Journal of Electrical Engineering 8 (2020) 27-45
doi: 10.17265/2328-2223/2020.01.005

An Assessment of Renewable Energy Options for Somalia Turkey Hospital

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Abstract: Somalia Mogadishu-Turkey Training and Research Hospital is only powered by diesel generator currently. In this paper, the energy demand of this hospital is supplied by determining the optimum hybrid power renewable generating system. Therefore, numerous hybrid renewable power generating systems including the components like diesel generator, wind turbine, photovoltaic (PV) and battery are considered in different configurations. Eventually, they are technically, environmentally and economically analyzed by using the well-known HOMER software. Furthermore, a sensitivity analysis is also performed considering variations in three important parameters, namely average wind speed, current diesel price and also solar radiation. According to the results, the optimal system is the standalone Wind/Diesel/Battery hybrid renewable energy system (HRES) with the configuration of 1,000 kW wind turbine, 350 kW diesel generator, 250 kW power converters and 750 batteries. Additionally, this system has the net present cost of $5,056,700 as well as the cost of energy as $0.191/kWh. Lastly, it is clearly occurred that the Wind/Diesel/Battery HRES is eco-friendlier than other HRESs.

Key words: Somalia, renewable power generating system, hospital, environmental assessment, hybrid systems, renewable energy.

Abbreviations

$C_{a,t}$	total annualized cost
CoE	cost of energy
CRF	capital recovery 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
HRES	hybrid renewable energy system
I	the real interest rate
i_0	the nominal interest rate
N	number of years
NPC	net present cost
R_p	project lifetime
$\%_L$	the percentage of hourly load
$\%_{PV}$	the percentage of solar power output
$\%_{WT}$	the percentage of wind turbine power output

Corresponding author: Bahtiyar Dursun, Ph.D., Prof. Dr., research fields: renewable energy, power systems, energy efficiency.

1. Introduction

Somalia lies on the eastern coast of the Horn of Africa bordering Kenya, Ethiopia and the Republic of Djibouti. Somalia is predominantly hot and dry most of 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 used by making some regulations with the support of Somalian Government. Somalia possesses abundant solar, wind and biomass energy resources that could be utilized for both household and industrial purposes. There are also opportunities for geothermal and wave energy exploitation. Both the Shebelle and Juba rivers have substantial potentialities for hydropower generation. Unfortunately, very few of these energy resources are utilized at present. Renewable energy sources, such as the solar, wind and biomass, could be harnessed with relatively moderate capital investments in a number of applications using existing technology

[1]. To improve welfare, productivity and security, it is significant to access to grid-supplied electricity in cities and non-grid modern energy services and products should be promoted to poor rural and nomadic people [2].

Many companies supply their energy needs either by grid or by 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. Due to the harmful gases in the atmosphere generated by the intensive use of diesel generators have increasingly caused the environmental pollution and climate change in Mogadishu. Difficulties caused by environmental pollution and climate change can diminish with the utilization of renewable power generating systems instead of the diesel generators [3]. Nowadays, using renewable energy resources as a power supplier in an energy system instead of conventional ones has been more popular. The system including more than one power supplier is called 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 [4]. They are rather useful alternative ways for supplying 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. It is hybrid systems that must be applied with the support of an auxiliary power supplier such as a diesel generator because of their instable and discontinuous natures. 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 the diesel generators. HRES's should be preferred instead of diesel generators in the isolated places. There are many studies in the literature related to the renewable based 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 in below. Orosz et al. [5] investigated techno-economic choices for health and education applications in sub-Saharan Africa. They obtained some meteorological data (insolation, temperature, and heating and cooling degree days) from NASA and they compared traditional electrification approaches, such as PV systems and diesel generators, with micro-concentrating solar power technology, photovoltaics hybridized with LPG/propane technology and solar thermal organic ranking cycle technology. Malik [6] has conducted a study to assess the renewable energy potential of Brunei Darussalam. He put forth the availability of renewable energies that could be harvested in Brunei. Ajao et al. [7] have evaluated off-grid and grid connected HRES options for University of Ilorin in Nigeria by using HOMER software. Moreover, Himri et al. [8] have presented techno-economic assessment for off-grid hybrid generation systems of a site in south western Algeria. In that study, they evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction by using HOMER software. Nfah [9] has suggested the optimal photovoltaic hybrid systems for remote villages in Far North Cameroon using a recent iterative optimization method based on desired annual number of generator working hours and the net present value technique. Similarly, Nfah et al. [10] have modeled solar/diesel/battery HRES for the electrification of typical rural households and schools in remote areas of the far north province of Cameroon with HOMER software. Olatomiwa et al. [11] have studied the feasibility of different power generation configurations for different locations within the geo-political zones of Nigeria. Lastly, Olatomiwa [12] has determined the optimal configurations of the HRES for rural health clinic application in three grid-unconnected rural villages in Nigeria. Somalia

Mogadishu-Turkey Training and Research Hospital is only powered by diesel generator currently. 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 turbine, PV panel, diesel generator and battery bank are considered. Furthermore, a sensitivity analysis is also performed considering variations in three important parameters, namely wind speed, diesel price and also solar irradiation. Finally, after determination of the optimum HRES, it is then compared to the other considered hybrid systems regarding emission gases composed of CO_2, CO, NO_x, CH_4 and SO_x which threaten the environment.

2. Description of Somalia, Mogadishu-Turkey Training and Research Hospital

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, Mogadishu-Turkey Training and Research Hospital has a-200-bed capacity. Its coordinates are 2°02′ N and 45°18′ E. 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, Mogadishu-Turkey Training and Research Hospital is shown in Fig. 1 [13].

2.2 Energy Demand of the Hospital and Electrification

Energy requirement of the hospital is currently supplied 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 the collected data are arranged as monthly for a whole year period (2017-2018). Total energy demand of the hospital is provided by four diesel generators with the capacity of three 800 kVA and one 1,100 kVA. According to the load data, the average daily energy demand of the hospital is about 8,000 kWh. The minimum load demand of the hospital occurs 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 about 15% because of the air conditioning in winter. Load profile of the hospital is demonstrated in Fig. 2. While the minimum load demand is about 140 kWh in the summer and the maximum load demand is about 480 kWh. Fig. 3 demonstrates a data map of the electric demand. This figure also shows the breakdown of the data series over the year and representing a 4% day-to-day variation. The 5% time-step randomness displays the fluctuations in electric power consumption of the village.

2.3 Available Renewable Energy Resources Assessment

2.3.1 Wind Speed

The wind speed data are measured in Somalia Mogadishu-Turkey Training and Research Hospital. It is analyzed between 2015 and 2017 years average hourly wind speed data measured at 10 m, 30 m and 50 m above the surface of sea level. It is shown in Fig. 4 [14].

