Techno-economic Feasibility Study of a Solar PV-Diesel System for Applications in Northern Part of Bangladesh

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Abstract- Renewable energy offers convenient energy solution to the population living in isolated areas. The residents can utilize the locally available energy resources for fulfilling their need for electricity. The availability of electricity in the darkness of night facilitates higher productivity. In this paper, design of a solar PV-diesel mini-grid system has been presented for a locality in Char Parbotipur (25.75°N 89.66°E). This island is situated 20 km north-east from Kurigram district, Bangladesh and surrounded by Brahmaputra river and Dudhkumar river, far from the national grid. Very few residents use stand-alone Solar Home Systems (SHS) and diesel generators. Diesel generators have environmental concern which can be minimized by using hybrid renewable energy systems. This paper aims at designing an optimal energy system consisting solar PV having diesel generator for fulfilling the load demand. The proposed energy system can generate electricity at a cost of \$0.461/kWh for a load of 115 kWh/day. Sensitivity analysis is presented to understand the effect of diesel price and solar irradiation on the cost of electricity and net present cost of the system. Comparison between the proposed hybrid renewable energy system and an energy system comprising diesel generator only are also presented to understand the effect of solar PV integration with diesel generators for environmental benefits. The solar PV-diesel energy system emits 53.68% lower CO_2 as compared to diesel generator.

Keywords Renewable energy, HOMER, solar energy, Mini-grid, diesel generator.

1. Introduction

Access to electricity is a vital factor for social and economic development of a country. The population of Bangladesh is increasing every year. Due to a large number of population, and growth in industrial and commercial sectors, the demand for energy is increasing rapidly. However, about 45% of the population does not have access to electricity from the national grid [1]. Bangladesh has many isolated communities that are not connected to the national grid. They fulfil their electricity demand mainly by stand-alone diesel generators. Diesel generators have economic and environmental concerns. Providing reliable and cost effective electricity to the people with no access to electricity is a great challenge. Though extension of grid is preferable to provide electricity to the rural areas, but extending the national grid to remote communities sometime is not feasible. In such cases off-grid hybrid renewable energy system options could be very useful.

Natural gas is the main source of energy supply in Bangladesh. About 61% of the total electricity production comes from natural gas [2]. This energy source is depleting at an alarming rate. Burning of natural gas produces greenhouse gases (GHGs) that are responsible for global warming. To mitigate this problem it is important to explore renewable resources (e.g. solar, wind, biomass, hydro, etc.). Bangladesh has a very good potential for solar energy. The country gets 4.67 kWh/m^2 solar energy per day [3]. Renewable energy resources (solar, wind, hydro, and biomass) are promising alternate means of generating power that can overcome the problems of diesel generators. Single use of renewable resources such as stand-alone PV or stand-alone wind is not reliable because the energy supply is not continuous. A hybrid energy system, combination of solar and diesel generator can satisfy demand reliably. The system can generate electricity with much lower GHG emissions compared to stand-alone diesel generators. Optimizing the system components of a hybrid renewable energy system with lower net present cost is the challenge.

Many studies have been carried out that conducted the techno-economic assessment of renewable energy systems around the globe. Zubair et al. [4] designed a hybrid energy system of 19.4 MW for a coastal region of Bangladesh where wind is abundant. The authors found that stand-alone PV or stand-alone wind system is not financially viable. A PV-wind-diesel generator system is financially feasible. The lowest cost of electricity can be obtained with 14% PV, 55% wind, and 31% diesel generator. Islam et al. [5] studied the feasibility of a hybrid renewable energy system for Saint Martin's Island, Bangladesh. A PV-wind-diesel generator system can produce electricity for the location at a cost of \$0.345/kWh. 14 tons of CO_2 can be reduced per year by replacing existing diesel generators by the hybrid renewable energy system. Mondal and Islam [6] conducted a viability study for a grid connected solar PV system in Bangladesh. Internal rate of return, net present cost, benefit-cost ratio were calculated in the study to check the viability. The same authors [7] conducted a feasibility study of a grid connected PV system of 500 kW and found the cost of electricity as \$0.20/kWh. Ngan and Tan [8] analysed the potential implementation of a hybrid PV-wind-diesel system in a city in southern Malaysia. Most of the energy comes from PV and a diesel generator due to low wind potential in that place. With the proposed hybrid system, CO_2 emissions were reduced by 35% with a cost of electricity of \$0.24/kWh. Chandel et al. [9] did an assessment of solar power plant in India. Electricity can be produced at a cost of \$0.24/kWh with a discounted payback period of 15.53 years. A hybrid renewable energy system was proposed by Rohani and Nour [10] for a remote area in western Abu Dhabi. Diesel generators were incorporated with wind and PV. Different combinations of wind turbines, solar PV, batteries, and generators were evaluated in order to determine the optimal combination for a 500 kW hybrid system based on the lower net present cost. The net present cost was found to be \$14,504,952 over 25 years. Greenhouse gas emissions from a small wind turbine and a diesel generator were assessed by Fleck and Hout [11]. The wind turbine system can reduce 93% of GHG emissions compared to the diesel generator system. Li et al. [12] performed a techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi, China. The authors found a variation in cost of energy (COE) between \$1.045/kWh to \$1.596/kWh, depending upon number of batteries. Rehman and Al-Hadhrami [13] proposed a solar PV-diesel-battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. For a diesel price of \$0.20/L, the cost of electricity (COE) of PV-diesel-battery with 21% solar penetration system and diesel only system was found to be \$0.219/kWh and \$0.190/kWh, respectively. Adaramola et al. [14] found that, at \$0.281/kWh, 791.1 MWh of electricity can be produced annually with a PV array of 80 kW, a 100 kW wind turbine, two generators with combined capacity of 100 kW, a 60 kW converter/inverter and a 60 Surrette 4KS25P battery. A sensitivity analysis was also conducted for wind speed, solar global radiation, and diesel price. The total net present cost, capital cost and the cost of electricity were found to be \$673,147, \$238,000 and \$0.420/kWh, respectively for an off-grid region in India [15]. Fadaeenejad [16] did an assessment of hybrid renewable power sources for rural electrification in Malaysia. The authors found that combination of photovoltaic-wind-battery is the most cost-effective. Different combinations of renewable resources and diesel generators were proposed to produce electricity with lower net present cost were proposed by different studies for different locations [17, 18, 19].

