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Assessment of Optimum Renewable Energy System for the Somalia–Turkish Training and Research Hospital in Mogadishu

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ABSTRACT

Somalia–Turkish Training and Research Hospital in Mogadishu, is only powered by diesel generator currently. In this paper, the energy demand of this hospital is utilized by determining the optimum hybrid renewable energy generating system. By HOMER, a sensitivity analysis has been made with emphasis on three significant variables such as average wind speed, present diesel price, and solar radiation. From the results, it can be said that an optimum system is the standalone wind-diesel-battery storage Hybrid Renewable Energy System (HRES) with the configuration of 1,000 kW wind turbine, 350 kW diesel generator, 250 kW power converters, and 300 batteries. Additionally, the net present cost of the optimum system is calculated to be $5,056,700 and its cost of energy is estimated to be 0.191 $/kWh. The present cost of energy for Somalia is 0.5 $/kWh. This shows that the energy cost for the proposed HRES is cheaper than the conventional one. Lastly, according to the results, it is clear that the wind–diesel–battery storage HRES seems more environment friendly than other HRESs.

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1. INTRODUCTION

Somalia is an African country in the east of Africa neighboring Kenya, Ethiopia, and the Republic of Djibouti. Somalia's weather is mostly warm and dry over the year. According to the energy statistics, it is the most advantageous country among other African countries by means of both conventional and renewable energy potentials. These potentials can be exploited through coordination with and regulations by Somalian government. Since Somalia has abundant renewable energy sources like solar energy, wind energy, and biomass energy, these sources can be used in both residential and industrial applications. Besides, it has a high potential for geothermal and wave energy sources. Although Juba and Shebelle rivers have the potential for hydropower production, nowadays, they are not being used efficiently. Wind, biomass, and solar-based renewable energy sources can be utilized by means of tolerable capital investment with current technology [1]. By expanding the use of grid-supplied hybrid consisting of both conventional and renewable energy sources and transmitting them to rural areas, welfare, productivity, and security will ensue [2]. Many companies supply their energy needs by either grid or diesel generators in Mogadishu, capital of Somalia. Diesel generators have intensively been used, especially for companies, hospitals, schools, etc. because grid is more expensive than diesel. The intensive use of diesel generators has emitted harmful gases into the atmosphere and increasingly polluted the environment and caused climate change in Mogadishu. Difficulties caused by environmental pollution and climate change can diminish employing renewable and alternative power generating systems such as fuel cells and hydrogen instead of diesel generators [3-5]. Nowadays, using renewable energy resources as a power supplier in an energy system instead of conventional ones has been more popular. The system including at least two or more power supplier is defined as a hybrid energy system. Such systems not only produce less harmful emission gases and are less dependent on fossil fuels but also need no grid connection like the conventional ones [6]. They are rather useful alternative ways to supply electricity demand to the remote and isolated places from city center when extending the gridline, which is comparatively more expensive. Besides, they can be used in the system to generate all or any given portion of the electricity demand depending on location, regional renewable energy potential, and green structure of the hybrid system. Hybrid systems must be applied with the support of an auxiliary power supplier such as a diesel generator because of their instable and discontinuous nature. Usually, diesel generators are used in the electrification of the isolated or remote consumers. As an alternative solution, hybrid energy systems can be proposed for diesel generators.

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HRESs should be preferred over diesel generators in isolated places. There are many studies in the literature related to the renewable HRES applications and their design, optimization, and parametric analysis. However, although there are many studies about HRESs, there are only few on Africa. Some of the conducted studies on Africa are summarized below. Pemndje et al. determined and compared the cost of energy of various hybrid systems for several off-grid facilities in North and Far North regions of Cameroon by integrating renewable sources and/or storage with diesel generators [7]. Orosz et al. evaluated health and education by means of techno-economic aspect for Sub-Saharan Africa. Using the meteorological data supplied by NASA, they compared conventional PV and diesel systems with micro-concentrating solar power and other related technology [8]. Malik presented a research to determine the renewable energy potential of Brunei Darussalam. He put forth the existence of renewable energy sources that could be applied in Brunei [9]. Ajao et al. evaluated off-grid and grid-connected HRES options for University of Ilorin in Nigeria using HOMER software [10]. Moreover, Himri et al. assessed techno-economic aspect of non-grid hybrid energy generation systems for a location in south west of Algeria. In that study, they evaluated the energy production, life-cycle costs, and greenhouse gas emission reduction using HOMER software [11]. Gholami et al. investigated the feasibility of renewable energy harvesting to meet the energy need of a dairy farm in Shahroud, Iran. HOMER software was used to determine the optimum system configuration. It was shown that although there was wind potential within the farm site, the most economical system would be a system consisting of a 100 kW biomass power plant and a 169 kW PV plant [12]. Nfah suggested the optimal photovoltaic hybrid systems for remote villages in Far North Cameroon using a recent iterative optimization method based on the desired annual number of generator working hours and the net present value technique [13]. Similarly, using HOMER software, Nfah et al. modeled solar/diesel/battery HRES for the electrification of typical rural households and schools in remote areas of the far north province of Cameroon [14]. Olatomiwa et al. studied the feasibility of different power generation configurations for different locations within the geo-political zones of Nigeria [15]. Lastly, Olatomiwa determined the optimal configurations of the HRES for rural health clinic application in three grid-unconnected rural villages in Nigeria [16]. Somalia–Turkish Training and Research Hospital in Mogadishu is currently only powered by diesel generator. In this paper, the energy demand of this hospital is supplied by determining the optimum hybrid power renewable generating system. Therefore, numerous HRESs in different configurations of wind turbines, PV panels, diesel generators, and battery banks are taken into account. Moreover, considering the significant data such as solar irradiation, wind speed, and diesel price, sensitivity analysis is conducted. Then, the optimum HRES is determined and at last, the optimum system is also investigated by means of its emitting gases such as CO_2, CO, NO_x, CH_4 and SO_x. These are air polluting and threatening gases. Finally, a hospital, presently fed by only diesel generators, is analyzed by means of techno-economical-environmental parameters if the energy is replaced by the hybrid renewable sources. This is the first attempt to use renewable energy for hospitals in Africa.

2. DESCRIPTION OF SOMALIA–TURKISH TRAINING AND RESEARCH HOSPITAL IN MOGADISHU

2.1. Location and population

Mogadishu is the capital of Somalia and it is the largest city with a population of 2,425,000. Somalia–Turkish Training and Research Hospital in Mogadishu has a 200-bed capacity. It is characterized by 2^{o} 2¨ North latitude and 45^{o} 18” East longitudes. The hospital has an approximate area of 13,500 m^2 with an indoor space that includes 12 intensive care beds, 14 newborn intensive care beds, 20 incubators, four operating rooms, a delivery room, as well as radiology and laboratory units. It is in service for the Somalian people since 2015. The location of the Somalia–Turkish Training and Research Hospital in Mogadishu is shown in Figure 1 [17].

