

Article

RURAL ELECTRIFICATION OF SOMALIA USING WT-PV-DG-BATTERY HYBRID SYSTEM

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Abstract: Around 14% of the global population does not have access to electricity. About 95% of those are living in rural Sub-Saharan Africa. Often in these regions, diesel generators are the only source of electricity. The operating cost of these diesel generators is high. However, solar and wind energy are available in most of African countries. This study presents the analysis of designing an off-grid hybrid system with a wind turbine, PV, diesel generator, and battery to power a hospital, school, and 200 household village in four locations across Somalia. The research investigated the availability of wind-solar resources in selected locations. Designing of the system and economic-technical calculations were performed using HOMER. The selection of the optimum design was based on the Cost of Electricity and Net Present Cost. The results show that for Kabaal and Ceel Buur, a WT-PV-DG-Battery is the optimal system as the wind resource in these regions is high. For Saakov and Baki, a PV-DG-Battery system proves to be optimum as the wind resource is limited here. The study also evaluated the control strategy and proved that combined dispatch was the most cost-effective for these locations. The study concluded that hybrid systems are more economical than diesel systems.

Keywords: Micro-grid, Rural Electrification, HOMER, Control strategy, Sensitivity analysis



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1. Introduction

In spite of recently increased electrification, large numbers of people are still living in the dark. For example, around 600 million Africans lack access to electricity [1], and the average electrification rate is only 45 % [2]. People living in these regions are poor and use diesel generators for electricity. Whilst electricity access does not necessarily mean life will improve, under development in the sector holds back progress, and problems in health, education, and livelihoods are exasperated. For example, in the health sector, an unreliable power supply can even cause loss of life. Surgeries can be delayed, and it is reported that that figures for maternal mortality are higher in African Countries than the rest of the world.[3] These can be avoided by providing a reliable and consistent power supply. Schools and households also experience difficulties due to electricity shortages. The excessive use of conventional systems like diesel generators, increase health problems and contribute to global warming. In such places where there is no grid, or the connection is weak, off-grid systems are an optimal solution. The off-grid renewable system can consist of individual renewable energy technologies (RET) such as wind or solar with battery energy storage. In addition, they can be hybridized with more than one RET and even supported by a backup diesel generator (DG). Options on the system can be modelled and optimized to find the best solution to the problem.[4] In Africa, where the cost to extend an existing grid to a remote location is very expensive, and the return on investment is low, then there is an opportunity for RET hybrid off-grid systems if an economical option

can be found. The cost of electricity in most African countries is so high [5]. Despite having good wind, solar resources, development in the renewable sector is so low, and green-house emission in these regions is high. Utilising these non-conventional resources has the potential to provide a cheap reliable source of electricity in these countries.

The aim of this study was to investigate opportunities for hybrid off-grid systems to solve electricity access issues in Somalia. The objectives were to identify and characterize the power requirements and demand profiles in Somalia. To then evaluate the availability of renewable energy sources and to develop a model of the off-grid system based on the load and resources. Finally, an economic evaluation was produced to yield optimal solutions. Somalia has low electricity access and what appears to be good solar and wind resources for hybrid systems. Four regions of Somalia with different climatic conditions were considered for this study. We simulated the hybrid system selected, and the techno-economic analysis was obtained. The load calculation for each location was based on a reasonable assumption of a village with a health clinic, school, and 200 households and a deferrable load for water pumping. This would enable a direct comparison of the outcomes for the different objectives to develop an optimal hybrid system. The techno-economic feasibility of the four locations was studied, including determining the size of the system, state of charge of the battery, the annual energy consumption, and the renewable energy percentage. The control strategy was studied carefully. The economic analysis was used to determine the Levelized cost of electricity (LCOE), net present cost (NPC), an initial capital cost. Emissions were also obtained from the analysis. A sensitivity analysis of the optimal solution of Kabaal was studied using wind and solar resources, load growth, discount rate, fuel cost, wind turbine, and PV capital cost as sensitivity parameters. The findings has the potential to be useful in planning off-grid systems in different climate zones of Somalia and beyond.

2. Materials and Methods

The methodology is divided into six sections based on the objectives, i.e., location context, load demand, availability of renewable energy resources, system description and component modelling, economic calculations, cost optimization, techno-economic constraints, sensitivity analysis.

2.1. Location context

The location for this study was selected as Somalia. The Federal Republic of Somalia is located at the horn of Africa. Bordered by Ethiopia to the west, the Gulf of Aden to the northern side the Guardafui channel, Somali Sea to the east, and by Kenya to the southwest.

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Figure 1. Somalia Map

The electrification rate of Somalia is 32.95 %. The rural estimated electrification rate is 4 %, and the urban electrification rate is about 33 %. The cost of electricity is high and ranges from 0.5- 1.5 \$/kWh. Somalia has a coastline of about 3300km and is shown to have good wind and solar re-sources, which are yet to be exploited. Somalia has one of the highest resource potential among African countries for wind and solar energy. Limited regulations , monopoly distribution control, poor infrastructure holds back development in renewable sector.[6] For this study, four locations in Somalia were considered, namely Kabaal (1), Ceel Buur (2), Saakov (3), and Baki (4), as shown in figure 1.

2.2. Load demand

Two types of loads were considered for this study. The primary load that should be met immediately and deferrable loads that can be delivered and the timing is not important. The load can be calculated as the: Energy consumption is given by E (kWh/day) = the number of appliances (n) power rating (kW) no. of hours of operation. In this study, the primary loads are that of a health clinic, school, and 200 rural households.

