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Technical and Economical Investigation of a Centralized and Decentralized Hybrid Renewable Energy System in Cadaado, Somalia

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Abstract: The purpose of this paper is to investigate the feasibility of a wind–solar hybrid system on and off-grid power system for electricity generation at a selected location in Somalia using the renewable energy optimization software HOMER. The simulation model was successfully applied to find the best simulation results based on the energy-efficient system for the specific load. The technical and economic performance of an on-grid and stand-alone combination of 25 kW wind power and 60 kW solar photovoltaic was investigated. Since the city of Cadaado has not yet installed its own standard modern electricity grid and due to the great need to reduce energy costs in Somalia, a feasibility study was conducted on how to supply electricity to a sampled residential consumption. Based on the basic characteristics of renewable energy sources in central Somalia, the on-grid wind and solar photovoltaic systems could be economically feasible.

Keywords: cost of electricity; hybrid renewable; optimal configuration; semi-urban electrification; Somalia; HOMER

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1. Introduction

Electrical energy resources have been among the most important research topics of humanity for centuries. People's interest and need for electricity after the industrial revolution has continued until today. The rapid development of technology increases the demand for electrical energy day by day [1].

In Africa, 650 million people do not have electricity, nor access to power, nor access to an industry [2]. If they had other means and capital, they would be very productive people. It is important that we do not lose sight of these people in our bid to grow economies and become more industrialized. One of the toughest problems in the world is as follows: how do you bring people out of extreme poverty without wrecking the climate in the process [3]? Conventional wisdom says it will require the burning of enough fossil fuels to cancel out any progress the developed world makes on emissions. However, in rural Somalia, a small experiment and simulation can be observed to see if it is possible to have green energy, decreasing the environmental catastrophe as well.

Somalia does not have enough generation facilities to provide electricity access to every household in the country [4]. The Somalians who have no power are based purely in rural areas. According to the latest report of IRENA [5], 34% of the total population has access to electricity [6]. The average electric power consumption per capita in Somalia is 20 kWh per year, which is less than 1 kWh per day for a household of five people [6]. This annual electricity consumption per capita is significantly lower than Nigeria and Sudan, which as of 2019 were 184 kWh per year and 395 kWh respectively, whereas the U.S.A. consumption per capita was 12,235 kWh in 2020 [7]. Once electricity is provided, the economic empowerment of people significantly increases [8]. With millions of rural

Somalians still disconnected from power, a small green energy startup attempts to bridge the gap. Many villages can be operated at the microgrids level, and they can generate power from renewable energy sources; that energy can be stored in batteries. In the 1990s, the price per watt of a solar panel was USD five or six. Nowadays it is USD 0.20 [9]. This has opened up a huge opportunity in Africa to deliver energy. Schools and homes need electric light and internet service. Agricultural labor, such as maize milling, does not have to be done by hand anymore. Electric pressure cookers eliminate the need to chop down trees or burn charcoal to make meals. All of these things raise the standard of living.

What if wind, solar and grid technologies could work together on one site? This means less impact on the environment, better integration of fossil-free energy into the power system, and reduced costs [10].

Due to the intermittent nature of solar power, it alone cannot meet 24 h load requirements [11]. Similarly, a stand-alone wind power system cannot generate electricity for a significant part of the year because of low and high shear wind speeds. These weaknesses of renewable energy sources can be overcome by creating a hybrid energy system consisting of at least two different energy sources that complement each other. It usually consists of a conventional generator powered by fossil fuel and a renewable energy source, such as wind, photovoltaic or a combination of photovoltaic and wind. Since at least one of the hybrid energy systems in the plant will continue to produce energy, the total energy production capacity in the plant will also increase. The microgrid and solar energy production complement one another perfectly: there is more solar production in summer and during the daytime, and the grid can supply energy during the night time. Together, they ensure smoother generation and balance out the electricity fed into the grid; it uses a shared grid connection point; the battery plays a vital role. The grid is operated at 50 Hz. Conventional fossil-fuel power plants are able to balance frequency deviations to ensure a stable power supply. Due to the growing share of solar power in energy production, more flexibility is needed, which batteries can provide. The battery not only stores electricity generated by the wind or solar, but it also keeps the grid frequency stable at 50 Hz [12]. The battery is able to react to any imbalance between electricity production and demand—in a split second. If the frequency is too high, the battery takes power from the grid to charge itself up. If the frequency is too low, the battery discharges power into the grid. Power fluctuations caused by wind turbines can only be balanced with conventional power plants or battery groups. Sufficient spare capacity should be reserved for unexpected sudden losses in wind farm production due to network failure or power plant shutdown due to excessive wind speed. In order to keep the system frequency within the appropriate limits, it is necessary to increase the technical capabilities of the spare conventional power plants or battery groups [13].

Many studies have been conducted on the performance and economic feasibility of hybrid energy systems and hybrid power systems have been found to exhibit lower production costs and higher reliability than systems using only one energy source. There are several studies in which the integration of solar cells and wind power generation plants into power systems is evaluated in terms of technical and economic factors. In these studies, the factors to be considered in the integration of wind power plants into power systems are evaluated in different categories, technologies, and from different perspectives. Some studies on hybrid systems published in this way are summarized below.

In the work of Wu et al. [14], the capacity of the diesel and photovoltaic (PV) power plant was optimized to meet the electrical load demand of an independent region. The battery capacity, area of 15 PV systems, and the fuel consumption of the diesel generator were optimized to minimize the life cycle cost of the system in the proposed hybrid system. For this purpose, a power management strategy was designed, and an effective metaheuristic technique was used in the study. From the results obtained from the study, it was concluded that the battery–diesel-photovoltaic system is environmentally and economically advantageous compared to a single PV system or a single diesel system for the studied region.

Diaf and friends [15] investigated the optimal design of a hybrid wind/PV system considering various environmental conditions. It was reported that the energy cost for hybrid system configurations is largely dependent on the renewable energy potential. As the locations studied have almost the same solar energy potential, it was found that the wind energy potential strongly affects the energy cost.

Eteiba et al. [16] investigated the feasibility of a PV/biomass hybrid renewable energy system with battery support status to provide the demanded power for a small village. In the study, the optimal capacity was determined using four different meta-heuristic techniques. It was found that the firefly algorithm achieves the minimum computation time and the best performance among other investigated algorithms.

