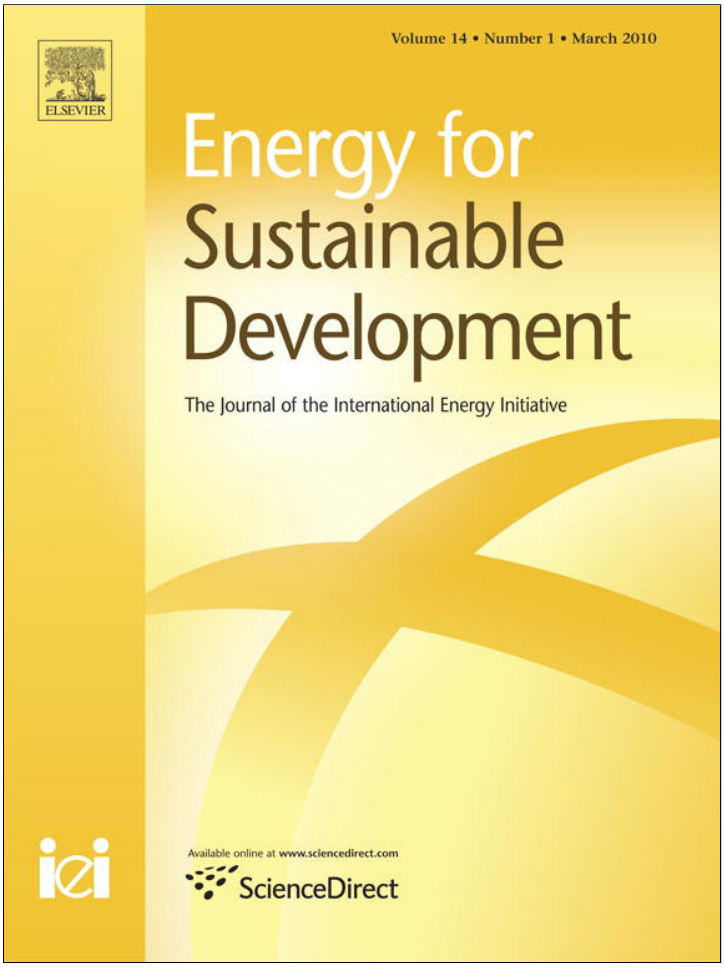
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Hybrid systems for decentralized power generation in Bangladesh

Alam Hossain Mondal *, Manfred Denich

Center for Development Research (ZEF), University of Bonn, Walter Flex Str. 3, 53113 Bonn, Germany

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ABSTRACT

When renewable energy technologies are used in decentralized and remote areas, they can be coupled with diesel generators to improve the total system reliability. In this paper, wind–diesel generator–battery, wind–photovoltaic (PV)–diesel generator–battery, PV–diesel generator–battery hybrid and diesel generator systems for generating electricity in the rural areas of Bangladesh are analyzed. The main objective of the present study is to determine the optimum size of systems able to fulfill the requirements of 50 kWh/day primary load with 11 kW peak load for 50 households for three remote sites located at Cox's Bazar, Sylhet and Dinajpur. The methodology applied provides a useful and simple approach for sizing and analyzing the hybrid systems using HOMER, an optimization model for renewable energies. The aim is to identify a configuration among a set of systems that meets the desired system reliability requirements with the lowest electricity unit cost. The result of the analysis is a list of feasible power supply systems, sorted according to their net present cost. Furthermore, sensitivity diagrams, showing the influence of solar radiation, wind speed and diesel prices on the optimum solutions are also presented. The analysis results show that PV (6 kW)–diesel generator (10 kW)–battery hybrid system is most economically feasible and least cost of energy is about 25.4 Tk/kWh (1 USD = 68.5 Taka). The result also indicates that the decrease in CO_2 emissions by using the feasible hybrid system with 40% renewable fraction is about 38% as compared to the diesel-only system.

Introduction

Currently, 1.6 billion people do not have access to electricity (WB, 2004). With an estimated world average growth rate of 2.8%, the electricity demand is expected to double between 1997 and 2020. At present, the grid electricity supply mainly meets the demand of the urban and industrial sectors in the developing countries, whereas most people live in the rural areas.

About 80% of the total population of Bangladesh lives in rural areas. Bangladesh lacks a sufficient electricity generation capacity and grid networks to electrify the whole nation and has never enjoyed 100% electrification (Uddin and Taplin, 2006). Per capita electricity generation in 2000–01 and 2005–06 were 129 kWh and 170 kWh, respectively (BPDB, 2006). Only 31.2% of the total population is connected to grid electricity (about 80% of urban and 23% of rural households), with the vast majority being deprived of a power supply (BBS, 2000, 2008). The government of Bangladesh has declared that it aims to provide electricity for all by the year 2020, though at present it has a high unsatisfied demand for energy, which is growing by more than 8% annually (PSMP, 2005). The Rural Electrification Board (REB), in its master plan of 2000, noted that it had supplied electricity services to about 31% of the total rural population. Its forecast for 2020 was a rural population of 97 million with electricity services, which would be about 84% of the total rural population (PSMP, 2005). Due to the high cost of transmission and distribution, a large number of rural settlements have not been connected to the grid, as they do not meet the load demand criteria. Therefore, it is very clear that many villages and isolated areas may not be connected in the near future to conventional electricity generation and distribution networks.