2.2.1. Health clinic load

The health clinic is an essential load as the electricity supply must be continuous without any outages. It is assumed, services are provided to treat the surrounding communities. The energy need for this rural healthcare is considered relatively low as the availability of medical equipment is low in these locations. Rural healthcare has been classified into three levels, according to the United States Agency for International Development.[7] Category 1: Limited services and staff with an electricity demand of 5-10kWh/day. Category 2: Medical equipment will be similar to the category one but differs in terms of the frequency of usage of the equipment. Electricity demand is estimated to be moderate, 10-20kWh/day. Category 3: A greater number of beds and contains more diagnostic devices such as blood typing equipment, X-ray machine, and multiple refrigerators. The average demand is estimated to be 20-30kWh/day. The health clinic considered for this study falls in category 3.

Table 1. Hospital Load.

Item	Quantity	Rated Power(W)	Hours Operated	Energy Used(kWh/day)
Lighting CFL(Indoor)	10	15	7	1.05
Lighting CFL (outdoor)	5	40	12	2.40
Fans	6	60	18	6.48
Refrigerator	3	130	24	9.36
Lab apparatus	2	250	5	2.5
Other lab apparatus	1	1200	3	3.60

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Figure 2. Hourly load variation of Health Clinic

The load of each equipment is presented in table 1. The total load of the study health clinic is 27.25 kWh/day. The peak load was estimated at 2.68kW. Figure 2 shows the hourly load variation of the health clinic. The load factor, as estimated by HOMER, was 0.35. Random variability was taken as 5% day to day and 5% step to step for this load profile, and the peak load will rise to 3.27kW. This is because the number of patients visiting the clinic is greater around mid-day. The load demand is assumed constant throughout the year.

2.2.2. Household and School load

The next load taken into consideration in this study was that of households located in the selected area. This load is carefully selected after research on African households.[8] In Somalian rural households, the electrical equipment is limited. The supply of electricity is often poor. A total of 200 households were considered for this study. The load profile of an individual Somalian household is shown in table 2. Education is important for the social and economic advancement of a country. In order to have a quality education, a reliable supply of electricity is essential. Most of rural Africa lacks electricity in schools. In this study, an average-sized school is considered, which has 12 classrooms, two offices, and four toilets. [9] Total load breakdown of the school load is shown in table 3. The estimated total load of the selected household is 0.895kWh/day. The total load of school was estimated to be 1.465kWh/day with a peak of 0.325kW. The highest energy consumed by households was during 19:00 to 22:00, which is considered the peak time.

Table 2. Household Loads.

Item	Quantity	Rated Power(W)	Hours Operated	Energy Used(kWh/day)
Lighting	4	15	6	0.36
Fan	1	60	4	0.24
TV	1	65	4	0.26
Radio	1	5	3	0.015
Charger	2	5	2	0.02

Table 3. School Loads.

Item	Quantity	Rated Power(W)	Hours Operated	Energy Used(kWh/day)
Lighting	6	15	4	0.36
Fan	2	60	5	0.60
TV	1	80	2	0.16
Radio	1	5	5	0.025
Charger	3	20	5	0.30
Microphone	1	20	1	0.02

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Figure 3. Hourly load variation of School and 200 Household

For feeding into HOMER, the School load and total household load of 200 houses were taken as a single load, which together comprised of 167.78kWh/day and the peak 20.88kW. Day to day variability is 5%, and the time step variability is also taken as 5%. The load factor is 0.33. Figure 3 shows the load variation per hour of School and 200 households.

2.2.3. Deferrable load

This type of load is given secondary priority and is fulfilled after primary loads are met. In this study, the water pump was considered which supply water to the village, school, and health clinic. The quantity of water need is $5m^3$ per day. For satisfying the need, two pumps were selected, which have a capacity of 550W each. It operates daily for 5 hours, and the peak load is 1.1kW. A storage capacity of three days was considered. The energy needed to pump water is calculated by,[10] The energy needed (kWh) = No of pumps \times storage days \times rated capacity of pumps \times number of hours in operation. The energy consumption was 16.50kWh. The annual average load per day is 5.5kWh/day, and the minimum load ratio was taken to be 65%.

2.3. Availability of renewable energy resources

Somalia enjoys good solar radiation and very good wind energy resource. Solar GHI and wind resources were crucial in accurately designing the system. The solar radiation data was obtained from the National Renewable Energy Laboratory database for the four selected locations [11]. Wind data was obtained from the Global Wind Atlas (GWA).[12]

2.3.1. Solar GHI Data

Solar GHI radiation and ambient temperature determine the power output of solar PV. For the location Kabaal, the monthly average GHI radiation is $5.63kWh/m^2/day$. August has the highest solar radiation. The average temperature of the location was measured at 27.2C. For location Ceel Buur, the average solar radiation is $5.69kWh/m^2/day$, and the average temperature of the location is 27.71C. In southern Somalia, i.e., Saakov, the average solar radiation is $5.86kWh/m^2/day$ and has a temperature of 27.85C. Baki has a high average solar radiation of $5.98kWh/m^2/day$ and an average temperature of 26.33C. See figures 4 and 5.

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Figure 4. Solar GHI Data

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Figure 5. Temperature Data

2.3.2. Wind data

The GWA 3.0 gave wind speed at anemometer heights of 10m, 50m, 100m, 150m, and 200m. The 50m anemometer height was taken for this study, see Figure 6. From the data obtained, Kabaal has the windiest location at 7.12 m/s average wind speed; on the other hand, Saakov has the lowest wind potential of 4.77 m/s average.

