Investigating the Feasibility of Stand-Alone Solar-Natural Gas Hybrid Power Generation System for Remote Island

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Abstract

Design, simulation, and economic analysis of a cost-effective and environment-friendly hybrid power generation system is investigated in this study. The proposed system is an intelligent combination of natural gas generators, PV modules, Li-ion batteries, and converters, designed by HOMER software based on real data of Maheshkhali Island, Bangladesh. Two natural gas generators are added to make sure uninterrupted electricity supply due to the alternating characteristics of renewable energy. With the net present cost of $78,788,445.92 and the cost of energy $0.1248/kWh, this system will be able to meet the electricity demand of 3,21,221 people of this island. The payback period is found 9.61 years and the emission of Greenhouse Gases (GHGs) will be reduced significantly as the renewable energy contribution of this system is 26.4%. In addition, the electrical load with a certain variability, the optimum size and performance of its different components, net present cost (NPC), annualized cost, and environmental impacts with a comparative study are analyzed in this research.

Keywords
Hybrid power generation, Renewable energy, Natural gas generator, Optimal configuration and Emission reduction.

1. Introduction
With rapid industrialization and development, electricity consumption in Bangladesh has drastically increased over the last two decades (Key Energy Statistics of Bangladesh, 2018). According to the Sustainable Development Goals (SDGs) tracker of Bangladesh Government till 2018, it is ensured that 90.1% of the total population has got electricity access (Sustainable Goals Tracker of Bangladesh, 2018). Moreover, per capita electricity generation has increased to

425.92 kWh found on the annual report 2018-19 of Bangladesh Power Development Board (BPDB) (Bangladesh Power Development Board, 2019). An electricity generation extension plan has been prepared by BPDB, aims to achieve a generation capacity of 24,000 MW by 2021 with a goal to provide electricity across the country for expected social and economic development (Ahmed et al. 2014). Due to the depletion of gas reserve and a drastic increase in fuel price, sustainable development with socio-economic growth needs to be maintained properly (Islam and Khan, 2017). On the other hand, the effect of greenhouse gas and global warming is the main concern all over the world. Besides, the rapid depletion of fossil fuel is another environmental issue that has already been investigated by different public and private organizations all over the globe (Chiari and Zecca, 2011; Hoel and Kverndokk, 1996; Nel and Cooper, 2009; Sebitosi, 2008; Ellabban et al. 2014). Thus, it is essential to generate sustainable electricity in Bangladesh with the incorporation of renewable energy.

Generally, hybrid power generation is a combination of renewable energy sources (e.g. solar or wind or biomass), a non-renewable energy source (e.g. natural gas or diesel generator or internal combustion engine) and an energy storage system (e.g. battery). The main benefits of hybrid power generation are that limitations of a specific energy source can be overcome by other sources. In addition, hybrid power plants are capital investments sensitive and if the technological capacity of an energy source is chosen poorly, then it will be difficult to change the technology after the plant is built. Therefore, it is necessary to choose the technological capacity effectively of hybrid power plants, in order to minimize the financial losses.

2. Literature Review

Several attempts have been taken to design various types of hybrid power generation systems for the remote island of Bangladesh previously. These studies considered various combinations of non-renewable and renewable energy sources. Feasibility analysis of hybrid system consists of solar-wind-battery-diesel was simulated for Saint Martin island of Bangladesh, along with sensitivity and emission analysis by Ullah (2015) who found that it was efficient for 100 households and 10 shops. For the same island, an optimization strategy was designed for hybrid power generation system, where the electricity generation cost is $0.345/kWh (Islam et al. 2012). Yusuf and Mustafi (2018) designed and simulated a solar-diesel hybrid system for remote island Kutubdia of Bangladesh, where it was found that the electricity generation cost is $0.2386/kWh. However, Yusuf et al. (2018) designed and simulated another hybrid power system for the remote island of Bangladesh which is comprised of solar-fuel cells and found the electricity generation cost is $0.1276/kWh. Another interesting analysis was done by Nandi and Ghosh (2010) for the same island which deals with 0% and 5% annual capacity of the shortage of wind–PV–diesel system and wind-diesel system. They found the feasibility of the wind-PV-diesel system with 0% capacity shortage and with wind-diesel system annual capacity shortage is found 5%. In another study, Salehin et al. (2016) designed and simulated a PV-Wind-Biogas generators hybrid system for isolated Kutubdia island of Bangladesh and presented the electricity cost was $0.42/kWh.

A hybrid system for the village of Kuakata, in the southern area of Bangladesh, was designed and simulated by Das et al. (2016), where the hybrid system is comprised of PV-wind-battery and found the cost of electricity is $0.161/kWh. Analysis of a hybrid power system consists of PV-wind-diesel generator designed for hilly region of Bangladesh and obtained the approximate electricity generation cost of $0.160/kWh (Prodhan et al. 2017). Installation cost and cost of electricity generation/kWh are investigated for solar-wind hybrid energy systems in the coastal region of Bangladesh and both the cost is reduced by 9% and 9-12% respectively (Podder et al. 2015). Techno-economic analysis of the hybrid power generation system (Zubair et al. 2012; Rashid et al. 2016) was done and found to be feasible at different conditions and criteria. Salehin et al. (2014) designed and modeled a PV-biogas-diesel hybrid energy system where the cost of energy was $0.217/kWh.