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

where V_{ave} is average wind speed (m/s), f_i is frequency and V_i is mean wind speed m/s. According to Eq. (1) average wind speed is calculated as 5.63 m/s. Considering the wind speed data, it can be emphasized that wind speed distribution ranges between 3.58 m/s and 7.26 m/s whereas the regional average wind speed is around 5.63 m/s. When the highest wind speed data occur in July the least wind speed data appear in April. The parameter weibull *k* is calculated as 1.71.

Fig. 1 The location of the Somalia, Mogadishu-Turkey Training and Research Hospital.

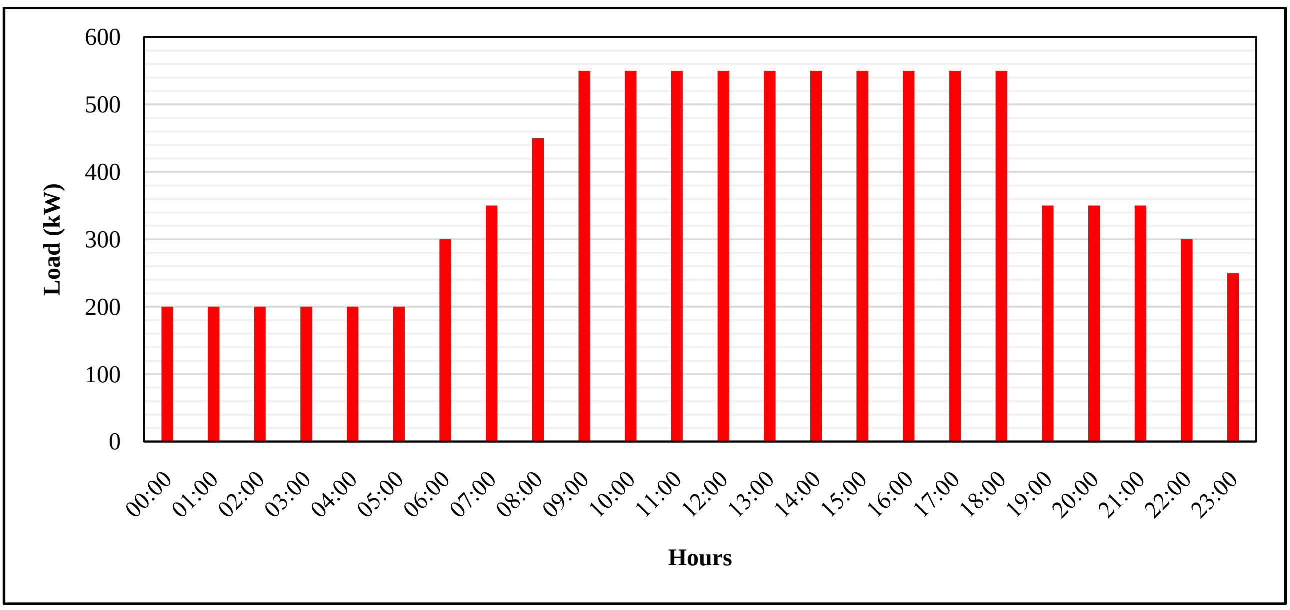


Fig. 2 Load profile of the hospital.

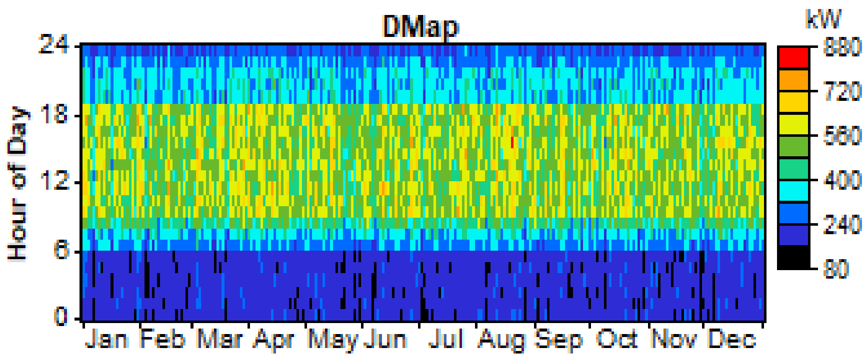


Fig. 3 Data map of electric load of the hospital.

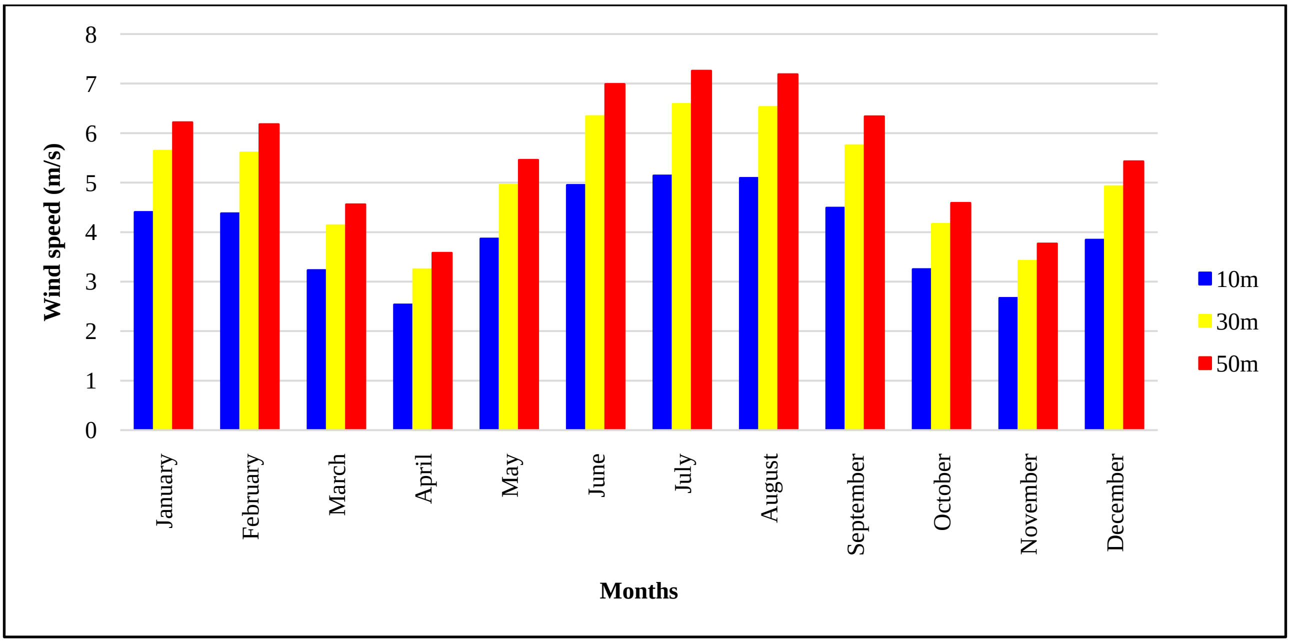


Fig. 4 The monthly wind speed data in Mogadishu, Somalia.