Electricity supplies to the rural and isolated areas of Bangladesh need to be reliable and sustainable in the long term. Renewable energy technologies are an important emerging option. Bangladesh is situated between 20.30 and 26.38° north latitude and 88.04 and 92.44° east longitude, which is an ideal location for solar energy utilization. Daily solar radiation varies between 3.8 and 6.5 kWh/m^2 (Islam et al., 2008). Recent studies on wind energy in Bangladesh show that some coastal areas have a good potential for small- and large-scale wind electricity generation. Solar and wind energy are intermittent. For this reason, diesel generator is also considered to ensure system reliability. In this study, solar PV–wind–diesel generator–battery, wind–diesel generator–battery, PV–diesel generator–battery and diesel generator alone are analyzed for different loads. The study areas comprised a coastal area (Cox's Bazar, 21.4° north latitude and 92° east longitude) with wind and solar potential, and two sites where the average solar radiation is lowest (Sylhet, 24.9° north latitude and 91.9° east longitude) and highest (Dinajpur, 25.6° north latitude and 88.6° east longitude). Based on the data from the National Aeronautics and Space

* Corresponding author.
E-mail addresses: alam_90119@yahoo.com, alam-hossain@uni-bonn.de (A.H. Mondal).

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Administration (NASA), the wind potential for power generation is too low at these two sites.

To develop a technically viable system, the hourly energy demand, resource availability and energy production need to be considered. Therefore, HOMER (Hybrid Optimization Model for Electric Renewables), the renewable energy-based system optimization tool developed by the US National Renewable Energy Laboratory (NREL), was used for all sites. HOMER is a general-purpose hybrid system design software that facilitates the design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical load (primary energy demand), renewable resources (solar radiation, wind speed data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. The software designs an optimal power system to serve the desired loads. HOMER performs hundreds or thousands of hourly simulations to ensure the best possible matching between supply and demand in order to design the optimum system. HOMER performs sensitivity analyses where the value of certain parameters (e.g. diesel price) can be varied to determine their impact on the cost of energy for the system in question (Shaahid and El-Amin, 2009). With HOMER, the effect of values which vary in time like electric load, wind speed and solar radiation, to the electric system is modeled. For each of these values, 8760 values are formed in HOMER. HOMER cannot model transient changes which are smaller than 1 h. However, it is expressed that, hourly value is sufficient in order to analyze the systems like the proposed type. Further details of HOMER will be given when appropriate in the various sections. Before installing a renewable energy system for power generation, economic analysis should be made. HOMER makes economic analysis and ranks the systems according to their net present costs.

Renewable energy resources

Solar radiation

HOMER synthesizes solar radiation values for each of the 8760 h of the year by using Graham algorithm. This algorithm produces realistic hourly data, and it is easy to use because it requires only the latitude and the monthly average values. The synthetic data displays realistic day-to-day and hour-to-hour pattern. The synthetic data are created with certain statistical properties that reflect global average values. So, data generated for a particular location will not perfectly replicate the characteristics of the real solar radiation. But tests show that synthetic solar data produce virtually the same simulation results as real data (Demiroren and Yilmaz, 2010).

No ground measurement data of solar radiation exist for Bangladesh. Monthly average solar data for selected locations based on NASA, HOMER (via internet using latitude and longitude) and recorded (Islam et al., 2008) are summarized in Table 1. NASA satellite data show that the annual average solar radiation at Cox's Bazar, Sylhet and Dinajpur is 4.77 kWh/m^2/day, 4.57 kWh/m^2/day and 4.99 kWh/m^2/day, respectively. The NASA dataset is used for the HOMER simulation.

Wind speed

When hourly wind speed data is not available, hourly data can be generated synthetically from the monthly averages. HOMER's synthetic wind speed data generator is a little more different to use than the solar data because it requires four parameters (Demiroren and Yilmaz, 2010):

The Weibull (k) value: k value is a measure of distribution of wind speed over the year. The default value is 2 because this has been shown to represent most wind regimes fairly accurately. The default value is used in this study.

The autocorrelation factor: this factor measures the randomness of the wind. Higher values indicate that the wind speed in 1 h tends to depend strongly on the wind speed in the previous hour. Lower values mean that the wind speed tends to fluctuate in a more random fashion from hour-to-hour. The autocorrelation factors tend to be lower (0.70−0.80) in areas of complex topography and higher (0.90−0.97) in areas of more uniform topography. In this study, 0.78 is used.

The diurnal pattern strength: it is a measure of how strongly the wind speed depends on the time of day. In most locations, the afternoon trends to be windier than the morning. Higher values indicate that there is a strong dependence on the time of day. In this study, 0.30 is used.

The hour of peak wind speed: it is simply the time of day that tends to be windiest on average throughout the year. In this study, 14:00 is used as the hour of peak wind speed (Nandi and Ghosh, 2009).

Table 1 shows the monthly wind speed average values for Cox's Bazar (Hossain and Badr, 2007). As seen from Table 1, the wind speed is relatively low during January, February, March and April compared to other months. These values are at 25 m height. For this reason, an anemometer height of 25 m is considered in HOMER simulations. The probability distribution function of wind speed data for Cox's Bazar

Table 1
Solar radiation and wind speeds at the study sites.

