical energy output and the chemical energy input of the generator. The fuel curve is characterized by the generator performance data that determines the fuel intercept coefficient and slope. The coefficient of the fuel intercept and the fuel slope values are utilized to generate the efficiency curve. The detailed model for the fuel and the efficiency curves utilized in this study was obtained from [32].

#### 2.1.4. Battery system

The battery system is a group of batteries in a bank. Unlike past studies that used kinetic battery models, this study uses a modified kinetic battery model. Although this model is based on the conventional kinetic battery model [33], the modified model takes account rate-dependent losses, the effects of temperature on capacity, and performance degradation over the lifetime of the battery. In contrast to the kinetic battery model, the modified model stores electrical energy based on the aforementioned parameters as well as the effect of temperature on the battery capacity, calendar degradation (used or idle), and cycle degradation (cycle fatigue on the battery) in each time step [9]. Table 1 provides the battery specifications used in this study.

Table 1 Battery data used in the microgrid model [9]

Battery	Parameter value
Type	Hitachi LL1500-G
Batteries per string	1
Voltage	8
Capacity	2170 Ah
Model	Modified kinetic battery model

### 2.2. Economic model

To evaluate the economic performance of the microgrid system, an economic model using the net present cost (NPC) and levelized cost of energy (LCOE) was utilized. The NPC encompasses the costs (of

initial construction, replacement, fuel, and maintenance) that would result during the project lifetime. The NPC was determined as follows:

$$NPC = \sum_{T=1}^N \frac{C_T}{(1+r)^N} \quad (1)$$

where  $C_T$  is the total annualized cost value,  $N$  is the project lifetime in years, and  $r$  is the nominal discount rate. The project lifetime to be considered is 25 years, as suggested in [7], while a nominal discount rate of 6.5% was utilized based on the annual real interest rate and the inflation rate information available in Oman [34]. The LCOE in this economic model was defined as in [28]

$$LCOE = \frac{C_T - c_{boiler} H_{served}}{E_s + E_{gs}} \quad (2)$$

where  $c_{boiler}$  is the boiler cost,  $H_{served}$  is the thermal load served,  $E_s$  is the total electrical load served, and  $E_{gs}$  is the total energy supplied to the grid each year. The thermal load was taken into account in this study to manage excess energy produced by the microgrid system. Table 2 shows the installation costs and lifetimes of the components that were utilized in this study.

Table 2 Component cost and lifetime used in the microgrid model

Component	Cost	Lifetime	Reference
Diesel generator	750 USD/kW	25000 hours	[29]
Wind turbine	721.6 USD/kW	25 years	[18]
PV system	1030 USD/kW	25 years	[36]
Battery	300 USD/kWh	10 years	[37]
Converter	750 USD/kW	15 years	[38, 39]
Thermal load contr.	200 USD/kW	20 years	[9]

### 2.3. Microgrid model

The developed microgrid model combines both renewable and non-renewable sources along with storage units. Thermal load was also incorporated in the microgrid model to observe the impact of excess electricity produced by the renewable energy sources. The daily load demand for Masirah Island was utilized as the load in this model. Fig. 1 shows the microgrid components, which included diesel generators, wind turbines, PV panels, inverters, batteries, the thermal load, and a thermal load controller.

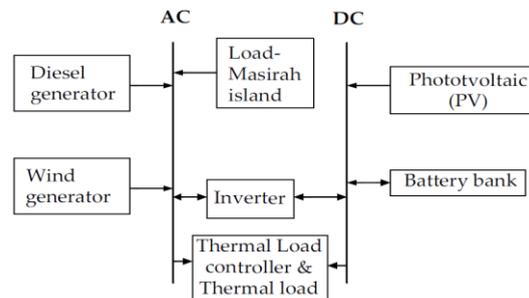


Fig. 1. Components of the microgrid model developed in HOMER Pro

The model of microgrid system in this study was developed using the HOMER Pro Microgrid tool, which utilizes the energy and economic models described in the previous section [28]. HOMER Pro simulates the developed microgrid model to evaluate its technical viability and calculate its life cycle cost in the provided time step. After finding microgrid configurations using simulation, the HOMER Pro

optimizer calculates and displays the optimal configurations of the microgrid that fulfill the designer's constraints based on the minimum NPC. HOMER Pro determines the NPC and LCOE for each optimal configuration using the initial capital cost of each component in the optimal system. The sensitivity analysis in the HOMER Pro tool was also utilized to test the performance of the optimal microgrid models under various uncertainties.

