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Feasibility study of renewable energy-based microgrid system in Somaliland's urban centers

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A B S T R A C T

The ever increasing and continuously unpredictable fluctuating diesel prices that power electricity generation has detrimental impact on the business climate in an area that fights to move away from recovery of post-conflict situation to a relatively rapid economic development. In view of this, this paper aims to investigate the possibility of supplying electricity from a renewable energy-supplemented hybrid system to Hargeisa, Somaliland's major urban center. The city has yet to establish its own standard modern electricity grid. Because of the great need to reduce energy costs in Somaliland, a feasibility study has been carried out on how to supply electricity to a sampled residential load. The electric load consists of only a primary type that is in-line with the present electricity consumption in the area. A software tool, hybrid optimization model for electric renewables (HOMER) is used for the analysis. The results of the techno-economic analysis indicate the economic prospect of achieving a 58% of renewable energy (RE) penetration. This consequently reduces the cost of energy (COE) by 30% and the total net present cost (NPC) of the simulated system by a further 25% as compared to a current diesel-only microgrid. The deployment of a hybrid microgrid shows the viability of a better economic prospect than the current "business-as-usual" scenario in Somaliland.

Contents

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1. Introduction

Renewable energy (RE) has recently attracted considerable global awareness. However, techno-economic feasibility studies of the RE potentiality in Somaliland are indeed very rare. To the best of the authors' knowledge, the work of Pallabazzer and Gabow [1] is probably the only one of its kind carried out in Somaliland. In fact, there is a need to investigate the application of RE sources and the ease of introducing them into the energy and electricity markets of Somaliland. In a country that has enormous solar and wind potential, but still faces extreme shortages of power, it is believed that this research is timely to address some of Somaliland's needs to drive forward its energy sector development for the purpose of improving energy scarcity levels as well as the national economy.

Due to the poor economic condition of the country, Somaliland is in need of alternative energy sources in small amounts (10–100 kW h/day) supplied throughout the territory. Thus, small and medium-sized hybrid systems are sufficient to contribute to the already existing energy production mechanisms so that the present and the near future energy demands are appropriately met. Having known that the amount of energy consumption has been globally accepted as development indicator [2], increasing energy production and reducing its costs might as a result lead to an increased energy consumption among the general public and hence accelerate the desired development targets.

Many researchers from different parts of the world have been studying hybrid micro-power systems (HMPS). The viability of the hybrid system depends on the quality of RE resources as well as the climatic, economic and regulatory conditions at that given location/country. Consequently, researchers universally gave much attention to the specific conditions of many different countries while proposing the best RE resource that could readily be of benefit to the given communities.

The research carried out on HMPS designs could be grouped into two major categories based on their research objectives. First, many research works look at the design aspects of the systems under study and focus on the knowledge contribution without giving much attention to in the area under study. Such studies include the works of Hafez and Bhattacharya [3] and Bagen and Roy Billinton's work [4], to name only a few. The second group of researchers focus on the techno-economic viability and/or the practical aspect of the hybrid systems in a given situation, most notably in areas where grids are not available such as rural areas [5–7] or island electrification [8–10]. In addition to that, researchers also focus on specific site applications such as a university campus [11], hotels [12] and resorts [13,14] or any other building that might require some considerable amount of electricity.

This work focuses on the second category. The uniqueness, however, of this study is the fact that it considers a post-conflict situation where the electricity shortage is due to the poor economic conditions and the scarcity of skilled human capital as opposed to low population density or remoteness of the locations considered. On that basis, a hybrid PV/Wind/Diesel microgrid system for an urban residential load is proposed in comparison with a diesel-only microgrid system using the performance metrics of net present cost (NPC), cost of energy (COE) and renewable fraction (RF).

Taking a close look, this study tries to achieve the following objectives:

1. To propose an RE-based power system for Hargeisa by conducting a techno-economic feasibility assessment.
2. To analytically justify that the high capital investment related to RE installation projects is superior to diesel-only based plants by reducing the energy costs of private utility operators as a result of the fuel cost reduction of the diesel generators.
3. To examine which uncertain parameter related to either RE resources or future fuel price fluctuations would affect most notably the economic prospect of a hybrid microgrid system.
4. To compare cost of technology options for electricity generation for the same specific community need.

1.1. Energy background of Somaliland

Somaliland is a *de-facto* state in the horn of Africa region. Due to the political instability in the country from 1980s to early 1990s and lack of recognition for its sovereignty status, the country has largely remained under-developed. The energy and in particular the electricity infrastructure of the country, as in the case of many African nations, is still grossly under-developed [15]. The people, whether urban or rural, mostly rely on the biomass resources to meet their energy needs. It is estimated as much as 87% of the energy sources are biomass resources [16]. Electricity is only available in urban centers and "is almost exclusively produced from imported diesel" [17]. Diesel-powered generators are generally available throughout Somaliland's urban centers. This causes extreme price fluctuations to its customers as oil prices depend on the world's fluctuating oil market prices.

Following right after the civil wars, private independent power producers (IPPs) slowly established electric utilities in the urban centers. The IPPs' mini-grids typically operate islanded (the many IPPs are not interconnected and every one manages their own small electrical distribution network). The diesel generators often operate at low-efficiency, part-load conditions due to the changing electrical demand coupled with low local technical know-how. The fully burdened cost of fuel for the IPPs is above $1.15/L [18,19].

Furthermore, according to a World Bank report [17], the electricity "network is characterized by poor servicing, inefficient production, aging generation and idle capacity. Power losses are estimated at between 25% and 40%, far from the 10% to 12% international target."

These network problems are basically due to the lack of established electricity institutions that would have administered the power industry. Without this, the electricity sector is generally left unregulated. Furthermore, customers face extreme and unpredictable price fluctuations in their electricity bills owing to, in addition to many others, the lack of fixed tariff system. The newly launched Somaliland investment guide [20,21] predicts that the electricity tariffs in Somaliland are "probably the highest in Africa" reaching as high as $1.4/kW h. On account of the scarcity of capable human capital in the IPPs' institutions and the poor economic income of the local population, Somaliland never had any type of conventional large-scale power plants and national grid either.

The conventional electricity supply produced by the centralized energy production systems is not only economically unattainable, but also lacks the appropriate electric infrastructure to equitably distribute power throughout Somaliland. Lack of water, electricity, and communication facilities in rural areas have caused uneven migration of people from rural to urban areas, resulting in an irregular population distribution. The dependence on wood and charcoal for fuel has inevitably led to deforestation and desertification due to the lack of re-plantation and soil rehabilitation schemes [22].

It is worth mentioning that the government of Somaliland (GoSL) has been trying to solve some of the adversities related to electricity and energy sector in general for the last five years. The GoSL has put in place the first Electrical Energy Act (currently discussed in the parliament), the first wind energy pilot plant and the first wind energy monitoring stations in four major urban centers in Somaliland [21]. In line with these government efforts, it is hoped that this study will potentially trigger future technical studies that will drive RE deployment in Somaliland. The study can also act as a typical case study for RE deployment for many other post-conflict territories dispersed throughout the world.