2.3.2 Solar Radiation

The solar irradiation map of Somalia is demonstrated in Fig. 5. It presents the average annual solar energy per square meter [15]. The red regions are areas with high solar irradiation levels and are considered the highest solar resource potential. Somalia's areas receiving high levels of solar radiation, hence, large geographical areas are classified as highly suitable for solar energy. Solar radiation data of the region are obtained with HOMER from NASA Surface Meteorology and Solar Energy database [14]. For coordinates in HOMER, 2°02′ N and 45°18′ E are used. These are the coordinates of Somalia, Mogadishu-Turkey Training and Research Hospital. HOMER synthesizes solar radiation values for each 8,760 h of the year by using Graham algorithm. This algorithm produces realistic hourly data and it is easy to use because it requires only latitudes and monthly averages. The synthetic data display realistic day-to-day and hour-to-hour patterns. Monthly average solar radiation values are demonstrated in Fig. 6. When the annual average solar radiation value and the average clearness index are calculated as 5.645 kWh/m^2/d and 0.565, respectively, as shown in Fig. 6 the monthly average daily solar radiation ranges from 3.26 to 7.61 kWh/m^2/d [16].

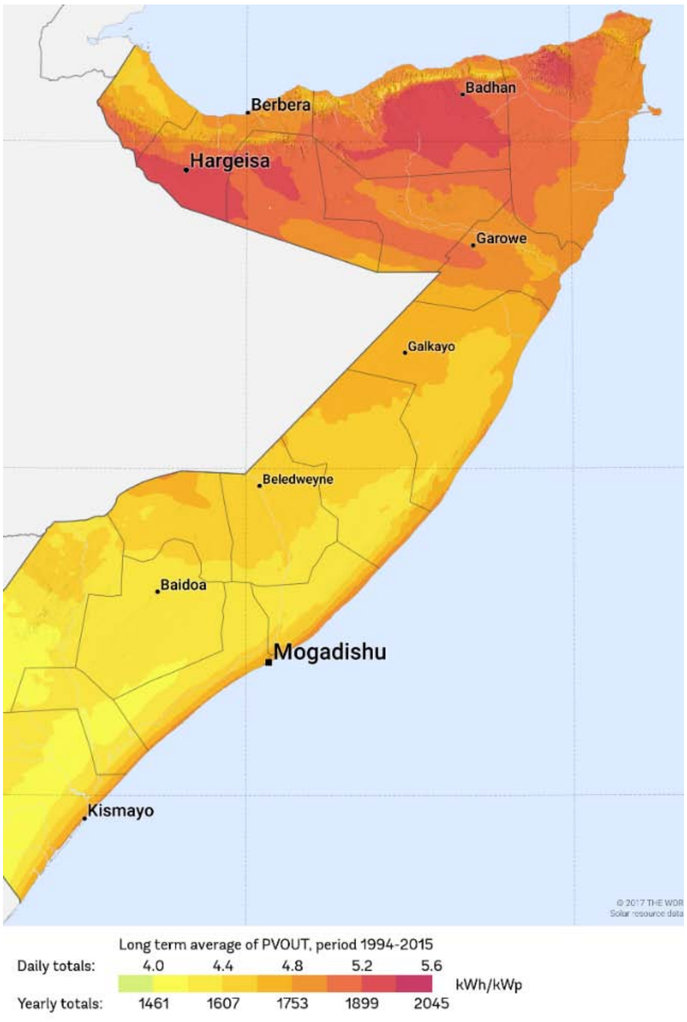


Fig. 5 Global horizontal irradiation (GHI) of Somalia (kWh/m^2).

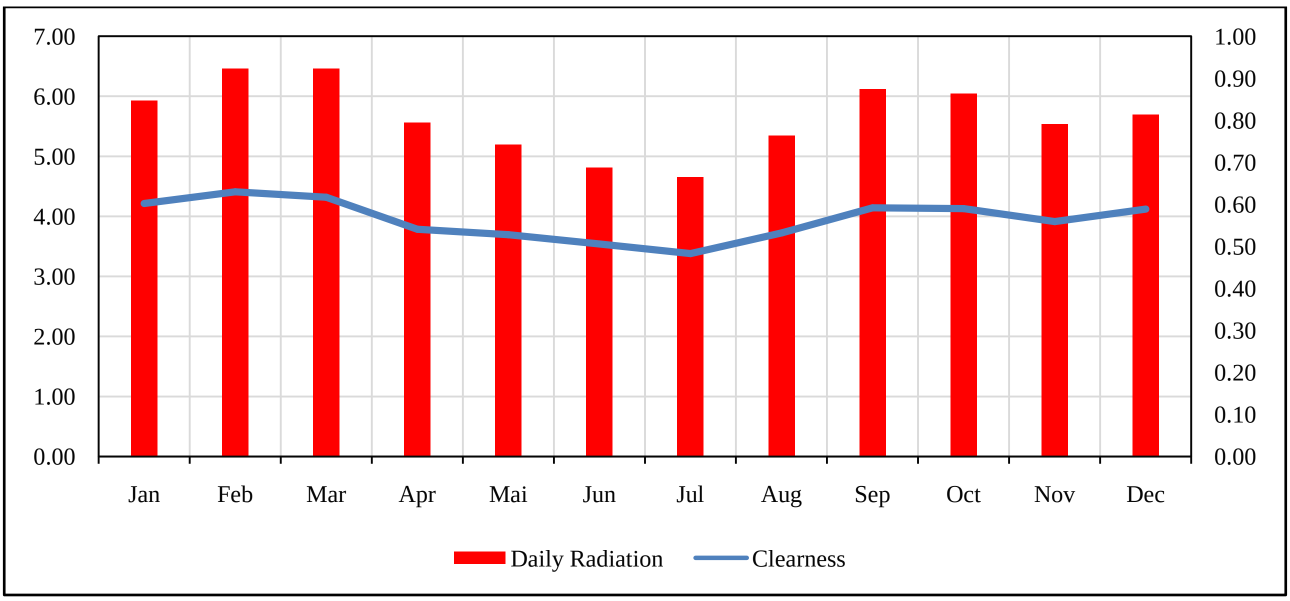


Fig. 6 Monthly average solar radiation value of the hospital.