In the study of Le et al. [17], the integration of large-scale wind power generation plants into the grid provided numerous benefits but caused serious voltage fluctuations and stability problems that need to be resolved. For this purpose, the optimization of energy storage systems with renewable energy sources is discussed and the actual findings are stated.

Many literature references have discussed the economic cost analysis of hybrid power system combinations, using various software, such as TRNSYS (a transient systems simulation) [18,19], NEPLAN [20,21], EnergyPLAN [22,23], H2RES (energy planning of islands and isolated regions) [24,25], RAPSim [26], RETScreen [27], and SolSim [28]. In addition, there is a lot of literature on design and analysis in the context of renewable energy power generation using HOMER software [29–32].

In a hybrid system to be investigated using Homer software, the power management and capacity of each component must be optimally determined to have a reliable and cost-effective power system. Using Homer software, it is possible to create different hybrid power systems, such as solar/wind/diesel, solar/hydrogen, wind/hydrogen, solar/wind/hydrogen, solar/wind/battery/hydrogen, solar/battery, wind/battery, solar/wind/battery, solar/diesel, solar/diesel/battery, and wind/diesel sources are used together.

In this study, the most suitable type and size of a hybrid system based on wind and solar energy were investigated for the city of Cadaado in Somalia. The hourly and daily electrical load profile values used in this study were taken from the work of [33,34]. In addition, an economic and technical feasibility study of the solar–wind hybrid energy system was performed using wind and solar data values. Furthermore, the contribution of solar, wind, and storage unit to energy production, energy cost, and total system cost was investigated for different hybrid systems. Finally, the sensitivity analysis of the on-grid and off-grid hybrid power system was processed in multiple optimizations, each with a different set of input assumptions. The aim of the sensitivity analysis is to examine how various sources of uncertainty impact the model and contribute to the model's overall uncertainty. This system was modeled in the HOMER simulation tool for comparison purposes based on economic energy analysis in order to fill the gap between the real-life operation and the simulation process of hybrid renewable energy systems projects.

It should be noted that there are no comprehensive feasibility studies on the optimal design of hybrid networks in Somalia's different climatic conditions in the literature and that the component and fuel prices of previous studies are not up to date. To fill this research gap, the conditions of the Cadaado region of Somalia, which has climatic differences, were examined. In addition, previous studies did not consider the possibility of selling electricity to the grid. Although the grid in Somalia is not functional, it was shown that if a healthy grid can be established one day, profits can be made from the electrical energy sold to the grid. In some of the previous studies, economic parameters, such as inflation and interest rate, were not applied based on the reality of the Somali economy. This study performs the optimization problem based on current data.

The rest of the paper is organized as follows: Section 2 describes the selected site and renewable energy potential. The design specifications of the two models are detailed in Section 3, while Section 4 contains the results of the data analysis in two sections and a discussion of the results. Section 5 allows general conclusions to be drawn from specific observations.

2. Selected Site and Renewable Energy Resources

Many studies in the literature [35,36] have raised scientific awareness of the possibility of high renewable energy availability in Somalia. Wind and solar are the country's main current renewable energy sources that can generate electricity. The combination of a diesel generator and two renewable energy sources are discussed in detail in the following subsections. Somalia is located in the Horn of Africa and has a total area of 637,657 km^2 (246,201 sq mi) and lies between latitudes 2° S and 12° N, and longitudes 41° and 52° E. Somalia receives an average of 2900 to 3100 h of sunshine per year, and Somalia's total daily radiation is one of the highest in the world [37]. The solar irradiance distribution all over Somalia is shown in Figure 1. Two different solar radiation zones can be identified; the northern and southern zones have different solar radiation range. Solar radiation in both zones can be roughly grouped as follows: 6.4–7.0 kW/m^2/day with about 12 h of sunlight in the north, and 5.5–6.4 kW/m^2/day in the south with about 11 days of sunlight hours per day [38].

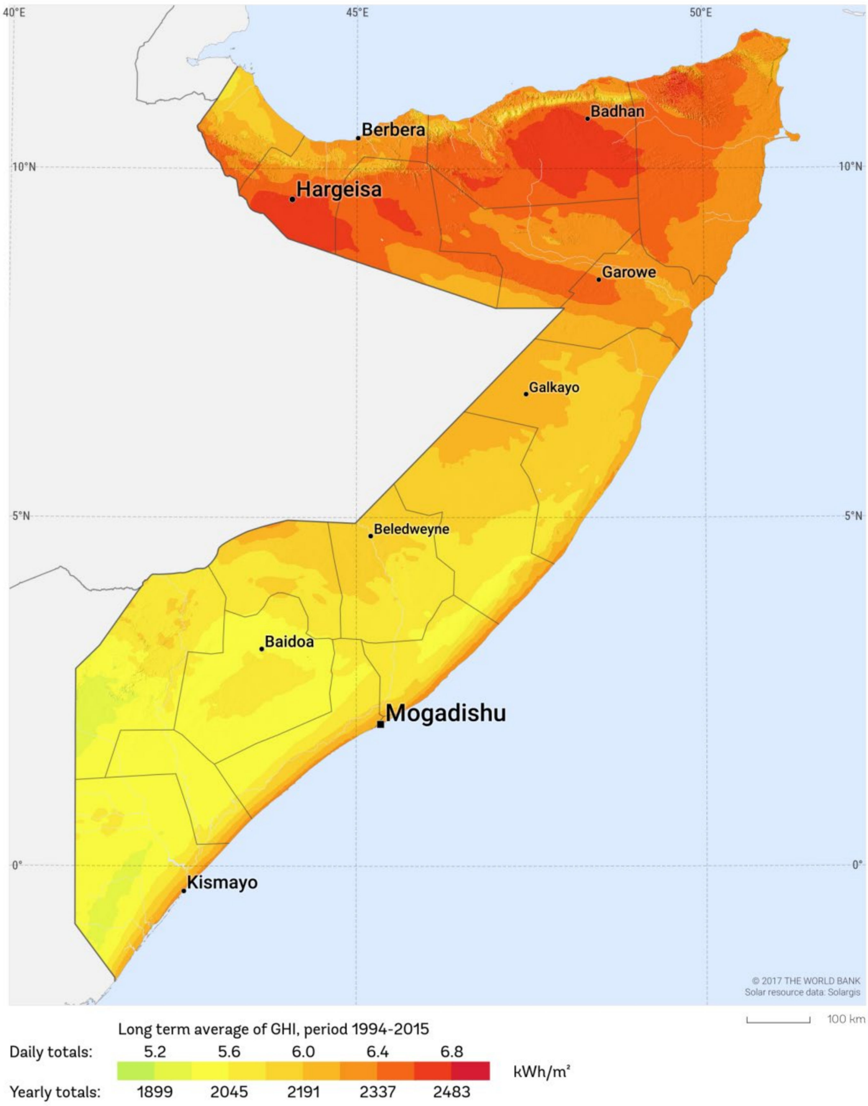

Figure 1. Solar radiation map of Somalia [39].