Month	Cox's Bazar				Sylhet				Dinajpur		
	Solar radiation (kWh/m^2/day)		Wind speed (m/s)		Solar radiation (kWh/m^2/day)			Wind speed (m/s)	Solar radiation (kWh/m^2/day)		Wind speed (m/s)
	NASA	HOMER	NASA (10 m)	Recorded (25 m)	NASA	Recorded	HOMER	NASA (10 m)	NASA	HOMER	NASA (10 m)
Jan	4.75	4.75	2.3	2.33	4.37	4.00	4.13	2.0	4.32	4.10	2.0
Feb	5.33	5.25	2.5	1.99	5.04	4.63	4.59	2.1	5.30	4.63	2.3
Mar	5.93	5.74	2.7	2.42	5.60	5.20	5.07	2.3	6.22	5.49	2.4
Apr	6.09	5.87	2.9	1.84	5.62	5.24	5.16	2.2	6.47	6.14	2.6
May	5.52	5.63	3.0	3.97	4.84	5.37	5.13	2.1	6.12	6.04	2.7
Jun	4.11	4.25	3.9	4.64	4.22	4.53	4.29	2.1	5.12	5.26	2.6
Jul	3.81	3.85	3.8	4.80	4.18	4.14	3.93	1.9	4.31	4.05	2.3
Aug	4.03	4.08	3.4	4.31	4.30	4.56	4.03	1.8	4.41	4.46	2.1
Sep	4.15	4.04	2.7	2.96	3.94	4.07	3.68	1.7	3.99	4.37	2.0
Oct	4.53	4.72	2.1	3.74	4.36	4.61	4.85	1.6	4.78	5.12	1.7
Nov	4.48	4.43	2.3	2.93	4.29	4.32	4.29	1.8	4.68	4.24	1.8
Dec	4.56	4.51	2.2	1.78	4.17	3.85	4.03	1.9	4.24	3.91	1.9
Annual	4.77	4.77	2.8	3.14	4.57	4.54	4.41	2	4.99	4.82	2.2

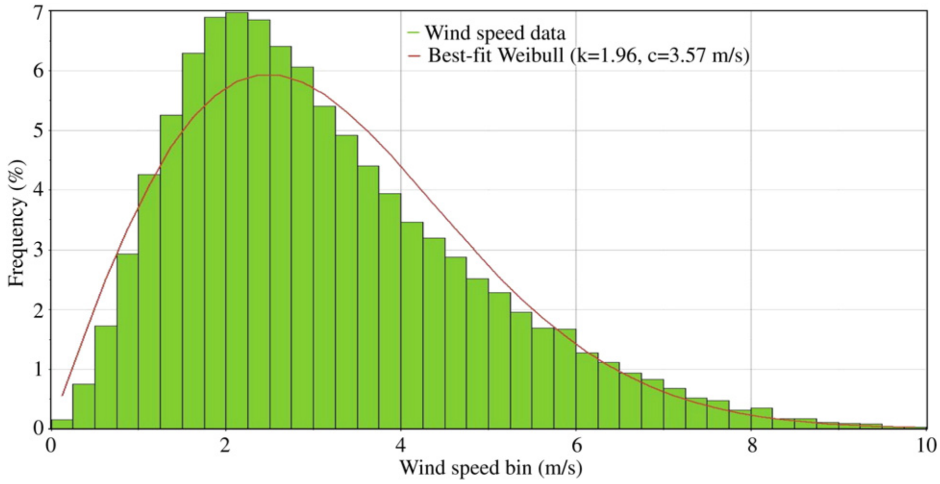

Fig. 1. Probability distribution function of wind speed data synthesized by HOMER.

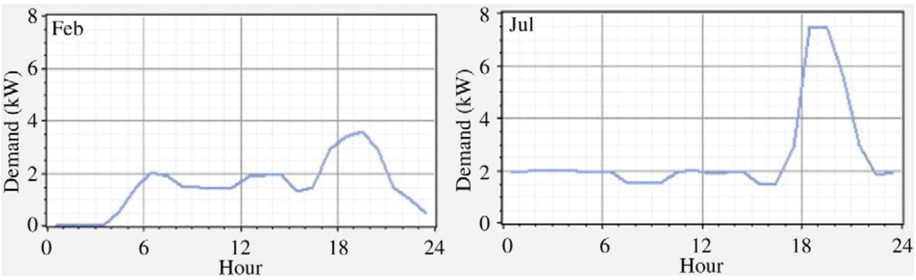

Fig. 2. Load profile on winter (February) and summer (July) for 50 households.

synthesized by HOMER is shown in Fig. 1. NASA-based wind speed data is also presented in Table 1 for the locations of Sylhet and Dinajpur. Because of the low wind energy potential at Sylhet and Dinajpur, solar PV–diesel–battery system and diesel-only system are considered on these sites.

Load profile

Deciding on the load is one of the most important steps in the design of the proposed hybrid systems. This study, a hypothetical model community of 50 families, each comprising of five family members, is considered. The household in the rural area is simple and does not require large quantities of electrical energy for lighting and electrical appliances due to not being connected with the national grid network. A rural household generally uses electrical energy for lighting, cooling and entertaining (Bala and Siddique, 2009). This load is based on 3 energy efficient lamps (compact fluorescent bulb, 15 W each), 2 fans (ceiling fan, 40 W each) and 1 television (TV, 40 W) for each family of the rural settings. Timing of electricity used for lighting is the same with only little variation during winter and summer due to timing of sun-set and sun-rise. Fans are used only in summer, normally at night. Average TV operating time is 5.5 h per day (Khan, 2006). The primary load or energy consumption pattern usually varies over 24 h and over different months of the year. Fig. 2 shows two load profiles on a day of summer (April–October) and winter (November–March). HOMER simulates the operation of a system by making energy balance calculations for each of the 8760 h in a year. Measured hourly load profiles are not available, so load data were synthesized by specifying typical daily load profiles and then adding some randomness of daily 10% and hourly 15% noise. These have scaled up the annual peak load to 11 kW and primary load to 50 kWh/day.

Proposed hybrid system components and costs

The proposed hybrid systems, PV–wind-diesel generator–battery for Cox's Bazar and PV–diesel generator–battery for Dinajpur and Sylhet consist of two diesel generators (15 kW, Gen1 and 10 kW, Gen2), PV array, wind turbine, battery and converter. One of the schematic diagrams is shown in Fig. 3.