However, from the best of the author's knowledge, there is no comprehensive study that has been investigated the feasibility of a solar-natural gas hybrid energy system on the Maheshkhali island of Bangladesh. In this island grid electricity is accessed to only 40% of rustic families (Nandi and Ghosh, 2010). A large number of families in the coastal areas are not connected with grid electricity. With the recent progression in the renewable energy and price hike of depleted petroleum products, hybrid energy systems are so much demandable as it works stand-alone for the remote area electricity supply. A stand-alone optimal solar-natural gas hybrid energy generation system is designed using HOMER software in which fixed capacity natural gas generators are added along with a feasible renewable energy technology to meet the electricity demand consistently and sustainably. Attention has been provided to the environmental pollution in this study which is significantly reduced due to the reduction of fossil fuel consumption.

3. Study Area

The study area Maheshkhali is a sub-district of Cox's Bazar, an amazing tourist spot with the longest sea beach of the world, and located about 390 km from Dhaka, the capital of Bangladesh (Roy et al. 2016). The Maheshkhali island is located within 21°28'N-21°46'N latitude and 91°51'E-91°59'E longitude and bordered by Cox's Bazar as well as Chakoria in the north. The eastern, northeastern, and southeastern part of Maheshkhali island is surrounded by the Maheshkhali channel. Maheshkhali island is surrounded by the Bakkhali river in the south (Ansary et al. 2000). On the northwestern side, the Kutubdia island separates Maheshkhali island by the Kutubdia channel. The extreme western and southwestern part of Maheshkhali island is open to the Bay of Bengal. The geographical location of Maheshkhali island is shown in Figure 1. Maheshkhali island exhibits a rather complex geological system on the eastern cliff coast of Bangladesh and geomorphologic peculiarities. Maheshkhali island, a sub-district, is comprised of nine unions which are the lowest administrative unit. The area of Maheshkhali island is 388.50 sq. km. (Ansary et al. 2000). A general description of Maheshkhali island is provided in Table 1.

Table 1: General information on Maheshkhali island (Sarker et al. 2017)

Population	3,21,221
Adult literacy rate (%)	30.18
Per capital income (BDT)	4,808.89
In land communication Strength (km)	284.85
Agricultural land (Hectors)	5,275.26
Distance from the main land (km)	89.3

Figure 1: Location of Maheshkhali island on Google map

4. Electricity Demand in Maheshkhali

The electrical load data of Maheshkhali, collected from elsewhere (Sarker et al. 2017), is used in HOMER with a 20%-time step and 10% day to day random variability. The electrical load in a year with random variability is presented graphically in Figure 2. From this simulation, it is found that the annual average electricity demand in this island is 85,978.18 kWh/day. The yearly average load is 3,582.4 kW, where the load factor is 0.54. The peak load of 6,642.2 kW is found in August.

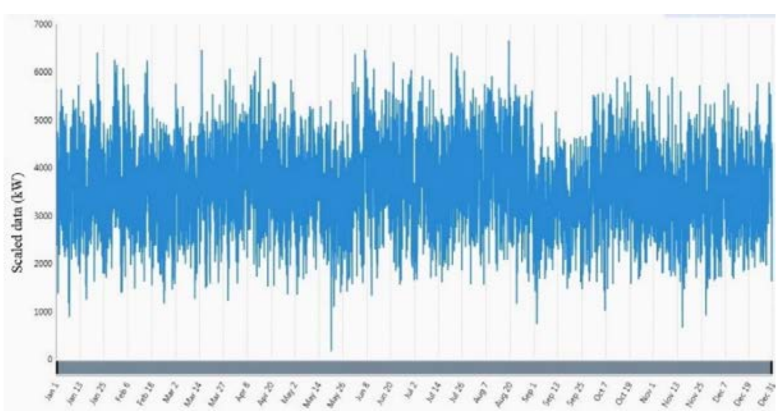

Figure 2: Electrical load of Maheshkhali in a year with random variability

5. Renewable Energy Resources in Maheshkhali

Maheshkhali island is furnished with renewable energy resources. The potentialities and feasibilities of solar and wind energy resources are described below.

5.1 Wind Energy

The monthly average wind speed data of Maheshkhali is imported in this software from NASA surface meteorology and solar energy database which is shown in Figure 3. Wind speed is varied from 2.70 m/s to 4.87 m/s at 50 meters above the earth's surface and maximum wind speed of 4.87 m/s is found in June. To operate a small wind turbine economically, the average wind speeds in a particular site need to exceed at least 6-8 m/s (Tan and Islam, 2004). Therefore, it is not viable to run a wind turbine proficiently and parsimoniously, as the average wind speed in Maheshkhali over a year is only 3.55 m/s, which is quite low.