For this study, a site in Cadaado city in the Galguduud region of Galmudug state in central Somalia, 600 km outside capital Mogadishu is selected. This place is located on latitude 6°07′ N and longitude 47°02′ E and at an elevation of about 311.75 m above sea level. Although the efficiency of the hybrid energy system depends on many parameters, it varies according to the material, production method, wind speed, and solar radiation, which are site-specific values that vary frequently. The monthly average daily global solar radiation values for the province of Cadaado were taken from NASA Surface Meteorology. Due to the monthly variation in global solar radiation, the monthly energy output value from solar PV differs every month. The clearness index is evaluated as the ratio of total solar radiation to total extraterrestrial radiation for the corresponding month [40]. The minimum value was observed in February and the maximum value in July. The monthly clearness index values varied between 0.58 and 0.68, and the fluctuations can be seen in Figure 2. Even the coldest months, January and February with temperatures around 20 °C, are the best months for energy production in Cadaado. In summer, the temperature is around 33 °C and it receives an average of 370.6923 h of sunlight per month. May and October are the rainiest months with 179.95 mm of precipitation. The weather mostly be considered clear.

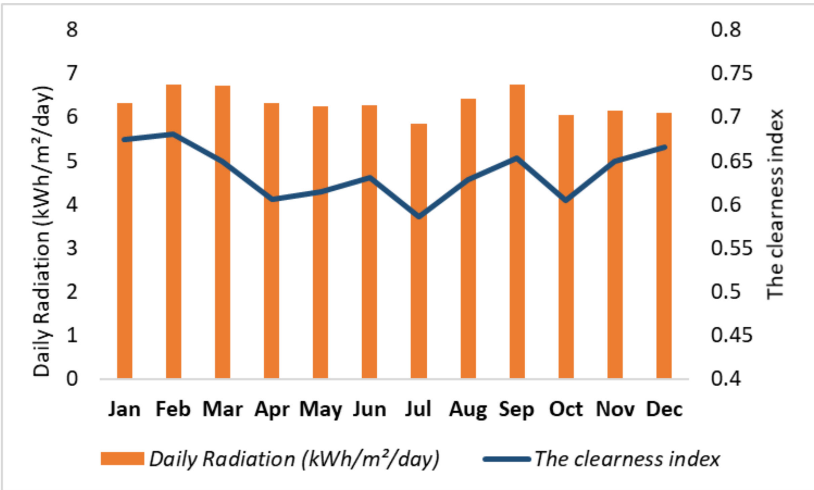

Figure 2. Averaged solar irradiance and clearness index for the selected area from Homer software.

Monthly average and hourly wind speed data for the city of Cadaado obtained from NASA are shown in Figures 3 and 4, respectively. It is noticeable that the maximum measured wind speed is in the period of June–August and the average annual wind speed exceeds 8 m/s, and it is the lowest in April. Based on wind speed data, it is proven that in Cadaado, wind energy is available most of the year and can be used to generate energy by reducing the use of diesel fuel.

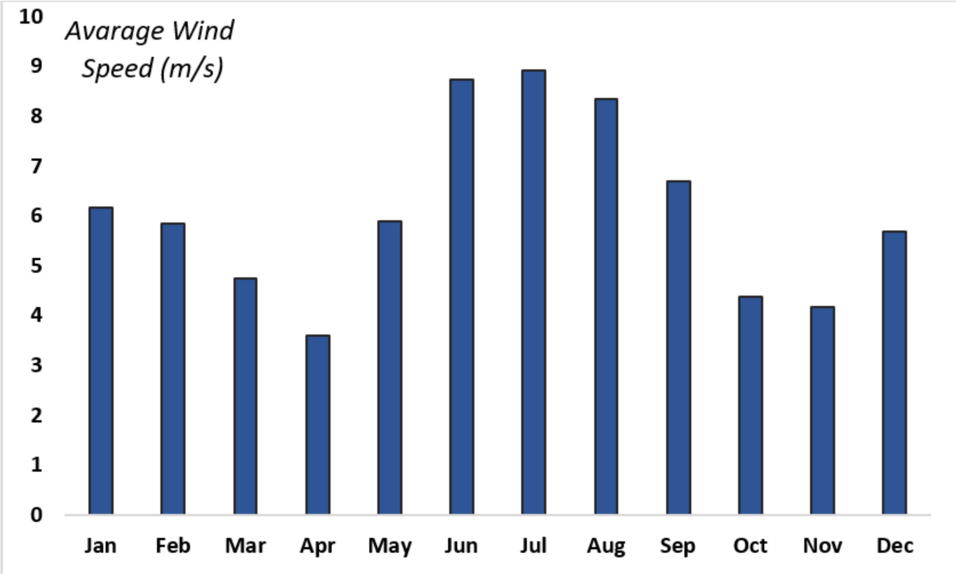

Figure 3. Monthly variation of the mean wind speed.