### 3. Case Study: A Remote Island Community Methodology

In this section, an overview of a remote island community on Masirah is given, followed by a summary of the available renewable energy resources on the island and the electricity demand by the community. The largest island in Oman, Masirah, is 95 km long north-to-south, and is located at about 15 km from the Al Wusta coast in Central Oman and 550 km away from the capital city, Muscat [24]. The total electrical load demand for this island community is 115.86 MWh/day, which includes residential, governmental and commercial, and industrial demand, which represent 54%, 40%, and 6% of the load, respectively [27]. Diesel generators are the only source supplying the electricity load demand for this island, which results in substantial greenhouse gas emissions and pollution. Moreover, the high cost of diesel fuel and the transportation of this fuel to this remote island increases the energy cost significantly, and may reduce its energy security. However, this island has significant potential to use wind and solar resources to produce clean energy, which would result in a reduction of fuel consumption and greenhouse gas emissions. Table 3 shows the specifications of the diesel generators used for power generation on Masirah Island [29].

Table 3 Details of the diesel generators used on Masirah Island

Manufacturer	Number of units	Unit installed capacity (kW)	Total installed capacity (kW)
KHD	4	3000	12000
MBS	5	265	1325
Caterpillar	2	1000	2000
CUMMINS	1	1000	1000
MAN	1	4000	4000

Masirah Island was chosen for the study in order to support the Sultanate's national vision of a tourism industry, as well as to promote smart grid research and development locally and regionally. The ultimate goals of this study are to build a smart grid on Masirah Island as a test case for isolated-community-based smart grid technologies, and to provide a base case study that can be imitated to investigate microgrid models for the other islands in the Sultanate. Inputs to the microgrid model for the remote island community of Masirah are described in the following subsections.

#### 3.1. Solar resources

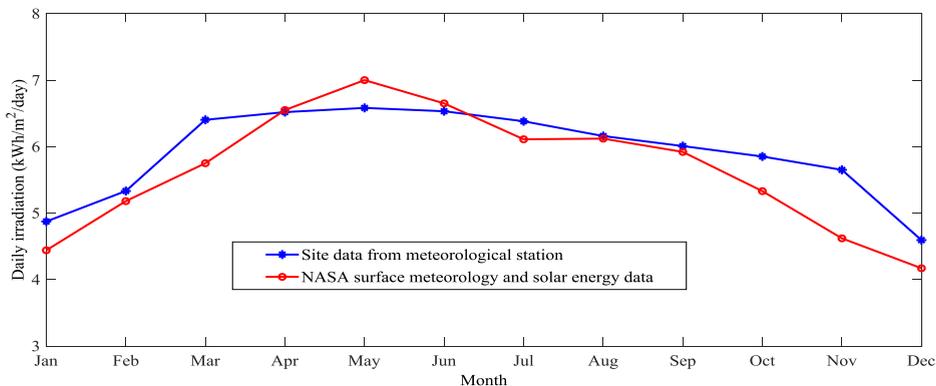


Fig. 2. Solar resource profile for Masirah Island

Two sets of solar resource profiles for Masirah Island are available for use as inputs to the microgrid model. One is from the NASA surface meteorology and solar energy database using the global positioning system coordinates in HOMER Pro. The other set of data was measured by the meteorological station located at the site, which has better accuracy than the data available in NASA database. Therefore, the solar resource data measured by the Masirah weather station, which was obtained through the Directorate General of Civil Aviation and Meteorology, was utilized in this investigation. Fig. 2 illustrates the solar irradiance profile for Masirah Island over a one-year period. The annual average solar irradiance for this island is  $6.38 \text{ kWh/m}^2/\text{day}$  [27].

### 3.2. Wind resources

Two sets of wind resource data are available for Masirah Island. One is the hourly wind speed data available through the NASA surface meteorology and solar energy database, which can be obtained using the coordinates of the site. The other set of data was measured hourly using the meteorological station at the site, and was obtained from the Directorate General of Civil Aviation and Meteorology in Oman. At the height of the anemometer, the annual average wind speed for these data sets are  $5.75 \text{ m/s}$  and  $5.54 \text{ m/s}$ , respectively [23, 40]. Fig. 3 describes the wind speed profile for Masirah Island, showing the monthly average wind speed over a one-year period. The more conservative data set measured at the meteorological station at the site, which should be more accurate for predicting the energy output of a particular wind turbine, was used in this investigation.