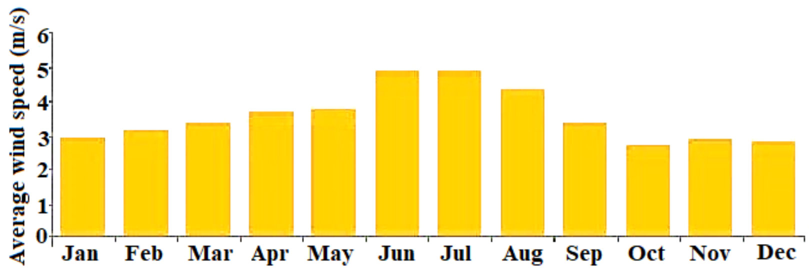

Figure 3: Monthly average wind speed data (NASA Surface meteorology and solar energy database)

5.2 Solar Energy

National Renewable Energy Lab database was used to collect the solar Global Horizontal Irradiance (GHI) data of Maheshkhali. Figure 4 shows the solar radiation data with clearness index. A higher value of the clearness index is observed from October to May. The solar GHI fluctuates from 3.853 kWh/m^2/day to 5.878 kWh/m^2/day with an annual average value of 4.76 kWh/m^2/day, where peak value was found in April. Solar GHI is high in the summer season (February to May) and low values are found in the rainy season (June to September).

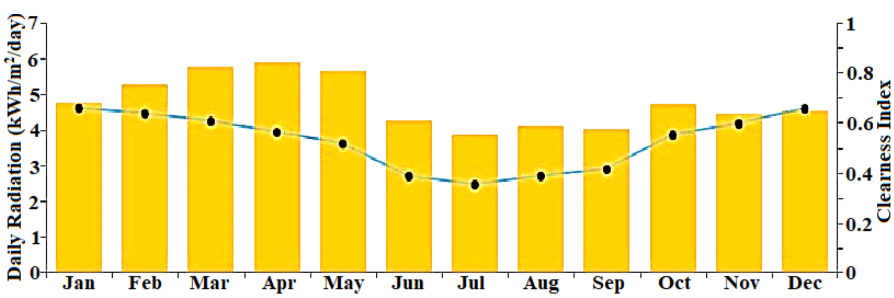

Figure 4: Monthly average solar global horizontal irradiance (National Renewable Energy Lab database)

6. Proposed Hybrid System

The proposed hybrid system is comprised of natural gas generators, PV panels, Batteries, and Converters. The lifespan of this system is designed for 25 years. Liquefied Petroleum Gas (LPG) generator of Jenbacher Company (J612 LPG) has been used in this study. The lifetime of these generators is 40,000 hrs. Highly efficient SG300MBF photovoltaic modules, made by an Italian company named PEIMAR, have been incorporated in this simulation. Apart from this, Powerwall 2.0; TESLA battery, and SUN2000-150KTL-50; HUAWEI converter has been added in this experiment. The lifespan of PV panels, batteries, and converters are 30, 10, and 15 years respectively. Figure 5 represents the proposed hybrid system in which two natural gas generators are connected to the AC bus whereas, in DC bus, PV panels and batteries are connected. Between the AC and DC bus, converters are placed. In this hybrid system, the electrical load is connected through the AC bus. The optimal size of the components in the hybrid power generation system is determined using HOMER optimizer. The technological capacity of the proposed hybrid system components is shown in Table 2.

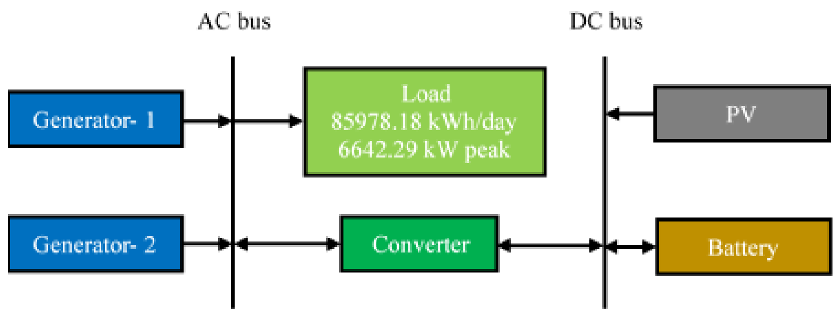

Figure 5: Diagram of the proposed hybrid power generation system

Table 2: System architecture

Device	Size
Flat plate PV	6100 kW
Natural gas generator	2 × 2,004 kW
Li-ion battery	11,022 kWh
Converter	2414 kW

7. Simulation Results and Analysis

7.1 Electrical Analysis

The following section provides the electrical analysis of simulation results. Table 3 represents energy production by different components, consumption, and excess electricity.