The rest of the paper is organized as follows: Section 2 describes the different data (mainly the load data and energy source information) used in the study. The design specifications of the two models are detailed in Section 3 while Section 4 presents the main results of the study. Section 5 draws general conclusion.

2. Data collection

2.1. Electrical load

One of the most important steps in this type of studies is proposing a realistic model of the electrical load. In this study, a typical contemporary Somali urban house load requirements are presented in Table 1. The most important uses of electricity in this house are mostly lighting, entertainment and refrigeration. In addition to these major usages, there are also other possible usages for electricity in an urban environment such as the use of electric washing machines, irons, and other electronic stuff. In a contemporary urban setting, these later equipment are considered essential amenities. However, the case in Hargeisa's urban population is different as the majority of the population are largely in poor economic condition when compared with the urban population of the developed countries. Unlike a typical modern household, most of Hargeisa's urban homes use charcoal as their main source of energy for cooking purposes and because of that, cooking appliances were not listed as an load appliance in Table 1. Electricity tariffs are still high throughout Somaliland's main urban centers. As a result, many household consumers' electronics are considered luxurious rather than a necessity for most of the households. Besides, a sample of 50 houses is used in this study in order to look at a reasonable urban scale of sampling.

Fig. 1 illustrates the load profile of the hypothetical community in Hargeisa. The average electricity consumption of the sample population is 1283 kW h/day with 211 kW of peak demand. The daily power load is generally represented by a base load with double peaks; one in the morning and another in the evening, and double troughs; the night-time and afternoon nap time. Unlike a conventional modern urban lifestyle, Hargeisa experiences an afternoon break where most of the city activities slow down between 1.00 pm until 4.00 pm. It is quite common that people will take a considerable rest time at their own houses with minimum household activities at this time of the day.

To make this synthetic load data look more practical-oriented, a *random variability* of 20% day-to-day and 15% *time-step-to-time-step* were introduced. These two inputs would allow the residential load to have some degree of variability at different times of the year.

2.2. Energy sources

The study conducted by Pallabazzer and Gabow [1] has revealed the scholarly awareness of the high prospect of RE availability in Hargeisa. The available RE sources that can provide electricity are wind and solar sources. The following sub-sections give the details of the two RE sources and diesel.

2.2.1. Solar energy resource

The daily radiation and clearness index of Hargeisa was taken from HOMER, which uses NASA satellite data at approximately this location. The data is imported online through HOMER software by entering the latitude (9°54′N) and longitude (44°03′E) of Hargeisa

Table 1
The electric consumption of common electronic consumer goods in a typical house in Hargeisa.

	Load usage	Power consumption (in W)	Hours used	kW h Consumption
1	TV and multimedia set	250	12	3
2	Lighting	200	12	2.4
3	Refrigerator	80	24	1.92
4	Washing machine	450	2	0.9
5	Electronics (laptop, PCs, printers)	150	12	1.8
6	Iron	1000	1	1
7	Other possible electronics	1500	10	15
	Daily consumption of a single house (kW h)			**26.02**
	Daily consumption of the whole sample population (kW h)			**1301**

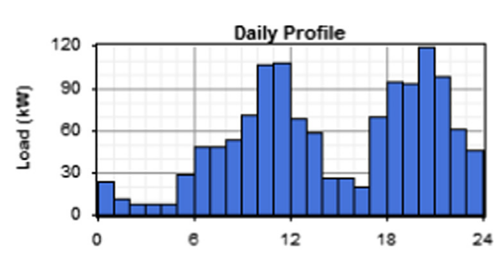

Fig. 1. Daily load profile of the 50 houses sample population.

in Homer's solar input window. Fig. 2 depicts Hargeisa's monthly average of two solar parameters, which confirms the steady availability of solar radiation throughout the year. The annual average solar radiation for this city is 6.4 kW h/m^2/day. Thus, solar radiation qualifies to be a considerable alternative source for hybrid microgrid system in Hargeisa city.

2.2.2. Wind energy resource

Pallabazzer and Gabow [1] highlight that the winds in Somaliland are more intense inland than near the sea, owing to the abrupt massif that covers all the territory. The wind regularity was also found to be almost the same throughout the country". Their work calculates the linear and cubic mean wind speeds of Hargeisa to be 11.6 m/s and 15.9 m/s based on anemometer data collected at government meteorological stations in the 1980s. Contrary to that data, the data records obtained from the NASA Surface Meteorology and Solar Energy website assessed a 10 year averaged annual wind speed for the Hargeisa city to be only 5.468 m/s at the same 10 m height [23]. Since even Pallabazzer and Gabow admit the data collected at the site in Hargeisa has "too poor resolution" and since their work does not also give the monthly averages of wind speed that are required for HOMER simulation, their data will not be used for the analysis of this study. Instead, data obtained from NASA will be used.

Fig. 3 illustrates the monthly averaged wind speed at Hargeisa. The wind speed is measured at 10 m height. It is observable that the maximum measured wind speed is within the period from June to September, reaching a monthly average wind speed of more than 8 m/s in July, while it is lowest in April. This information about wind speed in Hargeisa proves that wind energy can be exploited in generating supporting energy for the existing diesel stations in most of the months per year.

2.2.3. Diesel

Diesel is the source of energy of the dispatchable and back-up-oriented generators used in this study. In view of that, diesel price occupies a big concern in modeling or proposing any system.

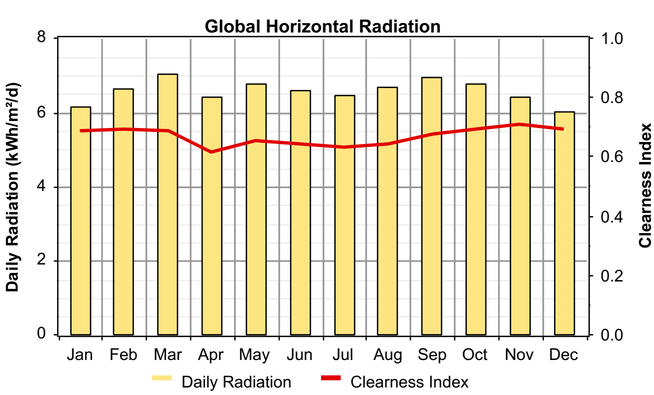

Fig. 2. Averaged solar irradiance for Hargeisa.

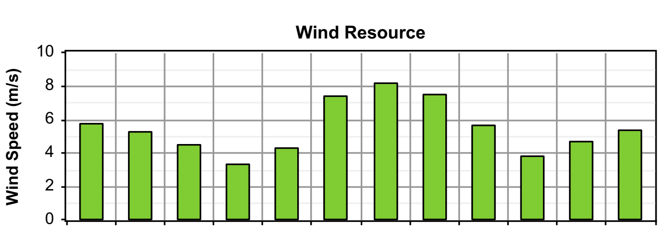

Fig. 3. Monthly averaged wind speed at Hargeisa.