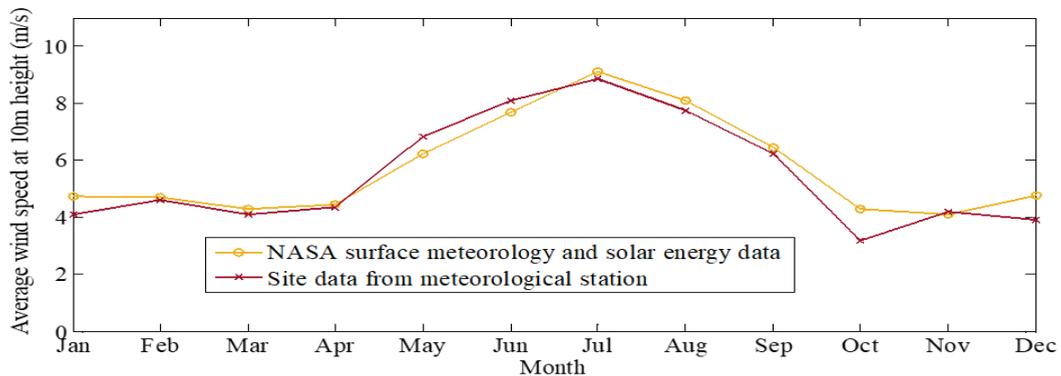


Fig. 3. Wind speed at the case study site over a one-year period

The wind turbines are located at a particular hub height to increase the average wind speed and hence the power captured. The hub height for the turbine considered in this study was  $44 \text{ m}$ , and the wind speed at the hub height was obtained using the following equation [41]

$$\frac{v_{hh}}{v_{rh}} = \left( \frac{h_{hh}}{h_{rh}} \right)^\alpha \quad (3)$$

where  $v_{hh}$  is the wind speed at the hub height in  $\text{m/s}$ ,  $v_{rh}$  is the wind velocity at the reference height in  $\text{m/s}$ ,  $h_{hh}$  is the hub height in  $\text{m}$ ,  $h_{rh}$  is the reference height at which the measurement was taken, and  $\alpha$  is the shear exponent used, as given in [41].

### 3.3. Electrical load

Electrical load data is an essential input for analyzing microgrid models. Fig. 4 illustrates the monthly average demand profile at Masirah Island. The energy consumed by the island community (residential, governmental and commercial, and industrial) is  $115.855 \text{ MWh/day}$  with a  $12.36 \text{ MW}$  peak load. The

hourly electrical load data were obtained from the local authorities, the Ministry of Transport and Communications, the Directorate General of Civil Aviation and Meteorology, and the Rural Areas Electricity Company, Oman. Fig. 4 reveals that the highest energy consumption for this community occurs in May, while the lowest energy demand is observed in January. This is due to the high load demanded for cooling requirements during the month of May, which is the hottest (average temperature 31 °C) month of the year.

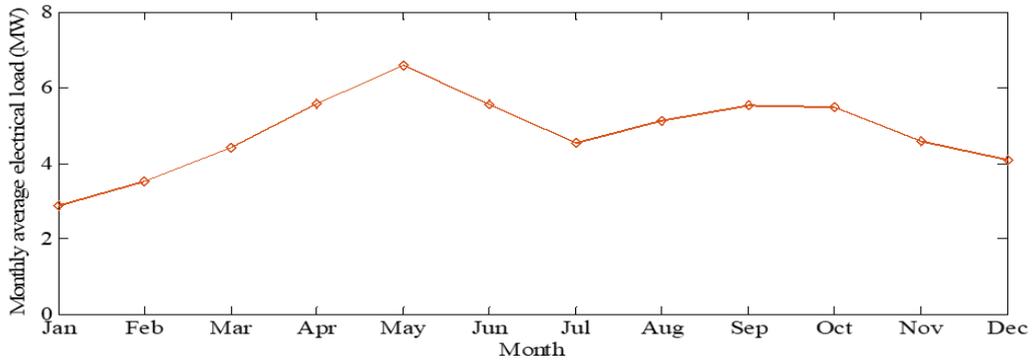


Fig. 4. Monthly average load profile for the microgrid at Masirah

Fig. 5 presents the average hourly load demand for the days with the maximum (May 1st) and minimum (January 7th) load demand, which were also considered in designing the microgrid model. The demand profile on May 1st shows that energy consumption gradually decreases between 1:00 AM and 6:00 AM, while between 6:00 AM and 9:00 AM it increases, and then remains steady until 1:00 PM. The load demand increases further from 1:00 PM until 4:00 PM. However, the most rapid increase in load demand is observed between 5:00 PM and 12:00 PM. This is due to the highest percentage of residential (54%) and commercial (40%) load occurring during this period. In addition, the use of cooling systems such as air conditioners by the residential, governmental, and commercial customers in the community is increased during this period. The demand profile on January 7th is similar to that of May 1st; however, the load demand is much lower because of lower utilization of cooling systems during this coolest (average temperature 23 °C) month of the year.