Table 3: Comparative production and consumption

Components	Energy(kWh/year)	Percentage (%)
Generator-1 output	15,702,713	45.9
Generator-2 output	9,496,659	27.7
PV output	9,036,906	26.4
Total production	34,236,278	100
Average demand	31,372,924	-
Excess energy	2,233,287	6.52

7.1.1 Natural Gas Generator Output

Two 2004 kW AC natural gas generators are used in this proposed system named as generator-1 and generator-2. The initial capital cost of a natural gas generator is lower compared to others, like fuel cell generator or diesel generator (Yusuf et al. 2018; Akram and Yusuf, 2019). The average combined fuel consumed by the two natural gas generators is 9,490 m^3/day and the amount of total fuel consumption in a year is 3,463,689 m^3. Figure 6 shows the annual fuel consumption by the natural gas generators. In addition, it illustrates the minimum and maximum fuel consumption each month all over the year. Figure 6 revealed that fuel consumption is so high during the beginning and end of the day when solar radiation is insufficient and unavailable.

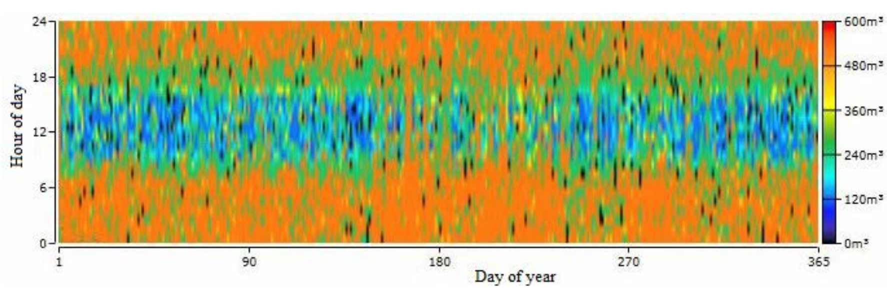

Figure 6: Fuel consumption by generators in a year

Hours of operation of these two generators in one year are 8,540 and 5,099 and the Number of Starts is 200/year and 1,595/year respectively. From the simulation, operation life is 4.68 years and 7.84 years for generator-1 and generator-2 respectively. The capacity factors of these generators are 89.4% and 54.1%. Whereas, fixed and marginal generation costs of both generators remain the same which are $245/hour and $0.00518/kWh respectively. Figure 7 and 8 shows the power generation profile of generator-1 and generator-2 respectively. Electricity produced in one year is 15,702,713 kWh and 9,496,659 kWh as well as mean electrical output of generator-1 and generator-2 are 1,839 kW and 1,862 kW respectively. Total fuel consumed by generator-1 and generator-2 in one year are 2,158,394 m^3 and 1,305,295 m^3 respectively. Mean electrical efficiency and specific fuel consumption of two generators remain the same which are 73.7% and 0.137 m^3/kWh. To calculate the mean electrical efficiency η_{gen} of the generators over the year Equation 1 is used in the HOMER optimizer.

$$\eta_{gen} = \frac{3.6 \times E_{gen}}{m_{fuel} \times LHV_{fuel}} \qquad (1)$$

Where, E_{gen} is the total yearly electrical production of the generator (kWh/year), m_{fuel} is the total yearly fuel consumption (kg/year) and LHV_{fuel} is the lower heating value of the fuel (MJ/kg). The factor of 3.6 arises because 1 kWh = 3.6 MJ.