There is limited study on renewable energy options for remote areas in Northern part of Bangladesh. Although there are some studies conducted for coastal areas, no study is reported to design a hybrid energy system for a community in Northern Bangladesh. The design of a hybrid system is very much location specific which depends on the local wind speed, solar irradiation, diesel price, etc. For policy making towards sustainability, it is necessary to conduct a comprehensive study on hybrid renewable energy system. The purpose of this study is to find the optimal hybrid energy system from the available resources for a particular off-grid location Char Parbotipur, Bangladesh. The electricity production, techno-economic and emission (CO_2) assessments for a hybrid energy system were carried out for the selected off-grid community. It is expected that the optimal energy system can provide a cost-effective solution with low environmental footprint for the community.

2. Methodology

The objective of this study is to conduct the techno-economic feasibility study of a Solar PV-Diesel mini-grid for northern region of Bangladesh. To achieve this objective, a suitable place is to be chosen, the available energy resources have to be assessed, the energy system has to be modeled and the energy system has to be optimized. Hence, an energy system consisting Solar PV, diesel generator and battery is designed for an island Char Parbotipur under Kurigram sadar upazila in Northern region of Bangladesh to satisfy a certain electrical load. A different energy system comprising only diesel gen-set is also modeled which satisfies the same electrical load to compare the effect of installing Solar PV on the economics and the environment.

The modeling of the energy system has been carried out using a computer software HOMER (Hybrid Optimization Model for Electric Renewable) which is a micro power design tool developed by NREL (National Renewable Energy Laboratory), USA [20]. HOMER can be used to model a power system's behavior and economics which includes installation and operational cost. Different design options for the power system can be compared using HOMER considering technical and economic merits and demerits. HOMER can be used to design both on-grid and off-grid power systems which may consist of Solar PV, wind turbines, diesel gen-sets, biomass power, batteries, etc. [21]. HOMER designs the system by performing the principal tasks namely simulation, optimization and sensitivity analysis to determine the most feasible power system architecture. HOMER simulates all the possible variation in system configuration that meet the load demand and discard the configurations that does not adequately fulfil the required load. Only the feasible system configurations are presented categorically based on total net present cost.

Char Parbotipur (25.75°N 89.66°E) is an island situated 20 km north-east from Kurigram district, Bangladesh under Kurigram sadar upazila and shown in Figure. 1. This island is surrounded by Brahmaputra River and Dudhkumar River. At present, there is no grid connection there and very few residents are currently using stand-alone Solar Home Systems (SHS) and diesel generators. The proposed energy system has been designed for a locality in this island to study the techno-economic feasibility. A synthetic load of 115 kWh/day has been considered for designing the energy system with day-to-day random variability of 15% and load factor of 0.298. In this system, only light and fan have been considered for the households (100 families) and market places covering 0.5 km^2 of area. Figures 2 and 3 show the seasonal variation of the electrical load and the demand map throughout the year.