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Figure 6. Wind Speed Data

2.4. System description and component modelling

2.4.1. Wind turbines

In this study, the wind turbine used is a 15kW machine manufactured by Enbreeze GmbH, Germany. It is a turbine designed to work at low- average wind conditions. The rated power is 15kW with a cut in speed of 2.5m/s and a hub height of 20m. The lifetime of the turbine is considered as 20 years. The capital cost of the turbine is \$88,221. The operation and maintenance cost of the turbine is \$496 per year [13]. The electrical power output of a wind turbine is obtained by [3]

$$P = 1/2\rho AV^3\eta \quad (1)$$

The wind speed at hub height is given by,

$$U_{hub} = U_a \times \left[\frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_a}{z_0}\right)} \right] \quad (2)$$

Where U_{hub} is the velocity at hub height, U_a is the velocity at anemometer height, Z_{hub} is the hub height of the turbine, Z_a is the anemometer height and Z_0 is the surface roughness length. The power curve of the wind turbine is shown in figure 7. Density correction was calculated by HOMER using the following equation,[14]

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Figure 7. Wind turbine power curve

$$P_{WT} = \left(\frac{\rho}{\rho_0}\right) \cdot P_{WT,sc} \quad (3)$$

Where P_{WT} is the output of the turbine, $P_{WT,sc}$ is the power output at standard test condition, ρ is the actual air density and ρ_0 in is the air density at the standard test condition.

2.4.2. PV system

The PV panel selected in this study is a mono-crystalline flat type, manufactured by Canadian Solar. [15] The rated capacity is 0.295kW, temperature coefficient -0.390, and operating temperature is 45C. The efficiency of this solar panel is 18.02%. Furthermore, the lifetime is considered to be 25 years with a De-rating factor of 80%. There is no tracing or MPPT system, and the ground reflectance is taken as 20%. PV depends upon the GHI

radiation of a particular day, and it varies from time to time. The PV power output of the system is given by,[16]

$$P_{pv-generator} = P_{mp-stc} \times \left(\frac{G}{G_{stc}} \right) [1 + K_t(T_{cell} - T_{stc})] \quad (4)$$

Where, G_{stc} is the standard test condition solar radiation, G is solar radiation (W/m^2), P_{mp-stc} is the rated power of the module, T_{stc} is the temperature at standard test condition, T_{cell} is the cell temperature and K_t is the power temperature co-efficient. The temperature of the cell is calculated by [3]

$$T_{cell} = T_a + \left[\frac{n \cdot temp - 20}{800} \right] G \quad (5)$$

T_a is the ambient temperature in degree Celsius, $n \cdot temp$ is the nominal temp (degree Celsius). The total power output of the panel is obtained by multiplying the power output of individual cells multiplied by the number of panels.

2.4.3. Diesel generator

The generator used in this study was 25kW, with an initial cost is \$12,500. The operation and maintenance cost was taken as \$0.03/operation hour. The minimum load ratio is 25%. The lifetime of the generator is taken as 15,000 hours. Fuel price in Somalia 1.1/litres. CO_2 emissions are 16.34g/L, and unburned HC is 0.72g/L with other particulates 0.098 g/L.[14] The diesel generator is a conventional system and ensures the reliability of the system. The modelling of fuel consumption of the diesel generator is done by HOMER using the formula, [14] [17]

$$F_{gen} = F_0 \times P_{gen-rated} + F_1 \times P_{gen-out} \quad (6)$$

F_0 is the fuel curve intercept coefficient F_1 is the fuel curve slope $P_{gen-rated}$ is the rated capacity of the generator (kW) and $P_{gen-out}$ is the electrical output of the generator. In HOMER the electrical efficiency is the ratio of electrical energy coming out to the chemical energy of fuel going in, [14] [18]

$$\eta_{gen} = \frac{3.6 \times P_{gen}}{m_{fuel} \times LHV_{fuel}} \quad (7)$$

$$RF = \left(1 - \frac{\sum P_{diesel}}{\sum P_{renew}} \right) \times 100 \quad (8)$$

Where, P_{diesel} is the power output of diesel generator and P_{renew} is the power output of the renewable source.

2.4.4. Battery Storage

In renewable hybrid systems, the battery capacity fluctuates due to the randomness of solar and wind energy. The battery comes into use when renewable sources are not available or is producing low and cannot meet the load demand. The size of the battery depends on a number of factors such as energy demand, the depth of discharge, temperature correction, and a lifetime of the battery and the rated capacity of the battery. The charge capacity of battery to supply the total load can be expressed as [19]

$$C_b = \frac{E_l \times S_d}{V_b(DOB)_{max} T_{fc} \eta_b} \quad (9)$$

Where E_l is the electrical load in (Wh), S_d is the battery autonomy in days, V_b is the battery voltage (V), $(DOB)_{max}$ is the maximum depth of discharge of storage, T_{fc} is the correction factor of the temperature, and η_b is the efficiency of the battery. The state of charge (SOC)

of the battery depends upon the production from renewables, its previous SOC, and the load demand. During the charging state, i.e., renewable production higher than the load demand, SOC can be expressed as [20]

$$SOC(t) = SOC(t-1) \times (1 - \sigma) + \left[E_{hybrid}(t) - \frac{E_l(t)}{\eta_{inv}} \right] \cdot \eta_b \quad (10)$$

During discharging, where renewable production is less than the demand the SOC is determined by, [21]

$$SOC(t) = SOC(t-1) \times (1 - \sigma) + \left[\frac{E_l(t)}{\eta_{inv}} - E_{hybrid}(t) \right] \quad (11)$$