2.3.3 Diesel

Diesel price is about 1 $/kWh in Mogadishu-Somalia. Since Somalia government plans to cut the subsidy on type of petrol and diesel, it means the price of diesel will vary extensively between 0.75 $/L and 1.3 $/L the last six months of 2017. Therefore, diesel price varies from 0.75 $/L to 2.5 $/L with an increment of 0.5 in the HOMER simulation to investigate its effect on the system cost.

3. Costs and Technical Details

3.1 Calculation of the Annual Real Interest Rate for Somalia

One of the inputs of the HOMER software is the annual real interest rate. The annual real interest rate is related to the nominal interest rate by Eq. (2):

$$i = \frac{i_0 - f}{1 + f} \quad (2)$$

where, i is the real interest rate, i_0 is the nominal interest rate (the rate at which you could get a loan), and f is the annual inflation rate. The real interest rate is calculated 0.69% by using Eq. (3) [17-19].

$$i = \frac{i_0 - f}{1 + f} = 0.0069 \quad \rightarrow \quad i = 0.69\% \quad (3)$$

In the simulations, the real interest rate was set to 0.69%.

3.2 Levelized Cost of Energy

The HOMER software defines the levelized *CoE* as the average cost/kWh of useful electrical energy produced by the system. The *CoE* can be calculated using Eq. (4).

$$CoE = \frac{C_{a,t}}{E_{p,AC} + E_{p,\mathrm{DC}} + E_{g,s}} \quad (4)$$

The total annualized cost is the sum of the annualized costs of each system component, plus the other annualized cost. Since the HOMER software uses it in the calculation of both the levelized *CoE* and the total *NPC*, it is an important value [17, 19].

3.3 Net Present Cost (NPC)

The present value of the cost of installing and operating a power system over the lifetime of a project is *NPC* and is also known as life cycle cost. The expected lifetime of the project analyzed in this study is considered as 20 years. The total *NPC* is the main economic output of the HOMER software. Based on *NPC*, all the systems are ranked and with the purpose of finding the *NPC* all other economic outputs are calculated. Eq. (5) can be used to calculate the *NPC* [17, 19].

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

The *CRF* is a ratio used in the calculation of the present value of an annuity. The *CRF* is given by Eq. (6).

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

Information about the cost and the technical detail of the main components of HRES is given below. Additionally, the project lifetime is 20 years. The annual real interest rate was set to 3.22% for Somalia. It should be noted that no cost subsidy is available from the government of Somalia [18].

4. Hybrid System Configuration and Components

The energy demand of the hospital is supplied from diesel generators with total power capacity of 3,500 kVA since the hospital started to serving to Somalia's people. As an alternative solution to this situation a HRES that consists of mainly PV panel, wind turbine, diesel generator, battery and converter is proposed. All components of both only diesel generator and proposed HRES are demonstrated in Figs. 7a and 7b. Some properties of the components of the hybrid system that are composed of size/quantity, capital cost, replacement cost and operation and maintenance costs are determined according to the references and presented in details in Table 1.

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

4.1 PV Panel

Sizing of the PV panel is set 656 kWp in order to fulfill the basic load demand of the hospital. Because the peak power demand of the hospital is about 750 kWp the sizing of PV panel is determined by selecting to be 20% more than peak power demand. When the load demand is met by the PV panel the rest of its energy is charged the battery bank. Since the hybrid system is the combination of PV panel, wind turbine and diesel generator, the size of the PV panel is varied from 250 kWp to 1,500 kWp with an interval of 250 kWp, to determine the effect of the financial costing of the HRES. The proposed PV panel is a 72-cell polycrystalline which is rated at 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. Data of costs and other technical specifications of the PV panel are shown in Table 1 in details [20, 21].

4.2 Wind Turbine

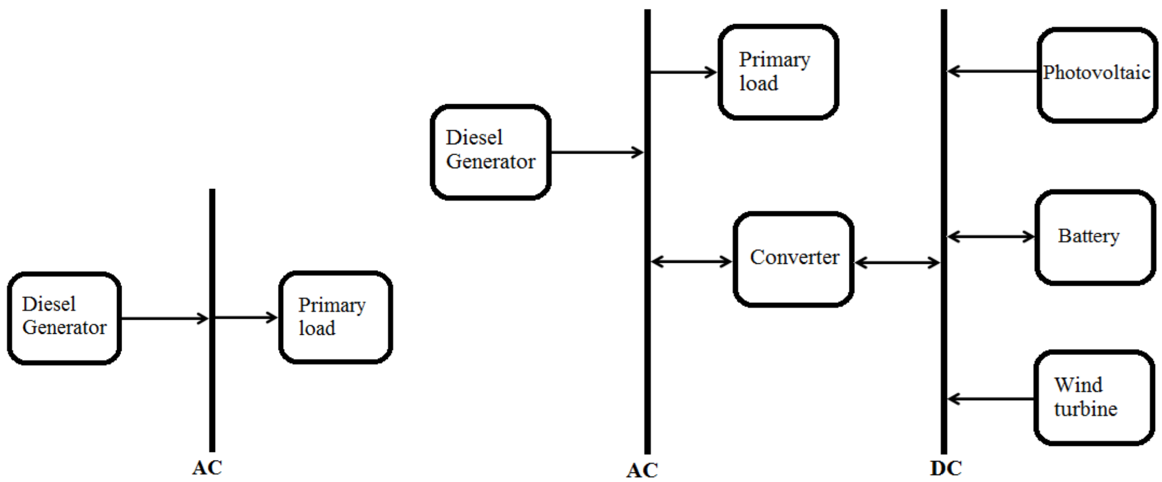
In Mogadishu-Somali, wind energy is another abundant renewable energy source. Hence, it is also selected as one of the basic load suppliers of the proposed system. Basically, wind turbines convert wind energy into other energy types. There are many kinds of wind turbines with 250 kW of power capacity. Power curves of wind turbines are demonstrated in Fig. 8. In this study, the most appropriate turbine model is selected among the five different wind turbines with 250 kW output power [22-26].

Eq. (7) which is used in many of literature sources, calculates the electrical power output of a wind turbine model.

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

The capacity factor is calculated by using Eq. (8) [27, 28].

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



(a) Diesel power generating system (b) HRES

Fig. 7 Descriptions of HRES and diesel energy system.

