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Research article

The optimal sizing and performance assessment of a hybrid renewable energy system for a mini-gird in an exclave territory

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Abstract: Single reliance on diesel energy has put a wide range of problems on off-grid power systems operating in remote areas of Oman. The operation of off-grid of an exclave territory of Oman is more complex, costly, and unsustainable. Hybrid Renewable Energy Systems has strongly emerged as a viable alternative to the current diesel generation plants. Proper component selection, optimum grid sizing, and performance evaluation in the economic, environmental, and reliability paradigms are crucial steps in their design process to optimize the intended benefits. This paper uses HOMER software to optimally retrofit a mini-grid power system in an excalved tiny territory of Oman. Medha region is an exclave territory of Oman and enclaved by the United Arab Emirates. Diesel-fueled generators supply the mini-grid of this tiny territory of Oman. Medha Wilyat's peak demand is 8 MW. This paper investigates the potential utilization of renewable energy to offset diesel fuel consumption, in which the price is persistently volatile and increasing. This study discusses the possibility of integrating renewable energy technologies like solar and wind with conventional power generation systems that use diesel and natural gas. Wind-natural gas-diesel-based hybrid system was found to be the most viable system compared to other combinations in terms of the cost of electricity generation. Wind energy accounted for 52.4%; natural gas accounted for 47.2%, whereas diesel accounted for only 0.44%. Another finding was that operating cost for the wind-natural gas-diesel combination was among the lowest of all combinations since renewable energy integration was highest among all combinations. This study clearly shows that the integration of renewable energy to displace diesel power generation can be cost-effective for off-grids and environmentally friendly through a substantial reduction of greenhouse gas emissions. Cost savings from displacing diesel from mini-grids are most likely to increase in the coming years.

Keywords: Sultanate of Oman; hybrid energy system; diesel; off-grid; electricity; greenhouse gas emissions

1. Introduction

The growing economies of the Gulf Cooperative Council (G.C.C.), including the Sultanate of Oman, require continually evolving approaches to power generation to satisfy their needs. A reliable power supply is critical to maintaining the country's economic growth. Oman's power sector has depended on natural gas reserves for power generation right from the inception of its power systems. Preserving natural resources and achieving environmental sustainability were established as national priorities in Oman's Vision 2040. Greater use of diversified renewable energy sources and a reduction in energy consumption are established goals to achieve this national priority in Oman's Vision 2040 document. This direction indicates Oman's strong desire to integrate renewable energy resources into power generation, which is currently based entirely on fossil fuels. The peak demand growth rate in Oman was recorded as 6% in 2017 [1]. Demand growth is expected to peak at 9530 MW in 2021 due to rapid industrialization in the region [2].

Oman is the Arabian Peninsula's third-largest country, with a land area of 310,000 km^2. The country has a dedicated Ministry for Environment and Climate Affairs, which has targeted a 10% threshold of renewable energy generation to the grid by 2025 [3]. Oman's electrical power sector is divided into three systems: the main interconnected system (M.I.S.), the Dhofar Power System (D.P.S.), and the remote area power system, which is administrated by the Rural Area Electrification Company (R.A.E.C.O.). R.A.E.C.O. is responsible for the electrification of rural areas and secures electrification funding through a mechanism established by Article 87 of Oman's Sector Law. All power generation plants under R.A.E.C.O. use diesel as fuel. Oman is connected to the Gulf Super Grid, which is the G.C.C.'s power-sharing network. The G.C.C. Interconnection Authority (G.C.C.I.A.) manages the Gulf Super Grid, which is the main interconnector of electric power-sharing between the countries. This grid, which includes energy from distributed generation, helps the individual countries transmit energy between themselves [3]. This practice enables a power transfer between Bahrain, Kuwait, Saudi Arabia, Qatar, the United Arab Emirates (U.A.E.), and the Sultanate of Oman.

In studies conducted in Oman by the C.O.W.I. international consulting group and partners in coordination with Authority for Electricity Regulation (A.E.R.) engineers, the potential for power generation was investigated. The studies looked at using solar technologies in various locations around Oman and wind energy in the country's coastal and southern regions. Oman receives daily solar radiation ranging from 5500–6000 Wh/m^2/day in July and 2500–3000 Wh/m^2/day in January. Similarly, previous studies showed that Oman had a typical wind speed of 5 m/s, with 2500 peak operational hours per year [3]. A study by the Public Authority of Electricity and Water along with the German Agency for International Cooperation (G.I.Z.) and the Fraunhofer Institute estimated that Oman could potentially generate 1.4 GW of power through P.V. cells [4]. Petroleum Development Oman (P.D.O.) undertook a major renewable energy initiative in Oman, initiating an energy-enhanced oil recovery project utilizing solar thermal power to produce steam to aid the extraction of heavy oil. The rated capacity of the plant was 1021 MW [4]. R.A.E.C.O. undertook another major initiative in the wind energy sector in collaboration with MASDAR (Abu Dhabi, U.A.E.). This massive wind energy project estimated a 50 MW. capacity in wind-rich Harweel in the Dhofar Governorate [4].