Where (t) is the state of battery at the hour (t), SOC(t-1) is the previous SOC at (t-1), σ is the discharging rate of the battery, $E_{Hybrid}(t)$ is total energy generated from PV and wind(kWh), $E_l(t)$ the load requirement at the time (t), η_{inv} and η_b is the efficiency of inverter and battery charging efficiency respectively. [22]

$$E_{Hybrid}(t) = E_{Wind}(t) + E_{PV}(t) \quad (12)$$

$E_{Wind}(t)$, $E_{PV}(t)$ are energy generated from wind and PV, respectively, in kWh. The storage bank life of the battery is calculated in HOMER using,[14] if limited by throughput.

$$R_{battery} = \frac{N_{battery} \times Q_{lifetime}}{Q_{throughput}} \quad (13)$$

If limited by throughput and time.

$$R_{battery} = \left(\frac{N_{battery} \times Q_{lifetime}}{Q_{throughput}}, R_{battery,f} \right) \quad (14)$$

if limited by time.

$$R_{Battery} = R_{Battery,f} \quad (15)$$

R is storage life in years, $N_{battery}$ is the number of batteries in storage, $Q_{Lifetime}$ is the throughput of a single battery in kWh, $Q_{throughput}$ and is the storage throughput annually (kWh/year), $R_{Battery,f}$ is the period of time the storage will last before replacement. The autonomy period of battery $A_{Battery}$ is defined as the ratio of battery bank size to that of the total load demand,[14]

$$A_{battery} = \frac{N_{battery} \cdot V_{nom} \cdot Q_{nom} \left(1 - \frac{Q_{min}}{100} \right) \times \left(\frac{24h}{day} \right)}{L_{av.prim} \left(\frac{1000wh}{kwh} \right)} \quad (16)$$

$N_{Battery}$ is the number of batteries, V_{nom} is the nominal voltage of a single battery (V), Q_{nom} is the nominal capacity of a single battery in Ampere hour (Ah), Q_{min} is the minimum SOC of battery in percentage and $L_{av.prim}$ is the average primary load (kWh/day).

2.4.5. Converter

A bidirectional converter was used in this study, and it maintains the flow of alternating current and direct current, i.e., acts as both rectifier and converter. The capital cost of the converter was taken as \$300, and the replacement cost was taken as 90% of the capital cost, i.e., \$270. The operation and maintenance cost was neglected. Efficiency was taken as 90%, and lifetime was assumed to be 15 years. The mathematical model is given below, [14] [23]

$$E_{inv(t)} = E_{pv(t)} \times \eta_{inv} \quad (17)$$

$$E_{battery} = \left[\frac{E_{battery(t-1)} - E_{l(t)}}{\eta_{inv} \times \eta_{discharge}} \right] \quad (18)$$

Where, $E_{inv(t)}$ is the energy output of inverter in kWh, $E_{pv(t)}$ is the energy output from the PV system, η_{inv} is the inverter efficiency, $E_{battery}$ is the energy output from the battery, $E_{l(t)}$ is the energy consumed by the electric load(kWh), $\eta_{discharge}$ is the efficiency of battery discharge. The rectifier helps to charge the battery from the electricity generated by the wind turbine.

$$E_{rec-out(t)} = E_{rec-inp(t)} \times \eta_{rec} \quad (19)$$

$$E_{rec-inp(t)} = E_{wt(t)} + E_{dg(t)} - E_{l(t)} \quad (20)$$

$E_{rec-out(t)}$ is the energy output from the rectifier in hour t (kWh), $E_{rec-inp(t)}$ is energy input to the rectifier in kWh, η_{rec} is the rectifier efficiency, $E_{WT(t)}$ is the energy generated from the wind turbine per hour (kWh), $E_{dg(t)}$ is the diesel generator output and $E_{l(t)}$ is the energy consumed by the load in kWh.

2.5. System Controller

2.5.1. Load Following

In the load-following strategy, the generator produces only enough power to satisfy the load demand. The battery is charged by renewable sources, mostly when the penetration is higher.

2.5.2. Cycle Charging

In this type of charging, batteries are charged to the set point given. The number of starts of the generator is reduced. Also, the charging- discharging cycle of the battery is also reduced.

2.5.3. Combined Dispatch

Combined dispatch is the best strategy as it improves the performance of the system than the LF and CC strategy. It makes efficient use of a generator. It utilises the CC strategy when the load is low and LF when the load is higher. Figure 8 shows combined dispatch flow chart. CD calculates the cost of every decision to obtain the lowest cost-effective solution. Three cases can be discussed. [24]

- The first case is when the electricity provided by the generator only feeds the load without charging the battery.
- The second case is when the generator meets the loads and also charges the battery with the remaining electricity.
- The next case is when the battery feeds the load alone. This can be explained as, if the renewable energy production is higher than the load demand, the power flow follows CC/LF strategy. If renewable production is low, it follows a different procedure.

If the $SOC = SOC_{min}$, The controller then compares the amount of money needs to run the generator at max capacity to feed the load, and by using the excess electricity, it charges the battery with that of feeding the load without charging the battery. The least cost is selected from both cases. If the $SOC > SOC_{min}$, three cases are compared, and one with the least cost is selected. The power flow is based on the least cost among the three cases. The cases are; Numbered lists can be added as follows:

1. Cost when the generator serves the load, and no battery is charged.
2. Run the generator at full capacity and serving the load and by excess electricity charging the battery.
3. Cost when the battery is discharged.

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Figure 8. Combined Dispatch Flow chart.

2.6. Final system configuration

Figure 9 shows the final design layout. The diesel generator and the wind turbines are connected to the AC bus bar with the PV system and battery connected to the DC bus bar. The loads are completely AC in this study, and a multi-directional converter is connected to the AC and DC bus bars, which has both inverter and converter configuration.