Currently, the diesel price in Hargeisa is 1.15 $/L [19] but this price is not constant; it fluctuates depending on the global market changes. The total NPC as well as the COE will change as the diesel price fluctuates. This increases the risk in the business and makes the utility vulnerable in the long term.

3. System design specifications

This section firstly details out the different scenarios modelled in the study. It then describes the software and the specifications of the components used. It finally gives the underlying assumptions and limitations of this study.

3.1. Case study development

The hypothetical residential load modelled for this study is a small area, described in Section 2.1 in detail, potentially located in Hargeisa's suburbs. It is expected that the residential location would be in the suburbs to ensure that the land availability for wind and solar resources would not pose a serious drawback to any potential deployment of this system on the ground. In terms of economic benefits and resource availability, it is more feasible to build these kinds of systems in a place where physical destruction is at its lowest level particularly for the wind resource. The load is assumed to operate in off-grid condition due to the lack of proper interconnection between Hargeisa's power producers. The schematic diagram of the stand-alone hybrid power system under investigation is shown in Fig. 4 whereby an AC load is supplied by a central AC feeder.

Hargeisa currently relies primarily (almost 100%) on diesel generators for electric power. To evaluate the impact of increasing wind penetration in Hargeisa, two scenarios are modelled with different rates of wind and PV penetration and diesel generators progressively replaced by wind farms and PV farms. The scenarios are briefly described here.

1. *Base* (*without-RE*) *scenario*: In the base case, energy is produced by three generators: small (with a capacity of 30 kW), medium (200 kW) and large (500 kW). The medium and large generators are base-load generators. In addition, to satisfy demand in any given hour, it may be necessary to have a small peak-load

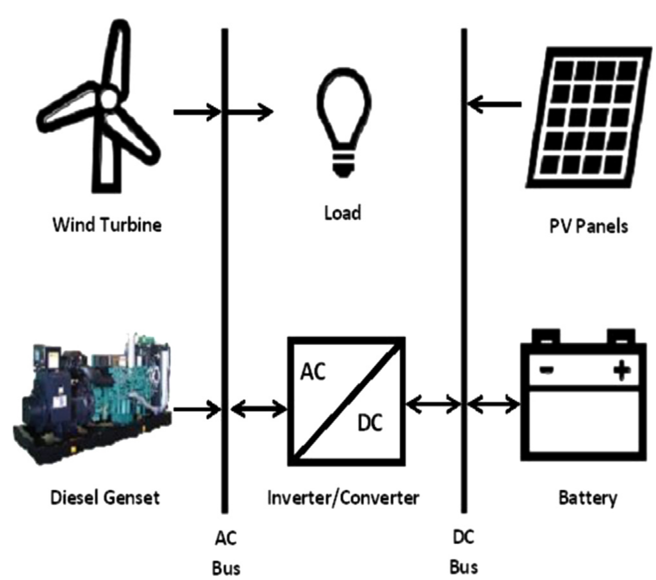

Fig. 4. The schematic diagram of the proposed system.

generator in place; it is inefficient for big generators to cater for peak loads.

2. *RE penetration scenario*: RE (Wind turbines and PV) are introduced to replace 500 kW of diesel generator. To do so, a great deal of wind capacity is required. Due to the intermittency of wind over the year, as much as 8 wind turbines, each with a capacity of 30 kW, are proposed in this study. In addition to that, as much as 100 kW and as low as 5 kW of PV resource is also considered during the optimization process of this simulation. Moreover, a battery system is added to the proposed model to act as a peak-solver for the times when wind and solar are unavailable.

Note according to the load modelled in this study, there are two troughs; in the morning and at night. The morning load coincides with the availability of solar resource. Wind power is mostly available at night, in the evenings and early mornings.

3.2. Simulation software: HOMER

This study was conducted using HOMER software which is developed in the National Renewable Energy Laboratory (NREL) in the United States. It was chosen because of its public availability for microgrid modeling, and its ease of implementation, though it takes time to grasp its complete and superb capabilities.

With HOMER software, not only the physical implementation of the microgrid system can be modelled, the life cycle cost including installing and operating costs are also modelled and compared with other design options based on the technical and economic aspects. The mechanism that HOMER software is based on can be categorized into three phases; simulation, optimization and sensitivity analysis. The simulation is an essential phase of the HOMER software process. It simulates the microgrid system for long-term operation and variety of system configurations. The resultant system configurations are then applied to an optimization process to obtain the system's most optimal configuration based on the cost and designer's decision variables. The decision variables include the size of the PV array and the number of wind turbines. Finally, the system's optimal configuration is subjected to a sensitivity analysis process in which multiple optimizations each with a different set of input assumption is accomplished. The purpose of the sensitivity analysis process is to know how sensitive the outputs are to the changes in the inputs.

3.3. Hybrid system components

There are five major system components to be designed for this study's renewable-based islanded microgrid system. These are the wind turbine, PV modules, diesel generators, power converters and battery banks. The study seeks to find the most optimal option of a suitable mix of these component sizes. In order to meet the AC load profile of the customers, the following system components were designed.

3.3.1. Diesel generator

There are three diesel generators modelled in this study; one in the small capacity range (with a capacity of 30 kW), one in the high capacity range (500 kW) and another in the medium capacity range (with a rated power of 200 kW). This has been considered in order to relate to the close scenario of electricity operators in Hargeisa where they normally have these different types of generation capacities based on one of the author's site visits. Larger generators are used for base load generation purposes while smaller ones are used to cater to the peak demand. Additionally, as the Somaliland Energy Policy document [16] highlights Perkins and Cummins being the two of the most popular generator sets in Somaliland, only these two types are considered in the modeling process. The various data of the generators were obtained from the manufacturer's data sheets [24]. It is worthmentioning that the lifetime of the generators was estimated to be around 15,000 h of operation.

Shahid and El-Amin [25] highlight that the diesel generators are generally sized to meet the peak demand of the power. The peak demand of the sampled population is about 211 kW. In this regard, only two diesel generators (the 30 kW and the 200 kW capacities) are enough to cover peak load and a spinning reserve of about 9% to overcome rapid changes in the load. The operating/spinning reserve is surplus electrical generation capacity (above the one required to serve the load) that is instantly available to serve additional loads. It provides reliable electricity supply even if the load was to suddenly increase or the renewable power output was to suddenly decrease [25].

Despite the large capacity of available diesel generation, the main objective of this study is to find a technically and economically feasible alternative to reduce the large dependence on diesel generators. Therefore, even though the design proposed in this study ensures the guaranteed electricity source from diesel generators, the aim always remains to reduce their operating hours. For that reason, to cater to the intermittency of RE sources, the optimized usage of battery banks that could economically replace the diesel usage to some extent is proposed in this study (*refer* Section 3.3.5 *of battery design specifications*).

HOMER lets the modeler to enter the fuel curve parameters that are based on the data given in the datasheets which are summarized in Table 2 for each diesel engine that was considered. The resultant fuel curves for each generator generated by HOMER are shown in Fig. 5.