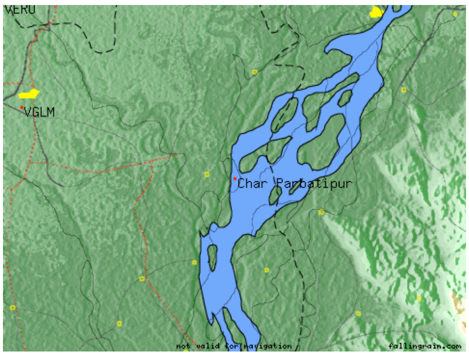

Fig. 1. Char Parbotipur on the map [22]

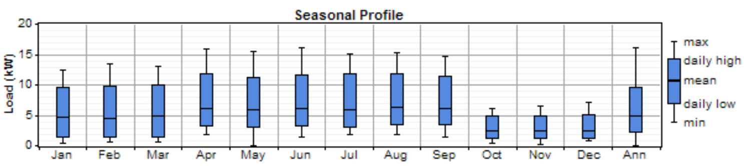

Fig. 2. Seasonal profile for the electrical load

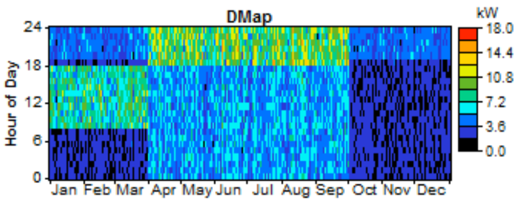

Fig. 3. The load demand map throughout the year

3. Energy Resources

In the study area, Char Parbotipur, two energy resources have been considered, solar irradiation and diesel. Solar PV makes use of solar irradiation to generate electricity and diesel generator uses diesel to do the same. The monthly solar irradiation data for Char Parbotipur has been obtained from National Aeronautics and Space Administration (NASA) [23] through HOMER software. Figure. 4 shows the average monthly solar radiation profile with a scaled annual average radiation of 4.56 kWh/m^2/day and an average clearness index of 0.504. The clearness index is a measure of the clearness of the atmosphere which is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the earth [21]. The shiniest days of the year are in the months of March-May (5.302, 5.840 and 5.467 kWh/m^2/day, respectively).

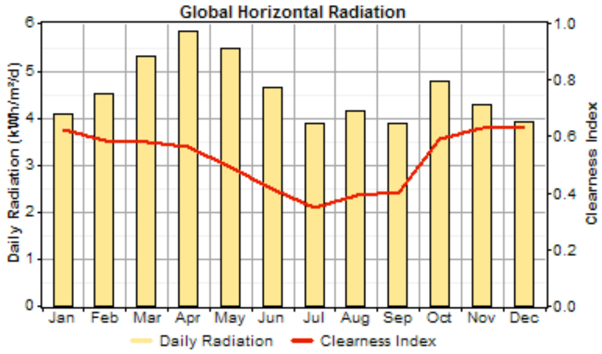

Fig. 4. Average monthly solar radiation profile for Char Parbotipur.

Diesel is a common liquid fuel extensively used for rural electrification using Diesel generators. Diesel having a lower heating value of 43.2 MJ/kg and a density of 820 kg/m^3 and price of \$0.9/L have been considered in this study. Although the price of diesel is \$0.85/L according to Bangladesh Petroleum Corporation [24], an additional \$0.05/L have been added with the diesel price considering the transportation cost to the rural area from the cities. Carbon content and Sulphur content have been considered as 88% and 0.33%, respectively.

4. Energy System Definition and Optimization

In the proposed hybrid energy system, Solar PV modules have been incorporated to utilize the available solar radiation in the study area. Diesel gen-set have been used for backup as a reliable source of electricity. Batteries have been considered for electricity storage to supply electricity in the absence of sunlight. For the project, an annual interest rate of 10% [4] and project life time of 20 years [15] have been considered. Maximum annual capacity shortage of 10% have been considered as system constraints [13]. Figure 4 shows the energy system comprising Solar PV- Diesel gen-set and battery. The pricing of the components have been taken from Hoque et al. [25].

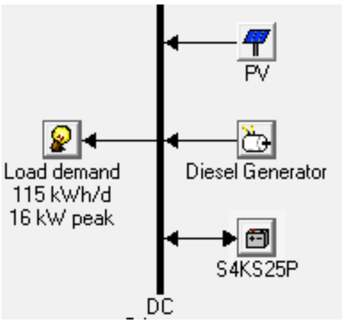

Fig. 5. Energy system comprising Solar PV-Diesel gen-set-Battery (Energy System-1)

A different energy system comprising only Diesel generators have been modeled to satisfy the same load to compare with the aforementioned energy system. All the system parameters have been kept the same. The energy system is shown in Figure 6.