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Figure 9. Final system configuration

2.7. Economic Calculations

The total life cycle cost (NPC), which is the total sum of initial capital cost, replacement cost, operating and maintenance cost, and the fuel cost and salvage cost was calculated. The total NPC can be expressed as, [14].

$$NPC_{total} = \frac{C_{ann,tot}}{CRF} \quad (21)$$

$$C_{ann,tot} = \sum_{N=1}^{N_{pv}} C_{ann,pv} + \sum_{N=1}^{N_{WT}} C_{ann,WT} + \sum_{N=1}^{N_{DG}} C_{ann,DG} + \sum_{N=1}^{N_{batt}} C_{ann,batt} + \sum_{N=1}^{N_{conv}} C_{ann,conv} \quad (22)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (23)$$

$$i = \frac{i' - f}{1 + f} \quad (24)$$

$C_{ann,x}$ is the annualized cost of each component, x being the components in the hybrid system, and is the sum of total capital cost, O&M, fuel cost, and salvage cost of the individual system. LCOE of the system is the cost per kWh of electricity produced and is found by HOMER using, [14]

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad (25)$$

$C_{ann,tot}$ is the total annualized cost (\$/kWh), and E_{served} is the total electrical load in kWh/year.

2.8. Techno-Economic Constraints

Constraints are important to obtain realistic solutions to the system. In this study, the discount rate is taken at 7.8%. An increase in the discount rate increases the risk perception. So, in order to minimize the risk, a low discount rate is considered for this study [25]. The inflation rate is taken at 5.20 % [26]. It is important to define this to a realistic value as it determines the economics of the system. Project lifetime is taken as 20 years, and no capacity shortage is considered in this study as the system designed is to be completely reliable.

2.9. Sensitivity Analysis

There can be a lot of uncertainties in the techno-economic analysis. Previous studies show these uncertainties affect the economics of the system and play a key role in the success of a project [27] [28]. For this study, fuel cost, discount rate, load growth, wind turbine capital cost, PV panel capital cost, Wind resource, and solar resource are considered as the sensitivity parameters. The selected parameter was varied within 25 % while keeping other parameters constant. The sensitivity model of the parameters with respect to NPC and COE was recorded in the form of a graph. In this study, sensitivity analysis is only performed on the optimal solution of Kabaal.

3. Results

The results of the four study sites and four system configurations are now presented. This includes optimal design and economically feasible solutions. The four system designs

were a Wind-PV-battery-DG system, Wind-DG-battery system, PV-DG-battery system, and a conventional stand- alone DG.

3.1. Kabaal

For Kabaal, the most cost-effective solution is a WT-PV-DG-BATTERY system, which has an LCOE of 0.284 \$/kWh, with CD as control strategy. See Table 4. So, this combination of the system is selected for which includes 2,007kWh deferrable load. The system when simulated using LF and CC strategy gave LCOE of 0.315 \$/kWh and 0.321\$/kWh respectively. The system contained no unmet load, which is important as this is developed for high reliability and zero outages. There was a surplus electricity production of 26,169 kWh/year, which is about 25% of the total. This can be used to power the neighbouring villages. This can be done either by storing excess power using the batteries and selling them to other consumers, and also by the peer to peer (P2P) energy trading method [29].

Table 4. Simulation result of Kabaal.

Item	PV-WT-DG-BAT	PV-DG-BAT	WT-DG-BAT	DG only
PV(kW)	17.3	32.1	0	0
WT(No)	1	0	1	0
DG(kW)	25	25	25	25
BAT(kWh)	55	67	25	0
CONVERTER(kW)	11.8	15.4	4.43	0
DISPATCH STRATEGY	CD	CD	CD	CD
NPC(\$)	315,910	394,000	355,241	568,508
COE(\$)	0.284	0.354	0.319	0.511
INITIAL COST(\$)	164,077	117,312	109,549.	12,500
OPERATING COST(\$)	9,713	17,766	15,718	35,570
R.F(%)	79	55.4	60	0

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Figure 10. Production of components in Kabaal.

Figure 10 shows the production of the components in each month. Production from the PV was nearly the same throughout the year. The wind speed was high for June, July, and August, and it resulted in the graph in figure 10. From the simulation, the mean output of the wind turbine and capacity factor was 6.44 kW and 43.3%, respectively. The total hours of operation obtained were 8,196 per year. Wind penetration was 79.2%, and the individual Levelized cost was 0.121\$/kWh. The mean output from the PV is 3.19kW, 76.6kWh/day. The capacity factor was 19.2%. PV penetration for the location was 39.3% and had a Levelized cost of 0.101\$/kWh. The hour of operation of PV was 4,346 hours/year. For the generator, the hours of operation were 1,645 hours per year. It has 662 starts per year, and the operational life obtained is 9.12 years. The fixed generation cost of the diesel generator is 1.71\$/kWh. The mean electrical output is 9.61kW. Another important aspect is fuel consumption, and the generator consumed 5,671 litres/year, i.e., 0.647 l/ hour. The string size of the battery is one, and these were connected in parallel. The total number of batteries was 55. The nominal capacity of the battery was 55kWh, out of which 33kWh is usable. The expected lifetime of the battery is 5.37 years. There is a loss of 1,832kWh/ year and a storage depletion of 8.70kWh/year. The annual throughput was 8,199kWh/year. The system had an IRR of 16.5%, which is above the threshold of 12%, in which the mini-grid operators in Africa consider a project to be viable [30]. The ROI of the system obtained is 12%. The payback year calculated was 5.8 years. Table 5 shows the emission comparison of selected system with that of a diesel generator system.

