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Design, Simulation, and Economic Analysis of an Optimal Mini-grid Solar-Fuel Cell Hybrid Power Generation System for a Remote Island of Bangladesh

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ABSTRACT
It is the international trend to promote renewable energy, as part of energy security as well as greenhouse gas emission reduction. Wind and solar energies can be used to supplement the conventional energy sources predominantly in remote coastal localities of Bangladesh. Feasibility study of renewable resources of Kutubdia, an off-grid remote island, is presented in this paper. Purpose of this study is to design, simulation, and economic analysis of a stand-alone optimal mini-grid Solar-Fuel cell hybrid power generation system in a remote island of Bangladesh to satisfy the energy demands in a sustainable way by HOMER ENERGY software. Three Fuel cell are added to ensure uninterrupted power supply due to the intermittent nature of renewable resources. Optimum size of different components, electrical load with a certain random variability, fraction of renewable energy, excess electricity, performance of its different components, environmental impacts, cost of energy(COE),net present cost(NPC), annualized cost are analyzed in this paper.

Keywords: Hybrid energy system; Mini-grid; Renewable energy; Fuel Cell; Environmental impact; HOMER optimizer.

1. Introduction

Bangladesh, for the first time in history, has fulfilled the eligibility criteria set by the United Nations to be recognized as a developing country, crossing over from the list of least developed countries (LDCs) [1].Electricity demand of Bangladesh is increasing day by day. At present, 83% of the total population has come under the electricity coverage and per capita generation has increased to 433 kWh. The government has already set a target to become a middle income country by 2021 and develop country by 2041. In the fiscal year 2016-2017, the highest peak generation was 9,479 MW with total generation capacity was 13,555 MW. Bangladesh Power Development Board prepared generation expansion plan to achieve generation capacity 24,000 MW by 2021 with the aim to provide quality and reliable electricity to the all people across the country for desired economic growth and social development [2]. Since Bangladesh is facing to the depletion of domestic gas supply, various issues such as sustainable development harmonizing with economic optimization, improvement of power quality, and the discipline of operation and maintenance for power plants need to be addressed holistically. Furthermore, energy subsidy is also a tough challenge, because there's always a concern that drastic increase of fuel and electricity prices may trigger another negative effect on the national economy. Integrating intermittent renewable energy resources, such as PV and Wind generation, to achieve CO_2 emission reduction is a priority task for most countries worldwide. However, such renewable resources have high initial cost, low utilization rate and intermittent generation [3].

The objective of "Renewable energy policy 2008" of Bangladesh is to achieve 10% of total energy demand from the renewable sources by 2020 [4]. Wind and solar energies are the most attractive renewable energy resources that can be used to complement the increasing demand of conventional energy sources particularly in Bangladesh [5,6]. Bangladesh has 4,01,678km power distribution line with 9.27% distribution system loss [2].But only about 40% of rural households have access to grid electricity [7]. Many remote localities along with the coastal areas are not connected to grid electricity. Hybrid renewable energy systems are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products [8]. A stand-alone optimal mini-grid hybrid power generation system is designed by using HOMER ENERGY software in which fixed capacity fuel cell generators are added along with a feasible renewable energy technology to meet the electricity demand in a reliable and sustainable manner. Environment pollution is considerably reduced as compared to any conventional system, due to reduction of fossil fuel consumption.

2. Site of Proposed Project

Kutubdia Island is famous for the Light-House and all other mysterious creation and divine beauty. It is surrounded by the Bay of Bengal.Administration of Kutubdia Thana was established in 1917 and was turned into an Upazila in 1983. It consists of 6 union parishads, 9 mouzas and 29 villages[9].It is an upazila of Cox's Bazar district in the division of Chittagong, Bangladesh. It is located in between 21°43' and 21°56' north latitudes and in between 91°50' and 91°54' east longitudes [10]. Adult literacy rate is about 35% with per capita income is 4884.49 BDT. Total area of Kutubdia is 215.8 km² in

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which agricultural land is 8903.22 hectors. Kutubdia is off grid area or remote area and distance from main land is 91 km [11].

3. Mini-Grid & HOMER software

A mini grid, also sometimes referred to as a "micro grid or isolated grid", can be defined as a set of electricity generators and possibly energy storage systems interconnected to a distribution network that supplies electricity to a localized group of customers. They involve small-scale electricity generation (10 kW to 10MW) which serves a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks. Mini-grids have a unique feature as they can operate autonomously without being connected to a centralized grid. Hybrid mini-grid systems often incorporate a 75-99% renewable supply. Conversely as the cost of fossil fuel increases, mini-grid systems are becoming more economically attractive as the cost of renewable energy resources decrease [12]. The HOMER (Hybrid Optimization of Multiple Energy Resources) micro grid software navigates the complexities of building cost effective and reliable micro grids that combine traditionally generated and renewable power, storage, and load management. HOMER is the global standard in microgrid software, based on decades of listening to the needs of users around the world with experience in designing and deploying microgrids and distributed power systems that can include a combination of renewable power sources, storage, and fossil-based generation (either through a local generator or a power grid). It is the world's leading micro grid modelling software. It was developed by the National Renewable Energy Lab (NREL), a division of the U.S. Department of Energy [13].