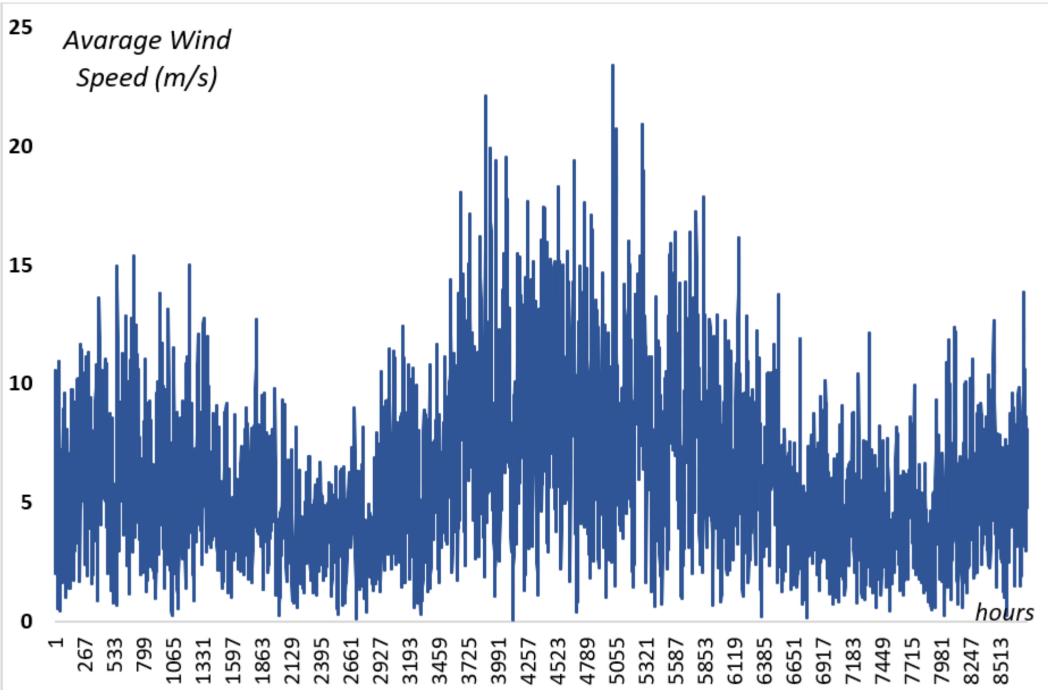

Figure 4. Hourly variation of the mean wind speed.

3. Electrical Load and Hybrid Energy Components

With hybrid energy systems, the electricity demand can be met by utilizing renewable energy sources for 12 months of the year. The electricity generation of photovoltaic solar panels and wind turbines varies according to climatic conditions. Therefore, they are not a very rich source of energy production on their own. In many applications and studies, planning and sizing of renewable energy systems, such as wind–solar, have been studied [14–17]. A hybrid electric system combines wind or solar photovoltaic technologies or can offer many advantages by using it over a single system. In the summer months, when the sun's rays are strongest and brightest, and the wind speed is low. In winter, when there is less solar energy, the wind speed is high. In cases where two energy sources are insufficient, energy continuity can be ensured by connecting a battery or generator to the system.

The average daily electricity consumption used in this study was found to be approximately 26 kWh for each household in the research conducted by [33,34,41]. A typical daily electricity consumption pattern for the selected location is shown in Figure 5. Electrical energy consumption reaches different values both in seasons and in different time periods during the day. The consumption on weekdays increases compared to weekends, and the consumption between 06:00–09:00 in the morning and 17:00–22:00 in the evening is higher than other times of the day. In this study, the predefined ensemble load profile was used in the HOMER program. The daily electricity consumption of the community is taken as 2612 kWh and it was observed that the peak power value during the day is 426.49 kW.

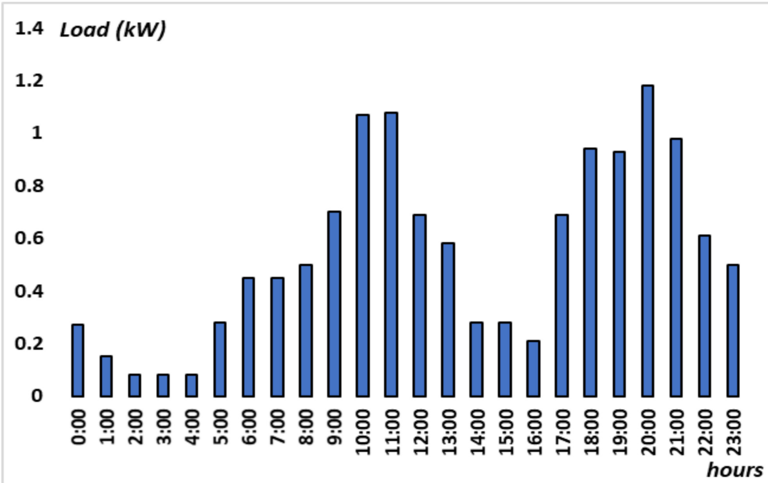

Figure 5. Typical daily electricity demand profile of the household in Somalia.

Apart from this, it is assumed that there is a 15% difference between the daily electricity consumption profiles on weekdays and weekends. The simulation analysis is performed for the area assumed to have an electrical load of 2612 kWh/day with and without reliable grid access. A total of 100 households can benefit from this facility at an average consumption rate of 2.6 kWh per day.

The feasibility and optimization study is compared with and without a grid system which consists of diesel generators, battery packs, and wind and solar energy conversion systems. The schematic diagrams of the on-grid and the off-grid system are shown in Figures 4 and 5. Detailed specifications of each used equipment in the plant along with the required input data are provided in the next sections.

3.1. Grid System

In this study, it is assumed that consumers will receive electricity from the grid at a price of 0.12 USD/kWh and if the plant has excess electricity and if the owner of the power facility sells that electricity to the grid; the price is assumed to be 0.08 USD/kWh. Unfortunately, currently, Somalia has no laws regulating the electricity industry. In the country, the cost of electricity is regulated by the Somaliland Energy Regulatory Commission. The cost of electricity in Somalia is amongst the highest in the world, at USD 0.5–1 per kWh [42]. Off-grid renewable energy can help to address the electricity affordability issues.

3.2. Photovoltaic and Converter

The cost of the solar modules is highly dependent on the power requirements, retailer, technology, brand, and size of the solar panel. The system consists of a 60 kW PV module that has 72 cell mono-crystalline and can produce a maximum of 1500 VDC. The typical lifetime of commercial PV panels is about 25 years, and at the end of this period, many panel companies give an 80% performance guarantee. The PV system's initial investment cost is taken as USD 2000 per kW.

The effects of temperature on solar panels were factored into the derating modeling factor. In order to take into account factors, such as wiring losses, shading, contamination of panels, and aging, the derating factor was taken as 96%, ground reflection was taken as 20% and no tracking system was included in the PV system. In addition to these losses, losses in DC/DC converter and DC/AC inverter are also taken into account for the inefficiency calculations.