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

Descriptions	Specifications
PV panel	
PV model	Sonali Solar S-300W PV panel [20]
Power (kW peak)	750 kWp
Capital cost	7,000 $/kW
Replacement cost	6,000 $/kW
Operating and maintenance cost	15 $/year
Lifetime	25 years
Wind turbine	
Wind turbine model	Fuhrlander 250 kW [25]
Rated power	250 kW
Capital cost	$480,000
Replacement cost	$480,000
Operating and maintenance cost	480 $/year
Lifetime	25 years
Diesel generator	
Turbine model	AKSA AC 350 Diesel Generator [29]
Rated power	350 kW
Capital cost	$30,260 or 116,500 TL
Replacement cost	$24,208 or 92,716 TL
Operating and maintenance cost	0.030 $/h
Lifetime	15,000 operating hours
Inverter	
Inverter model	Solectria SGI 250 [30]
Rated power	250 kW
Capital cost	655 $/kW
Replacement cost	655 $/kW
Operating and maintenance cost	10 $/year
Lifetime	15 years
Efficiency	95%
Battery bank	
Battery model	Surrette 6CS25P [31]
Capital cost	$400
Replacement cost	$300
Operating and maintenance cost	10 $/year

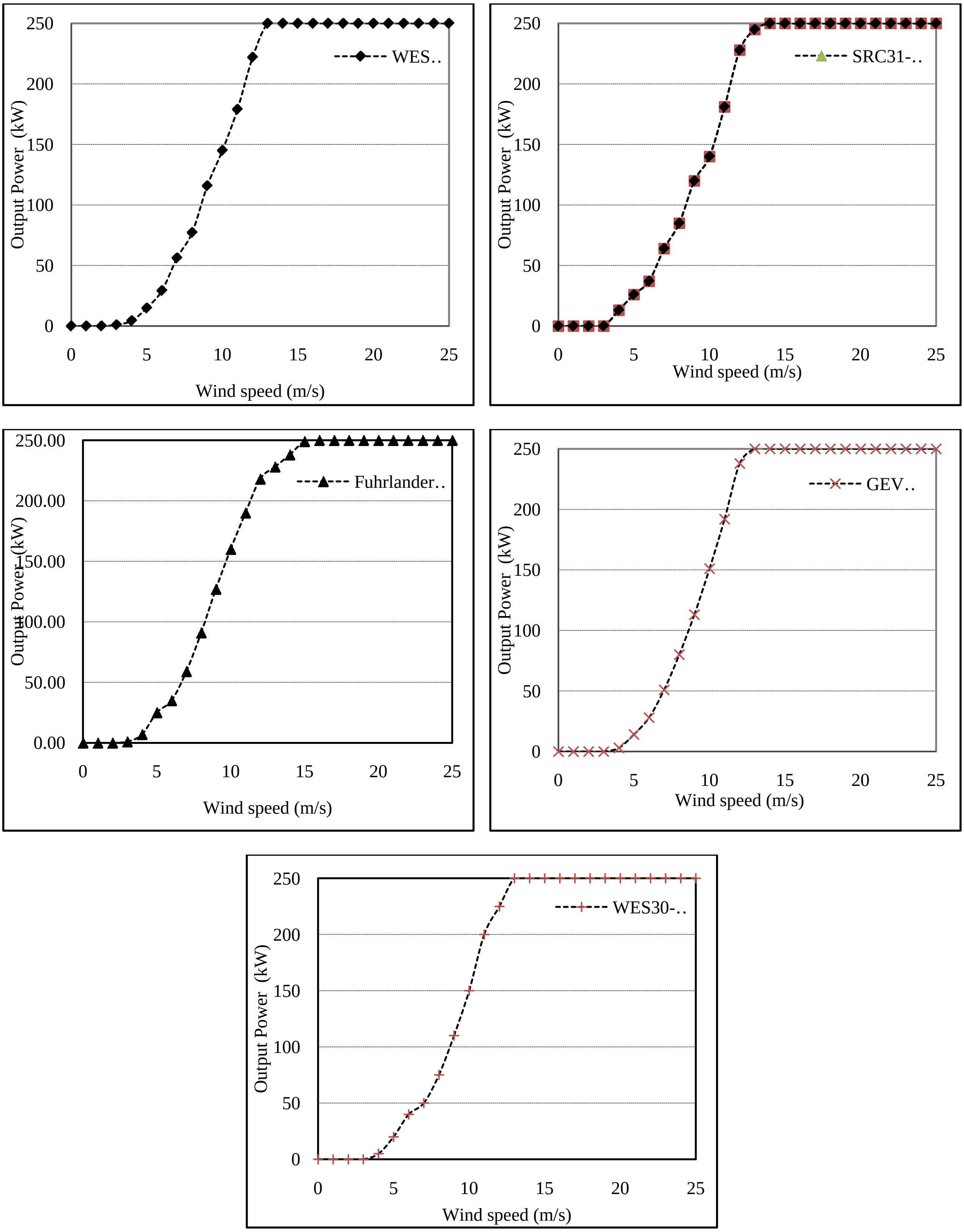


Fig. 8 Power curves of wind turbines.

Table 2 The total generated power from the wind turbines and capacity factor.

Model of wind turbine	WES 250kW [22]	SRC31-250kW [23]	GEV MPC 250kW [24]	Fuhrlander 250kW [25]	WES30-250kW [26]
Total generated power (kWh)	1,017,603	1,031,744	1,024,715	1,076,790	1,011,915
Output power × 17,520 (kWh)	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000
Capacity factor	23%	23%	23%	25%	23%

The total generated power by each wind turbine is calculated using the wind speed data between 2015 and 2017 for Somalia Mogadishu-Turkey Training and Research Hospital. The total generated power from the wind turbines and capacity factor are demonstrated in Table 2 [22-26].

When comparing the total power generated from the same power of different types of wind turbines, the wind turbine which generates the most energy and has the highest capacity factor should be selected. In this context, it is seen that Fuhrlander 250kW is the most suitable wind turbine for Somalia Mogadishu-Turkey Training and Research Hospital. Rated power of the wind turbine is about 250 kW and its hub height is 41 m. Its lifetime is 25 years. The rotor diameter and number of blades of the turbine are 29.5 m, 3 respectively. Cut-in, rated and cut-out wind speeds of the turbine are 2.5 m/s, 12 m/s, and 25 m/s, respectively. The costs of the capital, replacement, and an annual operating and maintenance of the wind turbine are $48,000, $480,000 and $480, respectively. In the HOMER tool, the quantity of the wind turbines varies between 0 and 4, and the optimum model of the HRES is determined by the economy analysis. Costs and other technical specifications of the wind turbine are shown in Table 1 in detail [32].

4.3 Diesel Generator

The output power of diesel generator is about 350 kW. In the general, the cost of a commercially available diesel generator may vary from 250 $/kW to 500 $/kW. For larger units per kW cost is lower and for smaller unit cost is more [33]. The model of diesel generator is AKSA AC350. In the simulation, the number of diesel generator varies between 0 (no diesel generator) and 3 [29].