Table 5. Emission Comparison

POLLUTANT	PV-WT-DG-BAT	DG ONLY SYSTEM	UNITS
Carbon dioxide	13,822	74,306	Kg/year
Carbon monoxide	86.3	464	Kg/year
Unburnt Hydrocarbons	3.80	20.40	Kg/year
Particulate matters	0.517	2.78	Kg/year
Sulphur dioxide	33.8	182	Kg/year
Nitrogen oxides	81.1	436	kg/year

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Figure 11. Production of components in Ceel Buur.

3.2. Ceel Buur

As with Kabaal, in Ceel Buur, the four cases, Wind-PV-DG-bat, Wind-DG-bat, PV-DG-bat, and DG alone system, were used. Detailed results of the simulation is given in table 6. From the simulation, the preferred solution selected is a WT-PV-DG-Battery system with CD and LCOE of 0.314\$/kWh. The system was also simulated using LF and CC dispatch strategy, and the COE was found to be 0.328\$/kWh and 0.332 \$/kWh, respectively. The wind turbine produced 43,877 kWh/year, which is lower than the Kabaal. PV and DG produced 36,421 kWh and 17,375kWh per year, respectively. Figure 11 shows the production of components in Ceel Buur. The renewable fraction of the system was 75.6%. There was no unmet load, and the excess electricity was 22% of total production. The mean output of the wind turbine obtained from the simulation is 5.01kW. The wind penetration in Ceel Buur was 61.6%. It operated for 7,918 hours per year. HOMER also calculated the Levelized cost, which was 0.156\$/kWh. The mean output from the PV system was 4.16kW. The capacity factor is 20.2%, and the mean output per day being 99.8kWh. The PV panels operated for 4,380 hours/year. The Levelized cost obtained was 0.095\$/kWh. The total hours of operation of the diesel generator in Ceel Buur were 1,677 hours per year. It had a total of 592 starts per year. The expected life was 8.94 years, and the fixed generation cost was 1.71\$/kWh. The mean electrical output from the generator was 6.25kW, and it consumed 6,127L of fuel per year. The specific fuel consumption was 0.353L/kWh. For the battery component, the expected life was 4.98 years. Lifetime throughput 48,800kWh and storage wear cost was calculated to be 0.419\$/kWh. HOMER also calculated a loss of 2,191 kWh/year and a storage depletion of 15.3kWh/year. Annual throughput was 9,809kWh. The IRR obtained for the system in Ceel Buur is 14%. The return of investment (ROI) is

Table 6. Simulation result of Ceel Buur.

Item	PV-WT-DG-BAT	PV-DG-BAT	WT-DG-BAT	DG only
PV(kW)	20.6	29.5	0	0
WT(No)	1	0	1	0
DG(kW)	25	25	25	25
BAT(kWh)	61	62	28	0
CONVERTER(kW)	13.4	14.8	3.95	0
DISPATCH STRATEGY	CD	CD	CD	CD
NPC(\$)	348,974	385,932	412,467	568,508
COE(\$)	0.314	0.347	0.371	0.511
INITIAL COST(\$)	174,464	109,310	110,305	12,500
OPERATING COST(\$)	11,164	17,697	19,331	35,570
R.F(%)	75.6	56.3	48.6	0

Table 8. Simulation result of Saakov.

Item	PV-WT-DG-BAT	PV-DG-BAT	WT-DG-BAT	DG only
PV(kW)	23.7	30.3	0	0
WT(No)	1	0	2	0
DG(kW)	25	25	25	25
BAT(kWh)	52	62	48	0
CONVERTER(kW)	14.1	16.3	7.48	0
DISPATCH STRATEGY	CD	CD	CD	CD
NPC(\$)	393,892	392,651	519,094	568,508
COE(\$)	0.354	0.353	0.467	0.511
INITIAL COST(\$)	179,719	111,536	227,466	12,500
OPERATING COST(\$)	13,702	17,952	18,657	35,570
R.F(%)	68.5	55.1	53.1	0

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Figure 12. Production of components in Saakov.

10%. The Simple payback year was found to be 6.4 years. Table 7 shows how emissions of the selected system are compared with the stand-alone diesel system.

Table 7. Emission Comparison

POLLUTANT	PV-WT-DG-BAT	DG ONLY SYSTEM	UNITS
Carbon dioxide	16,046	74,306	Kg/year
Carbon monoxide	100	464	Kg/year
Unburnt Hydrocarbons	4.41	20.40	Kg/year
Particulate matters	0.601	2.78	Kg/year
Sulphur dioxide	39.3	182	Kg/year
Nitrogen oxides	94.1	436	kg/year

3.3. Saakov

For Saakov, the most cost-effective solution is the system with PV-DG-Battery. Table 8 shows the simulation results obtained using different configurations. Saakov is a less windy location which has an average wind speed of 4.7m/s at 50m. This is low for the 15kW wind turbine to perform. Again, for Saakov, the control strategy used is combined dispatch. The COE while using CC and LF for the PV-DG-battery system was \$0.367/kWh and \$0.356/kWh, respectively. Total production from the PV system was 52,874 kWh/year, and the 25-kW generator produced 31,989kWh/year. The monthly electricity production from generator and PV is shown in figure 12. Excess electricity produced by the system was 8,748 kWh/year, which is about 10.3% of the total production. The mean output from the PV panel was 6.04kW and 145kWh/day. For PV, the hours of operation were 4380 hours per year and had a capacity factor of 19.8%. The PV penetration level was 73%. The diesel generator accounted for a total of 44.9% of total energy generation in Saakov and had a start of 793 times. The total hours of operation throughout the year and lifetime was calculated to be 2,914 hours and 5.15 years, respectively. The fixed generation cost was \$1.71/ hour. The mean electrical output obtained was 11kW. The fuel consumption was 11,137 litres i.e. 0.348L/kWh. The storage wear cost of the battery was \$0.419/kWh. Lifetime throughput was 49,600 kWh, and the expected life was around 3.80 years. Annual throughput was 12,749kWh/year, and there was a loss of 2,849kWh/ year. The IRR of the system was 17.6% and an ROI of 12.8% was obtained. The simple play-back year was 5.5 years. The selected system emitted 29,156 Kg of carbon per year compared to 74,306 Kg of that of DG only system.