Figure 1. The location of the Somalia–Turkish Training and Research Hospital in Mogadishu [18]

2.2. Energy demand of the hospital and electrification

Energy demand of the hospital is presently met by diesel generators. The average hourly load profile data are measured by technical department of the hospital. The load data are used in this paper after arranging the collected data into the monthly category for a whole year period (2017-2018). The electrical load demand is obtained from Somalia–Turkish Training and Research Hospital in Mogadishu [17]. Total energy demand of the hospital is provided by four diesel generators with a capacity of three 800 kVA and one 1,100 kVA systems. For the load data, the average daily energy demand of the hospital is around 8,000 kWh. The minimum demand load of the hospital is consumed between 22:00 and 08:00. The minimum load demand is about 200 kWh, whereas the maximum load demand is about 550 kWh. Since the climate of Mogadishu is dry, the load demand has increased by about 15 % because of air conditioning in winter. Load profile of the hospital is given in Figure 2. While the minimum load demand is about 140 kWh between June and August, maximum load demand is about 480 kWh. The data chart of the load demand is shown in Figure 3. In the figure, the breakdown of the yearly data series can be seen and accordingly, day-to-day change rate is 4 %. The 5 % time-step randomness shows variation in electric energy consumption of the hospital.

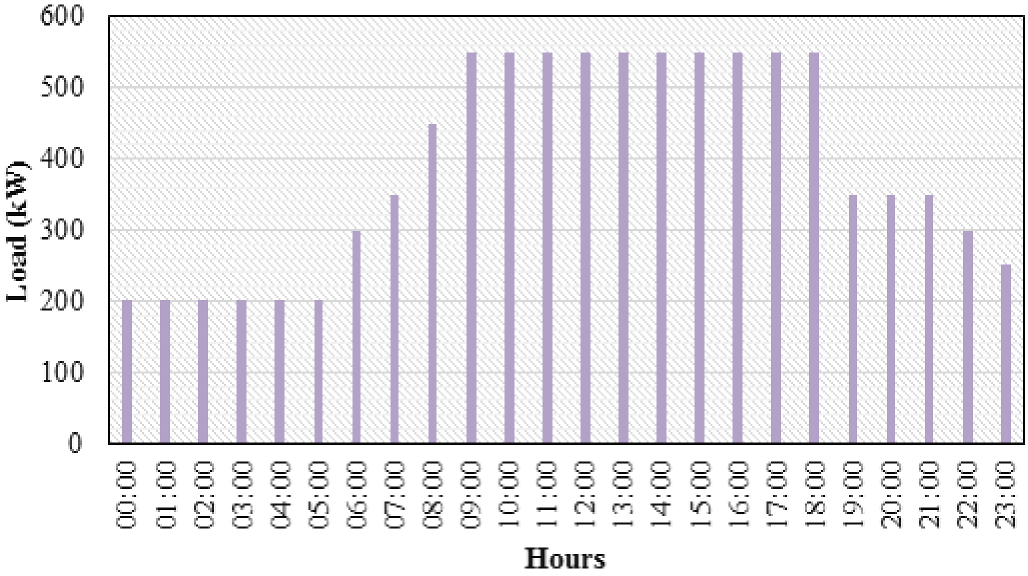


Figure 2. Load profile of the Hospital [17]

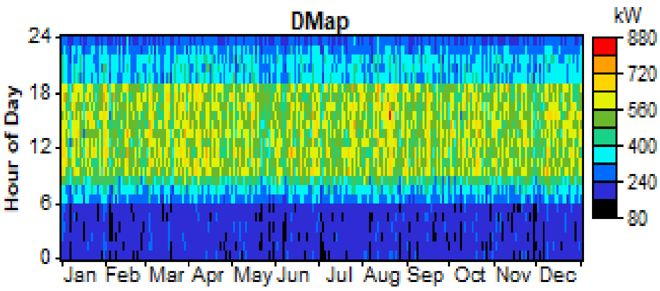


Figure 3. Data chart of electrical load of the hospital [17]

2.3. Available renewable energy resources assessment

2.3.1. Wind speed

The wind speed data for Somalia–Turkish Training and Research Hospital in Mogadishu is evaluated. The average hourly wind speed data between the years 2015 and 2017 was measured at 10 m, 30 m, and 50 m higher than the surface of sea level, as shown in Figure 4 [19].

$$V_{ave} = \left(\frac{\sum_{i=1}^{n} f_i V_i}{\sum_{i=1}^{n} f_i} \right) \quad (1)$$

where V_{ave} is the average wind speed (m/s), f_i is frequency, and V_i is mean wind speed m/s. According to Equation (1), the average wind speed is calculated at 5.63 m/s. Taking the wind speed data into account, it can be mentioned that the distribution of wind speed changes between 3.58 m/s and 7.26 m/s as the average wind speed of the region is about 5.63 m/s. While the highest wind speed occurs in July, the least wind speed appears in April. The parameter weibull k is calculated as 1.71.

2.3.2. Solar radiation

In Figure 5, Somalia's solar irradiation map is presented which shows the average yearly solar energy per square meter [20].

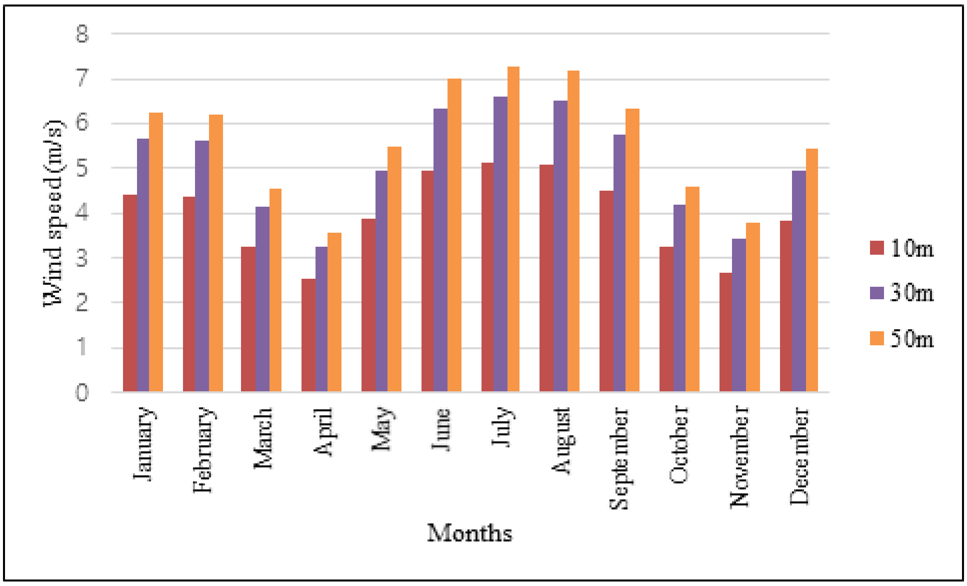


Figure 4. The monthly wind speed data in Mogadishu, Somalia [19]