3.3.2. Wind turbines

For this study a HY-30 kW AC wind turbine which is manufactured by Hua Ying Wind Power [26] was used. The capital cost of one turbine is $9000 [27]. The replacement cost is assumed to be the same as the capital cost, with an estimated annual operating and maintenance (O&M) costs of $100/yr. This cost value of O&M is set so that it is four thirds of the normal O&M reported in literature (which is $75/yr) [13] due to the presumed shortage of experienced technical engineers for wind systems in Hargeisa. The technology itself is new in the area [28].

The wind turbine characteristics data obtained from the suppliers were input into HOMER and the resulting power curve of the chosen turbine is shown in Fig. 6. Besides, the hub of this wind turbine is taken to be at a height of 25 m and is estimated to serve for 15 years; 5 years less than the normal lifetime to model a worst-case business setting. Optimal sizing is taken into account by inserting several units (1–8 turbine considerations).

3.3.3. Photovoltaic

The cost data of PV cells modelled in this study are obtained from the NREL website [29] and are summarized in Table 3.

Table 2
The fuel consumption data of each generator (*obtained from the datasheet of the respective generator*).

Label	G1 (large generator)	G2 (middle generator)	G3 (small generator)
Model	**Cummins**	**Cummins**	**Perkins**
Rated capacity	**500 kW**	**200 kW**	**30 kW**
Full load (L/h)	117	52	8.6
75% Load (L/h)	90.3	39	6.6
50% Load (L/h)	65.3	27	4.9

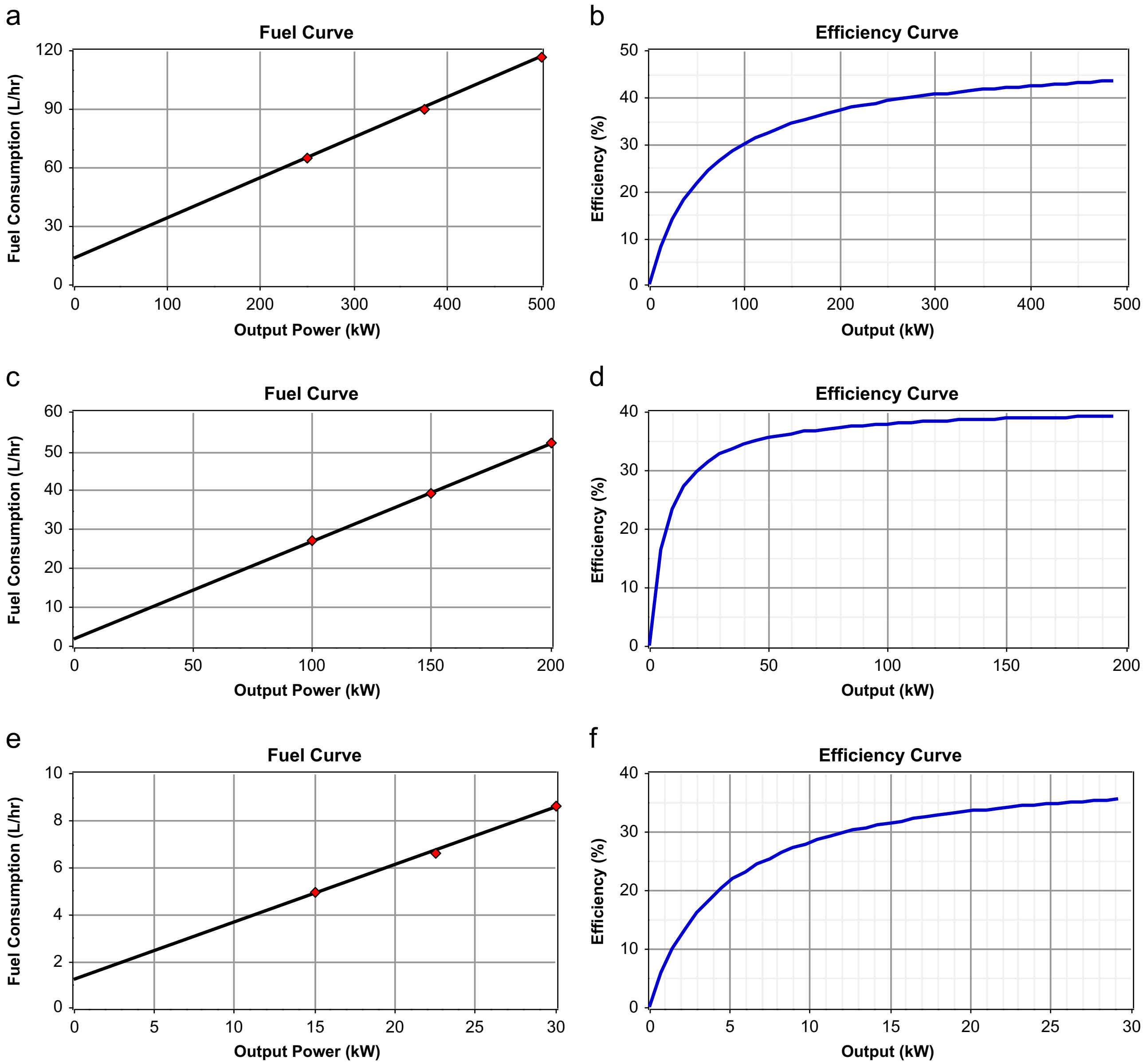

Fig. 5. The fuel curve and efficiency curves of each diesel generator considered in the study; (a) and (b) are for 500 kW generator; (c) and (d) are for the 200 kW generator; (e) and (f) are for the 30 kW generator.

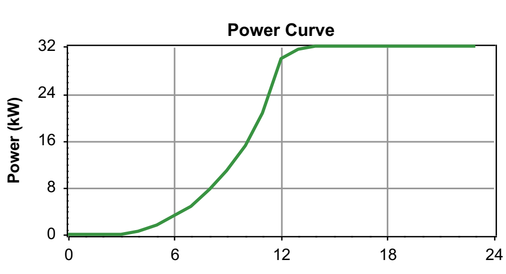

Fig. 6. The power curve of the HY-30 kW wind turbine.

Several different PV capacities were considered in the microgrid system. The PV capacity has been allowed to vary from 5 kW to 100 kW. The generated power of the PV is dedicated to support the load and charge the batteries when there are low levels of demand. To consider the worst-case scenario of a PV operation, the lifetime is assumed to be only 15 years, despite NREL's data indicating up to a 20 year period of a lifetime. This is to compensate any assumptions (such as no consideration of effect of temperature) made during this study that might affect the performance of the PVs in the long run. A derating factor of 90% is applied to the electricity production from each panel. On the practical site, the PV array is mostly installed with an inclination angle equal to the latitude of the site. A ground reflectance of 20% was also assumed in the study. Lastly, the study assumed no installed maximum power point tracking system in the setup to avoid additional costs incurred.