Diesel generator

The cost of a diesel generator depends on its size. The fuel used in HOMER is modeled by a linear curve characterized by a slope and an intercept at no load. For a capacity range of 5 kW to 45 kW, the slope and the intercept are respectively 0.33 l/h/kW and 0.05 l/h/kW (Nguyen, 2005). The diesel generators utilized are of 10 kW and 15 kW

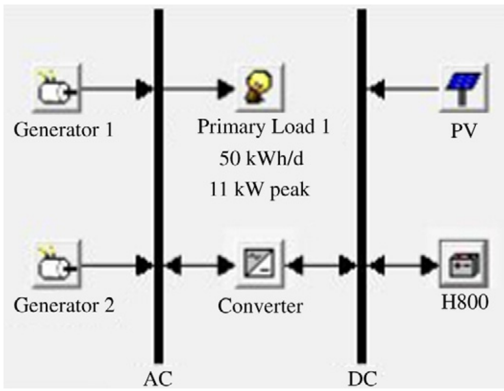

Fig. 3. One of the proposed hybrid systems for 50 households.

Table 2
Technical parameters and cost assumptions for diesel generators.

Parameter	Unit	Value
Capital cost (Mondal, 2005)	Taka (Tk)/kW	10,000
Replacement cost	Tk/kW	8000
Operation and maintenance cost	Tk/h	20 (10 kW), 30 (15 kW)
Operational lifetime	Hours	15,000
Minimum load ratio	Percent	10
Fuel curve intercept	$l/h/kW_{rated}$	0.05
Fuel curve slope	$l/h/kW_{output}$	0.33
Fuel price	Tk	45

Taka (Tk) Bangladeshi currency (1 USD = 68.5 Taka).

rated power each with technical and economic parameters furnished in Table 2.

Solar PV

HOMER deals with PV array in terms of rated kW, not in m^2. HOMER assumes that the output of the PV array is linearly proportional to the incident solar radiation. If the solar radiation is 0.80 kW/m^2, the array will produce 80% of its rated output. The PV modules composed of several solar cells are clustered in series–parallel arrangement to form solar arrays with the necessary capacity. In the proposed systems PV array sizes are considered: 0 (no PV), 2, 4 and 6 kW. The parameters considered for the simulation of solar PV are furnished in Table 3.

Solar PV panels become less efficient as their temperature increases. The power generation is roughly anti-linear in the temperature range under which panels are exposed and the temperature effect is also considered in this study. It is worth mentioning that HOMER's PV input page has a derating factor. This is used to compensate for the reduction in efficiency because real world conditions are somewhat less favorable than standard test conditions. The most important factor is temperature, but also dust and wiring losses have a small effect. The default value of derating factor is 90%. Slightly lower value should be used in very hot climates (Camerlynck, 2004). In this study, the default value is used. The energy production by the PV array is calculated using the following formula:

$$P_{PV} = f_{PV} {}^{*} Y_{PV} \left(\frac{I_T}{I_S}\right) \qquad (1)$$

Where f_{PV} is the derating factor, Y_{PV} is the total installed capacity of PV array, I_T is the solar radiation on the PV array (kW/m^2) and I_s is the incident radiation at standard test conditions (1 kW/m^2).

Wind turbine

The wind hybrid system was simulated in the model based on the technical data and economic parameters of the wind turbines Generic 3 kW. Technical and economic parameters for selected wind turbine are furnished in Table 4.

Battery

The Hoppecke 8 OPzS storage batteries are utilized in the hybrid systems. Their specifications are shown in Table 5.

Table 3
Solar PV array—technical parameters and cost assumptions.

Parameter	Unit	Value
Capital cost (Islam, 2005)	Tk/W	274
Replacement cost	Tk/kW	206
Operation and maintenance cost	Tk/kW/yr	50
Lifetime	Years	25
Derating factor	Percent	90
Tracking system	No tracking system 0.05	

Table 4
Technical and economic parameters of wind turbine.

Parameter	Unit	Value
Rated power	kW	3
Starting wind speed	m/s	4
Rated wind speed	m/s	13
Cut-off wind speed	m/s	15
Capital cost (J. lee, 2009)	Tk/kW	86,584
Replacement cost	Tk/kW	75,000
Operation & maintenance cost	Tk/yr/turbine	1000
Lifetime	Year	20

Table 5
Technical parameters and cost assumptions for battery.

Parameter	Unit	Value
Nominal voltage	Volt	2
Nominal capacity	Ah (kWh)	800 (1.6)
Maximum charge current	A	162
Round-trip efficiency	Percent	86
Minimum state of charge	Percent	30
Capital cost (Mondal, 2010)	Tk/kWh	7000
Replacement cost	Tk/kWh	6000
Operation and maintenance cost	Tk/kWh/yr	50

Converter

A power converter is used to maintain the flow of energy between the AC and DC components. 5 kW, 8 kW and 10 kW size converters are considered in the model. Table 6 shows the technical and economic parameters of the converter.

Hybrid system control parameters and constraints

HOMER assumes all prices escalate at the same rate over the project lifetime. With this assumption, inflation can be factored out of the analysis simply by using the real interest rate (inflation-adjusted) rather than the nominal interest rate (the rate at which you could get a loan) when discounting future cash flows to the present. This study used the real interest rate, which is roughly equal to the nominal interest rate minus the inflation rate. The real interest rate is considered as 5% and the project lifetime is taken on 25 years. The capacity shortage penalty is not considered. The system control parameters used in the simulation run are summarized in Table 7. The spinning reserve and system constraints are furnished in Tables 8 and 9, respectively.

Table 6
Technical parameters and cost assumptions for converter.