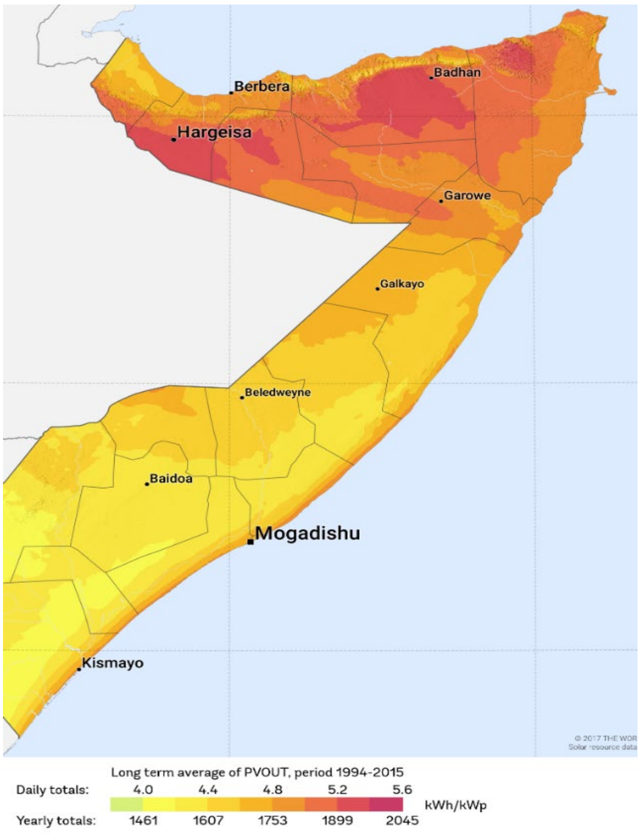


Figure 5. Global Horizontal Irradiation (GHI) of Somalia (kWh/m^2) [20]

In the figure, the area shown with red corresponds to high solar irradiation values. It means it has the highest solar energy potential. Since most of the locations of Somalia are exposed to high solar irradiation level, they are appropriate for generating electricity from solar energy. Sunlight radiation data of the location are achieved by HOMER from the database of NASA Surface Meteorology and Solar Energy [19]. For coordinates in HOMER, 2° 2¨ North latitude and 45° 18" East longitudes are used. These are the coordinates of Somalia–Turkish Training and Research Hospital in Mogadishu. Sunlight radiation data are synthesized for each 8,760 hours of the whole year by means of Graham algorithm, as a result of which hourly data are generated. The algorithm is very simple to use since it needs monthly averages and latitudes. The processed data show the realized day-to-day and hour-to-hour models. Monthly average solar radiation value is given in Figure 6. The annual average sunlight radiation value and the average clearness index are calculated as 5.645 kWh/m^2/d and 0.565, respectively. As shown in Figure 6, the monthly average daily solar radiation ranges from 3.26 to 7.61 kWh/m^2/d [21].

2.3.3. Diesel

Diesel price is about 1 $/kWh in Mogadishu–Somalia. Somalia government plans to cancel the support on type of petrol and diesel, meaning that the price of diesel may fluctuate intensively between 0.75 $/l and 1.3 $/l in the last six months of 2017. Therefore, diesel prices vary between 0.75 $/l and 2.5 $/l with an increment of 0.5 in the HOMER simulation to evaluate its effect on the system cost.

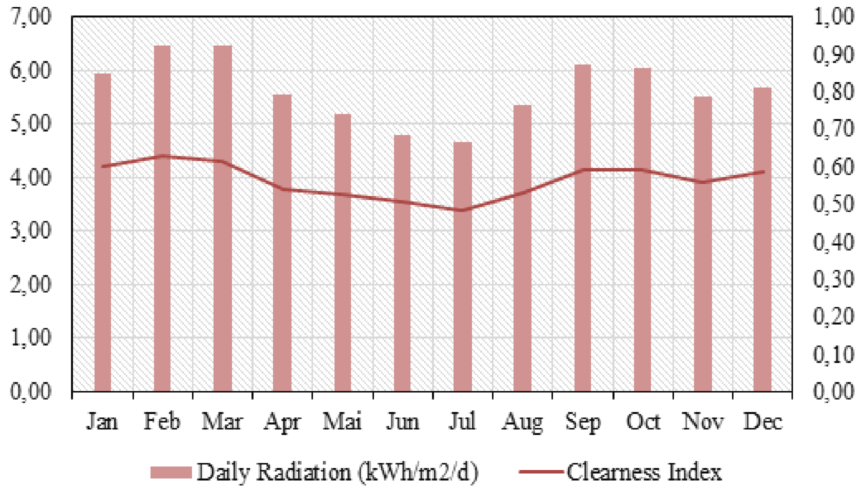


Figure 6. Monthly average solar radiation value of the hospital [21]

3. TECHNO-ECONOMIC ANALYSIS

3.1. Estimation of the annual real interest rate for Somalia

Annual real interest rate is a significant input parameter of HOMER in techno-economic analysis. The relation between annual real interest rate and nominal interest rate is shown in Equation (2):

$$i=\frac{i_0-f}{1+f} \tag{2}$$

where i corresponds to the real interest rate, i_0 the nominal interest rate which means the rate at which one can get a loan, and f the annual inflation rate. According to the previous year data, annual inflation rates i_0 = 6.09 % and f=3.22 % are used for Somalia. The real interest rate is estimated at 44.8 % using Equation (3) [22-24].

$$i=\frac{i_0-f}{1+f}=0.448 \qquad i=44.8\% \tag{3}$$

In the simulation process, the real interest rate is calculated at 44.8%.

3.2. Levelized Cost of Energy (CoE)

The average cost per energy of the generated energy is defined as CoE and can be estimated by Equation (4).

$$CoE=\frac{C_{a,t}}{E_{p,AC}+E_{p,DC}+E_{g,s}} \tag{4}$$

Total annual cost is defined as the summation of the cost of each system components and other yearly costs. It is used in the estimation of both levelized CoE and total NPC. Therefore, this parameter is very momentous [23, 24].

3.3. Net Present Cost (NPC)

NPC is the essential economic indicator of the HOMER software. It is defined as the current value of the cost of establishing and running any power system within the life cycle of the project, called as the life cycle cost. In this paper, the proposed life cycle of the project is assumed to be 20 years. For the calculation of NPC, all the systems are sorted and in order to find the NPC, all of other economic outputs are estimated. NPC can be calculated by Equation (5) [23].

$$NPC=\frac{C_{a,t}}{CRF(i,R_p)} \tag{5}$$

CRF is defined as the ratio used for the estimation of the current value of an annuity and presented in Equation (6).

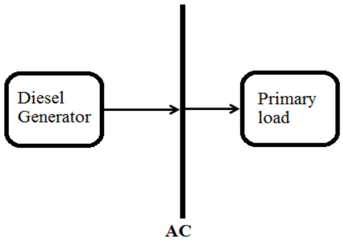
$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \tag{6}$$

As mentioned before, the lifecycle of the project is assumed to be 20 years. The annual real interest rate is 3.22 % for Somalia. It must be taken into account that Somalia government does not promote the installation energy [22]. Details of cost and technical information of the essential components of HRES are presented below.