3.3.4. Power converter

A converter is required to convert AC to DC or DC to AC. The installation costs for an 8 kW converter is $512 [30], with a similar replacement cost and O&M cost is considered practically zero.

Table 3
The input data of the various components in HOMER.

	Large G1	Medium G2	Small G3	PV				Wind turbine	Battery	Inverter
				PV1	PV2	PV3	PV4			
Size (kW)	500	200	30	100	5	20	50	30	1100 Ah	1
Capital Cost ($)	81,469.00	39,699.00	10,300	517,500	35,750	119,000	258,750	9000	2171	518
Replacement Cost ($)	81,469.00	39,699.00	10,300	51,7500	35,750	11,9000	25,8750	9000	2171	518
O&M ($/h)	0.2	0.1	0.05	0	0	0	0	300 ($/yr)	0	0
Sizes considered (kW)	40	500	200	100	5	20	50			24,30,36,42,48
Quantities	1	1	1	1	1	1	1	1,3,5,8	1,2,3,4	
Lifetime (yr)	15,000 (h)	15,000 (h)	15,000 (h)	15	15	15	15	15	20	15
Model	Cummins	Cummins	Perkins							

Assuming the cost curves are linear, the sizes considered in the optimization range from 24 kW up to 48 kW in steps of 6 kW. Conversions from AC to DC, and vice versa, are assumed to have efficiencies of 0.9 and 0.85, respectively. The converter is assumed to have a capacity of 100% relative to inverter and it can also operate simultaneously with an AC generator.

3.3.5. Batteries

The battery bank used in this hybrid system is the Surrette 6CS25P with 95 batteries per string. The chosen battery has a 4 V and 1900-Ah capacity. The battery's lifetime throughput is 10,569 kW h per battery. HOMER assumes that the properties of the battery remain constant throughout the battery's lifetime and are not affected by external factors such as temperature [31]. The cost of a single battery is $2171 [32], and a similar figure was taken as a possible replacement cost. The O&M cost is assumed to be negligible and hence was set to 0. The batteries were modelled as perfect storage devices with losses incurred only during charging and discharging [31]. The round trip efficiency of the battery is modelled to have a constant efficiency of 0.8. It is noteworthy that HOMER specified the battery's minimum state of charge (SOC) of this Surrette 6CS25P type to be at 40%.

The basic characteristics and capital costs of each of these candidate technologies are described in Table 3.

3.4. Simulation settings

HOMER models a lossless scenario due to the assumption of the close proximity between the dedicated generators and the customer load [31]. The load modelled is a residential load and only a maximum of 10% annual capacity shortage is considered as it is not as harmful and serious as in the commercial sector. In the modelled microgrids, multiple generators were allowed and they can also operate simultaneously in-line with earlier described design specification requirements of operating three diesel generators (*discussed in* Section 3.3.1).

The dispatch strategy considered in this study is the cycle charging (CC) mechanism. In this mechanism, the battery minimum SOC parameter (which is 40%) will force the generator to start at the SOC. The set-point SOC will force the diesel generator (considering no other source is available for charging) to continue to charge that battery until the battery reaches the set-point SOC which is chosen to be 80% in this study. This will maintain a sufficiently high load on the generator to get better efficiency and also prolongs battery life by avoiding deep discharges [33].

3.5. Financial assumptions and limitations

In reality, the costs assigned to the microgrid would differ from the estimates outlined above, and would almost certainly be in a more detailed and complex way rather than this straight forward and simplified form of only considering the capital, replacement and O&M costs of technology options. International Renewable Energy Agency (IRENA) report [34] indicates the costs could be modelled in a number of different ways, and each way of accounting costs of power generation brings its own insights. Other costs that can be examined include financing costs, land ownership costs, tariffs, the mounting hardware cost, the control system, wiring and total installation and management costs.

The analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used in this study is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improved transparency and confidence in the analysis, as well as facilitating the comparison of costs by technology for the same community needs in order to identify the key drivers in any differences. Additionally, to provide a technology comparison of microgrid economics, an average cost estimate is an acceptable proxy among the researchers. In-line with this assumption, neither a '*system fixed capital cost*' nor a '*system fixed O&M cost*' was specified in the HOMER simulation. Zero *penalty charges* for capacity shortage were also considered.

Besides, the simulation models a project period of 25 years and a 6% annual interest rate whilst also considering Hargeisa's weather, diesel price and current industry circumstances.

It is worthmentioning that HOMER assumes all prices inflate at the same rate over the project lifetime. According to the user support website [33] provided by HOMER Energy, this allows to factor inflation out of the analysis by using the real interest rate, and reporting all costs in constant dollars. Therefore, in order to model the effect of diesel price changes over time, a sensitivity analysis was carried out on the diesel price variable as suggested by HOMER's developers on the same website.

3.6. Other general assumptions in the study

There is a very limited documentation in regard to any data available about Somaliland for three major reasons. First, the lack of recent surveys (that show, for instance, electricity consumption patterns and behavior of the consumers) conducted in Somalia. Second, the treatment of southern Somalia and Somaliland as a single country in what surveys exist which complicates the extraction of any related information. Lastly, GoSL's department of energy has a very low operating budget and technical know-how. Consequently, the data collected in this research is based on various different sources that either explicitly or implicitly give the facts that could be related to Somaliland, particularly Hargeisa.

4. Results and discussion

4.1. Optimization results

Two scenarios were simulated by HOMER. The first case is a base case scenario of diesel-based microgrid system. The second case is a hybrid microgrid system with PV/Wind/Diesel sources. The main objective of the simulation is to evaluate and compare the two models in terms of efficiency and capital cost and to predict the effect of the future fuel price fluctuations. The optimization results of the two case scenarios are discussed below.

4.1.1. *First case: Diesel-based microgrid system*

A baseline case was optimized to represent the "business as usual" approach of providing all electrical power from diesel generators with no energy storage, renewables, or any other sources of electricity. The baseline case optimized the operational hours of three diesel generators to minimize the estimated fuel use over one year. It was assumed that the diesel-based plant would probably operate newly in the area. Therefore, the model included all the capital costs and the assumptions given in Section 3.

Fig. 7 shows three diesel generator configuration of the diesel-based system, and Table 4 illustrates optimized simulation results of this system. This configuration has a total NPC of $3064,630 and a COE of $0.408/kW h.

It is expected that the largest portion of the NPC comes from G2 (the medium generator), which is mainly utilized and that G3 (small generator) operates the rest of the time. However, HOMER indicates that it is uneconomical to operate G1 (largest generator) in this considered load operation by not considering it in the most optimized configuration. From the simulation results, G2 produces most of the electricity required by the load, amounting up to 92% of the total production while the rest of it is produced by G3. The modelled system produces an excess electricity of 8.32% and a zero capacity shortage.