Despite the abundance of solar energy in Oman and the dropping price of renewable energy technologies, the pace of the hybridization of the off-grids in Oman is still laggards. Various studies have shown that wind and photovoltaic power are the key sources of power that expand access to affordable off-grid power. An off-grid hybrid combination of solar P.V. cells and wind was found to be an optimal combination for Sokoto State in Nigeria. The optimal design was found using HOMER hybrid optimization software. The analysis input included daily data on electricity demand, solar irradiance, and available wind speed from a weather station [5]. An off-grid hybrid power generation system was optimized using HOMER for Tuktoyaktuk, a remote village in Northwestern Territories, Canada. Considering its remoteness from the main grid, the availability of energy resources and its geographic location, an optimized result for the region was to adopt an off-grid wind-solar PV-diesel hybrid system. Other critical factors to consider when selecting an optimized result is reduction capabilities in fuel's storage capacity, significant reductions in operating costs, and global greenhouse gas (GHG) emission rates [6].

A techno-economic feasibility analysis for various power combinations like diesel alone, wind-diesel-battery, PV-diesel-battery, PV-wind-diesel, and PV-wind-diesel-battery were studied for the isolated island of Masirah in Oman. Optimized results from HOMER showed that a PV-wind-diesel hybrid power system was ideal among the systems proposed due to 75% reduction in the cost of energy and a 25% reduction in GHG emissions as compared to Masirah Island's existing system [7]. Distributed power generation by integrating conventional power sources with renewable energy sources to meet power demands is gaining importance nowadays and is referred to as a hybrid power generation system. In a hybrid system, conventional power generation, which relies on fossil fuels like natural gas and diesel, is combined with nonconventional power generation sources like solar and wind. Distributed power generation combines renewable and conventional resources, adding reliability, flexibility, upgradability, and diversity into power systems.

A hybrid power system's performance with a combination of P.V. cells, wind, and diesel depends on metrological components, including the location's solar energy profile, ambient temperature, and wind speed. An optimization method considering the maximum power available with minimum capital costs was developed for building an integrated PV-wind-diesel hybrid system [8]. HOMER Optimisation results were used to determine an optimal configuration for a Malaysian grid-connected hybrid system. The configuration included P.V. cells and wind systems in the energy charging station. The configuration was established considering the load pattern and various meteorological factors for the site in question, and a sensitive analysis led to system optimization [9].

This article offers a feasibility analysis to demonstrate that the hybridization of off-grids in Oman is valid and secure. This information is highly required for the time being to reinforce the policies of the hybridization of mini-grid. This study also aims to provide the decision-makers with technical input on approaches and modes of hybrid systems configuration and optimization. The current paper deals with designing an optimal hybrid power system for the Medha region, which is an exclave territory of Oman and enclaved by the United Arab Emirates. Inside Medha, there is Nahwa, which is a second-order enclave of the United Arab Emirates. The Omani territory of Medha is situated between the Musandam Peninsula and the rest of Oman. Diesel-fueled generators supply the min-grid of this tiny territory of Oman. This paper investigates the potential utilization of renewable energy to offset diesel fuel consumption, in which the price is persistently volatile and increasing. In 2016, the sharp decline of oil prices and the financial pressures pushed the Government of Oman, to reform the domestic energy subsidies. Subsequently, the diesel prices by 41% from 0.44 USD in 2016 to 0.62 USD per litre in 2020. This paper proceeds as follows. Section 1 provided a brief review of materials and methods. Section 2 describes the modelling and the optimization process. Section 3, discusses the obtained results.

2. Materials and methods

2.1. Area description

Medha is located halfway between Musandam Peninsula and the rest of Oman. It forms part of Musandam Governorate. Medha is located in geographical coordinates 25º17'4" N latitude and 56º19'59" E longitude (Figure 1). Medha falls under R.A.E.C.O.'s power generation facilities for the Musandam Governorate. According to 2014 statistics, Medha has 939 electricity consumers. R.A.E.C.O. generates power mainly with diesel generators. Medha's installed capacity of power generation is 11.3 MW, with a peak demand capacity of 7.22 MW. Gross consumption of energy in the region is 28,493 MWh. Net energy consumption is 26,723 MWh [10]. According to R.A.E.C.O., Medha consumes 8,627,000 liters of diesel annually for power generation.

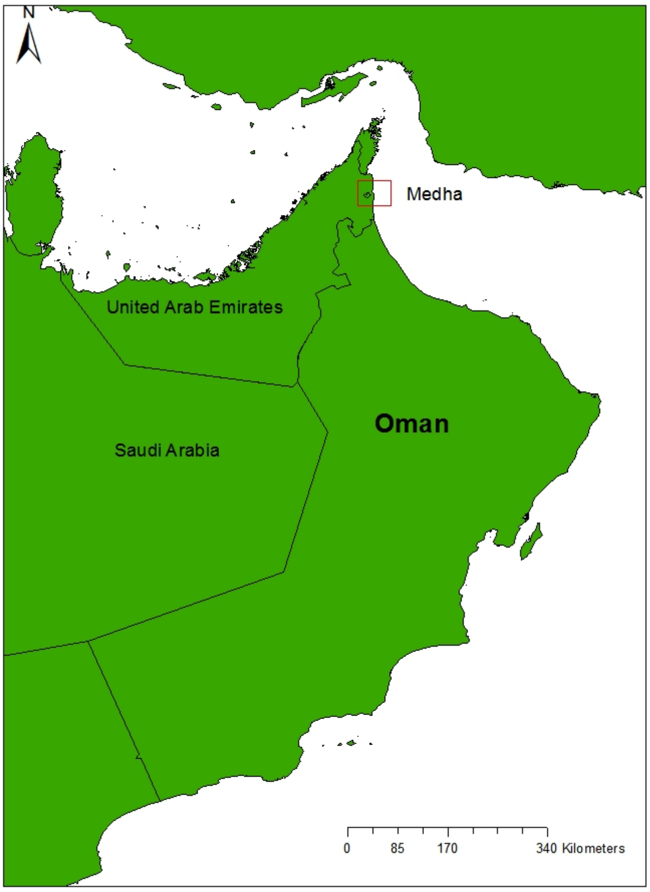

Figure 1. Geographical location of Medha.