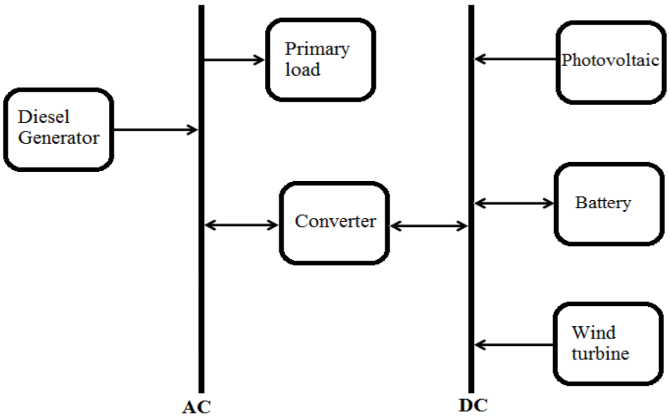
4. COMPONENTS OF THE HYBRID SYSTEM AND ITS COMPONENTS

The energy demand of the hospital has been supplied by diesel generators with a total power capacity of 3,500 kVA since the hospital started serving Somalia's people. As an alternative solution to this situation, a HRES consisting mainly of PV panels, wind turbines, diesel generator, batteries, and converter is proposed. All components of both only diesel generator and proposed HRES are shown in Figures 7(a) and 7(b). Some parameters such as size, capital cost, quantity, replacement cost, operation, and maintenance cost for the hybrid system are determined according to the references and presented in detail in Table 1.

Table 1 shows technical and economic parameters for components of the suggested HRES. The replacement cost is the cost of renewing a component after it breaks down. This cost may be different from the starting cost since not all of the components require renewing at the end of their lifetime period.



(a) Diesel power generating system



(b) HRES

Figure 7. Descriptions of HRES and Diesel energy system

Table 1. Technical and economic parameters for components of the suggested HRES

Descriptions	Specifications
PV Panel	
PV model	Sonali Solar S-300W PV panel [25]
Power (kW peak)	750 kWp
Starting cost	7,000 $/kW
Replacement cost	6,000 $/kW
Operational and maintenance cost	15 $/year
Lifetime	25 years
Wind turbine	
Wind turbine model	Fuhrlander 250 kW
Rated power	250 kW
Starting cost	$480,000
Replacement cost	$480,000
Operational and maintenance cost	480 $/year
Lifetime	25 years
Diesel generator	
Turbine model	AKSA AC 350 Diesel Generator [26]
Rated power	350 kW
Starting cost	$30,260 or 116,500 TL
Replacement cost	$24,208 or 92,716 TL
Operational and maintenance cost	0.030 $/h
Lifetime	15,000 operating hours
Inverter	
Inverter model	Solectria SGI 250 [27]
Rated power	250 kW
Starting cost	655 $/kW
Replacement cost	655 $/kW
Operational and maintenance cost	10 $/year
Lifetime	15 years
Efficiency	95 %
Battery bank	
Battery model	Surrette 6CS25P [28]
Starting cost	$400
Replacement cost	$300
Operational and maintenance cost	10 $/year
Lifetime	15

4.1. PV panel

The peak power demand of the hospital is about 656 kWp and the sizing of PV panel is determined at 20 % more than the peak power demand. Therefore, the sizing of the PV panel is selected as 750 kWp in case it supplies the demand load of the hospital. If the demand is met by the PV panel, then the rest of its energy is stored in the battery bank. Since the proposed hybrid system is a combination of PV panels, wind turbines, and diesel generators, the size of the PV panel changes from 250 kWp to 1,500 kWp with an increment of 250 kWp to determine the effect of the economic cost of the HRES. The proposed PV panel is a 72-cell polycrystalline whose output power is 300 Wp. The model of PV panel is Sonali Solar S-300W. There are 2,500 PV panels connected in series to generate 750 kWp. Costs and other technical information data of the PV panels can be found in Table 1 in detail [25-29].

4.2. Wind turbine

In Mogadishu–Somalia, another significant energy source is wind energy. Therefore, it is one of the essential load suppliers of the proposed system. Wind energy is mainly converted to other energy types by means of wind turbines. In the proposed system, wind turbines with 250 kW power will be used. Among the five different brand and model wind turbines with the same output power, the optimum one will be chosen and used in the proposed system [30-34]. Power charts of the different model wind turbines can be seen in Figures 8-12.

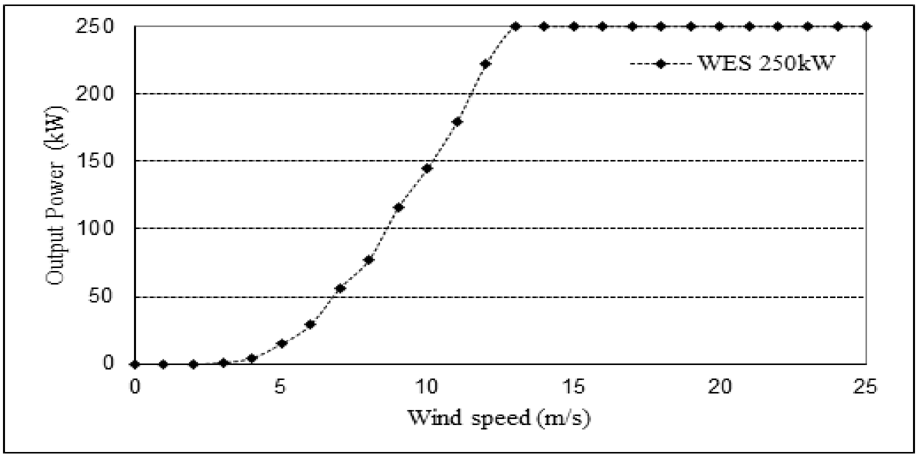


Figure 8. Power charts of WES 250 kW wind turbine [30]

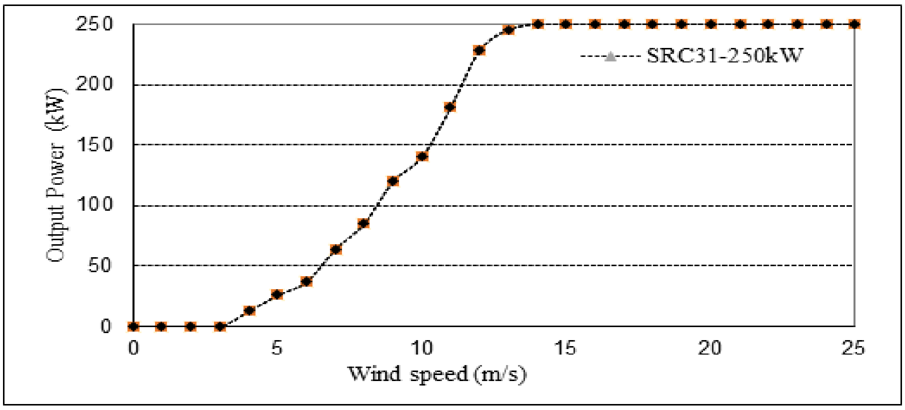


Figure 9. Power charts of SRC31-250 kW wind turbine [31]