Parameter	Unit	Value
Capital cost (J. lee, 2009)	Tk/kW_{rated}	14,933
Replacement cost	Tk/kW_{rated}	10,000
Lifetime	Years	10
Efficiency	Percent	90
Rectifier capacity	Percent	95
Rectifier efficiency	Percent	85

Table 7
System control parameters used in software.

Parameter	Option	Option used
Load following	Yes or no	Yes
Cycle charging	Yes or no	Yes
Apply set point	Yes or no	Yes
Set point state of charge	–	80%
Allowing multiple generators	Yes or no	Yes
Multiple generators can operate parallel	Yes or no	Yes

Table 8
Spinning reserve inputs.

Percent of annual peak load	0
Percent of hourly load	8
Percent of hourly solar output	0
Percent of hourly wind output	35

Table 9
Constraints used in HOMER.

Parameter	Value
Maximum unserved energy	0 (%)
Maximum renewable fraction	0 to 100%
Minimum battery life	N/A
Maximum annual capacity shortage	0, 4, 6 and 10%

The dispatch strategy is load following. A set of fuels is used to control the operation of the generators and the battery whenever there is insufficient PV or wind energy to supply the primary load. The cycle charging is a dispatch strategy whereby whenever a generator needs to operate with full output power to serve the primary load. The set point state of charge is a parameter which can be applied for the cycle charging strategy. If a set point state of charge is applied, once the system starts to charge the battery it will not stop until the battery bank reaches the set point state of charge. The operation strategy is as follows: in normal operation solar PV feeds the load for Sylhet and Dinajpur sites. Solar PV and wind turbine feed the load for Cox's Bazar site. The excess energy is stored in the battery until full capacity of the storage system is reached. The main aim of introducing battery storage is to import or export energy depending upon the situations. In the event, that the output from PV exceeds the load demand and the battery's state of charge is maximum, then the excess energy goes un-used. Two diesel generators are brought online at times when PV/PV–wind fails to satisfy the load and when battery storage is depleted.

Results and discussion

The optimum sizes of the technologies that meet the given load for the selected sites under the given conditions of renewable energy resources and based on a fixed dataset for diesel generators were simulated by HOMER. HOMER provides the results in terms of optimal

Sensitivity variables

Global Solar (kWh/m²/d) 4.99 Diesel Price (Tk/L) 45 Max. Annual Capacity Shortage (%) 5 Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

PV (kW)	Gen1 (kW)	Gen2 (kW)	H800	Conv. (kW)	Disp. Strgy	Initial Capital (Tk.)	Operating Cost (Tk/yr)	Total NPC (Tk.)	COE (Tk/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)
6		10	10	5	CC	1,860,665	333,663	6,563,288	25.415	0.43	0.00	5,661		2,484
6	15	10	10	5	CC	1,905,665	333,095	6,600,285	25.558	0.43	0.00	5,663	1	2,485
4		10	10	5	CC	1,312,665	377,049	6,626,766	25.662	0.31	0.00	6,447		2,847
6		10	10	8	CC	1,905,464	336,806	6,652,383	25.760	0.43	0.00	5,686		2,471
4	15	10	10	5	CC	1,357,665	376,410	6,662,773	25.800	0.31	0.00	6,449	2	2,846
6	15	10	10	8	CC	1,950,464	336,238	6,689,378	25.903	0.43	0.00	5,689	1	2,472
4		10	10	8	CC	1,357,464	378,840	6,696,819	25.933	0.30	0.00	6,450		2,832
6		10	10	10	CC	1,935,330	338,042	6,699,676	25.943	0.43	0.00	5,686		2,471
4	15	10	10	8	CC	1,402,464	378,158	6,732,195	26.069	0.30	0.00	6,451	5	2,825
6	15	10	10	10	CC	1,980,330	337,474	6,736,671	26.087	0.43	0.00	5,689	1	2,472
4		10	10	10	CC	1,387,330	380,077	6,744,111	26.116	0.30	0.00	6,450		2,832
4	15	10	10	10	CC	1,432,330	379,394	6,779,488	26.252	0.30	0.00	6,451	5	2,825
4		10	8	5	CC	1,290,265	390,321	6,791,425	26.299	0.31	0.00	6,623		3,207
4	15	10	8	5	CC	1,335,265	389,687	6,827,485	26.438	0.31	0.00	6,625	3	3,204
4		10	8	8	CC	1,335,064	392,169	6,862,275	26.573	0.31	0.00	6,622		3,204
6		10	8	5	CC	1,838,265	357,568	6,877,805	26.633	0.42	0.00	6,031		2,933
4	15	10	8	8	CC	1,380,064	391,535	6,898,334	26.713	0.31	0.00	6,624	3	3,201
4		10	8	10	CC	1,364,930	393,406	6,909,568	26.756	0.31	0.00	6,622		3,204
4		10	5	5	CC	1,256,665	401,291	6,912,439	26.767	0.31	0.00	6,734		3,789
6	15	10	8	5	CC	1,883,265	357,061	6,915,670	26.780	0.42	0.00	6,035	1	2,935
6		10	8	8	CC	1,883,064	358,093	6,930,011	26.835	0.42	0.00	6,012		2,905
4	15	10	8	10	CC	1,409,930	392,771	6,945,627	26.896	0.31	0.00	6,624	3	3,201
4	15	10	5	5	CC	1,301,665	400,576	6,947,367	26.902	0.31	0.00	6,735	3	3,786
6	15	10	8	8	CC	1,928,064	357,587	6,967,875	26.982	0.42	0.00	6,016	1	2,907
6		10	8	10	CC	1,912,930	359,330	6,977,303	27.018	0.42	0.00	6,012		2,905
4		10	5	8	CC	1,301,464	403,146	6,983,379	27.042	0.31	0.00	6,734		3,789
6	15	10	8	10	CC	1,957,930	358,824	7,015,168	27.165	0.42	0.00	6,016	1	2,907
4	15	10	5	8	CC	1,346,464	402,431	7,018,306	27.177	0.31	0.00	6,735	3	3,786
6		10	5	5	CC	1,804,665	370,471	7,026,059	27.207	0.42	0.00	6,221		3,445
4		10	5	10	CC	1,331,330	404,382	7,030,672	27.225	0.31	0.00	6,734		3,789
6	15	10	5	5	CC	1,849,665	369,730	7,060,617	27.341	0.42	0.00	6,222	1	3,444
4	15	10	5	10	CC	1,376,330	403,668	7,065,599	27.360	0.31	0.00	6,735	3	3,786
6		10	5	8	CC	1,849,464	372,325	7,096,998	27.482	0.42	0.00	6,221		3,445
6	15	10	5	8	CC	1,894,464	371,585	7,131,556	27.616	0.42	0.00	6,222	1	3,444
6		10	5	10	CC	1,879,330	373,562	7,144,291	27.665	0.42	0.00	6,221		3,445