Since the alternating current is required to convert the generated DC electricity to AC electricity and to be compatible with the grid, an inverter is added to the system and the DC voltage is converted into a 220 V, 50 Hz sine wave.

The easy and quick response Solectria String Sizer Tool [43] was used when choosing the size of the converter, and it was found that an on-grid PV inverter system is created and modeled PVI 50 KW inverter model can provide the required AC power output. The cost of the inverter is taken as USD 1000, the average efficiency of 96%, and the lifetime of a unit is 10 years.

3.3. Wind Turbine

Wind power has become an increasingly preferred energy source for reasons such as being a domestic energy source compatible with human health and the environment, being inexhaustible, saving fossil fuels, and decreasing the installation and operating costs day by day [44,45]. In this study, the EOX S-16 type wind turbine in HOMER's database was used and the technical data for this turbine are as in Table 1. The region's wind energy data were taken from NASA's database, which was integrated into the HOMER program. The turbine performance was analyzed by using the actual data obtained from manufacturers, and the power curve of the selected turbine is shown in Figure 6.

Table 1. The technical specifications of the selected wind turbine.

Characteristic	Specification
Power Capacity	25 kW
Rated wind speed	Average annual wind speed: 7.5 m/s (27 km/h) (17 mph)
Operating temperature	−20 °C to 40 °C (−4 °F to 104 °F)
Cut-in wind speed	2.75 m/s (9.9 km/h) (6 mph)
Cut-out wind speed	20 m/s (72 km/h) (45 mph)
Blade Length	7.6 m (24.9 ft)
Hydraulic tower—hub height	16.8 m (55.1 ft) or 23.8 m (78.1 ft)

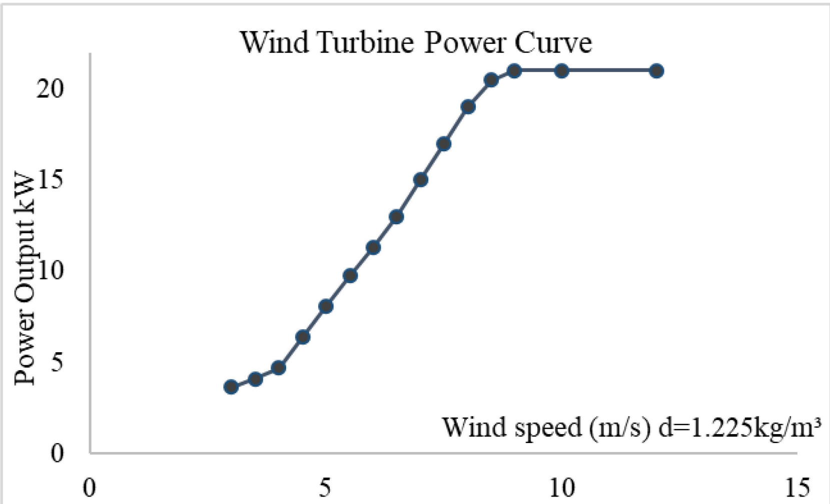

Figure 6. The power–speed curve of the wind turbine.

3.4. Diesel Generator

In this study, there are CAT brand two diesel generators with 160 kW and 44 kW capacities modeled, and their costs are USD 30,000 and USD 75,000, respectively. The price of diesel generators decreases inversely as their capacity increases, and the cost per kW of generators with larger capacity decreases. The large generator is assumed to be used for base load generation, while the small generator is used to meet peak demand. Various technical reports of CAT brand generators were obtained from the manufacturer's data specification sheet [46]. The lifetime of generators is estimated at 40,000 h of operation. Although the large-capacity generation of the generator was chosen, the main purpose of this study is to find a commercially, cost-effective, and technically viable alternative to reduce the dependency on diesel generators. Therefore, optimized use of batteries was proposed, which can economically replace the use of diesel due to the intermittent nature of renewable energy sources. HOMER assumes that a 160 kW generator consumes 10 L, 12 L, 15 L of fuel per hour at 50% load, 75% load, and full load, respectively, while 440 kW generator consumes 15 L, 16 L, 17 L of fuel per hour at 50% load, 75% load, and full load, respectively. In this study, the price of diesel fuel was taken as 0.8 USD/L. The produced power/efficiency and fuel consumption curves for both generators supplied by HOMER are shown in Figure 7.

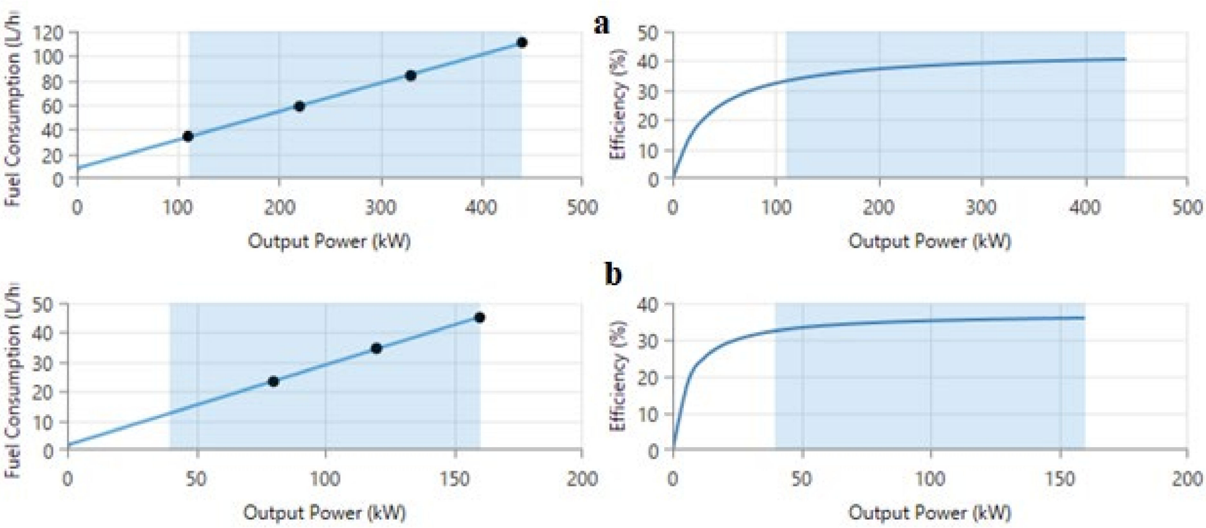

Figure 7. The fuel consumption and efficiency curves of 440 kW (**a**) and 160 kW (**b**) diesel generators.