4.4 Inverter

Output power of the power converter is 250 kW. It will entirely supply both the PV power and the excess power of the wind turbine that will remain after the load demand is met. Moreover, the power converter has a conversion efficiency of 95%. The model of the inverter is Solectria SGI 250. The initial and replacement cost and other specifications of the inverter are shown in Table 1 [30].

4.5 Battery Bank

In the HOMER software, the number of batteries varies between 12 and 144 (12 battery banks) with an increment of 12 batteries. The model name of the battery used in the proposed system is Surrette 6CS25P with a nominal capacity of 1,156 Ah and nominal voltage of 6 V. A single battery can store 6.94 kWh of energy. The battery bank is configured to be a total of 6 strings and there are two batteries in each string. Consequently, with a bus nominal voltage of 12 V, the battery bank includes 12 units of battery. As given in the datasheet provided by the HOMER software, the round trip efficiency of the battery is 80% and the minimum state of charge of the battery is 40%. The capital cost, replacement cost and operating and maintenance cost of the battery are demonstrated in Table 1 [31].

5. Operating Strategies

The proposed HRES is assumed to operate according to the load following dispatch strategy. According to this strategy, PV panel will charge the battery storage element. Wind turbines and diesel generator produce power only to meet the energy demand of the hospital. Basically, load following dispatch strategy tends to be the optimal in system with multiple renewable energies. The most important significance of this strategy may be its help to optimize the total NPC of the system and to reduce the excessive electricity production [34]. The operating reserve is the surplus operating capacity which ensures reliable electricity supply even if the load suddenly increases or renewable power output suddenly decreases. It can be calculated using Eq. (6) [35].

$$\text{Operating reserve} = \left(\%_L \times E_L\right) + \left(\%_{PV} \times E_{PV}\right) + \left(\%_{WT} \times E_{WT}\right) \quad (6)$$

6. Results and Discussion

A techno-economic analysis of any renewable energy system is required to evaluate its efficacy and economic viability. The analysis is very complex because it contains multiple generation systems. Also, the optimal design capacity of energy facilities is heavily dependent on electric demand and the level of renewable energy usage, which are difficult to be thoroughly evaluated in advance. To avoid excessive energy use, the design capacity must be determined in conjunction with operation planning, which is based on future demand and predicted energy production [36, 37]. Under the current conditions defined by 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, all configurations of HRES 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 0.360 $/kWh. Renewable fraction is about 0%. The energy demand of the hospital is supplied by only two diesel generators which are with 350 kW of output power. The annual average primary AC load of the hospital is estimated 2,436,836 kWh/year. In this hybrid system, the standalone diesel power generating system could generate 2,662,261 kWh/year with 159,453 kWh/year excess electricity.

6.2 Standalone Wind/Diesel without Battery Storage HRES

The standalone Wind/Diesel without battery storage HRES is the second cheapest system among the studied configurations. The total *NPC* is about $5,663,186. The *CoE* is calculated 0.213 $/kWh and results from the combination of 750 kW wind turbine and 350 kW diesel generator. Renewable fraction is about 56%. AC primary load of the hospital is estimated 2,436,836 kWh/year. In this hybrid system, when diesel generator could produce 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 cheapest system among the studied hybrid configurations. When the total *NPC* is about $5,418,316, *CoE* is calculated 0.208 $/kWh. The system configuration comprises of 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 about 10% 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 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 produces 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 2,436,836 kWh/year which comprises of 16% of PV, 35% of wind turbine, the rest of diesel generator. The diesel generator has operated 8,100 hours throughout the year.

6.6 Standalone PV/Wind/Diesel/Battery Storage HRES

The standalone PV/Wind/Diesel/Battery storage HRES is the third cheapest system among the studied hybrid configurations. The system configuration consists of 250 kW PV panel, 350 kW diesel generator, 330 kW wind turbine and 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 of 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.

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 is PV/Wind/Diesel/Battery system which is shown in Table 3. 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 is PV/Wind/Diesel/Battery HRES.

8. Sensitivity Analysis of the HRESs

In this study, while doing the sensitivity analysis for the HRES, three different sensitivity variables such as average wind speed, solar radiation and diesel prices are taken into consideration. In the sensitivity analysis, the sensitivity variables are considered to be in a proper range which can cover the probable changes in the model inputs in future. Table 4 demonstrates the ranging of three sensitivity variables which are wind speed, solar radiation and diesel price.

The total number of sensitivity cases is 125, which is calculated by multiplying of wind speed (5), solar radiation (5), and diesel price (5) multipliers. Some sensitivity cases and optimal system configuration under the current conditions are shown in Fig. 9.

Table 3 All emissions value 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/wind diesel/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

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

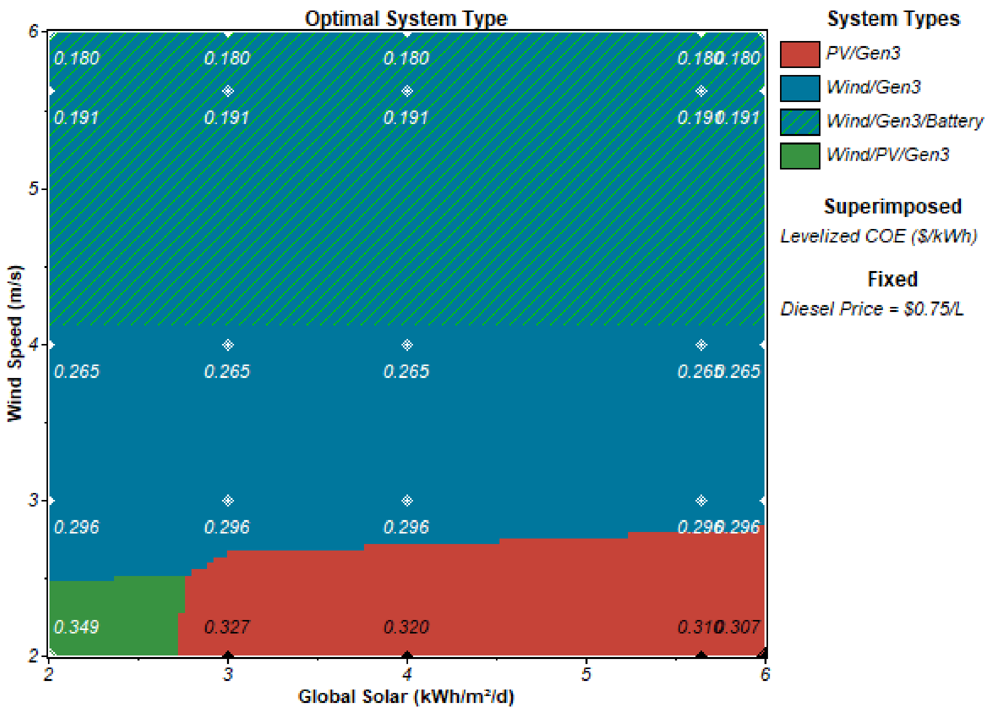
Wind speeds (m/s)	Solar radiation (kWh/m^2/d)	Diesel prices ($/L)
2	2	0.75
3	3	1
4	4	1.5
5.61	5.63	2
6	6	2.5