4. Electrical demand in Kutubdia

Based on data obtained from Ref. [11], the electrical load data of Kutubdia is imported in the software with 10% day to day and 20% time step random variability. The electrical load in a year with random is presented in Fig.1. Annual average electricity demand of this island is 15,108.21 kWh/day. The yearly average load is 629.51 kW and load factor is 0.54. Minimum load 29.39 kW is found in month of May and peak load 1,167.5 kW in the month of August.

5. Feasibility of Renewable Resources in Kutubdia

Solar and wind are the available renewable energy in this island. The potentials and feasibility of these sources are described below;

5.1 Wind energy

The monthly average wind speed data in this island, fluctuated from 2.70 m/s to 4.87 m/sat 50 meter above the surface of earth, is imported in this software from NASA Surface meteorology and solar energy database. Maximum wind speed 4.87 m/s is found in June. Studies have found that average wind speeds in a particular location need to exceed at least 6–8 m/s for a small wind turbine to be economically viable [14]. It is not feasible to operate a wind turbine proficiently and parsimoniously, as the average wind speed in Kutubdia over a year is only 3.55m/s, which is quite low.

5.2 Solar energy

Solar Global Horizontal Irradiance (GHI) data is taken from National Renewable Energy Lab database. Fig.3 shows the solar radiation data used in the simulations in which the left vertical axis represents the daily radiation data while the right one represents the clearness index. The solar GHI in Kutubdia is between 3.828 $kWh/m^2/day$ and 5.979 $kWh/m^2/day$. The annual average solar radiation is 4.81 $kWh/m^2/day$. Solar GHI is high (above the average) from February to May (summer season), with a peak in the month of April, while solar irradiance is low in July, August, and September due to rainy season.

6. Proposed hybrid system

The proposed hybrid system consists of fuel cells, PV panels, Converters, and Batteries. This power generation system is designed for 25 years' lifetime. The life span of PV panels, batteries, converter and fuel cells are considered as 20,10, 15, and8 years' respectively. The optimum size of all the components is determined by HOMER optimizer.Fig.4 shows the schematic diagram of proposed hybrid system. In this system, three 250 kW fuel cell generator are connected to the DC bus as it produces DC output. Battery bank and PV panels are also connected to the DC bus. Converter is placed between the two buses. Load is connected to the system through AC bus. The sizes of each component are shown in Table 1.

7. Simulation results and analysis

Result of simulation is divided into electrical analyses, environmental impact, and economic analyses which are described in the following articles. Dispatch strategy of this simulation was cycle charging.

7.1 Electrical analysis

Electrical analysis includes the simulation results and analysis of fuel cell generators and PV panel output, competitive electric production, renewable energy fraction, and performance of battery and converter. Table 4 represents energy production by different components, consumption, and excess electricity.

7.1.1. Fuel cell's output

In this proposed system, three 250 kW dc fuel cell generator are used. Average consumption of natural gas by these fuel cell is 2,351 m^3/day. Initial capital cost of each generator is $750,000 and operation and maintenance cost is $5/hour. Mean electrical efficiency is 48.2%. The expected life time is 50,000 hours and specific fuel consumption is 0.210 m^3/kWh. Capacity factors of these generators are 63.9%, 70.7% and 52.0% respectively. HOMER calculates the mean electrical

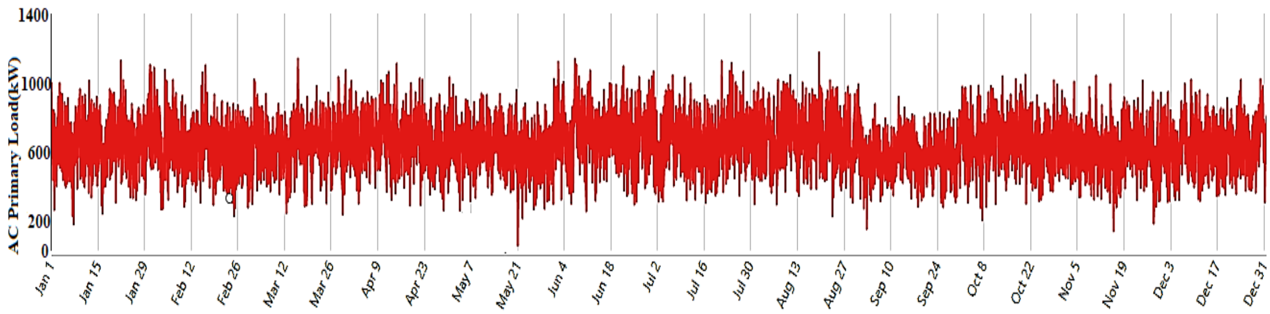

Fig.1 Electrical load of Kutubdia in a year with random variability [11].