2.2. Description of HOMER software

HOMER Pro is a microgrid software developed by HOMER Energy for designing optimal off- and on-grid hybrid power systems. Decision making in developing hybrid power generation systems is difficult for many reasons, including the availability of numerous technology options, variations in costs, and the availability of more energy resources. HOMER's optimization algorithms make it easier to evaluate many possible hybrid combinations. HOMER simulates the operation of a hybrid system by running energy balance in each step. Optimization results converge based on energy balance, and the best available combination is calculated based on the net present cost (N.P.C.), otherwise known as the lifecycle cost [11]. Different inputs are needed for an optimization analysis, including costs, resource data, technology components, and load data [12]. The steps taken in software operation are shown in Figure 2.

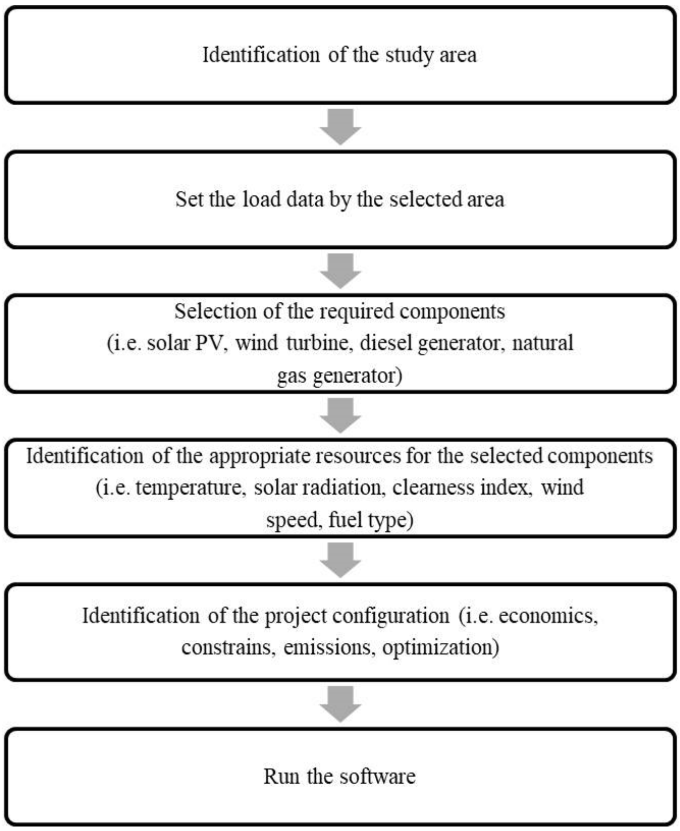

Figure 2. The steps followed in the operation of HOMER software.

2.3. Input data required for HOMER optimization

The required data for the Medha's load profile was obtained from the Electricity Regulation Authority (2019). Table 1 shows Medha's projected hourly demand in 2023. The data were gathered for a period of one year on a monthly basis. Peak demand in Medha varied along the year between 5–8 MW. The maximum peak demand (8 MW.) was recorded between May and September, whereas winter months reflected minimum demand in the region. The inflation rate in Oman is 2%, and the discount factor for the projects was set at 7.5% with a project lifetime of 25 years.

Table 1. Medha's hourly demand projection (kW) for 2023.

Time	January	February	March	April	May	June	July	August	September	October	November	December
0	3756.7	3756.7	4132.4	5852.6	7803.4	7803.4	7803.4	7803.4	7803.4	6828.0	4508.1	3756.7
1	3263.3	3263.3	3589.7	5811.2	7748.3	7748.3	7748.3	7748.3	7748.3	6779.8	3916.0	3263.3
2	2999.5	2999.5	3299.5	5694.4	7592.5	7592.5	7592.5	7592.5	7592.5	6643.4	3599.4	2999.5
3	2867.6	2867.6	3154.4	5541.5	7388.7	7388.7	7388.7	7388.7	7388.7	6465.1	3441.2	2867.6
4	2794.4	2794.4	3073.8	5384.2	7179.0	7179.0	7179.0	7179.0	7179.0	6281.6	3353.2	2794.4
5	2772.4	2772.4	3049.6	5168.5	6891.3	6891.3	6891.3	6891.3	6891.3	6029.9	3326.9	2772.4
6	3014.2	3014.2	3315.6	4777.4	6369.9	6369.9	6369.9	6369.9	6369.9	5573.7	3617.0	3014.2
7	3285.3	3285.3	3613.9	4476.3	5968.4	5968.4	5968.4	5968.4	5968.4	5222.4	3942.4	3285.3
8	3578.4	3578.4	3936.3	4440.3	5920.5	5920.5	5920.5	5920.5	5920.5	5180.4	4294.1	3578.4
9	3974.1	3974.1	4371.5	4512.3	6016.4	6016.4	6016.4	6016.4	6016.4	5264.3	4768.9	3974.1
10	4215.9	4215.9	4637.5	4539.2	6052.3	6052.3	6052.3	6052.3	6052.3	5295.8	5059.1	4215.9
11	4545.7	4545.7	5000.3	4530.2	6040.3	6040.3	6040.3	6040.3	6040.3	5285.3	5454.8	4545.7
12	4435.8	4435.8	4879.3	4651.6	6202.1	6202.1	6202.1	6202.1	6202.1	5426.9	5322.9	4435.8
13	4084.0	4084.0	4492.4	4939.3	6585.7	6585.7	6585.7	6585.7	6585.7	5762.5	4900.8	4084.0
14	3842.2	3842.2	4226.4	5438.2	7250.9	7250.9	7250.9	7250.9	7250.9	6344.5	4610.7	3842.2
15	3600.4	3600.4	3960.5	5928.1	7904.1	7904.1	7904.1	7904.1	7904.1	6916.1	4320.5	3600.4
16	3747.0	3747.0	4121.7	6000.0	8000.0	8000.0	8000.0	8000.0	8000.0	7000.0	4496.4	3747.0
17	3952.1	3952.1	4347.4	5307.8	7077.1	7077.1	7077.1	7077.1	7077.1	6192.5	4742.6	3952.1
18	4640.9	4640.9	5105.0	4480.8	5974.4	5974.4	5974.4	5974.4	5974.4	5227.6	5569.1	4640.9
19	5000.0	5000.0	5500.0	4233.6	5644.8	5644.8	5644.8	5644.8	5644.8	4939.2	6000.0	5000.0
20	4670.3	4670.3	5137.3	4516.8	6022.3	6022.3	6022.3	6022.3	6022.3	5269.6	5604.3	4670.3
21	4479.7	4479.7	4927.7	4786.4	6381.9	6381.9	6381.9	6381.9	6381.9	5584.2	5375.7	4479.7
22	4259.9	4259.9	4685.9	4970.7	6627.6	6627.6	6627.6	6627.6	6627.6	5799.2	5111.9	4259.9
23	3922.8	3922.8	4315.1	5307.8	7077.1	7077.1	7077.1	7077.1	7077.1	6192.5	4707.4	3922.8