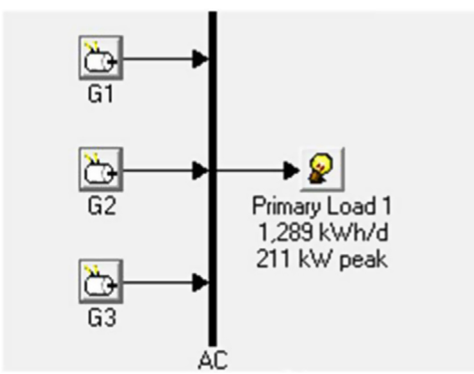

Fig. 7. The base-case of a diesel-only plant configuration in HOMER.

A closer look at how this system operates indicates that G2 and G3 generators operate 5996 h/yr and 2770 h/yr with 26.9% and 15.9% of capacity factors, respectively. Fuel consumption is 128,825 L/yr for G2 with marginal generation cost of $0.301/kW h. The rest of operational characteristics of the two generators are summarized in Table 5.

Another important result is the way the plant operates in a HOMER simulation. Fig. 8 shows a sample week of daily operation of the two diesel generators while trying to cover the load demand at each time step. It is evident that the 200 kW diesel generator, G2, is almost entirely under operation in order to cover the load with little rest periods on each particular day. This leads to extreme fuel consumption of the plant, increasing its operational costs considerably.

4.1.2. *Second case: Proposed hybrid microgrid system*

A new hybrid system that contains two RE sources (solar and wind) and two diesel generators with some capacity storage using battery banks is also modelled in HOMER. Fig. 9 shows the configuration of the hybrid system modelled in HOMER. The optimization results of this proposed system are summarized in Table 6.

The most outstanding result of the optimized hybrid microgrid system is the reduction of levelized COE to almost 30% of that of diesel-based case. The hybrid system is also lower than the base case by 25% in the total NPC which is basically due to the 43% reduction of the operating costs despite the staggering 634% of the initial capital cost increase that the new system is assumed to have. The lower operational cost is due to the lower electricity production of the combined energy contribution (only 42% of total

Table 4
Optimized techno-economic results of the base case.

	Generation output				**Total Gen**
		G1	**G2**	**G3**	
Output (kW h/yr)		0	471,318	41,857	513,176
% Output		0	92	8	100
	System parameters				
	AC load		**Excess electricity**	**Unmet electric load**	**Capacity shortage**
Output (kW h/yr)	470,485		42,690	0	2.33
%	91.68		8.32	0	0
	System economics				
	Levelized COE ($/kW h)		**Total NPC ($)**	**Operating cost ($/yr)**	**Initial capital ($)**
	0.408		2299,519	187,845	49,999

Table 5
Electrical and economic operations of the two diesel generators.

Electrical variables	**G2**	**G3**	**Economic variables**	**G2**	**G3**
Hours of operation (h/yr)	5996	2770	**Fuel consumption (L/yr)**	128,825	13,511
Capacity factor (%)	26.90	15.90	**Fixed generation Cost ($/h)**	4.95	2.12
Mean electrical efficiency (%)	37.20	31.50	**Marginal generation Cost ($/kW h)**	0.301	0.297

electricity) of the diesel generators in the hybrid system as compared to the diesel-based system.

The results also reveal that the lowest PV option (5 kW) considered in the optimization was included in the optimum result which allocates the solar energy to contribute a mere 2% of the total electricity output despite the almost steady availability of average monthly solar radiation throughout the year. This is due to the high capital cost of the PVs that eventually makes them uncompetitive with other technology options considered on a utility scale. In contrast to PV, the wind technology was the most favorite electrical source contributing 56% of the total electricity output. This is due to Hargeisa's excellent wind speeds during the four summer months. Fig. 10 depicts high electricity generation from the wind turbines during these months. On the contrary, wind power generation is lowest in April followed by October and then May.

It is also worthmentioning that a preliminary testing was conducted in order to properly size the batteries so that the share of wind energy source increases in replacement of diesel generation share. A close look at how each source contributes the electricity, including respective economic variables introduced by each source is summarized in Table 7.

It is important to note that these results are sensitive to reward given to renewable electricity generation; in this study it has been assumed renewable electricity attracts no special treatment. Should renewable generation attract significant reward, it would be expected that PV and/or wind generators combined with electricity storage would offer more attractive economics. This is notable given the fact that GoSL highlighted its 3 year tax holiday for international investors in Somaliland [35].

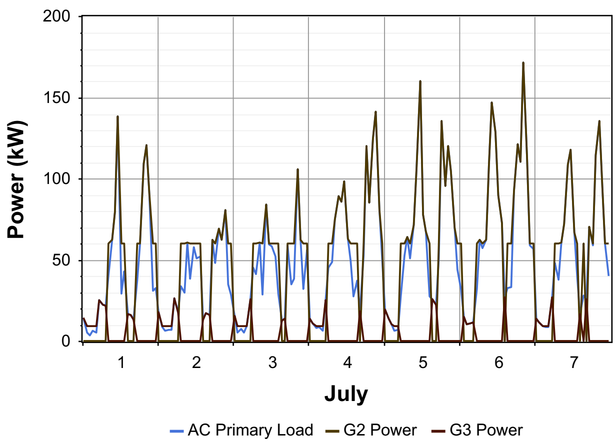

Fig. 8. Operational response of the diesel system to the load profile in 1st week of July.

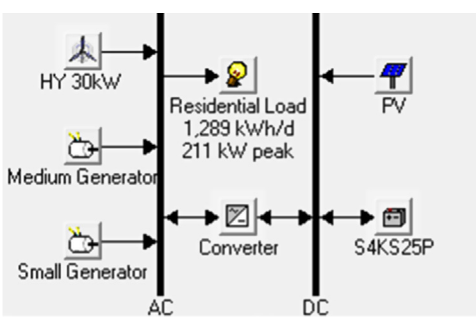

Fig. 9. Available portfolio of energy supply options in microgrid planning.

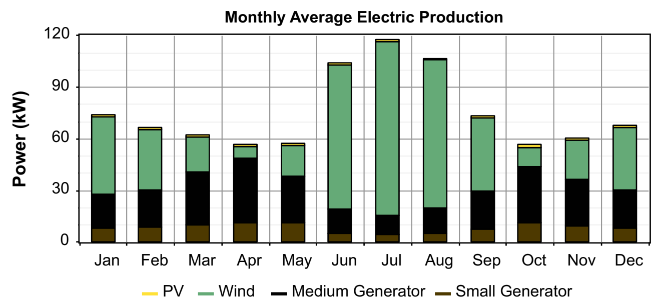

Fig. 10. Monthly average electricity production from the different sources.

Table 7
Techno-economic operation of the various sources of energy.

	G2	G3	Wind turbine	PV	Battery
Hours of operation (h/yr)	2375	2873	7405	4380	–
Capacity factor (%)	11.60	27.70	17.70	24.40	–
Fuel consumption (L/yr)	55,216	21,235	–	–	–
Mean electrical efficiency (%)	37.40	34.80	–	–	–
Marginal generation cost ($/kW h)	0.287	0.284			
Levelized cost ($/kW h)	–	–	0.0224	0.351	0.268

Table 6
Optimized techno-economic results of the proposed case.