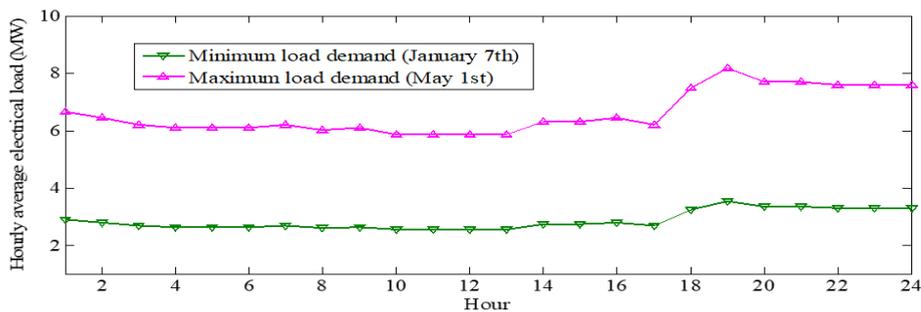


Fig. 5. Hourly electrical load for isolated microgrid at Masirah

### 3.4. Thermal load

The thermal load was introduced in the microgrid model to maximize the use of surplus energy produced by the renewable sources in the microgrid. The surplus energy results from the fact that the renewable sources produce energy at full capacity when the load is not high enough to consume this power and the storage is full. The predicted thermal load for Masirah Island is assumed to be 5% of the electrical load, as described in [4]. To model the thermal load in HOMER Pro, a thermal load controller

and boiler are required. The thermal load controller converts excess electricity into heat to serve as the thermal load. However, if there is any unserved thermal load remaining, the boiler will supply this load. It is important to mention that in this study, the excess electricity produced by the renewable sources, rather than the boiler, serves the total thermal load.

## 4. Results and Discussion

### 4.1. Remote island microgrid architecture

To identify the most feasible microgrid architecture with the lowest NPC, the simulation and optimization of five different scenarios were performed using the HOMER Pro Microgrid software. These scenarios were based on the microgrid design provided in Fig. 1. Table 4 summarizes the five different scenarios that were analyzed and discussed in this study.

Table 4 Summary of the studied scenarios

Scenario	Description of the scenario
Scenario 1	Completely diesel-based microgrid (Base scenario)
Scenario 2	Renewable-only mix microgrid (wind-PV-BS)
Scenario 3	Diesel and renewable source microgrid (PV-diesel-BS)
Scenario 4	Diesel and renewable source microgrid (wind-diesel-BS)
Scenario 5	Diesel and renewable source mix microgrid (wind-diesel-PV-BS)

The types and optimal sizes of the technologies in the developed microgrid models for five different scenarios are shown in Table 5. It can be seen that when diesel is the only power source in the microgrid (Scenario 1), 20.34 MW of diesel capacity is required to meet the load demand, whereas the renewable-only mix microgrid (Scenario 2) depends completely on wind, PV, and battery storage. The diesel-, PV-, and battery-dependent microgrid (Scenario 3) requires 7.6 MW of diesel capacity, which represents a reduction of 62.64% compared to the base scenario. This is due to the inclusion of PV generation in the microgrid model. Scenario 4, which is the diesel-, wind-, and battery-dependent microgrid, also requires a diesel capacity of 7.6 MW, which represents a 12.74 MW reduction in the diesel generation capacity. Finally, the diesel and renewable sources mix microgrid (Scenario 5) utilizes 5.6 MW diesel, 12.6 MW wind, 6.138 MW PV, and 9.51 MW battery storage capacity for an hour of backup. It should be noted that the diesel capacity required by the microgrid system in Scenario 5 (diesel-wind-PV-BS) is only 5.6 MW, which represents an approximately 72.5% reduction in diesel capacity compared to Scenario 1. This reduction in diesel capacity is achieved by adding renewable resources, wind and PV, at their most optimal capacities into the base case scenario.

Table 5 Combinations of technologies and their capacities in the optimal microgrid system for the different scenarios

Type, capacity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Diesel, MW	20.34	0	7.6	7.6	5.6
Wind, MW	0	10.80	0	16.2	13.5
PV, MW	0	42.16	10.736	0	5.65
Converter, MW	0	9.63	5.029	1.195	3.43
Battery, number	0	10800	540	215	548

Table 6 shows the economic performance of the optimal microgrids for the five different scenarios based on economic performance indicators such as the NPC, LCOE, and diesel fuel consumption. The LCOE and diesel consumption for the diesel-dependent microgrid (Scenario 1) are 0.211 US dollars (USD) per kWh, and 10.9 million L/year, respectively. The diesel fuel consumption and the LCOE are both high, as this base scenario microgrid uses only diesel power generation. The LCOE for the renewable-only mix microgrid (Scenario 2) is 0.189 USD/kWh, which is slightly lower than that of Scenario 1; this scenario involves zero diesel consumption. The cost of energy for Scenario 2 may not be very encouraging at this time. However, the continuous reduction in the price of these technologies could make this microgrid architecture a more attractive option in the future, which will be discussed later. The LCOE for Scenario 3, which is the diesel-, PV-, and battery-based microgrid, is 0.148 USD/kWh.