Because solar P.V. and wind turbines were selected as components in the current study, it was important to identify Medha solar radiation levels, clearness index, temperatures and wind speed resources. The monthly data required for the solar radiation, clearness index and wind speed were collected from the works of Al-Lawati, Dorvlo, and Jervase (2003), and Jervase and Al-Lawati (2012) [13,14]. Temperature values were downloaded from the National Aeronautics and Space Administration (N.A.S.A.) meteorology website. Table 2 shows monthly average solar radiation data, clearness index together with the monthly average temperature data.

Table 2. Monthly average solar radiation data, clearness index together with the monthly average temperature data at Medha, Oman.

Month	Solar radiation ($kWh/m^2/day$)	Clearness index	Temperature (℃)
January	4.000	0.599	19.980
February	4.730	0.606	20.900
March	5.560	0.604	23.840
April	6.240	0.600	28.080
May	6.560	0.594	32.410
June	6.600	0.587	34.390
July	6.450	0.580	35.180
August	6.150	0.580	34.440
September	5.600	0.584	32.520
October	4.840	0.591	29.410
November	4.140	0.599	15.540
December	3.790	0.601	21.810

Wind speed values were collected at 50 m above the surface of the earth for a period of 10 years (2000–2009) [14]. However, for the selected type of wind turbine (Leitwind 90 1000 kW), these values were calculated with the hub height of 98 m above the earth's surface. The wind speed for this hub height was extrapolated using a logarithmic profile or log law, which assumed that wind speed was proportional to the logarithm of height above ground (https://websites.pmc.ucsc.edu/~jnoble/wind/extrap/). For Medha, the surface roughness length of 0.01 m for a rough pasture was selected [11]. Table 3 shows Medha's monthly average wind speed at 50 m and 98 m above the earth's surface [14].

Table 3. Wind speed data of Medha, Oman (2000–2009).

Month	Wind speed in m/s (at height of 50 m)	Wind speed in m/s (at hub height of 98 m)
January	5.04	5.50
February	5.66	6.17
March	5.47	5.97
April	5.53	6.03
may	6.11	6.66
June	5.99	6.53
July	5.81	6.34
August	5.71	6.23
September	5.58	6.09
October	5	5.45
November	4.47	4.88
December	5.03	5.49

2.4. Modeling and optimization

Modeling and optimizing hybrid power systems involves selecting energy resources, creating a load profile of the modeled region, and selecting correct components based on local geographical and ambient conditions. In addition, it is necessary to set up constraints required for the simulations and, finally, execute the simulations. Currently, the power of Medha is produced by diesel generators. Therefore, diesel power generation systems are included in the schematic. Diesel is considered a costly option with high GHG emissions. In comparison, solar and wind are renewable energy technologies with good potential for power generation in Oman, per studies conducted by A.E.R. Oman [2]. Aside from solar and wind, other renewable energy technologies like a wave, tidal, geothermal, and biomass have only limited potentials. Power generation systems in Oman depend on natural gas. The initial cost incurred for the power plant would be low for a natural gas-based power plant, but installing capacity would be high for plants using natural gas. Because of this high cost, natural gas was not a choice for the off-grid remote area in Medha. Because power demand increases annually in remote areas' power systems, natural gas-based power systems are also considered with hybrid combinations in this study. Solar P.V.s and wind are the two renewable energy technologies found in this analysis of optimal hybrid combinations because of their potential in the zone in question. Non-renewable sources found in the hybrid system included diesel- and natural gas-based power generation.

2.4.1. Solar P.V. system used for HOMER analysis

The solar P.V. module considered for the analysis is a grid-following flat-plate P.V. system with a central inverter. The power capacity available is 1164 kVA. The advantage of the INGETEAM 1164 kVA P.V. module is that it can work comfortably without much voltage variation even at an operating temperature of 45 ℃. Table 4 shows the data of the solar panel used for HOMER analysis. Medha's monthly average temperature ranges between 30–40 ℃. This high ambient temperature would not deteriorate the output voltage and efficiency of the INGETEAM 1164 kVA P.V. system.