Table 10. Simulation result of Baki.

Item	PV-WT-DG-BAT	PV-DG-BAT	WT-DG-BAT	DG only
PV(kW)	21.6	28.9	0	0
WT(No)	1	0	1	0
DG(kW)	25	25	25	25
BAT(kWh)	53	58	29	0
CONVERTER(kW)	15.3	15.7	3.76	0
DISPATCH STRATEGY	CD	CD	CD	CD
NPC(\$)	380,196	371,076	473,948	568,508
COE(\$)	0.342	0.333	0.426	0.511
INITIAL COST(\$)	106,783	106,782	121,490	12,500
OPERATING COST(\$)	16,908	17,952	22,548	35,570
R.F(%)	72.20	58.6	38.6	0

Table 9. Emission Comparison

POLLUTANT	PV-DG-BAT	DG ONLY SYSTEM	UNITS
Carbon dioxide	29,156	74,306	Kg/year
Carbon monoxide	182	464	Kg/year
Unburnt Hydrocarbons	8.02	20.40	Kg/year
Particulate matters	1.09	2.78	Kg/year
Sulphur dioxide	71.4	182	Kg/year
Nitrogen oxides	171	436	kg/year

3.4. Baki

From the simulation, it has been found that PV-DG-battery was the cost-optimal solution. This site lies in a low wind speed location, so the system with wind turbines are not economically viable. The LCOE of the selected location was \$0.333/kWh. Solar PV constitutes 55,952kWh/year and DG constitutes 29,445kWh/year. Total production was 85,397kWh/year.

13.png 13.pdf 13.jpg 13.mps 13.jpeg 13.jbig2 13.jb2 13.PNG 13.PDF 13.JPG 13.JPEG 13.JBIG2 13.JB2 13.eps

Figure 13. Production of components in Baki.

Figure 13 shows the total production of respective components per month. Excess electricity in this system was 10.6% of the total production. The rated capacity of PV was 28.8kW and had a mean output of 6.39kW and 153kWh/day. The capacity factor was obtained to be 21.1%. PV penetration percentage was 78.6%. The PV operated for 4,344 hours per year, and the Levelized cost of PV was \$0.0877/ kWh. The diesel generator in this system operates for 2,595 hours/ year. It has a number of starts of 640 per year and an operational life of 5.78 years. The capacity factor was 13.4%. The fixed generation cost was \$1.71/kWh. The mean electrical output was 11.3kW. It consumes 10,179 litres of diesel/year. The specific fuel consumption was 0.34L/kWh. The nominal capacity of the battery unit was 58kWh. The storage wear cost was \$0.419/kWh. Lifetime throughput was 46,400 kWh, and the expected life was 3.54 years. There was a storage depletion of 9.41kWh/year and a loss of 2,930kWh/year. Throughput was 13,110kWh annually. The IRR of the system was 19.9 %, and the return of investment, ROI was 14.8%. The simple payback year is calculated to be 4.9 years. Table 11 gives a detailed emission of the PV-DG system in Baki.

Table 11. Emission Comparison

POLLUTANT	PV-DG-BAT	DG ONLY SYSTEMS	UNITS
Carbon dioxide	26,510	74,306	Kg/year
Carbon monoxide	165	464	Kg/year
Unburnt Hydrocarbons	7.29	20.40	Kg/year
Particulate matters	0.992	2.78	Kg/year
Sulphur dioxide	64.90	182	Kg/year
Nitrogen oxides	156	436	kg/year

3.5. Sensitivity Results

The sensitivity characteristic model for NPC and COE are shown in figure 14. As seen from the graph, the COE of the system is most sensitive to variation in Wind resources in Kabaal, followed by the discount rate, wind turbine capital cost, and discount rate. The load and solar GHI are having the least effect in the COE of the selected system. For the case of NPC, the wind resources and load demand growth had a more significant deviation from the base value, whereas Solar GHI and PV capital cost had the least deviation.

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14.JBIG2 14.JB2 14.eps

Figure 14. Sensitivity Analysis.

3.6. Discussion and Validation of Results

For the different locations of Kabaal, Ceel Buur, Saakov, and Baki, the results showed that the hybrid renewable system is an appropriate technology for their energy crisis. The LCOE and the Net Present Cost of the Hybrid system in all the locations studied were lower than the cost of electricity while using the DG system alone and lower than the price of grid-connected electricity in Somalia. Clearly, the price of electricity in Somalia is high between \$0.5-\$1.5/ kWh. Furthermore, the studies outlined that high wind speed locations were more economical for hybrid systems in Somalia. Carbon emissions were substantially reduced by the hybrid systems, 80% in Kabaal, 78% in Ceel Buur, 60% in Saakov, and 64% in Baki.