Moreover, the diesel consumption for Scenario 3 is reduced to 7.5 million L/year. This reduction originates from the integration of PV generation at the 43.8% penetration level. The diesel-, wind-, and battery-dependent microgrid in Scenario 4 has a LCOE of 0.122 USD/kWh. The diesel consumption in this scenario is reduced to 5.35 million L/year, which is almost a 50% reduction compared to the base scenario. This resulted from the addition of wind generation into the microgrid at an 80.5% penetration level. Lastly, the LCOE and diesel fuel consumption of the diesel-, wind-, PV-, and battery-dependent microgrid (Scenario 5) are 0.108 USD/kWh and 4.35 million L/year, respectively. The LCOE for this microgrid is reduced by 48.8%, while the diesel consumption is reduced by 60%, due to the integration of wind and PV generation at penetration levels of 68% and 27%, respectively.

Table 6 Economic comparison of optimal microgrid systems for different scenarios

Indices	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
NPC, millions of USD	142	108.3	84.8	69.9	63.6
LCOE, USD/kWh	0.211	0.189	0.148	0.122	0.108
Diesel consumption, L/year	10937772	0	7535277	5351610	4352456

Table 6 also clearly shows that the NPC declines as renewable technologies are integrated into the system. The NPC of the diesel-dependent microgrid (Scenario 1) is 142 million USD. The NPC for the diesel-, wind-, PV-, and battery-dependent microgrid (Scenario 5) is lower than that of the other microgrid architectures or scenarios. The NPC for the Scenario 5 microgrid is 63.6 million USD, which represents a 55% reduction over the Scenario 1 microgrid. Therefore, the diesel-, wind-, PV-, and battery-based microgrid (Scenario 5), which has the lowest NPC, LCOE, and diesel fuel consumption, was considered to be the most economical microgrid solution for Masirah Island. The breakdown of the NPCs for Scenario 1 (diesel only) and Scenario 5 (wind-diesel-PV-BS) microgrids are given in Tables 7 and 8.

Table 7 Details of the component costs in USD for the Scenario 1 (diesel-only) microgrid

Component	Capital cost	Replacement cost	O&M and annual cost	Salvage	Total component cost
Diesel generator	15787500	18867269	111758542	4157682	142255629
Wind turbine	0	0	0	0	0
PV	0	0	0	0	0
Converter	0	0	0	0	0
Battery	0	0	0	0	0
System	15787500	18867269	111758542	4157682	142255629

Table 8 Details of the component costs in USD for the Scenario 5 ( wind-diesel-PV-BS) microgrid

Component	Capital cost	Replacement cost	O&M and annual cost	Salvage	Total component cost
Diesel generator	0	472034.76	37775846.8	423843.96	37824037.60
Wind turbine	14850000.00	0	20334.39	0	14870334.39
PV	5828438.93	0	43800.00	0	5872238.93
Converter	1543938.66	468181.66	232555.99	92301.81	2152374.50
Battery	1710257.00	1439427.24	71712.63	324141.96	2897254.92
System	23932634.59	2379643.66	38144249.81	840287.27	63616240.34

To examine the energy balance performance of the microgrids in the different scenarios, the energy production and consumption by the microgrids are presented in Table 9. Microgrids in different scenarios produce sufficient energy to meet the load demand, except for that of Scenario 2. Although the Scenario 2 microgrid has a much higher production capacity with a significant amount of excess electricity, a very small proportion of the load remains unmet. This is due to the intermittency and non-dispatchable attributes of the wind and solar resources, on which this microgrid is completely dependent. The Scenario 3 microgrid has the lowest production capacity among all the diesel-renewable mix microgrids. However, its LCOE and NPC are higher than that of the microgrids in Scenario 4 and Scenario 5. Although the production capacity is not the lowest, the Scenario 5 microgrid has the best optimal production capacity, and thus has potential for better utilization.

From Table 9, it can be observed that a substantial amount of excess energy is available in the microgrids (Scenario 2 to Scenario 5), which comes from the excess electricity generated by the

renewable resources. The microgrids in Scenario 2 to Scenario 5 are able to convert excess electricity to serve the thermal load requirement of the microgrids. Since the thermal load requirement of the microgrid is relatively low, the microgrids still have some excess energy. This excess energy can be further utilized for potential heating or cooling applications in order to manage the microgrid energy production efficiently. Fig. 6 shows the most economically optimal microgrid model, diesel-wind-PV-BS (Scenario 5), developed in HOMER Pro software.