The efficiency of this P.V. module is 17.3%, which is relatively high compared to other available modules, which would reduce the coverage area and the number of modules required. Capital costs for the installation would be 1504 $. Replacement costs for the P.V. model would be 1316 $. The operation and maintenance costs for the P.V. cells would be 19 $/year.

Table 4. Data of solar panel used for HOMER analysis.

Parametre	Description/Value	Unit
Model	INGETEAM 1164 KVA (Generic P.V., grid following with central inverter)	-
Panel type	Flat plat type	-
Semiconductor	Monocrystalline silicon	-
Capacity	1164	KVA
Temperature coefficient	−0.4100	°C
Operating temperature	45	°C
Efficiency	17.3	%
Capital cost	1504	($)
Replacement cost	1316	($)
Operation and maintenance cost	19	($/year)

2.4.2. Wind turbine system used for HOMER analysis

The wind turbine model selected for analysis was Leitwind 90, with a capacity of 1 MW. per turbine. Table 5 shows the wind turbine details used in HOMER analysis. The hub height of the turbine is 98 m, and it has a 25-year lifespan. The power curve of the Leitwind 90 shows that, as wind speed exceeds 6 m/s, the turbine achieves maximum power capacity. Medha's wind data (Table 3) show that the minimum wind speed available in the region is 4.88 m/s, which exceeds the 3 m/s start speed of the Leitwind 90, ensuring the availability of power generation from wind turbines in all conditions. The capital cost for the Leitwind 90 turbine is 1,650,000 $ per turbine. Replacement costs per turbine are 1,600,000 $. The operation and maintenance costs per turbine would be 400 $/year.

Table 5. Wind turbine details used in HOMER analysis.

Parametre	Description/Value	Unit
Model	Leitwind 90 (L.T.W. 90)	-
Manufacturer	Leitwind	-
Rated capacity	1000	KW
Hub height	98	m
Capital cost	1,650,000	$
Replacement cost	1,600,000	$
Operation and maintenance costs	400	$/year

2.4.3. Diesel generator set details used in HOMER analysis

Diesel generators are commonly used in Oman's rural area electrification process. Details of the fuel and diesel generator considered for this analysis appear in Table 6.

Table 6. Data of the diesel generator set used for HOMER analysis.

Parametre	Value	Unit
Fuel's lower heating value (M.J./kg)	43.2	M.J./kg
Density of fuel (kg/m^3)	820	kg/m^3
Carbon content in fuel (%)	88	%
Sulphur content in fuel (%)	0.3	%
Fuel price ($/L)	1	$/L
Lifetime (Hours)	219,000	Hours
Capital cost ($)	600	$
Replacement cost ($)	500	$
Operation and maintenance costs ($/op. hr)	0.02	$/op. hr

2.4.4. Natural gas-based generator set used in HOMER analysis

Natural gas-based power plants are considered conventional power plants in Oman. Natural gas power plants are preferred over diesel power plants in the central interconnected system due to lower GHG emission rates compared to other fossil fuels and lower operating and initial costs when compared to the bulk units of other conventional power plants. The price of the natural gas considered in the system is 0.31 $/m^3. Natural gas-based generators have a 25-year lifespan. Natural gas-based power generation was considered in the hybrid combination to maintain stability as renewable energy sources can fluctuate in power output. The Details of the natural gas fuel and generator considered for this analysis appear in Table 7.

Table 7. Data of the natural gas based generator used for HOMER analysis.

Parametre/Unit	Value	Unit
Fuel's lower heating value	45	M.J./kg
Density of fuel	0.790	kg/m^3
Carbon content in fuel	67	%
Sulphur content in fuel	0.0	%
Fuel price	0.31	$/L
Lifetime	219,000	Hours
Capital cost	400	$
Replacement cost	333	$
Operation and maintenance costs	0.0025	$/op. hr

2.4.5. Constraints set in HOMER for optimization

To set the project, it is necessary to identify the required economics, constraints, emissions, and optimization. For the economics section, the nominal discount rate was set at 7.5%, the expected inflation rate was set at 2%, and the project lifetime was assumed to be 25 years. All constraints were kept at zero and, because Oman does not impose penalties on emissions, they were also kept at zero. For the optimization section, the minutes per time step was set at 60.

3. Results and discussions

The various hybrid options were optimized using HOMER, and results were obtained based on net present cost (N.P.C.) in dollars, C.O.E. in dollars per kWh, the operating cost for each combination in dollars per year, the initial capital cost incurred in each combination, the renewable energy fraction (%) achieved while meeting annual power demand and total fuel spent on each combination. Additionally, emissions were analyzed for each combination to determine the number of constituent gases emitted, including CO_2, CO, NO_x, SO_2, particulate matter (PM), and unburnt hydrocarbon.

Table 8 shows various options considered for optimization using HOMER and its results. The net present cost of the combination should be the lowest price possible for the best combination. The optimized combination should have low C.O.E. in dollars per kWh. The base case selected for optimization was power generation by diesel generators because Medha is presently electrified entirely by diesel generators, which results in a high C.O.E. as the entire power demand is met with diesel generators. Optimization results showed that the diesel-based C.O.E. was 0.307 $/kWh, which is very high compared to hybrid combinations. The net present cost of the project is 197 million $, which is also very high compared to other available hybrid combinations. As a result of these findings, base case operating costs were very high, with 14.2 million $ spent annually for 12,806,809 liters of fuel. The renewable energy fraction seemed highest for a PV-wind-diesel combination (option nine; 55.4%), but the combinations appeared to not be feasible as the net present cost, C.O.E., and initial, and operating costs were found to be very high compared to the other hybrid options.