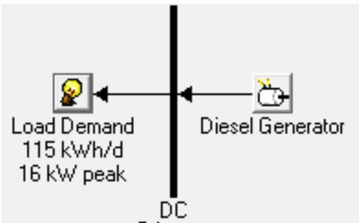

Fig. 6. Energy system comprising Diesel gen-set only (Energy System-2)

Solar photovoltaic (PV) panels utilizes the incident solar irradiation and produce electricity. They are connected in series and DC current is obtained. The panels considered have no tracking system and are modeled as fixed and tilted with a slope of 25.98^o (the latitude of the site). 240 W_p PV panels have been considered with a capital cost of \$3.75/W_p and a replacement cost of \$3.125/W_p with a life time of 20 years. The operation and maintenance cost has been considered to be \$6.25/year [25].

A 4 kW diesel generator with a capital cost of \$312.5/kW has been considered after doing market research on the availability of the diesel generators. Operation and maintenance cost has been considered as 0.385\$/hr [25]. The lifetime has been considered as 15000 hr with a minimum load ratio of 30%. The generator is considered to have intercept coefficient of 0.05 L/hr/kW_{rated} and slope of 0.33 L/hr/kW_{output} [26]. The efficiency curve is shown in Figure 7 as generated in the software.

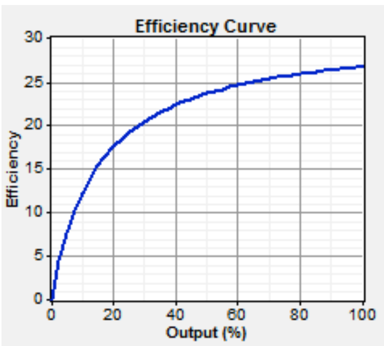

Fig. 7. Efficiency curve for the diesel generator.

Batteries have been considered due to the intermittent nature of solar resources. In this study, Surrette 4KS25P batteries have been used with a nominal voltage of 4V and capacity ratio of 0.245. Six batteries are connected per string resulting 24 V bus. The batteries have a nominal capacity of 1,900 Ah (7.6 kWh). The capital cost of a battery has been considered as \$87.5/kWh whereas replacement cost and operations and maintenance cost have been considered as \$75/kWh and \$0.625/year, respectively [24]. The capacity curve and lifetime curve for Surrette 4KS25P are shown in Figure 8 and Figure 9.

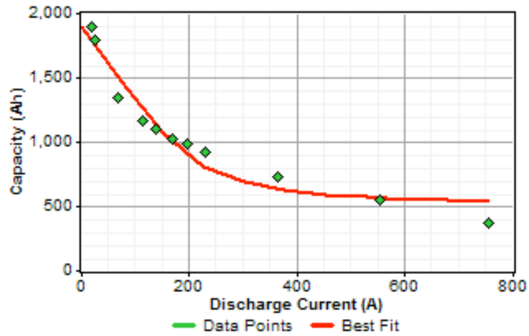

Fig. 8. Capacity curve of Surrette 4KS25P [26]

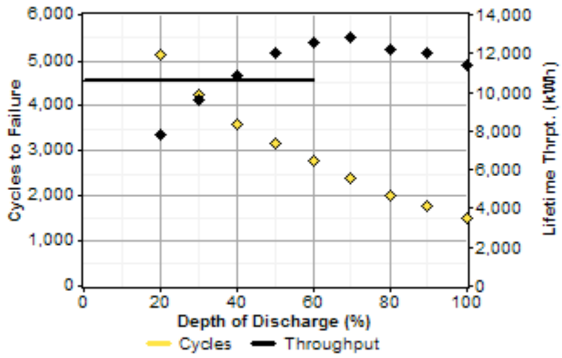

Fig. 9. Lifetime curve of Surrette 4KS25P [26]

5. Results and Discussions

Using the input data, HOMER has optimized the system architecture for fulfilling the load demand of 115 kWh/day with a hybrid system comprising Solar PV, diesel generator and battery (Energy system-1). The optimized system consists of 14.40 kW of PV modules, 4 kW of diesel generator and 30 S4KS25P batteries with a total net present cost of \$149,112 and operating cost of \$8,417/year. The levelized cost of electricity is found as \$0.461/kWh with renewable fraction of 51.1%. The diesel generator is to run for 6,008 hours consuming 7,894 liters of diesel.

The optimized power system has a total net present cost of \$149,112. Among the system components, diesel generator has the highest share (43.56%) in the cost closely followed by PV modules (39.86%). The detailed cost analysis is presented in Table 1. The cash flow diagram over the project life time are shown in Figure 10 and Figure 11.