Table 9 Comparison of the energy production and consumption for the different scenarios

Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Energy production, GWh/year					
Diesel generator	42.28	0	29.6	20.02	17.11
Wind turbine	0	24.67	0	41.13	30.61
PV	0	72.71	18.53	0	9.75
Renewable fraction	0	100%	29.8%	52.6%	59.5%
Total	42.28	97.39	48.13	61.15	57.47
Energy consumption, GWh/year					
Electrical load	42.28	42.98	42.28	42.28	42.28
Thermal load	0	2.11	2.11	2.11	2.11
Excess energy	0	47.26	3.74	18.87	13.08
Unmet energy	0	0.29	0	0	0

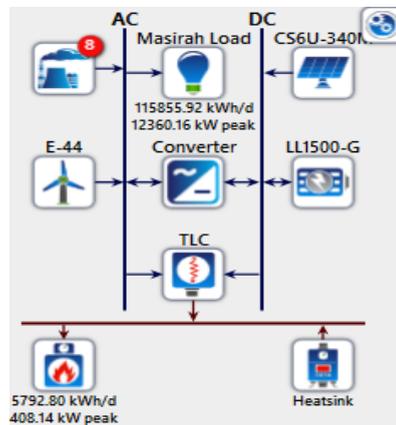


Fig. 6. Components of most economic microgrid (wind-diesel-PV-BS) model proposed for Masirah Island

To compare the environmental impacts of the microgrids in the five different scenarios, the emissions of different pollutant materials are presented in Table 10. The renewable-only mix microgrid (Scenario 2) produces almost zero emissions. However, the Scenario 5 microgrid (wind-diesel-PV-BS) reduces emissions significantly compared to the Scenario 1 microgrid (diesel only). The Scenario 5 microgrid reduces the total system emissions from 32104 to 12792.6 tons/year, which is a reduction of approximately 60%. This indicates that the Scenario 5 microgrid can perform well in terms of minimizing environmental impact.

Table 10 Comparison of emissions for different scenarios (in tons/year)

Pollutant	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Carbon dioxide	31824	0	21927	14932	12662
Carbon monoxide	43	0	26	17.50	17
Unburned hydrocarbons	3	0	2.50	1.70	1.24
Particulate matter	4	0	0.65	0.50	0.35
Sulfur dioxide	79	0.007	54	37	31
Nitrogen oxides	151	0	108	101	81
Total	32104	0.007	22182.5	15089.7	12792.6

#### 4.2. Sensitivity tests

Seven sensitivity variables (diesel price, wind turbine cost, PV module cost, wind speed, solar irradiation, battery cost, and battery life) were considered in this study. The advanced search space feature in HOMER Pro was utilized to introduce a large number of alternatives in order to examine the robustness of the most economically optimal microgrid scenario. Each microgrid scenario was tested for 432 sensitivity cases. In total, 658996 systems were simulated for 432 cases and about 2.84 billion alternatives were examined. The total time required for the simulation was 82 hours on a personal computer with a 3.40 GHz Intel (R) Core (TM) i7-6700 processor and 16 GB of RAM. The performances of the optimal system types for different sensitivity variables presented in this subsection.

Considering the present cost of diesel fuel, batteries, wind turbines, and PV modules, a wind-diesel-PV-BS microgrid would be useful for the remote isolated load on Masirah. The optimal system type shown in Fig. 7 reveals that the levelized cost of energy is 0.108 USD/kWh (at 6.38 kWh/m<sup>2</sup>/day and 5.54 m/s) for a wind-diesel-PV-BS microgrid for application in Masirah Island. In the low wind speed region, a wind-diesel-PV-BS microgrid is still the optimal system, but produces energy at a higher cost. However, this cost of energy is still lower than that of the diesel-only system. This indicates that such a microgrid system has great potential for deployment on other remote islands or areas in the Sultanate, which have relatively lower wind speeds. The cost of energy decreases to 0.084 USD/kWh for the higher wind speed region. Although increasing diesel price by 37% [24, 29] has no effect on the optimal system type; however, the LCOE increases to 0.130 USD/kWh at the current annual average wind speed and solar irradiation of Masirah Island. In addition, the LCOE increases significantly for sites with low wind speed.