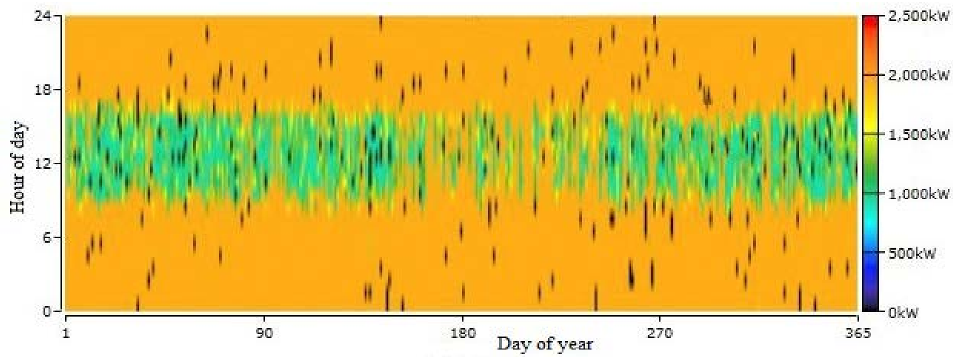

Figure 7: Annual power generation by generator-1

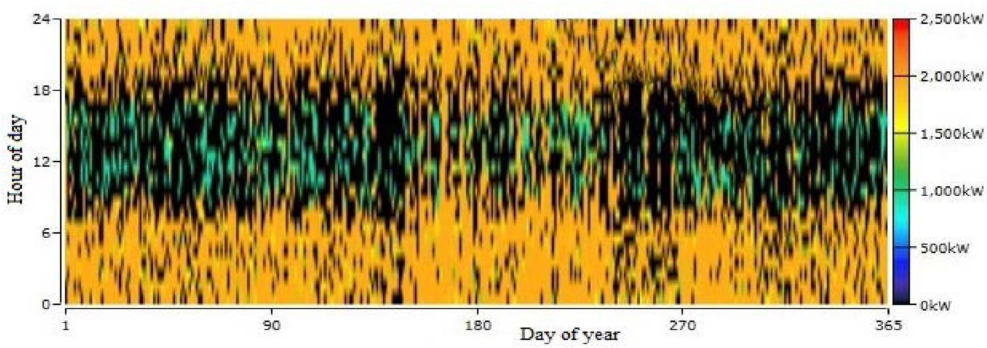

Figure 8: Annual power generation by generator-2

7.1.2 Photovoltaic Panel (PV) Output

The size of the flat plate PV panels found by the HOMER optimizer is 6100 KW. The PV panels produce 24,759 kWh/day and 9,036,906 kWh/year, where HOMER considers its capacity factor 16.9% and Figure 9 shows the annual power output of PV panels. The maximum and mean output is 5,887 kW and 1,032 kW respectively. PV penetration is 28.8% and efficiency at standard test conditions is 19.1%. Hours of operation in one year are 4370 and levelized cost is $0.0194/kWh. Equation 2 is used to calculate the PV array output (PPV) in HOMER optimizer.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_C - T_{C,STC} \right) \right] \qquad (2)$$

Here, considering the standard test conditions Y_{PV} is the rated capacity of the PV array (kW), f_{PV} is the PV panel radiating factor (%), in the current time step $\bar{G}_T$ is the solar radiation incident on the PV array (kW/m^2), $\overline{G_{T,STC}}$ is the incident radiation at standard test conditions (1 kW/m^2), α_P is the temperature coefficient of power (%/°C), T_C is the PV cell temperature in the current time step (°C), $T_{C,STC}$ is the PV cell temperature under standard test conditions (25℃).

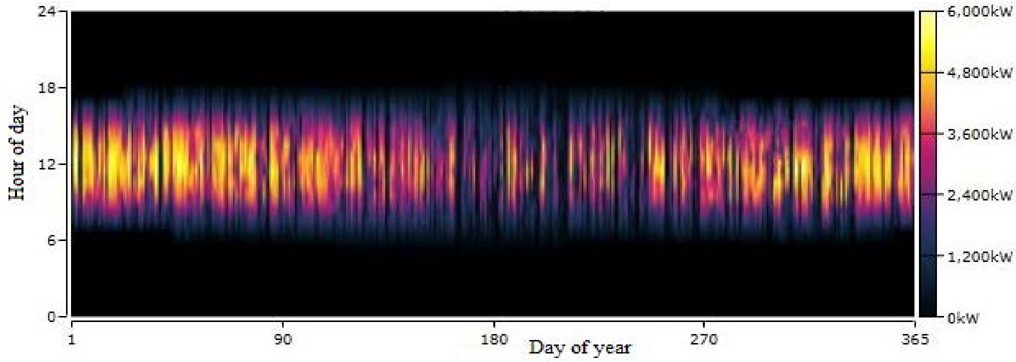

Figure 9: Annual power output by PV panels

7.1.3 Performance of Battery and Converter

During energy shortage, the stored energy of batteries from surplus electricity is used. The bus voltage of batteries is 220 V and the minimum state of charge is set to 40%. The state of charge of the batteries used in the proposed system is shown in Figure 10 throughout the year with hours of the day. Annual throughput of 11,022 kWh Li-ion battery is 2,886,556 kWh/year. The average energy cost of the batteries is $0.00507/kWh. The input and output energies of the batteries are 3,057,782 kWh/year and 2,723,171 kWh/year respectively.

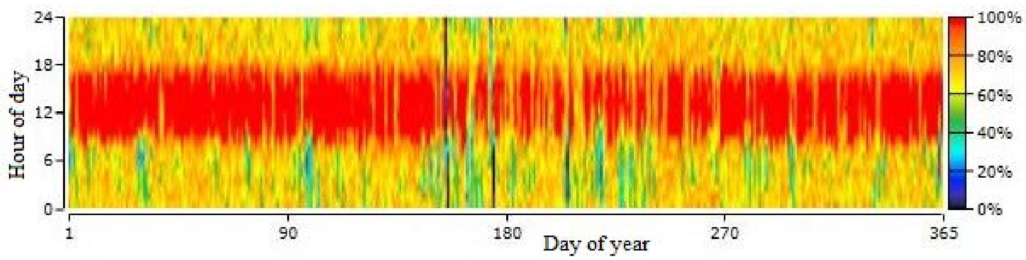

Figure 10: State of charge in the battery

Converters are placed between the AC bus and DC bus in order to convert DC power to AC and vice versa. The size of the inverter and rectifier is 2,414 kW and 1,207 kW with capacity factor 37.3% and 15.7% respectively. The mean output of the inverter and rectifier is found to be 901 kW and 190 kW respectively. The inverter and rectifier output in a year is shown in Figure 11 and 12 respectively. Hours of operation in one year are 6,160 and 2,597 respectively. Input and output energies of the inverter in one year are 8,133,031 kWh and 7,889,040 kWh respectively. And the input and output energies of the rectifier in one year are 1,715,488 kWh and 1,664,023 kWh respectively.