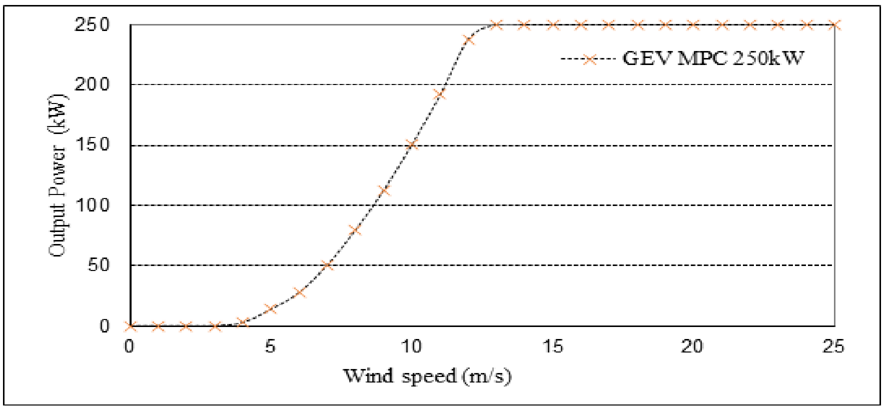


Figure 10. Power charts of GEV MPC 250 kW wind turbine [32]

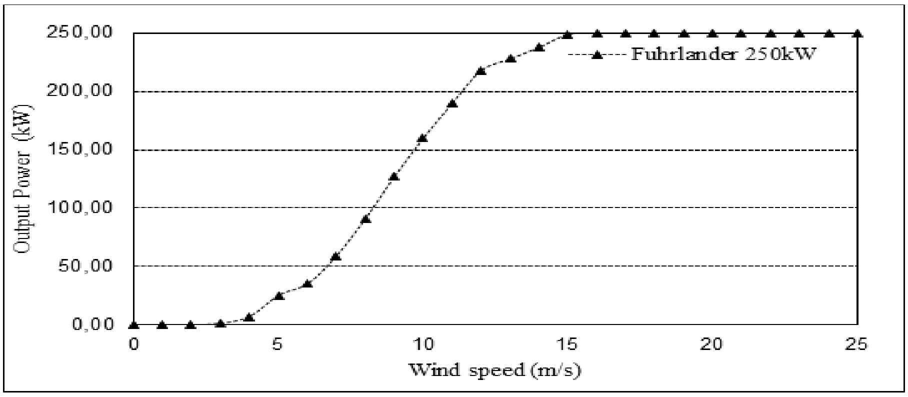


Figure 11. Power charts of Fuhrlander 250 kW wind turbine [33]

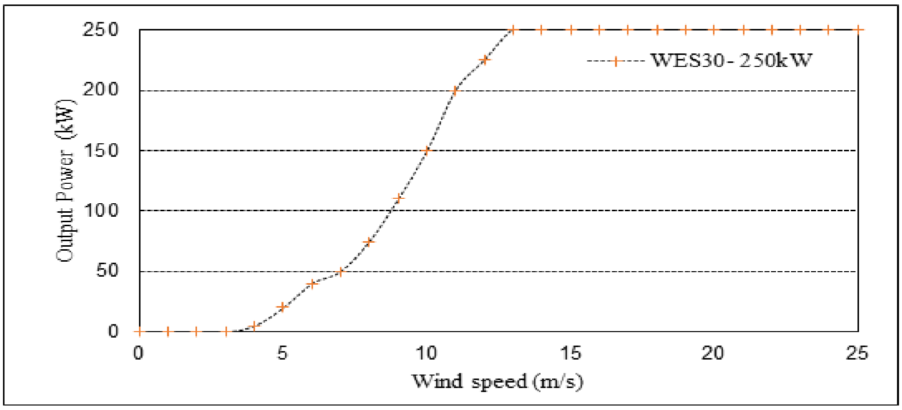


Figure 12. Power charts of WES30-250 kW wind turbine [34]

By using Equation 7 which is implemented in various research articles, the electrical output power of a wind turbine model can be calculated.

$$P_e=\begin{cases} 0 & v<v_c \\ P_{eR}\dfrac{v-v_c}{v_R-v_c} & v_c \le v \le v_R \\ P_{eR} & v_R \le v \le v_F \\ 0 & v>v_F \end{cases} \quad (7)$$

The capacity factor can be estimated by Equation 8 [35, 36].

$$CP=\frac{\sum_{i=1}^{17520} P_{e_i}}{17520.P_{eR}} \quad (8)$$

The total power produced by each wind turbine is estimated by the use of wind speed data from the years 2015 to 2017 for Somalia–Turkish Training and Research Hospital in Mogadishu. The total power produced by the wind turbines and their capacity factors are given in Table 2 [30-34].

Table 2. The overall power production of the wind turbines and their capacity factors

Model of wind turbine	WES 250 kW [30]	SRC31-250 kW [31]	GEV MPC 250 kW [32]	Fuhrlander 250 kW [33]	WES30-250 kW [34]
Total generated power (kWh)	1,017,603	1,031,744	1,024,715	**1,076,790**	1,011,915
Output power x 17520 (kWh)	4,380,000	4,380,000	4,380,000	**4,380,000**	4,380,000
Capacity factor	23 %	23 %	23 %	**25 %**	23 %

In the comparison of the wind turbines with the same output power, the one producing the highest energy and having the biggest capacity factor should be chosen as the optimum wind turbine. In this sense, it is notable that Fuhrlander 250 kW is the most appropriate wind turbine for Somalia–Turkish Training and Research Hospital in Mogadishu. The wind turbine has about 250 kW output power and its hub height is 41 m. It has a life cycle of 25 years. It has a rotor diameter of 29.5 m and is equipped with 3 blades. It has Cut-in speed of 2.5 m/s, rated speed of 12 m/s, and cut-out wind speed of 25 m/s. It has capital cost of $48,000, replacement cost of $480,000, and annual operational and maintenance costs of $480. In HOMER, the quantity of the wind turbines changes from 0 to 4 and the optimum type and model of wind turbine used in the HRES is decided by the techno-economic analysis. Costs and some other detailed technical properties of the wind turbines are shown in Table 1 [37].

4.3. Diesel generator

The output power of the diesel generator used in the proposed system is about 350 kW. Generally, the price of diesel generators used in the industry may vay between 250 $/kW and 500 $/kW. The cost per power is lower for high-powered units and similarly, the cost per power is higher for low-powered units [38]. Diesel generator is AKSA AC350 in model. In the simulation, the number of diesel generators varies between 0 (no diesel generator) and 3 [26].

4.4. Inverter

The power converter has a rated power of 250 kW and it can thoroughly meet both PV power and residual power of the wind turbine after meeting the load demand. Moreover, the power converter has a conversion efficiency of 95 %. The model of the inverter is Solectria SGI 250. The starting and replacement cost and other specifications of the inverter are shown in Table 1 [27].

4.5. Batteries

The quantity of batteries used in the HOMER changes between 12 and 144 pieces. One battery bank consists of 12 batteries and, therefore, the quantity is a multiple of 12. In the proposed HRES Surrette 6CS25P model batteries are used whose nominal capacity is 1,156 Ah and nominal voltage is 12 V. Each battery can store energy about 6.94 kWh. Battery bank is designed to be six rows and two columns. Finally, Nominal bus voltage of the battery bank including 12 pieces of batteries, is 12 V. According to the datasheet information provided by HOMER, the batteries have 80 % round trip efficiency and they have minimum state of charge level of 40 %. The starting cost, replacement cost, and operational and maintenance cost of the batteries are shown in Table 1 [28].