Fig. 4. Optimization results for PV-diesel-battery system for a solar radiation of 4.99 kWh/m^2/day, diesel price of 45 Tk/L, maximum capacity shortage of 5% and minimum renewable fraction of 0%.

systems and the sensitivity analysis. In this software the optimized results are presented categorically for a particular set of sensitivity parameters like solar radiation, wind speed, diesel price, maximum annual capacity shortage and renewable energy fraction. Long term global solar radiation, wind speed, electrical load for 50 families, in addition to the proposed hybrid systems' technical details and costs, constraints, controls, type of dispatch strategy, etc. formed an input to the HOMER. HOMER performs thousands of hourly simulations over and over in order to design the optimum hybrid system. The software uses life cycle cost to rank order these systems. An hourly time series simulation for every possible system type and configuration is performed for one complete year. A feasible system is defined as a hybrid system configuration that is capable of meeting the load. A key objective is to compare the levelized cost of energy (COE) and the greenhouse gas (GHG) emissions of the diesel generator-only system with those of various hybrid systems. HOMER gives the opportunity to design a cost-minimizing power system that provides a tailor-made power supply for the specific load demand (Hrayshat, 2009).

Optimization results

The optimization results for a global solar radiation of 4.99 kWh/m^2/day (annual mean value at the site of Dinajpur, where the off-grid community is located), minimum renewable fraction 0% and the diesel price in Bangladesh, which currently equals 45 Tk/L are summarized in Fig. 4. The first column shows the presence of PV array, the second and third columns indicate the presence of diesel generators (Gen1 and Gen2). The fourth column shows the presence of battery storage, the fifth column indicates the presence of the converter, while the sixth column shows the size of PV array considered in a particular case. The ninth column shows the number of selected batteries utilized, while the tenth column shows the converter size in kW. The eleventh and twelfth columns show dispatch strategy and initial capital cost respectively. The fifteenth column shows cost of electricity (COE, Tk per kWh) and the sixteenth column shows the renewable energy fraction (PV penetration).

The hybrid system comprised of 6 kW PV array, a diesel generator (Gen2) with a rated power of 10 kW and 10 storage batteries in addition to 5 kW converter is found to be the most feasible system with a minimum total net present cost (NPC) of 6.56 million Taka, COE of 25.41 Tk/kWh and a renewable energy fraction of 43% as shown in Fig. 4. This is merely due to the high cost of diesel and optimal solar radiation at the location under investigation. This PV–diesel generator–battery hybrid system is found to be the most economically feasible at all investigated locations in this study. Due to the low intensity of wind speed at Cox's Bazar site, wind hybrid is not selected as a most economically feasible system.

Fig. 5 depicts the details related to energy generated by PV and diesel system, excess electricity, un-met load, capacity shortage and renewable fraction for the most economically feasible system applicable for all investigated locations. It can be seen from Fig. 5 that with the above system configuration, un-met load is 0 kWh and an excess energy of about 8% is generated. It should be mentioned here that this excess energy produced goes to waste due to lack of demand. This figure also indicates that the monthly average hybrid PV–diesel generated power is high during summer months as compared to other months. This is a favorable characteristic because electricity demand is high during the summer months in Bangladesh.

Sensitivity results

The HOMER model simulates all the systems in their respective search space for each of the sensitivity values. In the present study global solar radiation (3.8, 4.3, 4.8, 5, 5.3, 5.6, 5.9, 6.2 and 6.5 kWh/m^2/day), diesel price (45, 55, 75, 90, 100, 120 and 140 Tk/L), wind speed (2.8, 3, 3.3, 3.5 and 3.8 m/s only for Cox's Bazar site), maximum annual capacity shortage (5, 8 and 10%) and minimum renewable energy fraction (0, 10, 20, 30 and 50%) are used as sensitivity variables. A total of 4725 sensitivity cases were examined for each system configuration.