Concerning the impacts of varying sensitivity variables on the hybrid renewable power generating systems configuration, following comprehensive findings from all possible sensitivity cases shown in Fig. 9 can be further expressed:

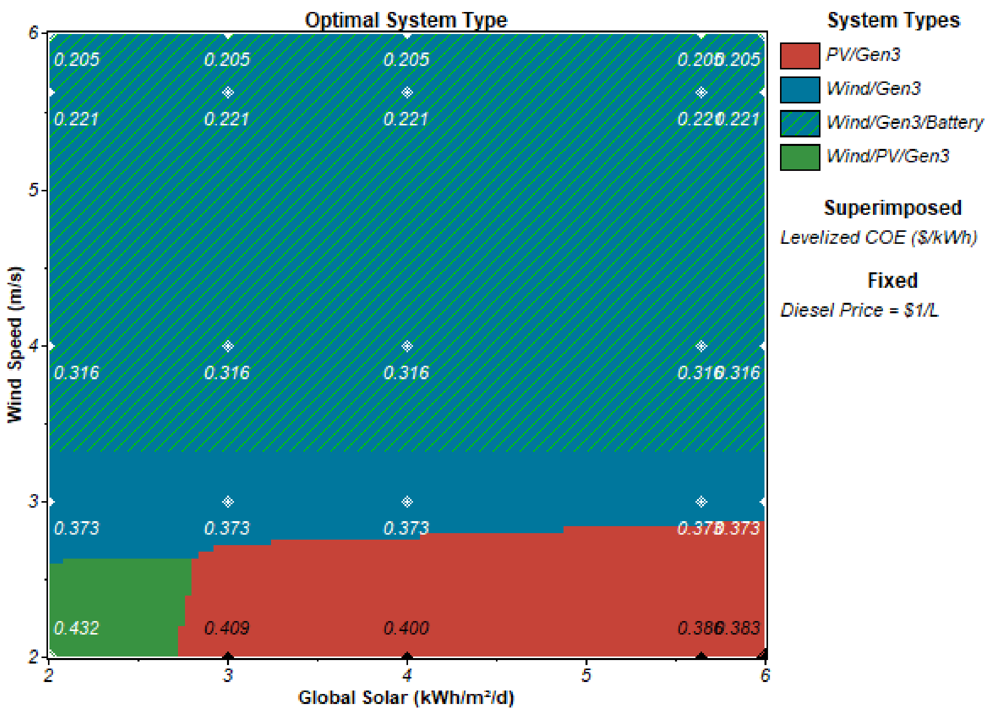
(1) For the lowest diesel value of 0.75 $/L, while both wind speed value varies from 2 m/s to 3.4 m/s and solar radiation value is lower than 2.8 kWh/m^2/d, the optimal hybrid system is Wind/PV/Diesel HRES. Moreover, when wind speed value is between 2.4 m/s and 3.4 m/s and solar radiation value is upper than 3 kWh/m^2/d, the optimal hybrid system is also Wind/PV/Diesel HRES. Furthermore, both wind speed value is lower than 2.4 m/s and solar radiation value is upper than 2.8 kWh/m^2/d, the optimal hybrid system is also PV/Diesel HRES. Similarly, when wind speed value is between 3.3 m/s and 3.5 m/s and solar radiation value is upper than 4.6 kWh/m^2/d, the optimal hybrid system is also 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 optimal hybrid system is Wind/Diesel HRES. Lastly, wind speed is upper than 5 m/s and for all solar radiation values, the optimal hybrid system is also Wind/Diesel/Battery HRES.

(2) For the lowest diesel value of 1.50 $/L, while both wind speed value varies from 2 m/s to 2.6 m/s and solar radiation value is above than 2 kWh/m^2/d, the optimal hybrid system is Wind/PV/Diesel HRES. Similarly, when both wind speed value varies from 2.6 m/s to 3.2 m/s and solar radiation value is above than 2 kWh/m^2/d, the optimal hybrid system is also Wind/PV/Diesel HRES. In addition, when wind speed value is between 2 m/s and 2.6 m/s and solar radiation value is upper than 2 kWh/m^2/d, and wind speed value is between 3.2 m/s and 3.7 m/s and solar radiation value is upper than 2 kWh/m^2/d, and wind speed value is between 3.7 m/s and 4 m/s and solar radiation value is upper than 2 kWh/m^2/d, wind speed value is upper than 4.5 m/s and solar radiation value is upper than 5.3 kWh/m^2/d, under these conditions the optimal hybrid system is Wind/PV/Diesel/Battery HRES. Moreover, when wind speed value is between 3.7 m/s and 4 m/s and all solar radiation values, and wind speed value is between 4 m/s and 4.5 m/s and all solar radiation values, and wind speed value is upper than 4.5 m/s and solar radiation value varies from 2 kWh/m^2/d to 6 kWh/m^2/d, under these conditions the optimal hybrid system is Wind/Diesel/Battery HRES.