5. OPERATION STRATEGIES

The proposed HRES intends to work with the load following dispatch strategy, which means that the energy produced by PV panels will be stored in the batteries and diesel generator and wind turbines will generate energy only for meeting the energy demand of the hospital. Mainly, load following dispatch strategy seems to be the optimum one for systems with multiple renewable energy sources. The most important significance of the strategy may be its contribution to optimizing the total NPC of the system and to decrease the excessive power production [39]. The operating reserve is the excessive operating capacity ensuring secure power supply although the load instantly goes up or renewable power output instantly goes down. Operating reserve can be estimated by Equation (9) [40].

$$\text{Operating reserve}=\left(\%_{L}\times E_{L}\right)+\left(\%_{PV}\times E_{PV}\right)+\left(\%_{WT}\times E_{WT}\right) \quad (9)$$

6. RESULTS AND DISCUSSION

Renewable energy systems must be analyzed in the techno-economic terms to determine its efficiency and economic feasibility. Since the system includes multiple generation systems, the analysis may be very complex. Moreover, the optimum design of the energy production system is related to the load demand and the use of renewable energy sources, which is hard to analyze completely in detail. The capacity of the designed system must be in accordance with operation planning to prevent excessive energy. Future load demand and predicted energy production must be planned [41, 42]. All configurations of HRES with the present parameters, average wind speed value of 5.61 m/s, average solar radiation of 5.63 kWh/m^2/d, and diesel fuel price of 0.75 $/l are examined in the next sections.

6.1. Standalone diesel power generating system

The standalone diesel power generating system is the expensive system among the studied hybrid configurations. The total NPC is about $9,608,750 and CoE is calculated at 0.360 $/kWh. Renewable fraction is about 0 %. The energy demand of the hospital is supplied by only two diesel generators with an output power of 350 kW. The annual average primary AC load of the hospital is estimated at 2,436,836 kWh/year. In this hybrid system, the standalone diesel power generating system could generate 2,662,261 kWh/year with the excess electricity of 159,453 kWh/year.

6.2. Standalone wind/diesel without battery storage HRES

The standalone wind/diesel without battery storage HRES comes after the standalone wind/diesel/battery storage HRES by means of the least NPC. The total NPC of this system is about $5,663,186. The CoE is calculated to be 0.213 $/kWh and results from the combination of 750 kW wind turbine and 350 kW diesel generator. Renewable fraction of the system is about 56 %. AC primary load of the hospital is estimated to be 2,436,836 kWh/year. In this hybrid system, while diesel generator is able to generate 1,508,223 kWh/year, the wind turbine generates 1,016,096 kWh/year. The diesel generator has operated 8,245 hours throughout the year.

6.3. Standalone wind/diesel/battery storage HRES

The standalone wind/diesel/battery storage HRES is the best configuration by means of net present cost and cost of energy.

When the total NPC of the system is about $5,418,316, CoE is 0.208 $/kWh. The system configuration comprises 350 kW diesel generator, 330 kW wind turbine, 200 kW inverter, and 300 batteries. Renewable fraction is about 34 %. In this hybrid system, when diesel generator could generate 1,657,635 kWh/year, the rest of it generates from wind turbine. The diesel generator has operated 7,372 hours throughout the year. The use of the battery storage has decreased by about 10 % of the operation hours of the diesel generator.

6.4. Standalone PV/diesel without battery storage HRES

The standalone PV/diesel without battery storage HRES consists of 350 kW diesel generator, 250 kW PV panel, and 200 kW inverter. When the total NPC is about $7,989,642, the CoE is calculated at 0.308 $/kWh. Renewable fraction is about 16 %. In this hybrid system, when diesel generator could generate 1,997,114 kWh/year, the rest of it is produced from PV panel. The diesel generator has operated 8,057 hours throughout the year.

6.5. Standalone PV/wind/diesel without battery storage HRES

The standalone PV/wind/diesel without battery storage HRES consists of 250 kW PV panel, 350 kW diesel generator, 330 kW wind turbine, and 200 kW inverter. When the total NPC is about $6,836,281, CoE is calculated 0.258 $/kWh. Renewable fraction is about 45 %. In this hybrid system, AC primary load of the hospital is estimated at 2,436,836 kWh/year which comprises 16 % of PV, 35 % wind turbine, and the rest of diesel generator. The diesel generator has operated 8,100 hours throughout the year.

6.6. Standalone wind-PV-diesel-battery storage HRES

The standalone wind-PV-diesel-battery storage HRES comes after the standalone wind/diesel without battery storage HRES by means of the least NPC. The system configuration consists of 250 kW PV panel, 350 kW diesel generator, 330 kW wind turbine, 200 kW inverter, and 300 batteries. When the total NPC is about $6,302,950, CoE is calculated 0.238 $/kWh. Renewable fraction is about 49 %. In this hybrid system, AC primary load of the hospital is estimated 2,436,836 kWh/year, which comprises 464,481 kWh/year of PV, 1,016,096 kWh/year of wind turbine, 1,171,352 kWh/year of diesel generator, and rest of batteries. The diesel generator has operated 6,934 hours throughout the year. The excess energy of the standalone PV/wind/diesel/battery storage HRES is 101,958 kWh/year. The payback period is calculated to be about 5 years. The cost of energy is about 0.5 $/kWh for Somalia and the daily Load is 8,000 kWh. Now that the NPC of the system is $5,056,700, the payback is assumed to be about 5 years.

7. ENVIRONMENTAL ASSESSMENT OF THE HRESs

With the aim of reducing the CO_2 emission, several optimization attempts have been made for the hospital. When all power system configurations are examined by means of greenhouse gas emissions such as CO_2, CO, SO_x etc., the most appropriate and least CO_2 emission value of HRES belongs to PV/wind/diesel/battery storage system, which can be seen in Table 3. Moreover, Table 3 shows all pollutants and emission values of all HRES. As Table 3 is studied in detail, the diesel power generating system produced the greatest CO_2 emissions, while the lowest emission value belonged to PV/wind/diesel/battery HRES.

Table 3. All emission values for hybrid renewable power generating systems

Pollutant	Only Diesel (kg/yr)	Wind/Diesel (kg/yr)	Wind/Diesel/Battery (kg/yr)	PV/Diesel (kg/yr)	PV/Wind/Diesel (kg/yr)	PV/WindDiesel/Battery (kg/yr)
Carbon dioxide	3,044,463	1,699,208	1,536,476	1,960,666	1,513,318	1,282,406
Carbon monoxide	7,515	4,194	3,793	4,840	3,735	3,165
Unburned hydrocarbons	832	465	420	536	414	351
Particulate matter	567	316	286	365	282	239
Sulfur dioxide	6,114	3,412	3,086	3,937	3,039	2,575
Nitrogen oxides	67,055	37,426	33,841	43,184	33,331	28,245