Table 1. Cost summary of the Energy system-1 (Net present cost)

Component	Capital cost ($)	Replacement cost ($)	O&M cost ($)	Fuel cost ($)	Salvage ($)	Total ($)
PV	56,520	0	3,193	0	0	59,443
Diesel Gen.	1,250	3,168	205	60,482	-147	64,957
Battery	19,950	5,449	161	0	-847	24,712
System	77,450	8,616	3,558	60,482	-994	149,112

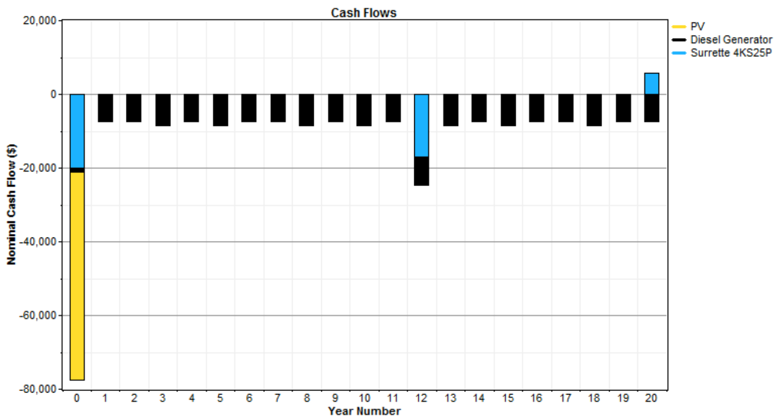

Fig. 10. Cash flow diagram for the project by components

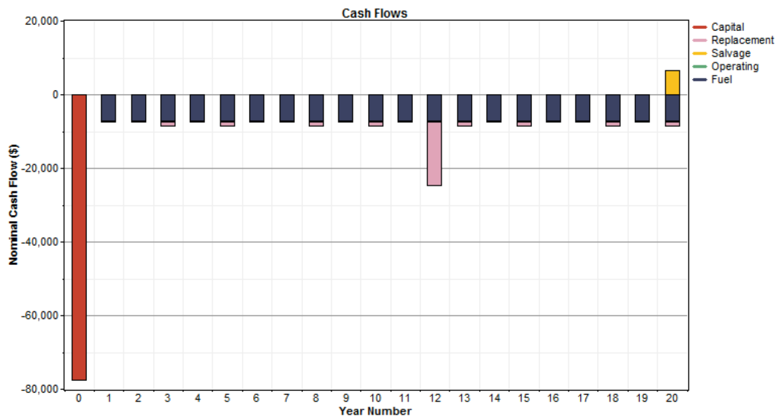

Fig. 11. Cash flow diagram for the project by cost type

Energy system-1 produces 41,511 kWh/year of electricity where PV array produces 51% (21,233 kWh/year) and the rest 49% is produced by Diesel gen-set. The system has excess electricity of 625 kWh/year (1.5%) and capacity shortage of 4,060 kWh/year. This excess electricity can be used to supply some deferrable load such as water pumping or any unexpected additional load [14]. The optimized power system generates electricity with a renewable fraction of 51.1%. Figure 12 shows the monthly average electricity production by Energy System-1.

In the optimized system architecture, the solar PV has rated capacity of 14.4 kW with a capacity factor of 16.8%. The PV modules have mean output of 58.2 kWh/day and has penetration of 50.6%. The modules operates 4,379 hours in a year with a levelized cost of \$0.329/kWh. Figure 13 shows the PV output throughout the year.

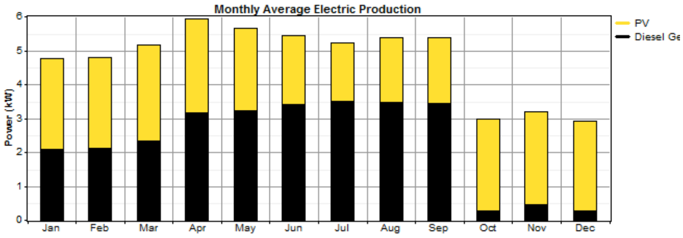

Fig. 12. Monthly average electricity production from Energy System-1

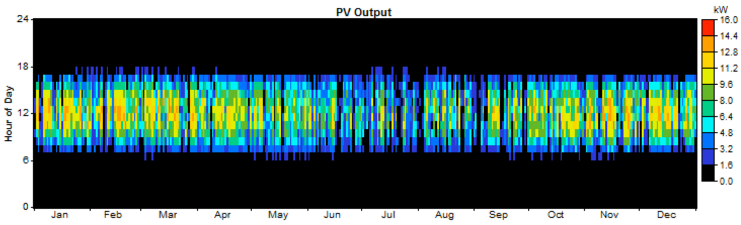

Fig. 13. PV output throughout the year for Energy System-1

In the optimized system architecture, 4 kW diesel generator is used with a capacity factor of 57.9%. It operates for 6,008 hours in a year with fixes generation cost of \$0.251/hr. The generator has specific fuel consumption of 0.389 liter/kWh and mean electrical efficiency of 26.1%. Figure 14 shows diesel generator output throughout the year.