Table 8. Summary of financial analysis based on optimization results for Hybrid combinations in Medha, Oman.

Options	Contribution (%)				NPC ($)	COE $/kWh	RF* (%)	Operating cost ($/Year)	Initial cost ($)
	P.V.	Wind	Natural gas	Diesel					
Option 1	0	52.4	47.2	0.440	48.9 M	0.0761	43.9	2.41 M	16.3 M
Option 2	3.16	51.6	44.9	0.383	49.9 M	0.0776	45.8	2.35 M	18.1 M
Option 3	0	54.5	45.5	0	51.6 M	0.0801	41.9	2.47 M	18.1 M
Option 4	3.03	49.4	47.5	0	52.7 M	0.0820	40.7	2.55 M	18.2 M
Option 5	0	0	100	0	61.3 M	0.0953	0	4.29 M	3.20 M
Option 6	0	0	99.9	0.0789	61.7 M	0.0959	0	4.29 M	3.50 M
Option 7	3.67	0	96.3	0	61.9 M	0.0963	0.747	4.20 M	4.95 M
Option 8	3.67	0	96.3	0	62.2 M	0.0966	0.747	4.20 M	5.25 M
Option 9	17.8	52.1	0	30.1	121 M	0.188	55.4	6.48 M	33.3 M
Option 10	0	58.8	0	41.2	125 M	0.194	46.0	7.65 M	21.0 M
Option 11	23.4	0	0	76.6	185 M	0.287	13.5	12.4 M	17.1 M
Option 12	0	0	0	100	197 M	0.307	0	14.2 M	4.80 M

*RF: Renewable Energy Fraction.

Table 9 shows the emission trends of various combinations tried for the optimization in HOMER. Emission analysis shows different emissions of CO_2, CO, PM, unburnt hydrocarbons, SO_2, and NO_x emissions for the various options. CO_2 emissions reached their maximum of 33,582,341 tonnes per year for the standalone diesel-based system (option 12), which was Medha's base case. A standalone system of natural gas-based power generation contributes 25,441,433 tonnes per year. As the combinations were tried with the hybrid renewable energy systems, CO_2 emissions reduced gradually. C.O. emissions due to the incomplete burning of non-renewable fuels such as diesel and natural gas were highest (179,988 tonnes/year) in option 6, a hybrid combination of diesel and natural gas. SO_2 emissions were highest for option 12, a diesel-based power generation (61,568 tonnes/year). As the renewable energy integration percentage increased, the SO_2 emissions reduced. Unburnt hydrocarbon, PM, and NO_x emissions showed a similar pattern in optimization results. The emission rates of these pollutants seemed highest for option 12, standalone diesel-based power generation system, followed by option 6, combination of natural gas- and diesel-based power generation system. As the renewable energy integration rate increased, emission rates gradually decreased.

Table 9. Summary of emission analysis based on optimization results for hybrid combinations in Medha, Oman.

Options	Emissions in tonnes/year					
	CO_2	CO	UHC*	PM**	SO_2	NO_x
Option 1	14,080,495	99,284	5269	849	312	19,028
Option 2	13,627,477	96,117	5101	822	276	18,421
Option 3	14,656,317	103,681	5503	887	0	19,871
Option 4	14,987,359	106,023	5627	907	0	20,320
Option 5	25,441,433	179,977	9552	1,539	0	34,494
Option 6	25,450,238	179,988	9553	1,539	50.0	34.496
Option 7	24,779,387	175,294	9304	1,499	0	33,596
Option 8	24,779,387	175,294	9304	1,499	0	33,596
Option 9	14,826,798	76,706	4071	656	27,183	14,701
Option 10	17,923,502	92,727	4921	793	32,860	17,772
Option 11	28,631,038	148,122	7861	1267	52,491	28,388
Option 12	33,582,341	173,737	9221	1486	61,568	33,298

*UHC: Unburned hydrocarbon; **PM: Particulate matter.

Relevant feasible options to grasp the potential pathways for the hybridization of the off-grid of Medha can be extracted from Tables 8 and 9 as follows :

- Option 1 comprises a hybrid combination of wind-natural gas-diesel, with a percentage of production divided as 52.4% from a wind turbine, 47.2% from a natural gas generator, and 0.44% from a diesel generator.
- Option 3 comprises a hybrid combination of wind turbine-natural gas generators with a production percentage of 54.5% from a wind turbine and 45.5% from the natural gas generator.

- Option 4 comprises a hybrid combination of PV-wind turbine-natural gas generator with a production percentage divided as 3.03% from P.V., 49.4% from the wind turbine, and 47.5% from the natural gas generator.
- Option 5 comprises of a standalone natural gas power system with a 100% production from the natural gas generator.
- Option 9 comprises of a hybrid combination of PV-wind turbine-diesel generator with a production percentage divided as 17.8% from P.V., 52.1% from the wind turbine, and 30.1% from the diesel generator.
- Option 10 comprises of a hybrid combination of wind turbine-diesel generator with a production percentage divided as 58.8% from the wind turbine and 41.2% from the diesel generator.
- Option 11 comprises of a hybrid combination of PV-diesel generator with a production percentage divided as 23.4% from P.V. and 76.6% from the diesel generator.
- Option 12 comprises of a standalone diesel power system with a 100% production from the diesel generator.