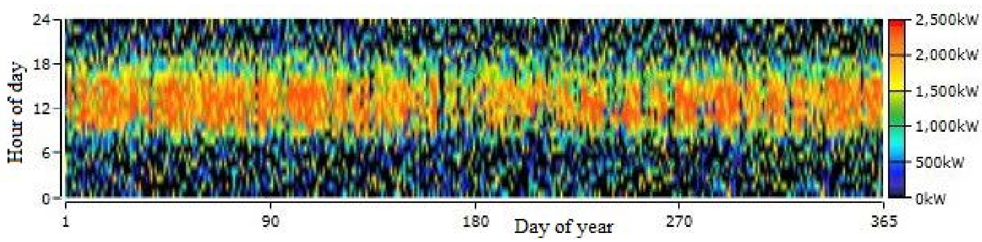

Figure 11: Inverter output in a year

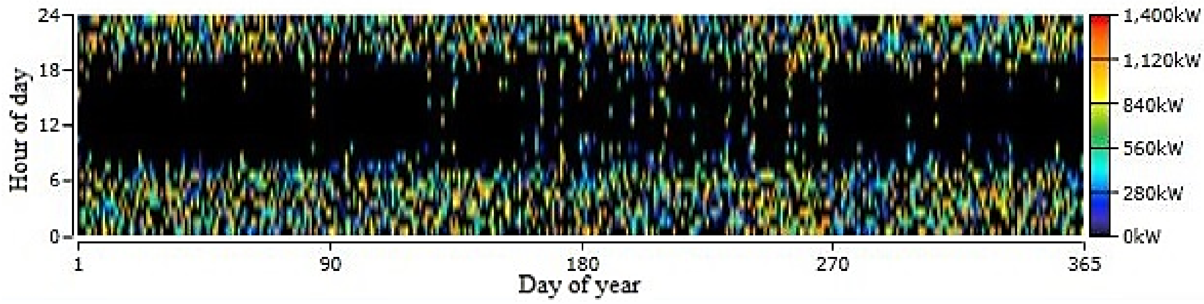

Figure 12: Rectifier output in a year

7.1.4 Electricity Production

The average electricity production per month in a year by this hybrid power generation system is shown in Figure 13. The amount of total electricity production in one year is 34,236,278 kWh where generator-1 and generator-2 produce 45.9% and 27.7% of electricity respectively. The rest portion of electricity is produced by PV panels. So, renewable energy fraction is 26.4%. Since the amount of total primary load is 31,372,924 kWh/year, the excess electricity is 6.52% of total generation.

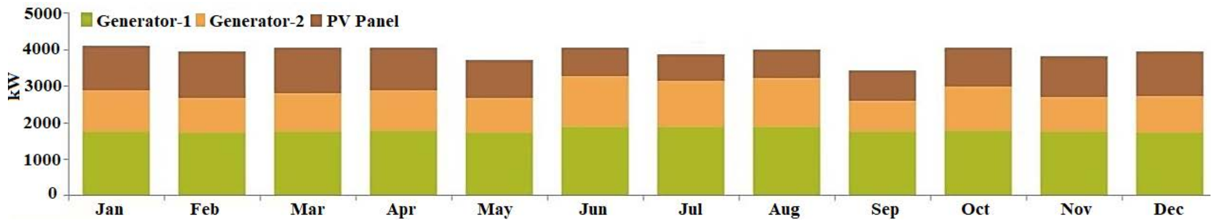

Figure 13: Monthly average electricity production by generators and PV panels

7.2 Economic Analysis

HOMER finds the different simulation results and arrange them in ascending order in terms of initial capital costs, operating costs, net present costs, and cost of per unit electricity. From these results, an optimal system was chosen considering the lowest cost of different types. The cash flow of the proposed hybrid system for 25 years is shown in Figure 14 based on the capital cost, operating cost, salvage cost, fuel cost, and replacement value. Figure 14 represents that capital cost is incurred at the beginning of the hybrid generation system whereas replacement cost occurred several times during 25 years and salvage value is found at the end of the 25 years. Annualized costs are summarized in table 4.