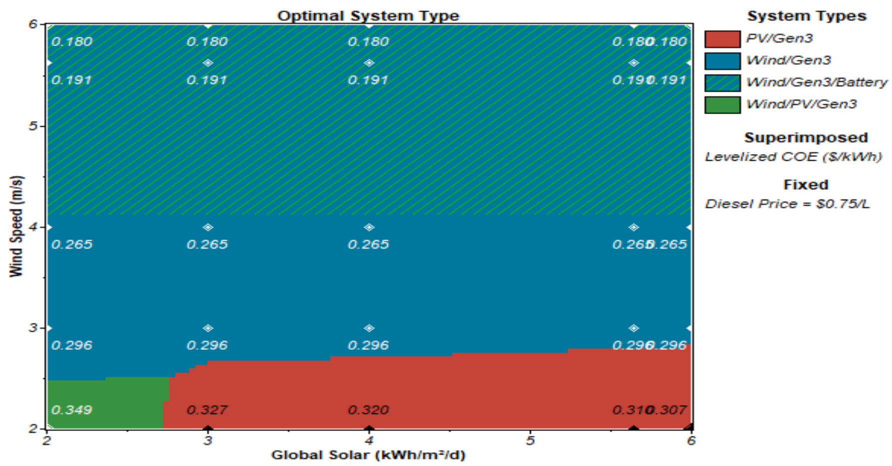
8. SENSITIVITY ANALYSIS OF THE HRES

This paper examined three different sensitivity variables: average wind speed, solar radiation, and diesel price. The variables of the sensitivity analysis are determined to be in a suitable range to tolerate the variation of the inputs in the future. Table 4 shows the range of three sensitivity variables including velocity of wind, sunlight radiation, and diesel cost.

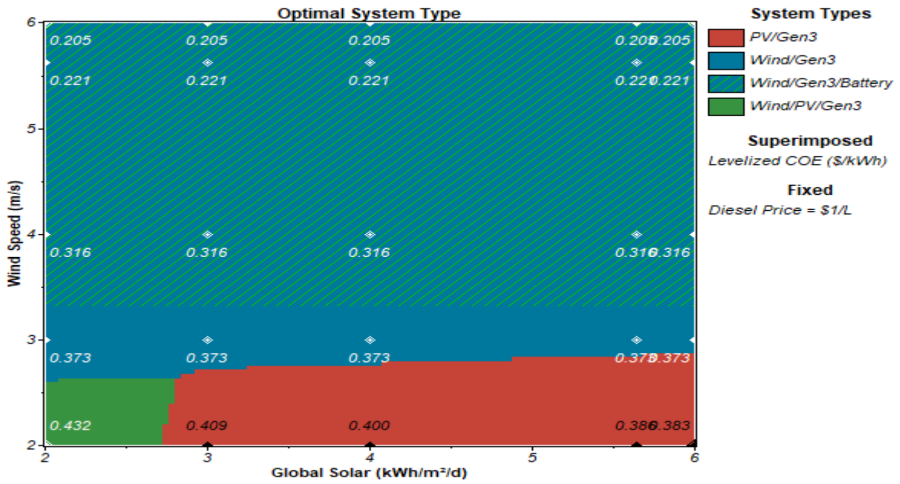
Table 4. Different wind speed and diesel prices values considered in the sensitivity analysis

Wind speeds (m/s)	Solar radiation (kWh/m^2/d)	Diesel prices ($/l)
2	2	0.75
3	3	1
4	4	1.5
5.61	5.63	2
6	6	2.5

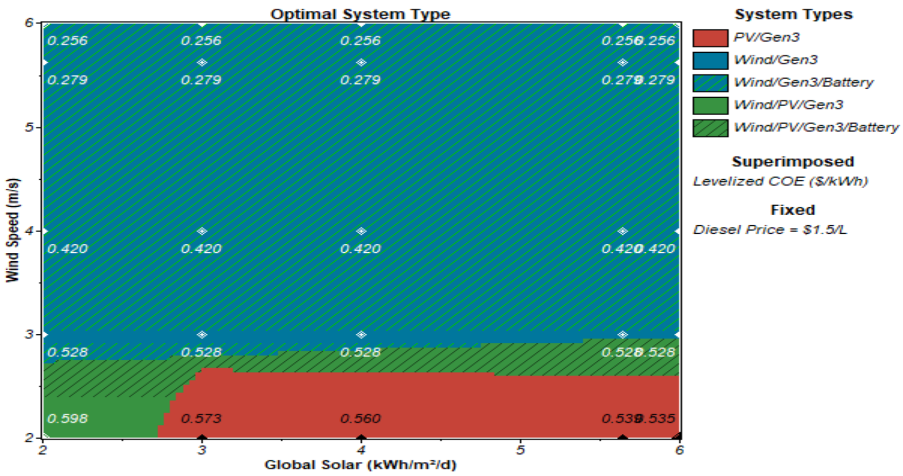
There are totally 125 sensitivity situations, estimated by the multiplication of wind speed (5), solar radiation (5), and diesel price (5). Different sensitivity situations and the optimum configured system with the present conditions are shown in Figure 9.



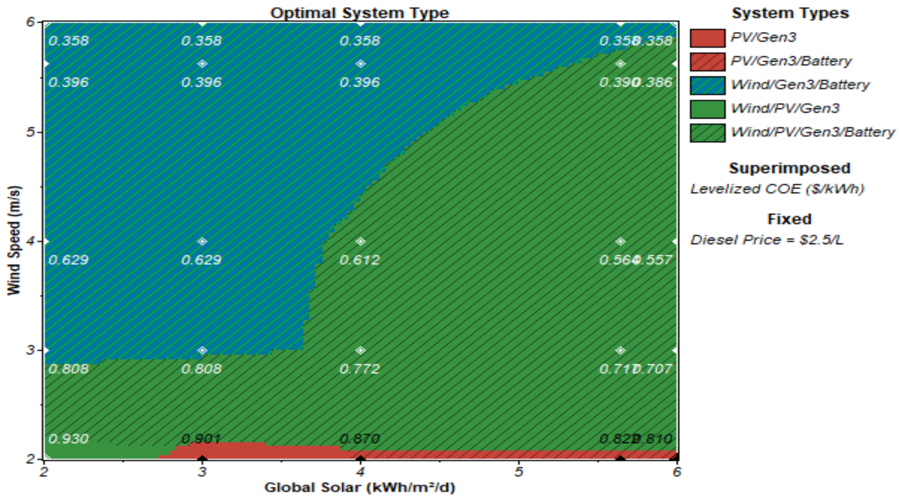
(a) Diesel price=0.75 $/l



(b) Diesel price=1.0 $/l



(c) Diesel price=$1.50/l



(d) Diesel price=$2.5/l

Figure 9. Different sensitivity situations and optimum configured system with the present conditions

Concerning the effects of changing sensitivity variables on the hybrid renewable power-generating systems configuration, detailed results of every feasible situation are given in Figure 7, which can be elaborated below comprehensively:

- For the least diesel fuel cost of 0.75 $/l, while both wind speed values vary from 2 m/s to 3.4 m/s and solar radiation value is lower than 2.8 kWh/m^2/d, the optimum hybrid system is wind/PV/diesel HRES. Moreover, in case the wind velocity value varies from 2.4 m/s to 3.4 m/s and sunlight radiation value is greater than 3 kWh/m^2/d, the optimum hybrid system with wind/PV/diesel HRES. Furthermore, if wind speed value is lower than 2.4 m/s and solar radiation value is higher than 2.8 kWh/m^2/d, then the optimum hybrid system is PV/diesel HRES. Similarly, in the situation that wind speed value ranges between 3.3 m/s and 3.5 m/s and solar radiation value is greater than 4.6 kWh/m^2/d, the optimum hybrid system is wind/PV/diesel/battery HRES. While wind speed value is between 3.6 m/s and 4.9 m/s and for all solar radiation values, the optimum hybrid system is wind/diesel HRES. Lastly, in case wind speed is higher than 5 m/s and for all solar radiation values, the optimal hybrid system is wind/diesel/battery HRES.