Fig. 6 shows optimization results in terms of wind speed and diesel cost. Fig. 7 exhibits the sensitivity analysis results in terms of global solar radiation and diesel price for maximum annual capacity shortage of 5%. Figs. 6 and 7 show which of the possible two systems i) PV–Gen2–battery and ii) wind–PV–Gen2–battery will be feasible in terms of levelized COE, values of which are scattered over the figure and expressed in Tk/kWh at a particular solar radiation/wind speed and diesel price. This type of graphical representation of the optimal system type provides information that a particular system will be optimal at a certain solar radiation or a certain wind speed and a certain diesel price. Furthermore, the solar radiation, wind speed and diesel price

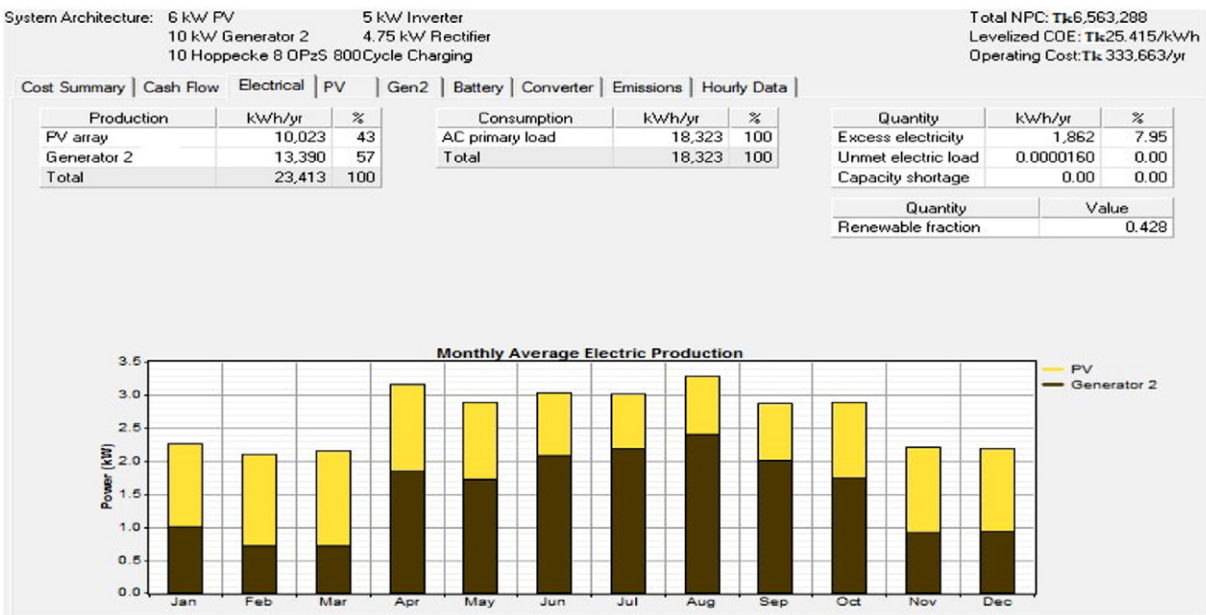

Fig. 5. Energy yield for the feasible hybrid PV–diesel–battery system.

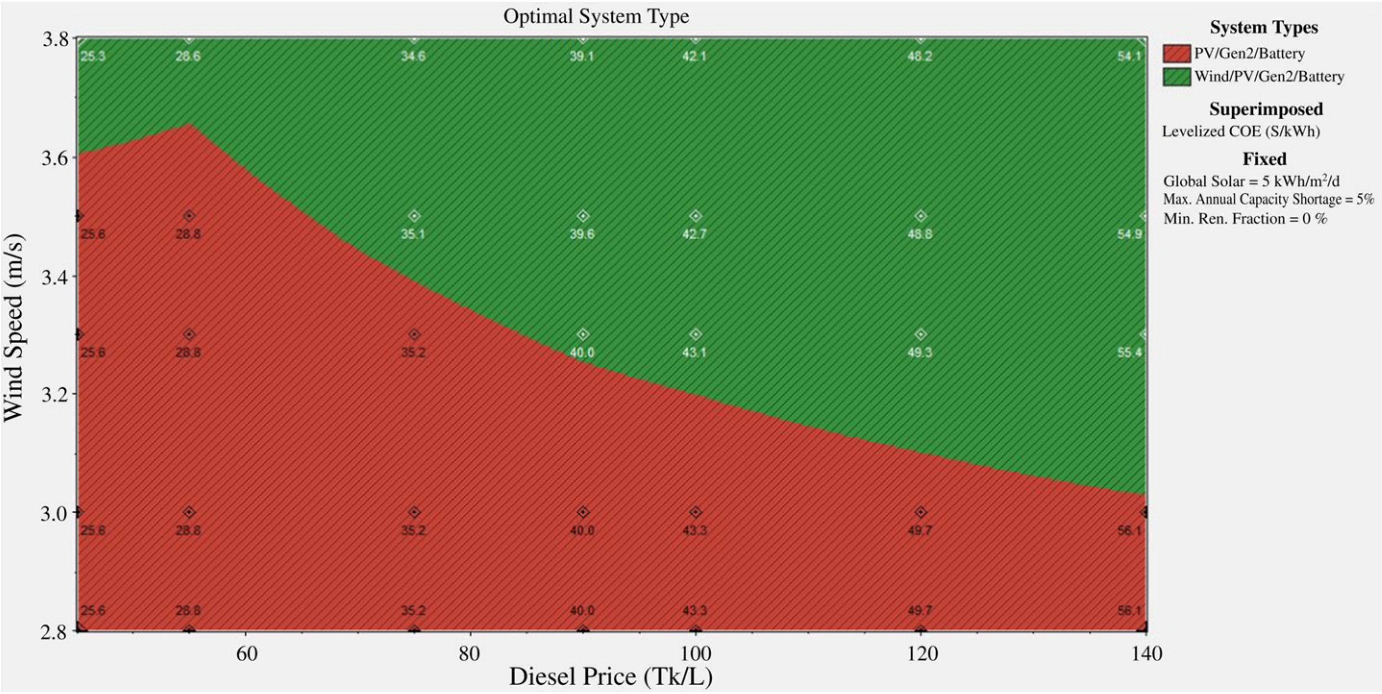

Fig. 6. Type of optimal systems in terms of wind speed and diesel price with global solar radiation 5 kWh/m^2/day, maximum capacity shortage of 5% and minimum renewable fraction of 0%.

are usually site-dependent, so one can conclude that at a particular solar radiation or wind speed and fuel cost the system will be optimal for a particular place or location.