Generation output (kW h/yr)					
G2 (medium generator)	**G3 (small generator)**	**Wind turbine**	**PV**	**Battery annual throughput**	**Total generation**
203,446 31%	72,685 11%	372,376 56%	10,694 2%	20,867 –	659,202 100%

System parameters (kW h/yr)			
AC load	**Excess electricity**	**Unmet electric load**	**Capacity shortage**
470,485 72.9%	178,678 27.1%	0.00 0.00	0.00 0.00

System economics			
Levelized COE ($/kW h)	**Total NPC ($)**	**Operating cost ($/yr)**	**Initial capital ($)**
0.288	1723,403	106,803	367,102

4.2. Microgrid operation and control

Given the various generation sources and the presence of batteries as storage units in the microgrid, it is of interest to consider the mode of operation of the microgrid. An optimal dispatch pattern of generators for the islanded system is of interest.

It is worthnoting that, according to the HOMER Energy support group website [33], “HOMER simulates the operation of hybrid systems for every hour (or minute) of the year. In doing that, it makes decisions to switch on and off the generator in each time step. It minimizes the cost to use the generator only when the wind is insufficient”.

Fig. 11 shows the load/supply balance of G2 for a sampled period of one-week operation. Note the sampled week is the same week chosen for the previous diesel-only case presented in Fig. 8. It is obvious that the number of starts of the diesel generator was reduced to only 9 short-lived starts in the whole week, which is basically due to the high availability of the wind energy at this season in Hargeisa.

According to Whitefoot et al. [36], HOMER uses a rule-based strategy to sequentially decide the dispatch at each time increment, linked only to other time increments through the boundary conditions of energy storage state-of-charge (SOC). Using the cycle charging strategy that was chosen in this study, HOMER decides the minimum cost dispatch strategy at each time increment while attempting to only run diesel generators at maximum load, using excess generator power to charge energy storage [36]. In addition, this strategy seeks to reduce battery degradation by using a soft target for the lower bound of battery SOC. Lambert et al.’s HOMER modelling document [31] contains more details on HOMER's dispatch strategy.

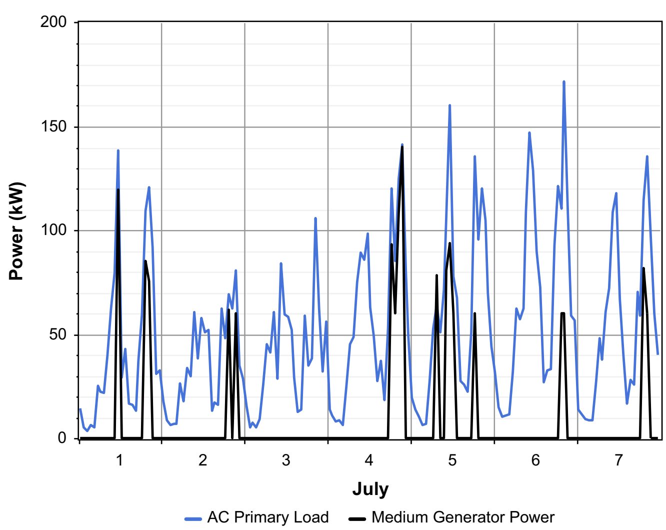

Fig. 11. Operational response of the 200 kW diesel system to load profile in 1st week of July.

For this study, a very good day that shows how HOMER dispatches the generators when the RE sources are in extreme shortages is shown in Fig. 12. In that day, the batteries supply the low demand during the early part of the day. As the demand increases, and low RE source availability persists around the midday, the 200 kW generator (medium generator) comes into operation to take over the load demand. Batteries also get charged during those hours and hence relieving the need for generator during the second period of low demand in the afternoon session.

4.3. Sensitivity analysis

In a hybrid renewable-based microgrid system, it is highly crucial to carry out a sensitivity analysis on several important variables that affect the proposed system's overall cost as well as its feasibility technical-wise. Sensitivity analysis is normally applicable to uncertain parameters that have been estimated during the system design and that might have significant effect on the NPC. With HOMER, by specifying a range of values, it can be determined how important that variable is, and how the results change depending on its value. In other words, the *sensitivity* of the outputs to changes in the input of that variable could be easily observed.

For the proposed PV–Wind–Diesel system, there are several variables that are uncertain considering the situation in Hargeisa. First, the authors believe that since the RE data are based on the satellite estimation of the area, it is highly important to have the ground data logging system that could accurately measure the weather in a long period of time. Accordingly, the RE resources’ scaled annual averages were varied by a 20% increase and decrease as shown in Table 8.

Furthermore, despite a higher O&M cost consideration (for the wind turbine) than the one reported in the literature during the design stage of the HOMER modelling (refer Section 3.3.2), it is still necessary to consider the O&M as a sensitivity parameter during

Table 8
Summary of resource and component sensitivity variables used in this study.

Variable name	Solar resource Annual global solar	Wind resource Annual average wind speed	Wind turbine O&M multiplier
Unit	(kW h/m^2/d)	m/s	$/yr
Estimated value	6.4	5.468	100
Range of uncertainty	±20%	±20%	Two and four folds
Input values	7.680 5.120	6.562 4.374	2 4

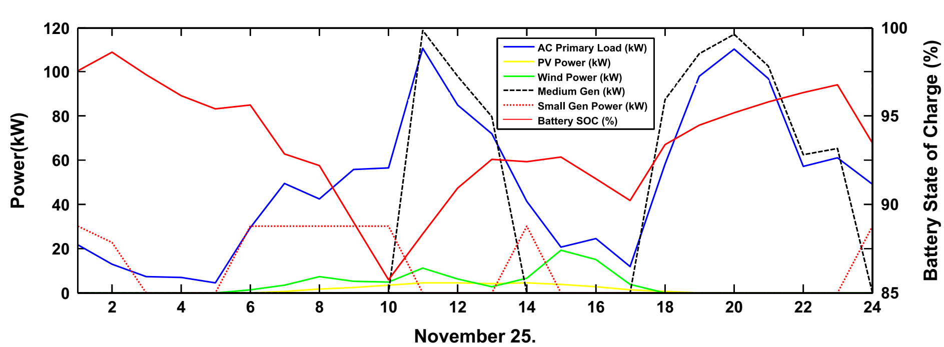

Fig. 12. The operational condition of the various sources in different load demand.

the analysis as presented in Table 8. This is due to the fact that wind turbine technology has a rare presence in the electricity generation market of Somaliland [28] and there are barely any skilled technicians or system engineers who could easily maintain any technical failures. For that reason, the normal O&M cost can easily go higher if foreign technicians are called in for any malfunction of the turbines. In that respect, it has been decided to consider an O&M cost of two and four orders of magnitude higher than the estimated cost in the simulation.

The third variable that is worth considering is the fuel price variation over the system's life cycle. This is highly crucial in a microgrid system where diesel generators are part of the system components under consideration. The diesel price was increased from $0.8/L up to $2.0/L in steps of $0.2/L.