3.5. Battery

ESS 850V batteries with a capacity of 471 Ah were used in the simulation. The cost of a selected single battery is assumed USD 900, and a similar figure was taken as a possible replacement cost. The operation and management (O&M) cost is considered negligible and thus was set to 0. Because of the high battery prices, the battery cost has a very significant effect on the net present cost. If batteries are not used for backup power, the cost of renewable energy systems is reduced. The battery can be selected at large power as well as at small power; however, as soon as the power increases, the total costs will increase significantly. The technical data and capital costs for the subsystems used in the simulation are described in Table 2.

Table 2. The details of different system components used in this study.

	Diesel Generator_1	Diesel Generator_2	Solar PV	Inverter	Battery	Wind Turbine
Capital Cost ($)	75,000	30,000	2000	1000	900	9000
Size (kW)	440	160	60	30	471 Ah	25
Replacement Cost ($)	70,000	28,000	1000	1000	750	7000
O&M cost	0.1 USD/h	0.09 USD/h	USD 10	0	0	USD 200
Model	CAT 550 kVA	CAT 200 kVA	SMA-60	Ideal-30 kW	ESS 100 kW/400 kWh	EOX S-16
Lifetime	40,000 h	40,000 h	25 years	10 years	20 years	30 years

3.6. Financial Assumptions and Simulation Settings

The construction period of the project is assumed to be 2 years, and the lifetime of the project is taken to be 25 years. Although the real interest rate in Somalia has fluctuated significantly in recent years, it is not possible to reach certain information. In this study, the interest rate was determined as 11%. According to the latest available information, the inflation rate in Somalia is 4.1% [47].

3.7. HOMER Software

It was observed that deterministic data are used in the calculations of many systems established with renewable energy sources, and cost analyses were made according to annual average values. The stochastic changes in the nature of renewable energy were not added to the system [48,49].

In the present study, a hybrid system was modeled with HOMER software in order to meet the energy demands of the city of Cadaado, and the system is compared by making economic–technical analyses in accordance with the availability of the grid.

HOMER offers design options to the user by modeling the behavior of the energy system, the cost of installation, the income and expenses that may occur during life, resources which should be used in various situations, within the framework of technical and economic values. Among the software that can model hybrid systems, HOMER software comes to the fore due to reasons such as ease of use, the closeness of the results to reality, and more efficient calculation of resources. A lot of studies have been performed on the application of hybrid systems to examine the economic and technical feasibility analysis of various hybrid energy systems [28–31]. More detailed information regarding Homer software can be found in [50].

Moreover, it is important to validate the models developed using the HOMER software for their accuracy, as a different error range was found when performed using a weather database, different system, locations, and components compared to all the articles reviewed. For this reason, the accuracy rate of the existing hybrid energy systems models in the literature is taken as a reference to determine whether the error is acceptable or not, and to ensure that the output is reliable. The validation is done by simulating a system with approximately the same input parameters: features, output power, and components and comparing the output with real system data [51]. For system validation, the literature results from HOMER contain an error of 5.52% for monthly energy deviation [52].

In this study, the effect of time-varying inputs, such as electric charge, wind speed, and solar radiation, is also modeled by using the HOMER program. For each of these inputs, 8760 values (hourly data) are created for one year in the program. The data that need to be imported into the HOMER program are load, renewable resources, characteristics and costs of system components, and various information about optimization. These data are obtained from literature research and manufacturers. As a result, it is decided to plan the most suitable system model.

4. Findings and Discussion

Hybrid energy systems for the city examined within the scope of the study were examined in two different aspects as off-grid and on-grid systems. PV panels and wind turbines are used to obtain renewable energy in the on-grid system. In addition to the wind turbines and the PV panels, the batteries for energy storage, the diesel generators in cases where the electrical energy required by the system could not be met, were used.

4.1. Design of Stand-Alone and Hybrid Renewable Energy System

In this system, 23.8 m high 1140 kW wind turbine, 219 kW flat type PV panel, 58.5 kW converter, 160 kW, and 440 kW two diesel generators and 256 pieces of 400 kWh lithium-ion battery were selected. The schematic diagram of the stand-alone hybrid power generation system is shown in Figure 8.

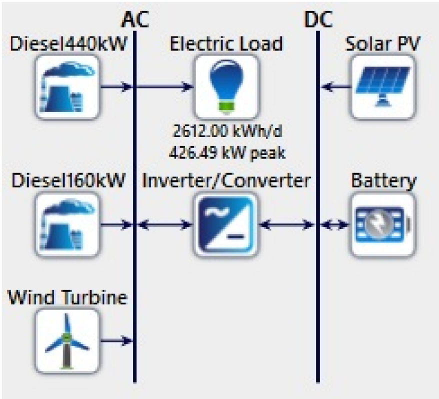

Figure 8. Schematic diagram of the off-grid hybrid system.

In this scenario, most of the electrical load of the selected site is covered by solar PV. With HOMER, the most suitable generator power was found to be 160 kW. Using the values in Table 2, the NPC was found to be USD 1.35 million and the levelized cost of energy was found to be 0.108 USD/kWh for the project life of 25 years. Annual fuel consumption is 11,308 L/year and fuel cost is 118,342 USD/year, specific fuel consumption is 0.304 L/kWh and average electrical efficiency is 33.4%. The annual production and consumption results are given in Tables 3 and 4, and the HOMER simulation results are given in Figure 9. The results reveal that the lowest wind option considered in the optimization was included in the optimal result, which allocates the wind energy to contribute more than 4% of the total electricity output, despite the almost steady availability of average monthly wind speed throughout the year. This is due to the high capital cost of the wind turbines that eventually makes them uncompetitive with other technology options considered on a utility scale. In contrast to wind, solar technology was the favorite electrical source of the total electricity output. This is due to Cadaado's excellent wind speeds all year. The figure depicts high electricity generation from the solar panels almost all year. On the contrary, wind power generation meets about 4% of consumption throughout the year.