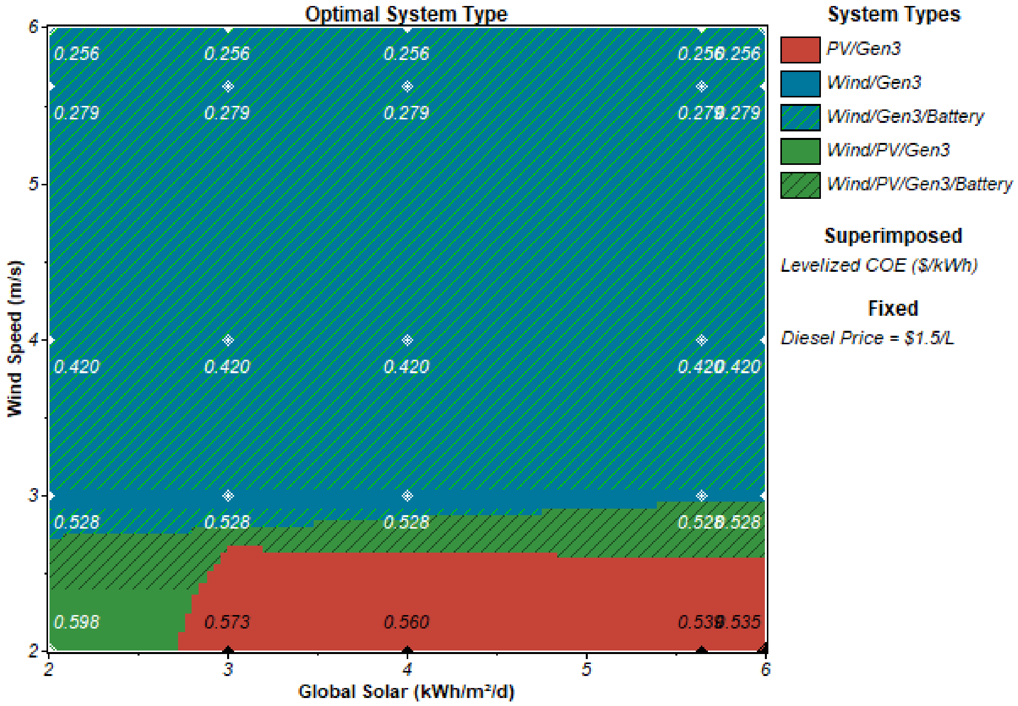
(3) For the lowest diesel value of 2.50 $/L, while wind speed value varies from 3.8 m/s to 6 m/s and solar radiation value is lower than 3.2 kWh/m^2/d, and wind speed value varies from 3.8 m/s to 6 m/s and solar radiation value is between 3.2 kWh/m^2/d and 3.8 kWh/m^2/d, the optimal hybrid system is Wind/Diesel/Battery HRES. In addition, when both wind speed value varies from 3.8 m/s to 6 m/s and solar radiation value is between 3.1 kWh/m^2/d and 6 kWh/m^2/d, and wind speed value is between 2.8 m/s and 3.8 m/s and all solar radiation values, and wind speed value varies from 2 m/s to 2.8 m/s and solar radiation value is upper than 4 kWh/m^2/d, under these conditions the optimal hybrid system is Wind/PV/Diesel/Battery HRES. Lastly, when wind speed value is between 2 m/s and 2.8 m/s and solar radiation value is upper than 2 kWh/m^2/d, and wind speed value is between 3.2 m/s and 3.7 m/s and solar radiation value is lower than 5 kWh/m^2/d, the optimal hybrid system is Wind/PV/Diesel HRES.



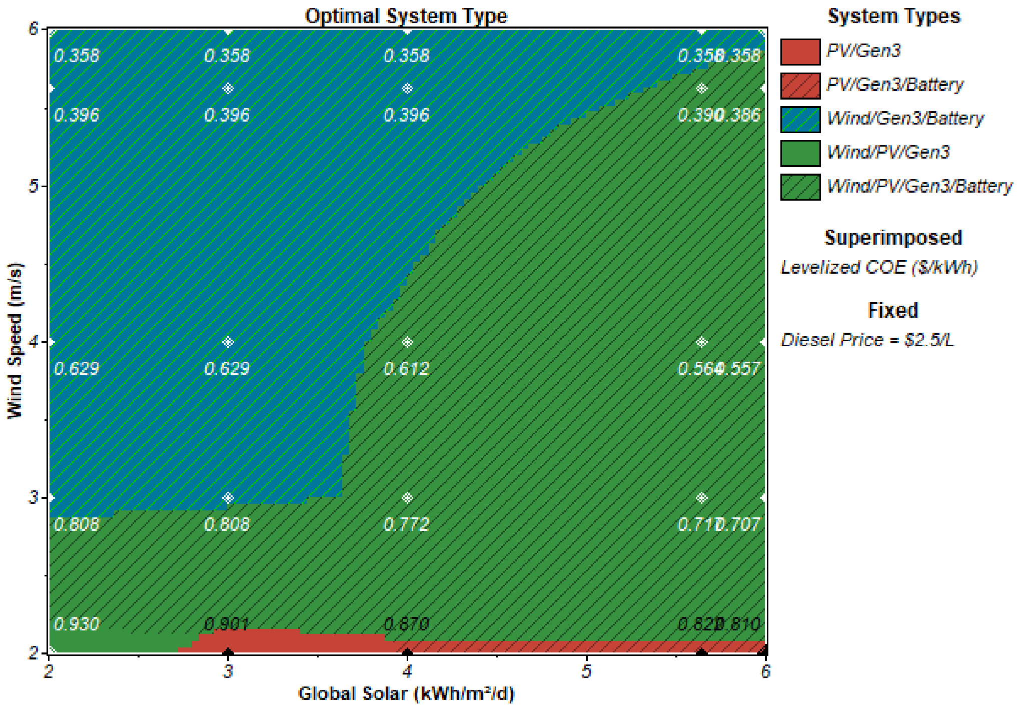
(a) Diesel price = 0.75 $/L



(b) Diesel price = 1.0 $/L



(c) Diesel price = 1.50 $/L



(d) Diesel price = 2.5 $/L

Fig. 9 Some sensitivity cases and optimal system configuration under the current conditions.

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%.
- Operating hours of the diesel generator in HRES vary in the range of 6,712-8,760 h. In this context, it is useful to state that, for the case of the stand-alone diesel system, the amount of the diesel consumed is 1,156,127 L and operating hour of the diesel generator is 8,760 h/year. This has shown that, with the introduction of PV and WTs and also with a remarkable decrease in the diesel fuel consumption, there will be a great reduction in emissions which are in the range of 42%-100%. PV/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%.
- *CoE* values for all available optimal hybrid systems, excluding the stand-alone diesel system, occur in the range of 0.208 $/kWh to 0.359 $/kWh.
- For the current average wind speed, current diesel price and solar irradiation values of the hospital that is 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 HRES fulfills the energy demand of the hospital completely. AC primary load of the hospital is approximately 2,436,836 kWh/year which comprises of 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 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 the hazardous emission gases 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 less (more than 50% lower) compared to the diesel generator system. Moreover, the new hybrid systems never produce harmful emissions or partially emissions according to the renewable fraction values of the system. It is an interesting and a good feature of such systems that hybrid systems are not only more economical than only diesel generator systems, they are also more environmentally friendly.
- Examining the effects of the minor or major change 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/.
- For high diesel prices,

(1) It is the Wind/Diesel/Battery hybrid system at the low wind speed values.

(2) It is the PV/Wind/Diesel/Battery hybrid system at the moderate wind speed values.

(3) It is the PV/Wind/Diesel/Battery hybrid system at the high wind speed values.

Acknowledgements

I thank to the Director of Somalia Mogadishu-Turkey Training and Research Hospital. Also, I am grateful to lecturer Ali Karakoc and his colleagues at the Somalia Mogadishu Recep Tayyip Erdogan Vocational School of Health Sciences of the University of Health Sciences, Turkey.

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