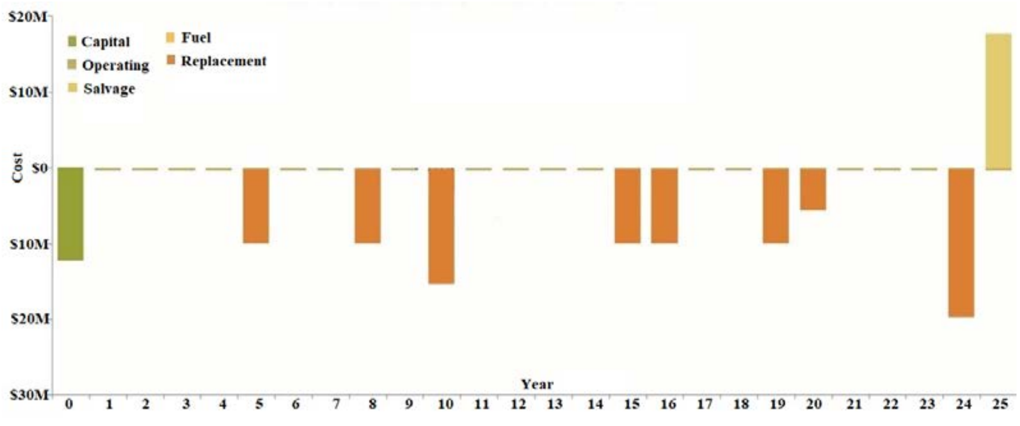

Figure 14: Cash flow in 25 years by cost type

Table 4: Annualized costs by components

Components	Capital ($)	Replacement ($)	Operating and Maintenance ($)	Fuel ($)	Salvage ($)	Total ($)
Generator-1	49,687.04	1,912,576.70	8,540.00	81,587.30	208,372.18	1,844,018.86
Generator-2	49,687.04	1,115,052.73	5,099.00	49,340.14	255,747.36	963,431.56
PV	197,009.13	0.00	0.00	0.00	21,317.74	175,691.39
Battery	269,676.43	417,768.08	0.00	0.00	87,542.53	599,901.98
Converter	41,988.26	0.00	289,732.94	0.00	0.00	331,721.20
System	608,047.91	3,445,397.51	303,371.94	130,927.44	572,979.81	3,914,764.98

Cash flow by component and annualized cost by component is revealed in Figure 15 and 16 respectively. On the other hand, the net present cost by component is presented in Table 5 and Figure 17. The price of natural gas in the power sector in Bangladesh is $0.037/m^3 and the yearly inflation rate is 6.15% (Yusuf and Mustafi, 2018). The fuel cost of natural gas generators is $130,927.44/year. From this simulation, the operating and net present costs are $3,306,717/year and $78,788,450/year respectively and the cost of electricity is found $0.1248/kWh which indicates an economic and feasible system.