Table 3. Annual electricity production.

ON-GRID			OFF-GRID		
Production	kWh/yr	%	Production	kWh/yr	%
Solar PV	253,687	3.73	Solar PV	94,882	7.24
Grid Purchases	376,321	5.53	Diesel_160kW	37,147	2.83
Wind Turbine	6,173,968	90.7	Wind Turbine	1,178,949	89.9
Total	6,803,975	100	Total	1,310,977	100

Table 4. Annual electricity consumption.

ON-GRID			OFF-GRID		
Consumption	kWh/yr	%	Consumption	kWh/yr	%
AC Primary Load	953,380	14.9	AC Primary Load	953,123	100
DC Primary Load	0	0	DC Primary Load	0	0
Deferrable Load	0	0	Deferrable Load	0	0
Grid Sales	5,427,497	85.1	Total	953,123	100
Total	6,380,877	100			

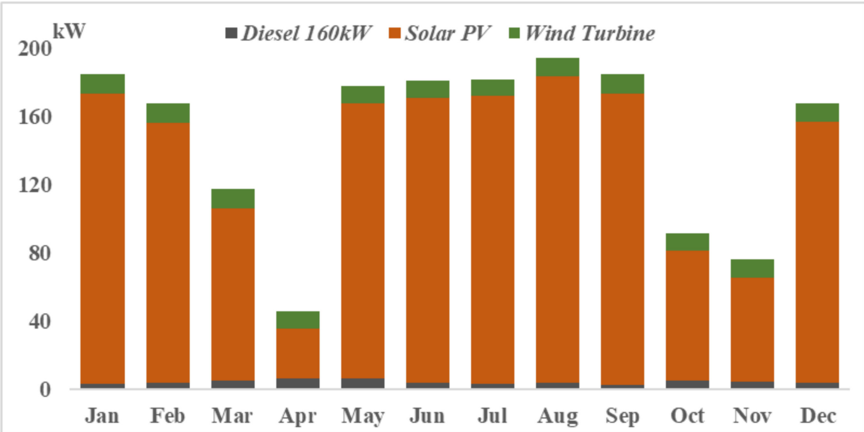

Figure 9. Monthly average electric production for the period of one year.

4.2. Design of On-Grid and Hybrid Renewable Energy System

In this system, a 23.8 m high 264 kW wind turbine, 871 kW flat type PV panel, 640 kW converter, 10 piece of 400 kWh lithium-ion battery, and grid line were selected. Figure 10 shows the renewable grid-tied energy system for electricity generation.

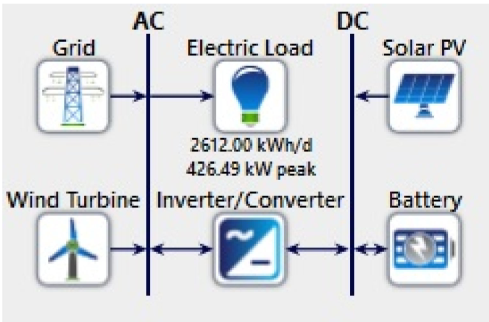

Figure 10. Schematic diagram of the on-grid hybrid system.

The installation cost is USD 4.18 million, the annual maintenance and operating cost is 315,658 USD/year, and the unit cost of the consumed energy is 0.000632 USD/kWh. It is assumed that the unit price of the mains electricity is 0.12 USD/kWh. A total of 85.1% of the generated energy, 5,427,497 kW, was sold to the grid; 3.73% of the consumed energy was produced from PV, 90.7% from wind turbines, and 5.53% was provided by the grid. The HOMER simulation results are shown in Figure 11.

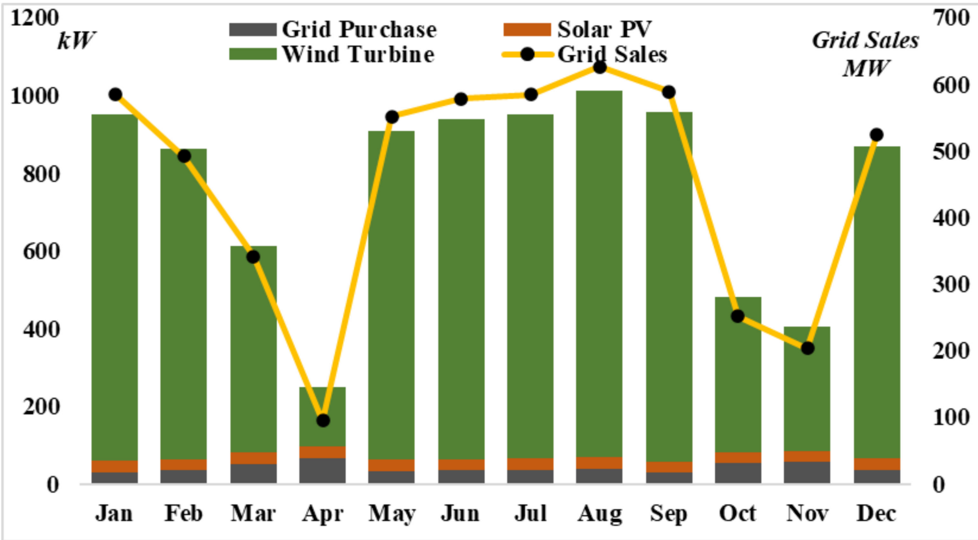

Figure 11. Monthly average electric production for the period of one year.

The fact that the wind energy generation in the grid system has a higher share in electricity generation compared to the off-grid scenario shows the effect of the electricity sales and purchase price in the grid on the energy generation strategy. It was concluded that the grid system is better in terms of economy and greenhouse gas emissions, compared to the system that produces with a diesel generator. While the renewable energy usage rate is 97.2% in the off-grid system, it is 94.5% in the on-grid system. The fact that 94.5% of the electrical power of the system is provided by solar panels shows that the grid is not needed effectively, and that Somalia is rich in renewable energy resources.

5. Sensitivity Analysis

It is important to perform a sensitivity analysis on several statistically significant variables that affect the investment cost and technical feasibility of the proposed hybrid system. In the sensitivity analysis, the change in the optimal solution as a result of the value changes in the objective function and constraint coefficients can be examined. The analysis helps determine which risks or uncertainties may affect the project more economically. By specifying a range of values in the Homer program, it can be determined how much the variable affects the results. In the study, 20 different scenarios were simulated as all variables summarized in Table 5, and the results were evaluated.