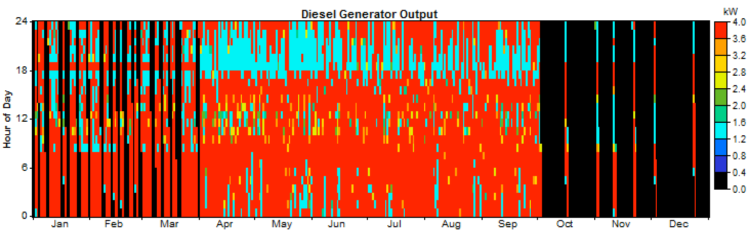

Fig. 14. Diesel generator output throughout the year

30 S4KS25P batteries are incorporated in the system architecture obtained from HOMER with nominal capacity of 228 kWh. The batteries have annual throughput (the amount of energy that cycled through the battery over the year) of 13,507 kWh/year with average energy cost of \$0.193/kWh. Figure 15 shows the battery bank state of charge throughout the year.

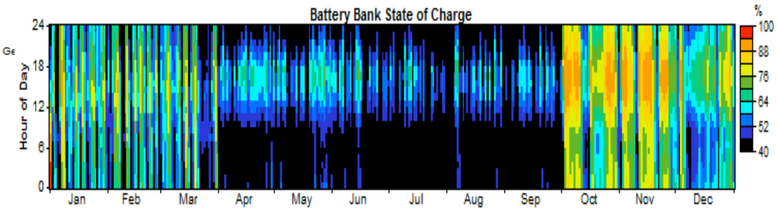

Fig. 15. Battery bank state of charge (SOC) throughout the year

The Solar PV-diesel generator-battery power system emits 20,786 kg/year of CO_2 and 51.3 kg/year of CO in a year. SO_x and NO_x emissions are 41.7 kg/year and 458 kg/year, respectively.

As discussed in the earlier section, a separate energy system (Energy System-2) comprising only diesel generator is designed to satisfy the same load demand (115 kWh/day) to compare with Energy system-1. Using the input data, HOMER has optimized the system architecture for Energy system-2 to be 8 kW of diesel generator with a total net present cost of \$143,044 and operating cost of \$16,508/year. All the costs are calculated for the base year of 2014. The levelized cost of electricity is found as \$0.423/kWh. The diesel generator consumes 17,039 liters of diesel. The detailed cost analysis is presented in Table 1. The cash flow diagram over the project life time is shown in Figure 16.

Energy system-2 produces 41,015 kWh/year of electricity with 3.09% excess electricity and capacity shortage of 2,225 kWh/year. Figure 17 shows the monthly average electricity production by Energy System-2.

In the optimized system architecture, 8 kW diesel generator is used with a capacity factor of 58.5%. It operates with fixes generation cost of \$0.502/hr. The generator has specific fuel consumption of 0.415 L/kWh and mean electrical efficiency of 24.5%. Figure 18 shows diesel generator output throughout the year.

Table 2. Cost summary of Energy system-2 (Net present cost)

Component	Capital cost (\$)	Replacement cost (\$)	O&M cost (\$)	Fuel cost (\$)	Salvage (\$)	Total (\$)
Diesel Gen.	2,502	9,407	671	130,559	-96	143,044
System	2,502	9,407	671	130,559	-96	143,044

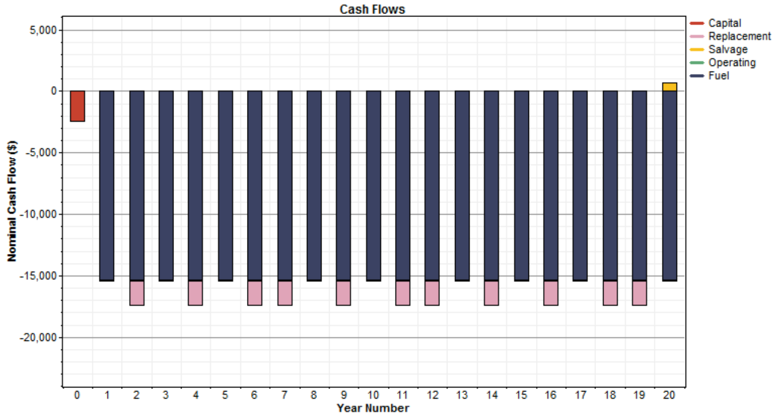

Fig. 16. Cash flow diagram for the project by cost type

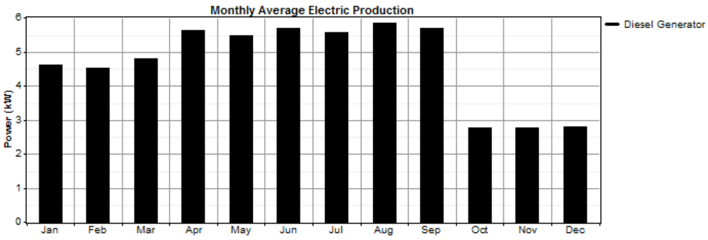

Fig. 17. Monthly average electricity production from Energy System-2

Energy system-2 produces 41,015 kWh/year of electricity with 3.09% excess electricity and capacity shortage of 2,225 kWh/year. Figure 17 shows the monthly average electricity production by Energy System-2.