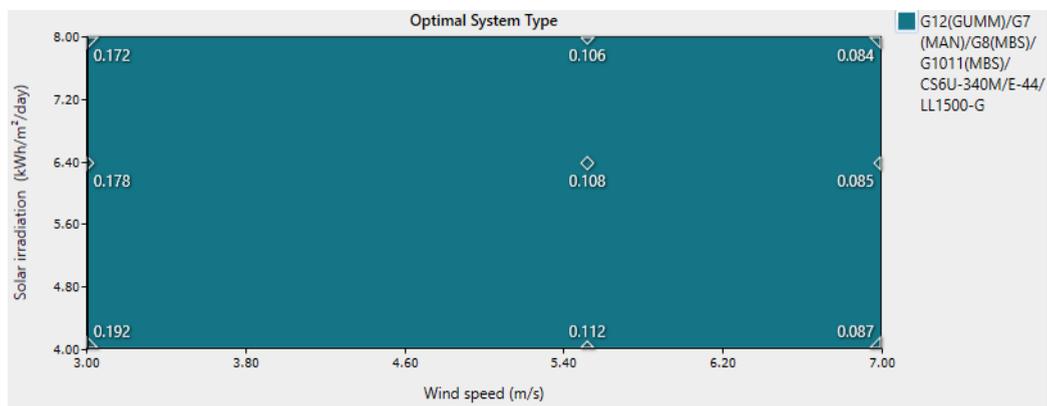


Fig. 7. Optimal system type at a diesel cost of 0.64 USD/L and the present cost (Table 2) of wind turbines, PV modules, and batteries

Due to the decreasing trends in the cost of wind turbines, PV modules, batteries, and the improvement in battery lifetimes [42], the sensitivity test for the Scenario 5 micrigrid was carried out by considering reduction in the cost of renewable energy technologies and increases in battery lifetimes. Battery lifetime variation was introduced by increasing the degradation level. In this study, the battery lifetime was increased from 10 (20% degradation) to 20 (40% degradation) years. The cost multiplier of wind turbines and PV modules were set to 0.5 based on the trend found in [42], which represents a 50% reduction in cost. It can be seen from Fig. 8 that the LCOE for the optimal system, wind-diesel-PV-BS microgrid, is significantly reduced. This observation also reveals the important finding that the LCOE (0.110/kWh) in the low wind speed region becomes almost equal to the LCOE (0.108 USD/kWh) at the present cost of technologies and the present average solar irradiation (6.38 kWh/m<sup>2</sup>/day). It worth mentioning that the Sultanate has many low wind speed sites with very good solar irradiation. The lowest LCOE (0.062 USD/kWh) is observed for the higher wind speed region and at the present average solar irradiation.

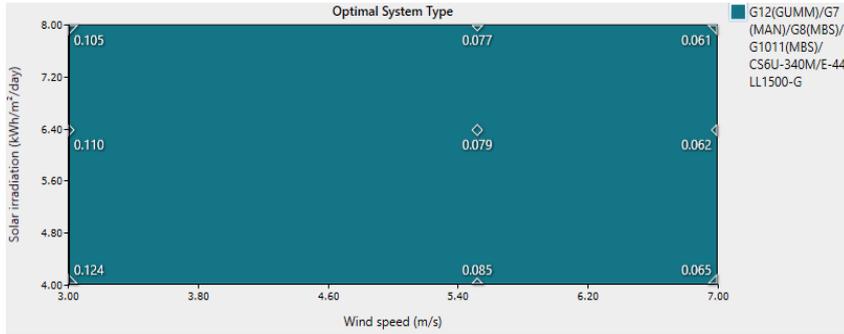


Fig. 8 Optimal system type at a diesel cost of 0.64 USD/L, with cost multipliers of 0.5 for wind turbines, 0.5 for PV modules, and 0.8 for batteries, and a battery life of 20 years

The sensitivity test results for the 100% renewable mix microgrid (Scenario 2) are shown in Figs. 9-10. Considering the present cost of the technologies, the LCOE of a wind-PV-BS microgrid for Masirah Island is 0.189 USD/kWh, as shown in Fig. 9. The LCOE is 0.162 USD/kWh for higher wind speed sites, while it is 0.215 USD/kWh for lower wind speed sites. It is important to note that the optimal system type does not change for a wide range of variations in the availability of wind and solar resources. This indicates that a wind-PV-BS-based microgrid (Scenario 2) is feasible for 100% renewable energy integration. However, the LCOE is almost doubled in compared to the wind-diesel-PV-BS (Scenario 5) based microgrid.

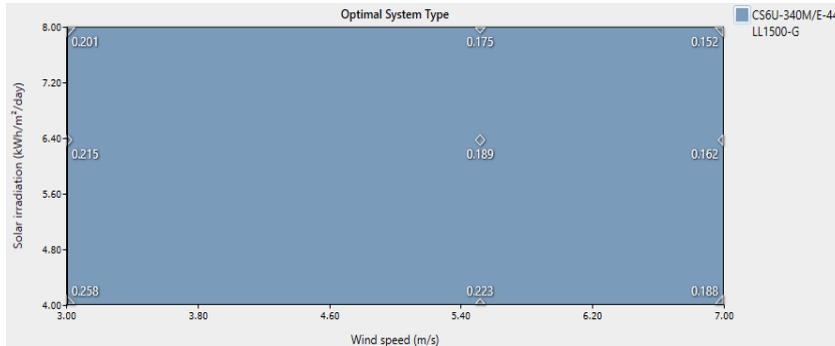


Fig. 9 Optimal microgrid system for 100% renewable energy production at the present cost of the technologies

Fig. 10 shows the optimal microgrid system for the 100% renewable mix with cost multipliers of 0.5 for wind turbines, 0.5 for PV modules, 0.8 for batteries, and a battery life of 20 years. Using the cost of these technologies, the LCOE for a wind-PV-BS microgrid is substantially reduced (0.105 USD/kWh). This indicates the feasibility of establishing a 100% renewable mix microgrid that can produce low cost energy. In addition, a PV-BS based microgrid was found to be an optimal system for very low wind speed sites; however, the associated LCOE is very high.