Table 5. Summary of component and resource sensitivity variables used in the simulation.

	O&M Cost	Annual Average Wind Speed	Annual Global Solar Radiation	The Interest Rate	Diesel Fuel Cost
Unit	USD/year	m/s	kWh/m^2/d	%	USD/L
Changes	2,3 times multiplier	±15	±15	6, 8, 10, 12	0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4

Considering the situation in Cadaado for the suggested solar–wind–diesel energy system, first, it is still necessary to consider O&M as a precision variable during the design phase of HOMER modeling. This is because the wind turbine and solar panel technologies are not manufactured in Somalia and there are hardly any engineers who can fix any technical faults. Therefore, if specialists are called from abroad for any malfunction in the system, the O&M cost may increase. For this reason, it was decided to consider an O&M cost that is two and three times higher than the estimated cost in the simulation.

Furthermore, it is extremely important to have a system that can accurately measure weather data, as renewable energy data are based on a satellite estimate of the region.

Accordingly, annual averages of renewable energy sources were changed with an increase and decrease of 15%.

The third variable to consider is the effect of interest rate on optimal system configurations. While the increase in interest rates increases investment costs, it affects investments negatively. The interest rate increased from 6% to 12% in increments of 2%.

The fourth variable to consider is the change in fuel price throughout electricity generation. Because the diesel generator is an important part of the microgrid system components. The prices of diesel raised from 0.7 USD/l to 1.4 USD/l in increments of 0.1 USD/l.

The cost of energy is most sensitive to the interest rate and O&M cost as the spider graph shown in Figure 12 which HOMER produced. The cost increase of the NPC is around USD 200,000 for every 2% interest rate change. For every wind turbine O&M cost multiplier, the NPC increases around USD 120,000. Consequently, investors should take out loans at the lowest rate and have a local mechanic and engineer for the wind turbine. On the other hand, a 15% decrease or increase in solar radiation and wind speed had an almost negligible effect on the total NPC as shown in Figure 12. Therefore, this is a key issue that these parameters should be taken into consideration during future investments.

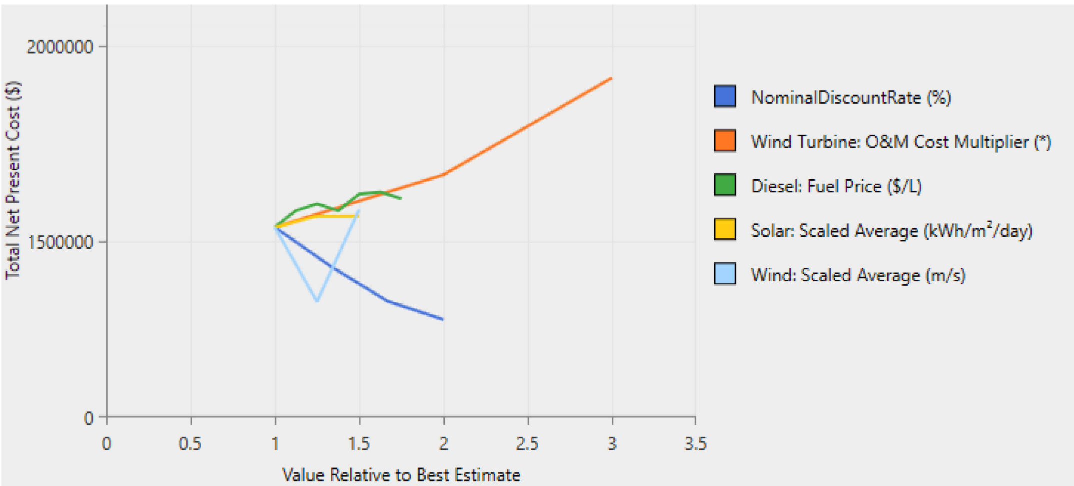

Figure 12. The spider graph of five sensitive variables.

6. Conclusions

In this study, a hybrid renewable energy system was designed in accordance with the electrical load requirement of Cadaado city, Somalia, and HOMER software was used in this design process. In this design, analysis was carried out according to the scenarios of off-grid and on-grid, and these two scenarios were compared with each other. During the design process solar energy, wind effects, and dynamic parameters of the region were taken into account.

Necessary costs were determined, and cost analyses were performed. As a result of this study, it has a positive effect on the economic cost of the networked system, compared to the off-grid system. In addition, it made a positive contribution to the environment by not using diesel fuel.

According to the simulation results, it was observed that the batteries should be used effectively in the hybrid system, and the installation cost of the selected system was USD 215,958, the operation cost was USD 18,029 and the net current cost of the whole project was USD 598,958. It was also revealed that the unit energy cost has decreased to USD 0.164.

Studies can be increased to make hybrid energy production systems, which support the use of domestic resources by increasing the rate of use of renewable energy sources, save fossil fuel consumption, and contribute positively to the environment by reducing greenhouse gas emissions; according to the results of the study, hybrid power generation systems can be applied in Somalia.

The reliable electricity supply through the use of hybrid systems can reduce poverty, improve economic growth and the standard of living of semi-urban inhabitants. The off-grid hybrid solar–wind hybrid system is well positioned to address the unique challenges presented reduction of greenhouse gas emissions, Somalia's lack of infrastructure, high costs of resident services. Moreover, the reasons such as the high rate of use of renewable energy sources in the grid system and the insufficient need for fuel use in the diesel generator made the grid come to the fore.

The optimal design for the electricity generation system was analyzed by entering the existing market values into the HOMER simulation program. Then, within the scope of sensitivity analysis, 20 different scenarios were simulated, and the results were compared.

Furthermore, using the sensitivity analysis results, the findings of this study can be applied to evaluate other parts of Somalia and communities in neighboring countries with similar fuel prices, wind speeds, and global solar radiation data as in this study.

The power estimation algorithms performed in this study can be used as an estimation method for potential different locations using different data sets. On the other hand, the proposed algorithms for sizing the optimal hybrid power generation system can be used as a tool in the design stages of hybrid renewable energy power generation systems for systems that need energy, such as electric vehicle charging stations.

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