The system is comparable to other studies such as by Tahir Matallah, Nahed Ghodhbane [31] where they modelled a hybrid system in Tunisia and the LCOE obtained was \$0.26/kWh and CO₂ emission by 29% than by using DG, Olatomiwa & Blanchard [3], simulated a system for rural health care in Nigeria, and the COE was \$0.27/kWh for the location considered and the carbon dioxide reduction obtained was about 90%. The studied system was also comparable to other studies such as a microfinance institution in Nigeria by Ayodele & Mishra [32], where the COE obtained was \$0.66/kWh, and there was a reduction of 50% in CO₂. From Aghenta & Iqbal's [23] modelling of a hybrid system for a house in Benin, a COE of \$0.4734/kWh was obtained. The COE is so low for some of the studies due to the selection of economic constraints such as discount rate and inflation rate, and also due to the greater availability of solar and wind resources. The system shows low COE when these values are high. In this study, we used an accurate inflation rate based on the World Bank data for Somalia.

The control strategies used in the study by Ansong[33], Sigarchian[34], Rezzok, and Mellit [35] were Load Following, but a study by Blanchard [3] utilized by Cycle Charging. C.K. Seng [24] performed a study on both CC and LF and concluded that the CC strategy obtained the most efficient result. All the papers studied either used CC or LF strategy. This study used a Combined Dispatch strategy and compared the results obtained with that while using CC and LF strategy whereby CC and LF control strategies were giving higher COE than the CD strategy. CD is also more environmentally beneficial than the other two methods as the emission level were lower due to the efficient use of generator.

If more studies are done on CD technology, the previous studies may achieve even better results. It should be noted that the wind data obtained from Global Wind Atlas contains multiple constraints, and the associated uncertainties could lead to slightly incorrect wind speed data. Zahoa & Guo [36] used a more accurate model, which was a combination of numerical simulation, statistical modelling, and optimization. Accurate wind data will make the system more realistic. Also, a tracking system was not included in this study, and a research lead by Rahimi [37] found that using hybrid wind sun-tracking improves the performance of the PV cell by 49%. The load profile used in this study was estimates of load patterns, which will change for individual houses, schools, and the health clinic. Aghenta [23] used B-opt software to determine the energy consumption in a house in Nigeria accurately and then model the hybrid system. Previous studies [38] [39] [40] show that the load consumption, Discount rate, capital costs, solar and wind resources, Fuel cost all have an impact on the micro grids. From the sensitivity analysis in Kabaal, it is seen that the increase in wind speed has a high impact on the COE and NPC of the system in this location as the wind turbine performs better.

4. Conclusion

The study shows that Somalia has excellent wind energy potential, especially in the coastal regions. Still, access to electricity in Somalia is very low. Moreover, the cost of mains electricity in Somalia is high ranging from \$0.5 to \$1.50 per kWh. So, it is assumed that most poor people in this country cannot afford this high price. Apart from the high cost of electricity, the study also identified the lack of reliable sources of electricity in health clinics and schools in regions of Africa. The literature even found that unreliable electricity causes child mortality and maternal mortality. Most remote places use diesel generators for electricity as grid extension to rural regions is very expensive. The use of diesel generators also emits a large amount of carbon dioxide and other pollutants.

This paper presents a solution to tackle the high cost of electricity, the unreliability of power and pollution. An off-grid hybrid system configured as a Wind-PV-DG-battery was used in this study. A total of four locations in Somalia were selected for the study (Kabaal, Ceel Burr, Saakov, and Baki). Different configurations with PV- Wind- DG and battery were analysed under different solar, wind, and temperature conditions. The load used in this study comprised a health clinic, school, 200 households, and two water pumps to provide water supply to the community. The load calculation was carried out by the analysis of electrical equipment used and the daily hours of operation. The total load of the system selected consisted of 195.03kWh/day primary load and 5.5kWh/day deferrable load. The software used in this analysis was HOMER. This modelling software optimizes different configurations to give the cost-optimal solution with zero outages.

The study identified that Kabaal and Ceel Burr were located in the region of high wind potential, and a hybrid system consisting of Wind-PV-DG-Battery was the best solution. Kabaal and Ceel Buur have COE of \$0.297/kWh and \$0.326/kWh, respectively. NPC of the locations are \$330,440 and \$363,180. For the less windy locations, Saakov and Baki, the hybrid system configuration of PV-DG-Battery was the best solution having COE of \$0.353/kWh and \$0.333/kWh, respectively. Saakov and Baki have an NPC of \$392,651 and \$371,076. The study also identified that Combined Dispatch offered the best control strategy for the locations since it gives the lowest COE compared to the LF and CC strategies. Also, the CD had lower carbon emission than CC and CF strategy. Emissions of CO₂ from a stand-alone diesel generator system were 74,306kg/year, and the hybrid systems identified reduced this by 80% in Kabaal, 78% in Ceel Buur, 60% in Saakov, and 68% Baki. The study also showed that the economic performance of the system is susceptible to wind energy resource, load growth, and discount rate. So, to conclude, this study shows how effective hybrid systems can be in remote rural regions. The study also provides information on how effective control strategies help to improve the system. Due to its low cost of energy, reliability, low emission, more studies in this field can help to improve the electrical scenario in remote places across the globe.

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Abbreviations

CC	Cycle Charging
CD	Combined Dispatch
COE	Cost Of Electricity
DG	Diesel Generator
E	Energy
GHI	Global Horizontal Radiation
GWA	Global Wind Atlas
IRR	Internal Rate of return
LCOE	Levelized Cost of Electricity
LF	Load Following
MPPT	Maximum Power Point Tracking
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
PV	Photovoltaics
RF	Renewable Fraction
ROI	Return of Investment
SC	Salvage Cost
SOC	State of Charge

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