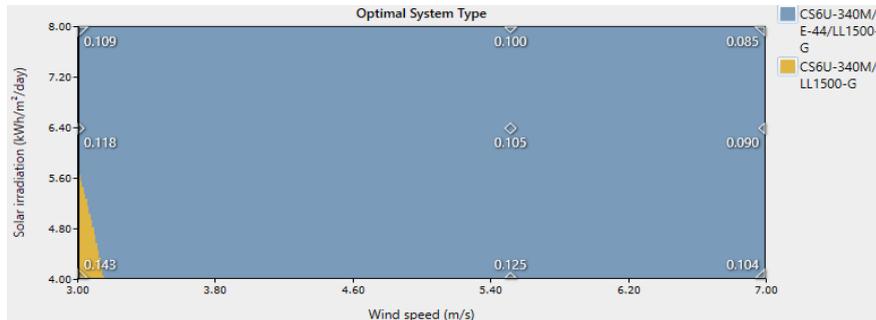


Fig. 10 Optimal microgrid system for 100% renewable energy production with cost multipliers of 0.5 for wind turbines, 0.5 for PV modules, and 0.8 for batteries, and a battery life of 20 years

## 5. Conclusions

This paper presents the optimum design, economic evaluation, and comparative analysis of microgrid systems based on their total net present cost, energy cost, power generation, excess electricity, and pollutant emissions. Five different microgrid scenarios, namely, diesel-only, wind-PV-BS, PV-diesel-BS, wind-diesel-BS, and wind-diesel-PV-BS microgrids, were modeled and simulated. The wind and solar energy resources available in the largest Omani island, Masirah, were considered in this study, with the aim of using these resources to partially or fully replace the existing diesel generators. An industry standard tool, HOMER Pro microgrid software, was utilized to carry out this study.

The analyses clearly showed that a wind-diesel-PV-BS microgrid is the optimal system, with the lowest net present cost (NPC) and levelized cost of energy (LCOE) compared to the existing diesel-only system. The NPC and LCOE of this wind-diesel-PV-BS microgrid are 63.6 million USD and 0.108 USD/kWh, respectively, while they are 142 million USD and 0.211 USD/kWh for the diesel-only system. The formation of this microgrid would also save the diesel consumption by 6.6 million L/year. The use of this microgrid would reduce total pollutant emission by 60% compared to that of the diesel-only system. Moreover, a significant (62.64%) reduction in diesel generation capacity was shown for the wind-diesel-PV-BS microgrid, which would result in a substantial reduction in diesel fuel consumption. In addition, the wind-PV-BS microgrid was found to be the most environmentally friendly system, and would prevent a significant amount of pollutant emissions.

Analysis was performed to efficiently manage the excess electricity produced by the renewable sources in the microgrid. This analysis revealed that the utilization of a thermal load controller is an effective way of converting excess electricity into usable thermal energy rather than dumping this excess energy. Some excess thermal energy was found after serving the required thermal load in the microgrid. This is due to the lack of sufficient thermal load demand in the microgrid.

Sensitivity analyses were conducted to examine the robustness of the microgrids under various uncertainties, such as variations in the diesel price, wind speed, solar irradiation, wind turbine cost, photovoltaic cost, battery cost, and battery lifetime. These analyses affirmed that a wind-diesel-PV-BS microgrid is an optimal and robust system that would be able to supply the load required for Masirah Island despite variation in the aforementioned variables. In addition, the variation in the cost of these renewable technologies, which is expected to decrease in coming years, will reduce the levelized cost of energy significantly in the future.

The analyses also revealed that the renewable-only mix microgrid (wind-PV-BS) is feasible for Masirah Island; however, the associated levelized cost of energy is very high at the present technologies cost. Sensitivity test results indicated that the renewable-only mix microgrid has the potential to produce low-cost energy if the trend of cost reductions for renewable technologies continues. However, the integration of more cost-effective storage in the microgrids would reduce the cost of the energy further; this aspect merits further investigation. Finally, the HOMER Pro Microgrid software was found to be an effective tool to design, evaluate, and analyze microgrid systems for remote locations.

## Conflict of Interest

The authors declare no conflict of interest.

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