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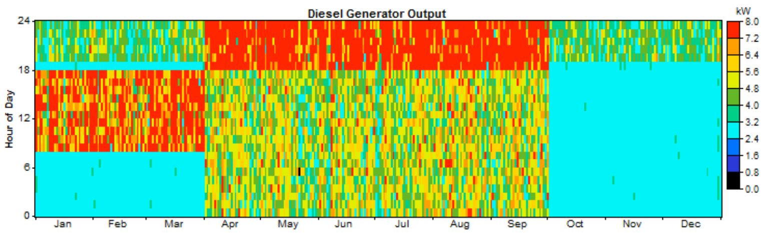

Fig. 18. Diesel generator output throughout the year (Energy System-2)

The Diesel generator-battery power system emits 44,870 kg/year of CO_2 and 111 kg/year of CO in a year. SO_x and NO_x emissions are 90.1 kg/year and 988 kg/year, respectively.

Table 3 shows the comparison between Energy System-1 and Energy System-2. It is seen that Energy system-1 will require \$149,112 as total net present cost which is higher than that of Energy System-2 (\$143,044). Energy system-2 will be requiring more fuel cost since it runs only on diesel whereas Energy System-1 can utilize both PV and diesel generator. Levelized cost of electricity for the Energy System-1 is \$0.038 higher per kWh of electricity. As emissions of pollutants are concerned, Energy system-1 will have lower environmental impact since Energy system-2 emits more CO_2, CO, SO_x and NO_x which are harmful for the environment.

Sensitivity analysis is carried out to understand the effect of varying different parameters in system configuration. Sensitivity analysis allows to assess the flexibility of the system. In this study, sensitivity analysis has been carried out by varying the diesel price and solar irradiation to understand the effect on levelized cost of electricity and total net present cost. Figure 19 and Figure 20 show the effect of variation in diesel price and solar irradiation on levelized cost of electricity and total net present cost, respectively.

Table 3. Comparison between Energy System-1 and Energy System-2

	Total net present cost ($)	**Fuel net present cost ($)**	**COE ($/kWh)**	**CO_2 (kg/year)**	**CO (kg/year)**	**SO_x (kg/year)**	**NO_x (kg/year)**
Energy System-1	149,112	60,482	0.461	20,786	51.3	41.7	458
Energy System-2	143,044	130,559	0.423	44,870	111	90.1	988

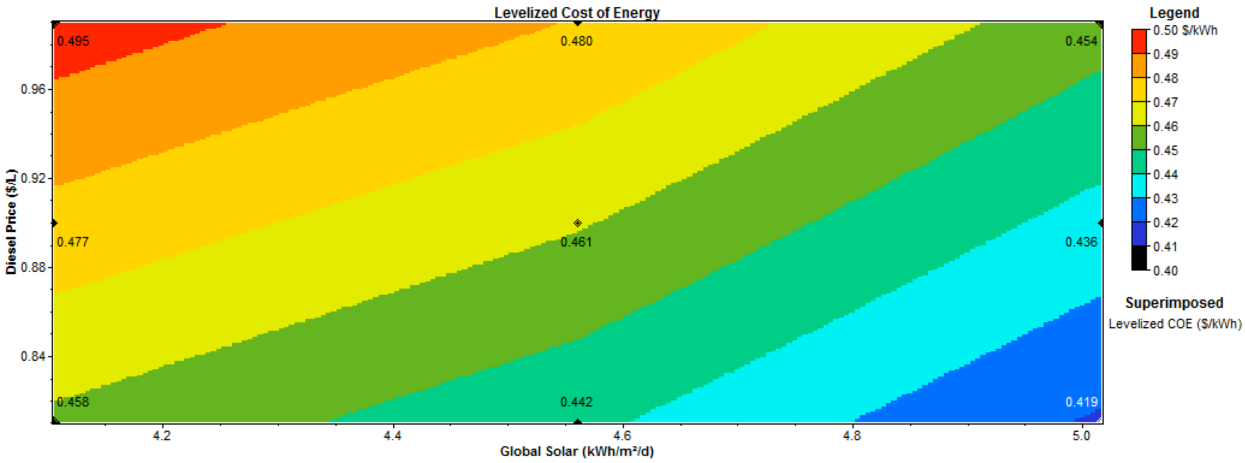

Fig. 19. Effect of variation of diesel price and global solar irradiation on levelized cost of electricity