The system shown in Figs. 6 and 7 reflects that PV–diesel–battery system is feasible for any selected diesel price with a fixed wind speed of 3 m/s. The system that for 3.2 m/s wind speed or more and diesel price of 100 Tk/L or more, the wind–PV–diesel hybrid system becomes economically feasible. This is in favor of utilizing the PV–diesel–battery system to supplement the off-grid remote houses with electricity, since the current diesel price is about 45 Tk/L in Bangladesh.

Greenhouse gas emission reduction

One environmental externality associated with electricity generation is carbon dioxide emissions from any fossil fuel combustion. Carbon dioxide is the most important greenhouse gas (GHG), responsible

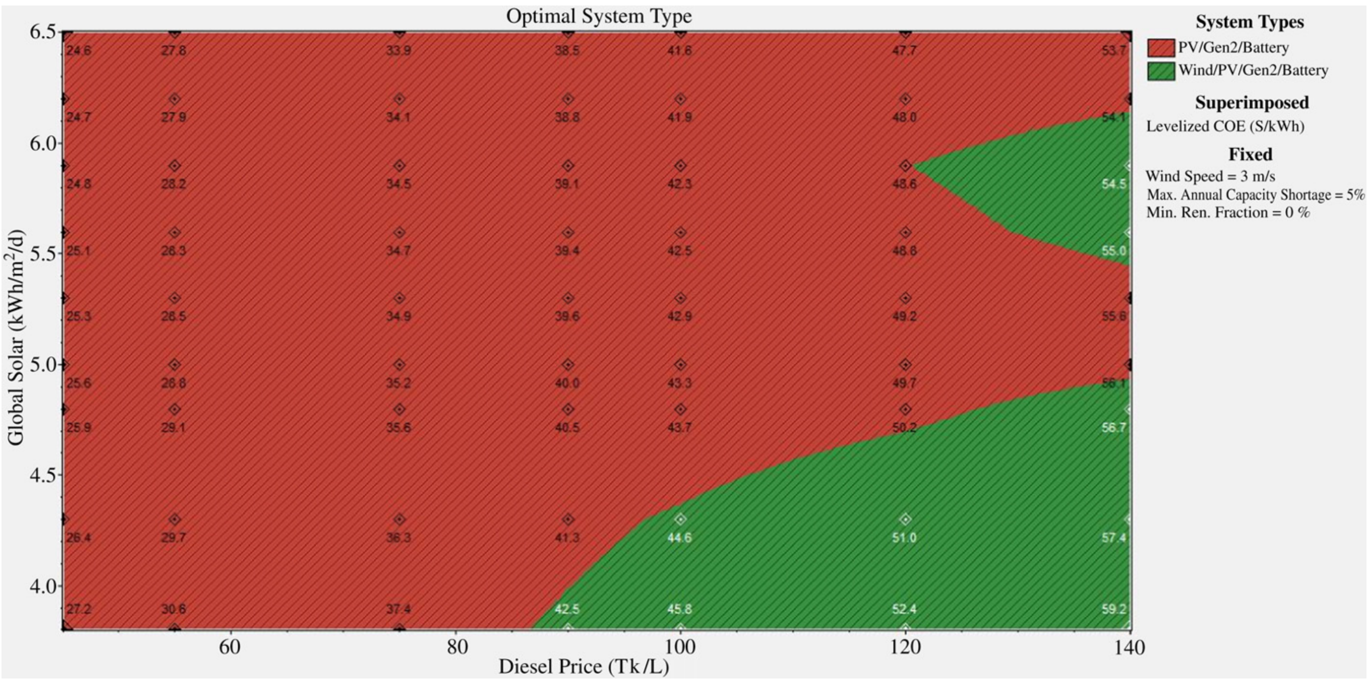

Fig. 7. Type of optimal systems in terms of solar radiation and diesel price with wind speed 3 m/s, maximum capacity shortage of 5% and minimum renewable fraction of 0%.

for climate change, and we are increasingly involved in determining the magnitude of GHG emissions associated with different activities. The diesel generator system being used at the selected sites is considered and HOMER calculates that a total of 24,681 kg per year of CO_2 adds into the local atmosphere of a village consist with 50 families based on the diesel's lower heating value 43.2 MJ/kg, density 820 kg/m^3 and carbon content 88%. The PV–Gen2–battery system can bring down the quantity of the CO_2 to 15,421 kg per year with 40% renewable energy fraction. This shows a reduction of approximately 38% of CO_2 every year.

Conclusions

This study indicates that the selected locations blessed with a considerable annual average global solar radiation (3.81–6.47 kWh/m^2/day), are prospective candidates for the deployment of PV–diesel–battery hybrid power system. The simulation results for all selected locations indicate that the most economically feasible system for 50 rural off-grid households would be composed of 6 kW PV array together with a 10 kW diesel generator and 10 numbers of batteries of which each has a nominal voltage of 2 and capacity of 800 Ah, and the penetration of solar PV is 43%. Due to high diesel cost only diesel-based power generation is not economically feasible. This study also indicates that the remote settlements located in Bangladesh are prospective candidates for the deployment of the proposed PV–diesel–battery hybrid system for electricity generation due to the favorable daily average solar radiation which varies between 3.8 and 6.5 kWh/m^2 and the diesel price is almost the same all over the country. Utilizing this system for electricity generation—in comparison with the diesel generator-only situation would decrease the operating hours and consequently the diesel consumption of the generators and would lead to reduction in emissions of GHG.

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