Results of cost analysis for optimal options are shown in Figure 3 and emission analysis of the optimal options are shown in Figure 4. Cost analysis results show that the C.O.E., N.P.C., operating cost, and initial costs are the key deciding factors for finding an optimal design for a distributed generation system. Optimization results clearly show the following:

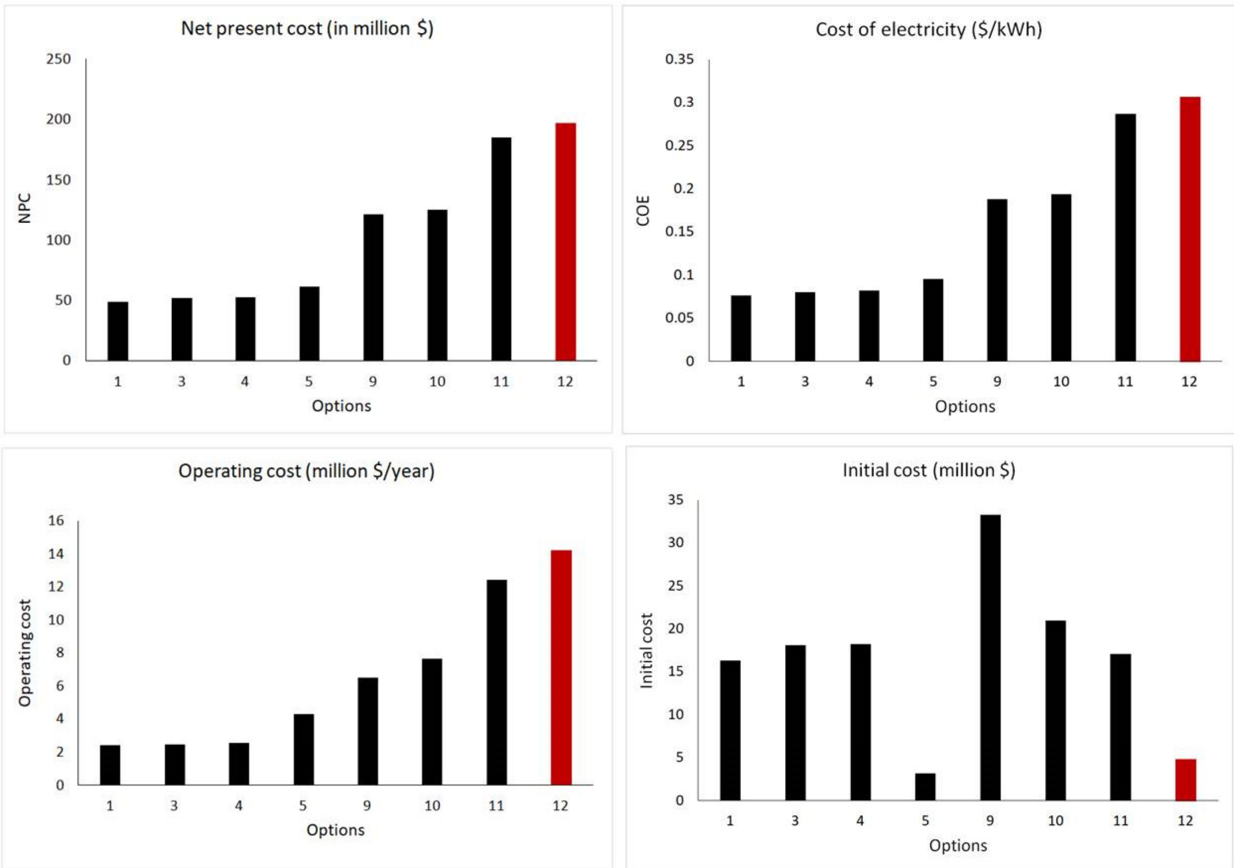

Figure 3. Results of cost analysis after optimization.