To determine the sensitivity of the system's COE to those three variables, a sensitivity analysis using HOMER was carried out. Multiple values for each variable were input into HOMER, covering the range of uncertainty of each. HOMER produced the spider graph, shown in Fig. 13, showing that the COE is most sensitive to the diesel price (because the diesel price line is the steepest). The cost incurred, based on the NPC, is around $1000,000 for every $1 diesel price change in the market. As a result, the operators of the system are encouraged to reduce the diesel generators' dependency and aim to constantly reduce their share in the electricity production to the lowest level as possible.

The variation in wind speed is the second highest in the spider graph of Fig. 13. The results in the figure indicate with a 10% increase of wind speed, the NPC of the whole system could potentially reduce by $100,000. However, it is notable that these numbers do not alter the investment decision as much as the diesel variation does in terms of NPC spread. On the other hand, a 20% of either increase or decrease in solar radiation and a maximum of four times increase of the estimated O&M costs of the wind turbines have shown almost a negligible effect in the total NPC as the spidar graph depicts (Fig. 13). Therefore, for any future investors, these two parameters should be lowly regarded during the investment decision.

4.3.1. *Effect of load demand increase*

It is worthmentioning that HOMER assumes that the load profile remains constant over the system lifetime, so that it needs to simulate only one year of system operation [31]. However, the

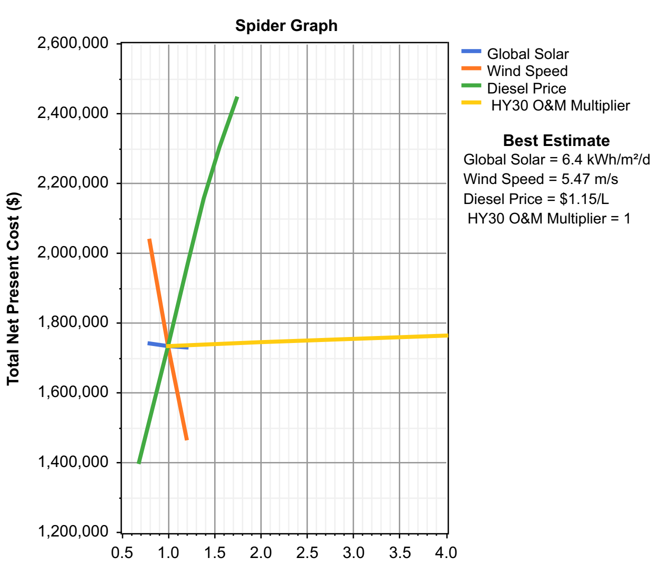

Fig. 13. The spider graph of the three sensitivity variables input into HOMER.

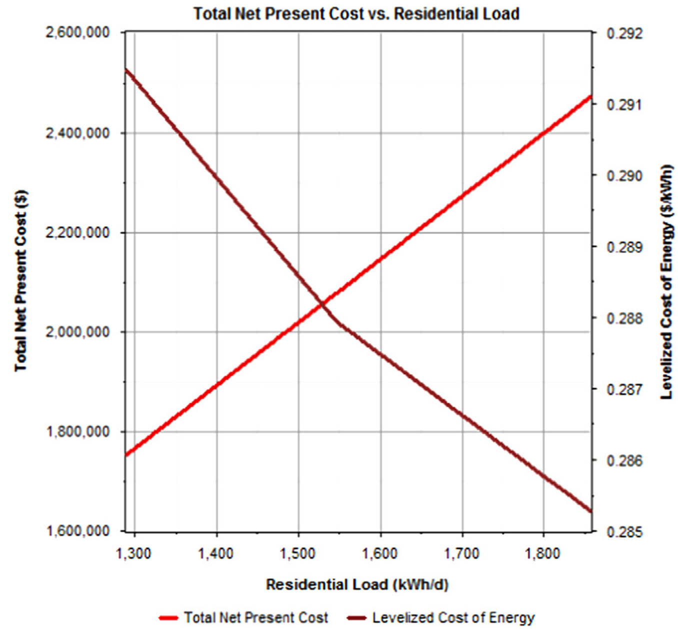

Fig. 14. A line graph showing the effect of increasing demand with respect to NPC and COE.

load modelled in this study extremely cuts out many urban consumer goods such as electric cookers, ovens and water heaters. With time and with the possible reduction of electricity tariffs, the behavior of the customers is expected to match that of a modern urban house. This introduces increased load demand to the simulated microgrid.

For that reason, in order to analyze the effect of a larger load demand, sensitivity analysis was carried out on the size of the primary load. Multiple runs with increasing load size were run using HOMER to analyze the effects of a changing load size.

If the load increases by 20% and then the resultant load also increases by another 20%, which is a 44% increase of the original load, the total NPC will increase by 40% as the levelized COE decreases by just 2% (as shown in Fig. 14). This is because, with more loads, the operating hours of the diesel generators will increase by 26%, leading to a 51% increase of operational costs. This depicts that the diesel generators are the system's major spinning reserve providers. As a result, this system arrangement will have a significant effect on NPC of the microgrid in the event of a future load growth of the given residential area. Therefore, it is highly advisable for designers to take this effect into account.

On the other hand, the mere reduction of LCOE is due to the reduction of excess electricity from 27.2% to only 17.6% when the load is at its highest modelled (refer Fig. 14). This indicates that the excess electricity which is primarily produced by the wind turbines also serves as reserve generation and can be utilized with more load growth in times of more wind power but their contribution is comparatively too small as spinning reserve technology providers.

5. Conclusion

In this article, a techno-economic study of a hybrid PV/Wind/Diesel Microgrid has been provided to supply a designed load profile with reasonable daily average. The area considered in this study is Hargeisa, Somaliland's major urban center. Using HOMER simulation software, the prospects of adding a considerable share of RE penetration are analyzed. Optimization modeling plus sensitivity analyses were conducted to compare technically as well as economically the benefit of either a diesel-only scenario or a hybrid case. NPC and COE were used as the major economic parameters in the analysis. Results show that the diesel-based power system is about 1.5 times more expensive, based on NPC results, than a hybrid microgrid system at the present diesel price, making it an expensive option. It has also been revealed the possibility of almost 58% RE penetration that can serve the local electricity demand with a COE of just USD 0.288/kW h. This COE is almost a 30% reduction of the base case. This study also finds that wind is more economical than PV systems in Hargeisa.

Finally, this study is expected to contribute to the knowledge of RE potentiality in Somaliland. In that regard, and in terms of policy-related contributions, the study acts as a source that provides and uncovers, in scholarly terms, the suitable usability and potentiality of RE resources to the government and other local or international investors. It also exhibits a local-oriented analysis of hybrid power system viability in Somaliland for the industry operators and other interested parties in Somaliland by emphasizing what key drivers need to be focused. Lastly it demonstrates the cost-effectiveness of the proposed system and the possibility of reducing diesel dependence in Somaliland's electricity market.

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