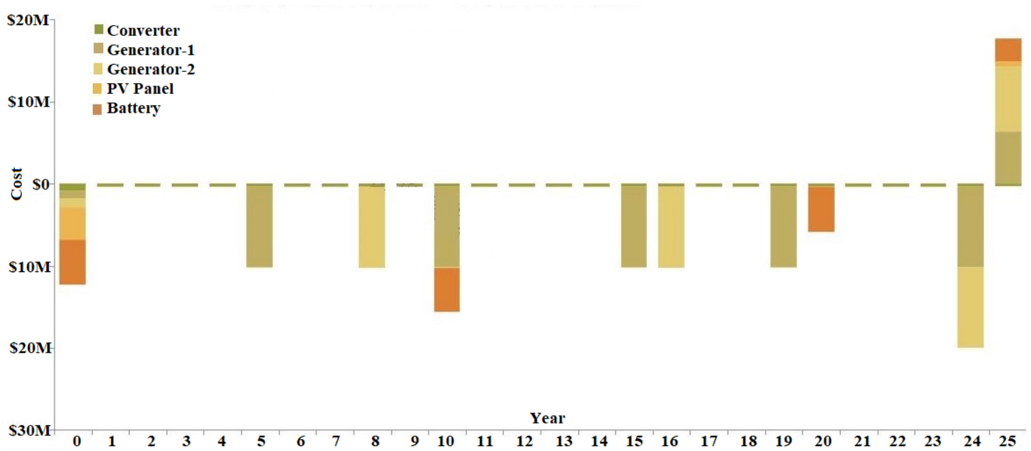

Figure 15: Cash flow by components

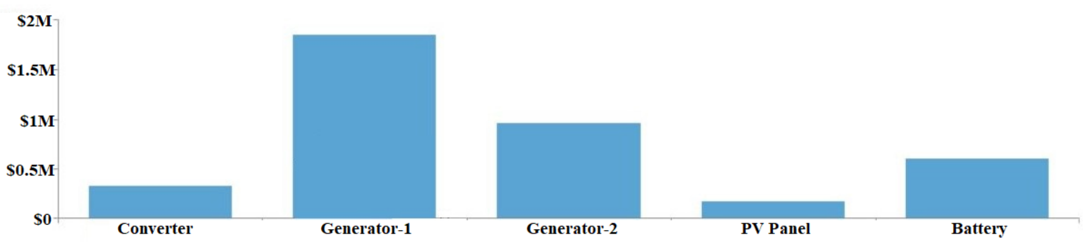

Figure 16: Annualized costs by components

Table 5: Net present costs by components

Components	Capital ($)	Replacement ($)	Operating and Maintenance ($)	Fuel ($)	Salvage ($)	Total ($)
Generator-1	1,000,000.00	38,492,462.88	171,875.79	1,642,023.52	4,193,692.41	37,112,669.78
Generator-2	1,000,000.00	22,441,518.78	102,622.33	993,018.29	5,147,163.99	19,389,995.40
PV	3,965,000.00	0.00	0.00	0.00	429,040.23	3,535,959.77
Battery	5,427,500.00	8,407,988.11	0.00	0.00	1,761,878.32	12,073,609.79
Converter	845,054.42	0.00	5,831,156.77	0.00	0.00	6,676,211.19
System	12,237,554.42	69,341,969.76	6,105,654.88	2,635,041.81	11,531,774.95	78,788,445.92

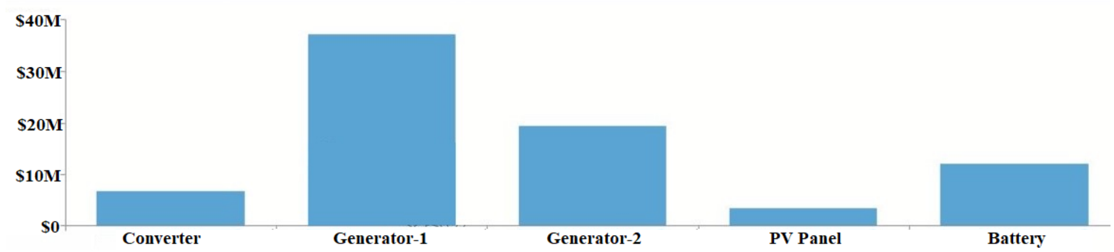

Figure 17: Net present cost by components

7.3 Comparative Study

A comparative study is done for the same electrical load on Maheshkahli island with a solar-diesel generator hybrid power generation system (Akram and Yusuf, 2019). Table 6 shows a comparison between this hybrid system and the solar-diesel hybrid system with respect to net present cost, operating cost, cost of energy, and renewable energy fraction. It reveals that all types of costs are lower than the solar-diesel system with the increased integration of renewable energy. Table 7 represents the comparison of emission of different pollutants with the solar-diesel system. A significant amount of emission is reduced in this proposed hybrid system due to the use of natural gas and an increased amount of renewable energy integration. Therefore, it is concluded that the solar-natural gas hybrid system is very much cost-effective and environmentally friendly off-grid power generation system for Maheshkahli island of Bangladesh.

Table 6: Comparison of cost

Power Generation System	Solar-Natural Gas	Solar-Diesel (Akram and Yusuf, 2019)
Net present cost ($)	78,788,445.92	118,517,700.00
Operating cost ($/year)	3306717.00	5,584,142.00
Cost of energy ($/kWh)	0.1248	0.1877
Payback period (years) (for selling price 0.20 $/kWh)	9.61	18.57
Renewable energy fraction (%)	26.4	22.4

Table 7: Comparison of emission of different pollutants

Power Generation System	Solar-Natural Gas	Solar-Diesel (Akram and Yusuf, 2019)
Pollutants	Emissions (kg/year)	Emissions (kg/year)
Carbon Dioxide	6,687,268	17,775,532
Carbon Monoxide	22,237	6,254
Unburned Hydrocarbons	0	2,556
Particulate Matter	627	605
Sulfur Dioxide	0	44,096
Nitrogen Oxide	46,656	150,641

8. Conclusions

This investigation presented the optimal configuration of a stand-alone hybrid power generation with components capacities and cost analysis with a prime focus on the environmental issues. This optimal configuration minimized the electricity generation cost from a combination of the solar-natural gas generator while fulfilling the electricity demand by taking consideration of several technical and environmental issues. The findings of this study are as follows:

- Electricity generation cost found from this study is $0.1248/kWh which is much lower and more convenient for the hybrid power generation system.
- The hybrid system is designed for 25 years with the net present costs of $78,788,445.92 and will be able to meet the electricity demand of 3,21,221 people of this island without the electricity from the grid. The payback period is found 9.61 years for this system. Net present cost, operating cost, cost of electricity, and

the payback period of this system is much lower than the proposed hybrid generation system on the same site (Akram and Yusuf, 2019).

- Environmental pollution is considerably reduced due to increased use of renewable energy fraction of 26.4% and the use of natural gas instead of diesel as a fossil fuel.

Therefore, to meet the electricity demand in remote localities like Maheshkhali island, this proposed system could be a perfect and feasible long term economic and environment friendly solution. Future analysis could be done on the collaborative energy management in Maheshkhali island where the PV panels would be configured in the house rooftop with the integration of one or more non-renewable sources.

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