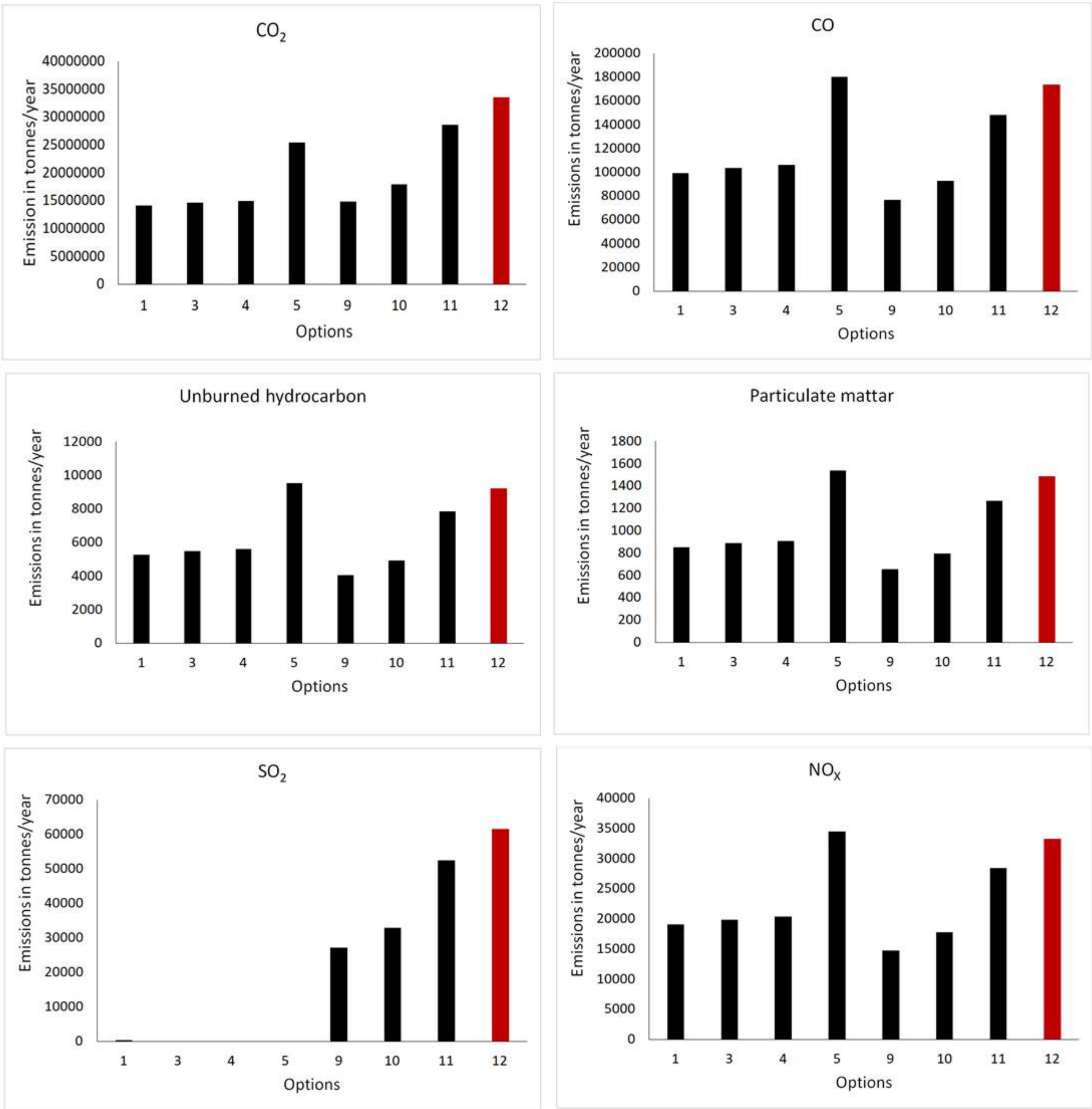

Figure 4. Results of emission analysis after optimization. 1 = option 1 (wind 52.4%, natural gas 47.2%, and diesel 0.440%); 3 = option 3 (wind 54.5% and natural gas 45.5%); 4 = option 4 (PV 3.03%, wind 49.4%, and natural gas 47.5%); 5 = option 5 (natural gas 100%); 9 = option 9 (PV 17.8%, wind 52.1%, and diesel 30.1%); 10 = option 10 (wind 58.8% and diesel 41.2%); 11 = option 11 (PV 23.4% and diesel 76.6%);12 = option 12 (diesel 100%).

- Introducing a hybrid energy combination will reduce the N.P.C., C.O.E., and operating costs and lead to optimal solutions. Moreover, the emission of pollutants like CO_2, CO, SO_2, N.O.X., PM and UHC will be reduced if renewable energy is included in the combination.
- The hybrid combination of renewable energy technologies like wind with natural gas and

diesel is preferred over standalone diesel-based power generation and standalone natural gas-based power generation since the N.P.C., C.O.E. and operating costs are lower even though standalone systems' initial costs are lower.

- Emission analysis done using HOMER for all combinations show that non-renewable energy utilization for power generation will increase the emission of all pollutants, and especially CO_2, SO_2, CO, and NO_x.
- The wind-natural gas-diesel hybrid combination has the lowest C.O.E. and N.P.C. and is the optimal solution given by HOMER for meeting Medha's load profile.

The overall findings of this study are consistent with the findings reported in Barelli et al. in 2019 [15], which demonstrates that the hybridization of mini-grid, the integration of renewables and energy storage sources are crucially important to the sustainable development of energy access and service quality in remote areas of developing countries. Aziz et al., 2019, Berbaoui, 2018, Ani, 2016, Gan et al., 2014 achieved a similar pattern of results, demonstrating the environmental and economic benefits of renewable-based hybridization to offset diesel energy generation in remote areas [16–19].

4. Conclusion

A wind-natural gas-diesel-based hybrid system shows promise in helping the Medha region meet its 8 MW. maximum load demand. The optimization results of HOMER identified this option as optimal for Medha. Oman's government wants to promote renewable energy technologies, including solar P.V. and wind energy, in order to reduce pollutant emissions. Optimization results showed that the renewable energy fraction of the total power delivered can be increased to 43.9% by introducing wind energy in Medha's energy mix. N.P.C. for option one is 48.9 million $, which would make a wind-natural gas-diesel hybrid system an ideal combination for Medha. The government would benefit by reducing the vast subsidies it currently offers residents to offset the price of diesel. These subsidies constitute about 80% of the current C.O.E. in Medha. Oman's capacity shortage is considered zero while designing these optimal results for Medha, which ensures the reliability of the power supply. The present diesel generation systems in Medha can be supplemented with renewable energy and natural gas power generation, like wind energy. Renewable energy sources have an inherent disadvantage in the fluctuation of its power output. This disadvantage could be balanced by steady power generation from the natural gas and diesel systems and will avoid the loss of load, which could happen in the system. This design, which is optimal for Mehda, would be environmentally friendly, especially in consideration of the fact that GHG emission rates show reduction trends as compared to existing standalone diesel power plants when renewable energies are in place.

Conflict of interests

All authors declare no conflicts of interest in this paper.

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