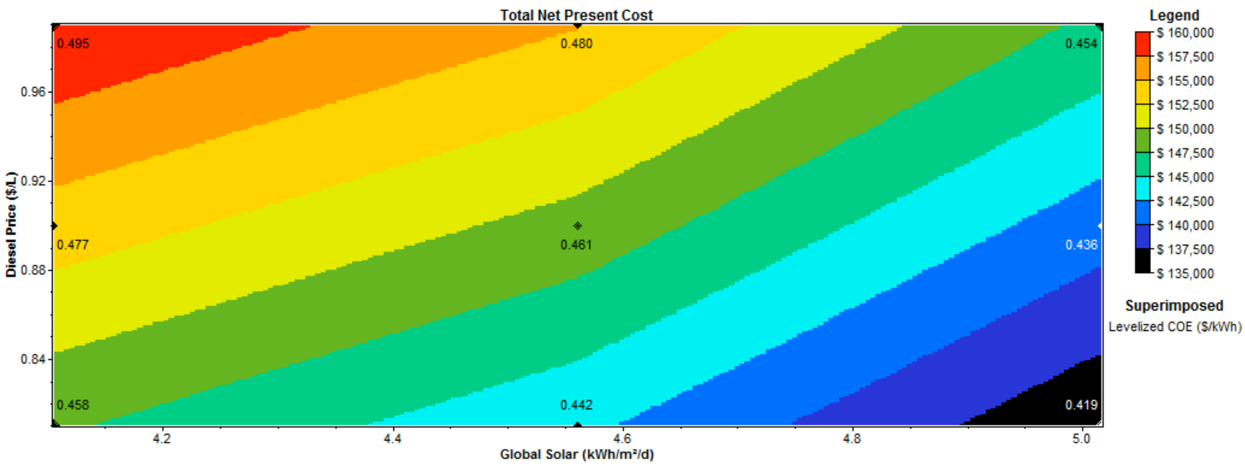

Fig. 20. Effect of variation of diesel price and global solar irradiation on total net present cost

6. Conclusion

Char Parbotipur is an island in Kurigram district situated in the northern region of Bangladesh. With the absence of national electricity grid, most of the people lack electricity as do the residents in other remote areas in Northern Bangladesh. Based on the solar resource present in the area and diesel as available fossil fuel resource, a hybrid energy system as designed using HOMER. The net present cost of the system is $149,112 and levelized cost of electricity is found as $0.461/kWh. Sensitivity analysis is also presented to understand the effect of variation in diesel price and total net present cost.

When compared with a hybrid energy system comprising only diesel generator for the generation of electricity, it has been found that integration of Solar PV with diesel generators is suitable with a lower environmental impact. Such hybrid renewable energy systems can be considered as attractive alternative for the people in Northern region of Bangladesh.

The COE of PV-diesel system (system 1) is only $0.038 higher than diesel generator (system 2). But system 1 offers 53.68% lower CO_2 emissions than system 2. Besides the integration of renewable resources with the conventional energy systems is in consistent with the government policy of Bangladesh which is to produce 10% of the country's electricity by renewables by 2020.

Appendix

$$\text{GHG emissions} = V*D*C*FO*(CO_{2M.W}/C_{M.W}) \quad (1)$$
$$COE=AC/ES \quad (2)$$
$$NPC=R_t/(1+i)^t \quad (3)$$

Where,
V– Volume of fuel
D– Density of fuel
C– Carbon percentage of fuel
FO– Fraction oxidized of fuel
$CO_{2M.W}$– Molecular weight of carbon dioxide
$C_{M.W}$– Molecular weight of carbon
COE– Cost of electricity
AC– Annualized cost (including amortization of the capital costs and operational costs)
ES– Sum of the energy supplied for the load yearly
NPC– Net present cost
R_t– The net cash flow, i.e. cash inflow – cash outflow, at time t
i– The discount rate
t – The time of the cash flow

HOMER assumes the fuel curve is a straight line with a y-intercept and uses the following equation for the generator's fuel consumption:

$$F = F_0 Y_{gen} + F_1 P_{gen}$$

Where F_0 is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). The units of F depend on the measurement units of the fuel. If the fuel is denominated in liters, the units of F are L/h. The units of F_0 and F_1 depend on the measurement units of the fuel as well. For fuels e.g. diesel denominated in liters, the units of F_0 and F_1 are L/h.kW. [21]

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