- For the lowest diesel value of 1.50 $/l, in a situation where wind speed value varies from 2 m/s to 2.6 m/s and solar radiation value is above 2 kWh/m^2/d, the optimum hybrid system is wind/PV/diesel HRES. Similarly, in case where both wind speed value varies from 2.6 m/s to 3.2 m/s and solar radiation value is above 2 kWh/m^2/d, the optimum hybrid system is wind/PV/diesel HRES. In addition, if the wind speed value is between 2 m/s and 2.6 m/s and solar radiation value is greater than 2 kWh/m^2/d, then the wind speed value is between 3.2 m/s and 3.7 m/s and solar radiation value is greater than 2 kWh/m^2/d. Or, wind speed value is between 3.7 m/s and 4.0 m/s and solar radiation value is greater than 2.0 kWh/m^2/d; or, wind speed value is greater than 4.5 m/s and solar radiation value is higher than 5.3 kWh/m^2/d. Under these conditions, the optimum hybrid system is wind/PV/diesel/battery HRES. Moreover, the optimal hybrid system is wind/diesel/battery HRES in a condition where (a) wind speed value is between 3.7 m/s and 4 m/s and all solar radiation values, (b) wind speed value is between 4 m/s and 4.5 m/s and all solar radiation values, and (c) wind speed value is higher than 4.5 m/s and solar radiation value varies from 2.0 kWh/m^2/d to 6.0 kWh/m^2/d.

- For the lowest diesel value of 2.50 $/l, the optimum hybrid system is wind/diesel/battery HRES in a condition where (a) wind speed value varies from 3.8 m/s to 6.0 m/s and solar radiation value is lower than 3.2 kWh/m^2/d and (b) the wind speed value varies from 3.8 m/s to 6.0 m/s and solar radiation value is between 3.2 kWh/m^2/d and 3.8 kWh/m^2/d. In addition, the optimum hybrid system is wind/PV/diesel/battery HRES in a condition where (a) wind speed value varies from 3.8 m/s to 6.0 m/s and solar radiation value is between 3.1 kWh/m^2/d and 6.0 kWh/m^2/d, (b) wind speed value is between 2.8 m/s and 3.8 m/s and all solar radiation values, and (c) wind speed value varies from 2.0 m/s to 2.8 m/s and solar radiation value is higher than 4.0 kWh/m^2/d. Lastly, the optimum hybrid system is wind/PV/diesel HRES in a condition where wind speed value is between 2 m/s and 2.8 m/s and solar radiation value is greater than 2.0 kWh/m^2/d, or where wind speed value is between 3.2 m/s and 3.7 m/s and solar radiation value is lower than 5.0 kWh/m^2/d.

9. CONCLUSIONS

The following remarks or conclusions can be drawn from the study after examining and analyzing all the results obtained from the figures and tables which were received from the HOMER software.

- Renewable fraction rates of the hybrid renewable power generating systems range between 0 % and 75 %.
- Diesel generator used in the proposed HRES operates between 6,712-8,760 hours according to the case. In this sense, it can be said that in a situation with stand-alone diesel system, the diesel generator operates 8,760 hours per year and consumes 1,156,127 liter of diesel fuel.
- Due to the contribution of PV panels and wind turbines, the use of diesel generator and the consumed diesel fuel will be lowered. This will also lead to a great decrease in emissions between 42 % and 100 %.
- Wind/diesel/battery HRES is the most environmentally friendly system among the studied systems. PV/wind/diesel/battery HRES has the least emission value which is 42 %.
- The systems, except stand-alone diesel generator, have a CoE between 0.208 $/kWh and 0.359 $/kWh.
- For the current average wind speed, current diesel price and solar irradiation values for the hospital located in Mogadishu–Somalia, the optimum hybrid system is wind/diesel/battery HRES with the optimal hybrid configuration system that includes a 350 kW diesel generator, a 330 kW wind turbine, a 200 kW inverter, and 300 batteries. In addition, the net present cost and the CoE of this system are about $6,302,950 and 0.238 $/kWh, respectively. Furthermore, renewable fraction is about 49 %.
- Optimal HRESs fulfill the energy demand of the hospital completely. AC primary load of the hospital is approximately 2,436,836 kWh/year which comprises 464,481 kWh/year of PV, 1,016,096 kWh/year of wind turbine, 1,171,352 kWh/year of diesel generator, and the rest of the batteries. The diesel generator has operated 6,934 hours throughout the year. The excess energy of the standalone PV/wind/diesel/battery storage HRES is 101,958 kWh/year.
- Using diesel generator as the only power supplier, the CoE of the system is 0.360 $/kWh. Furthermore, this system produces high amounts of hazardous emission gases, as mentioned in Table 2.
- Converting the system into a complete or nearly complete renewable hybrid power generating system, the CoE of the hybrid systems is fairly lower (more than 50 % lower) than the diesel generator system. Moreover, the new hybrid systems never produce harmful emissions or partial emissions according to the renewable fraction values of the system. Hybrid systems are not only more economical but also more environmentally friendly.
- Examining the effects of minor or major changes in the sensitivity variables such as average wind speed, current diesel price and solar radiation value, for the numerous combinations of sensitivity variables, the most suitable hybrid systems are in order of wind/diesel/battery, PV/wind/diesel/battery, wind/PV/diesel, wind/diesel, PV/diesel/battery, and PV/diesel.
- Compared with the study of Olatomiwa which is entitled "Optimal configuration assessments of hybrid renewable power supply for rural healthcare facilities", made for the similar region, Nigeria, the results showed that optimal renewable hybrid system determined by HOMER could be far more preferable than the standalone diesel generator by means of energy cost and gas emissions.
- The payback period is calculated to be about 5 years.
- For high diesel prices,

(i) it is the wind/diesel/battery hybrid system at low wind speed values.
(ii) it is the PV/wind/diesel/battery hybrid system at moderate wind speed values.
(iii) it is the PV/wind/diesel/battery hybrid system at high wind speed values.

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NOMENCLATURE

$C_{a,t}$	Total annualized cost
CoE	Cost of Energy
CRF	Capital Recovery Factor
CP	Capacity Factor
$E_{p,AC}$	Ac primary load served
$E_{p,DC}$	Dc primary load served
$E_{g,s}$	Total grid sales
F	The annual inflation rate
f_i	Frequency
HRES	Hybrid Renewable Energy System
i	The real interest rate
i_0	The nominal interest rate
N	Number of years
NPC	Net Present Cost
P_e	Electrical output power of a wind turbine
P_{eR}	Rated electrical power
R_p	Project lifetime
v_i	Mean wind speed
v_c	Cut–in wind speed
v_f	Cut-out wind speed
$\%_L$	The percentage of hourly load
$\%_{PV}$	The percentage of solar power output
$\%_{WT}$	The percentage of wind turbine power output

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