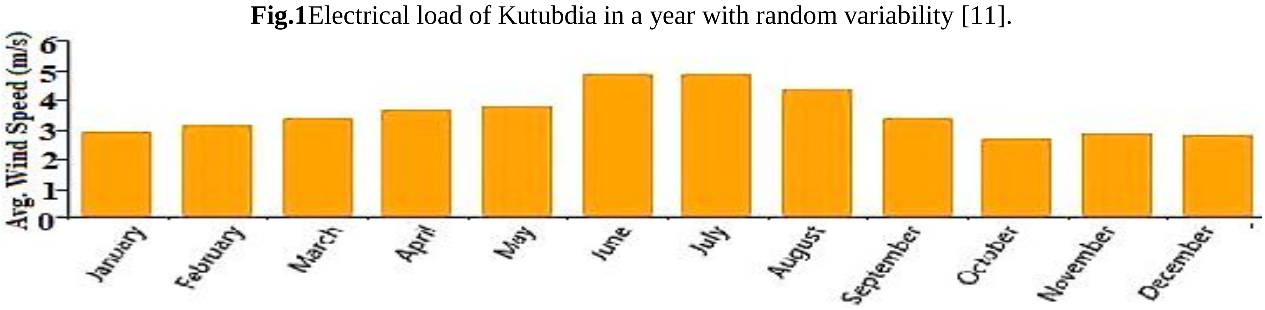

Fig.2 Monthly average wind speed data (NASA Surface meteorology and solar energy database).

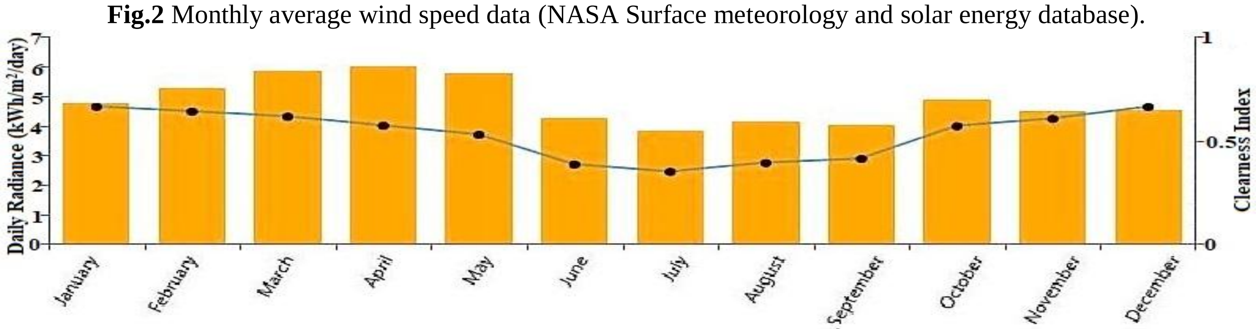

Fig.3 Monthly average solar global horizontal irradiance (National Renewable Energy Lab database).

efficiency (η_{gen}) of the generator over the year, defined as the electrical energy out divided by fuel energy in, which is shown in the following equation;

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

where E_{gen} is the generator's total annual electrical production (kWh/yr), m_{fuel} is the generator's total annual fuel consumption(kg/yr) 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.

7.1.2 PV output

Flat plate PV panel is considered in this proposed system to harness solar energy. Efficiency at standard test conditions is 13% and nominal operating cell temperature is 47°. By using Homer optimizer, the size of flat plate PV panel is found 1,419 kW. PV panels produce 2,161,610 kWh/yr and 5,922 kWh/day, and its capacity factor is 17.4%. Maximum and mean output is 1,407 kW and 247 kW respectively. HOMER uses the following equation to calculate the output (P_{PV}) of the PV array.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) [1 + \alpha_P (T_C - T_{C,STC})] \quad (2)$$

Table 1 System architecture.

Device	Size
Flat plate PV	1,419 kW
Fuel Cell	750 kW
Lead Acid Battery	3,584 kWh
Converter	1,633 kW

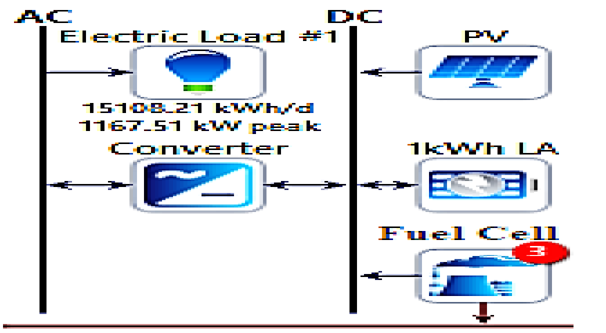

Fig.4 Diagram of power generation system.

Here, Y_{PV} is the rated capacity of the PV array under standard test conditions (kW), f_{PV} is the PV derating factor(%), $\overline{G}_T$ is the solar radiation incident on the PV array in the current time step(kW/m^2), $\overline{G}_{T,STC}$is the incident radiation at standard test conditions (1 kW/m),

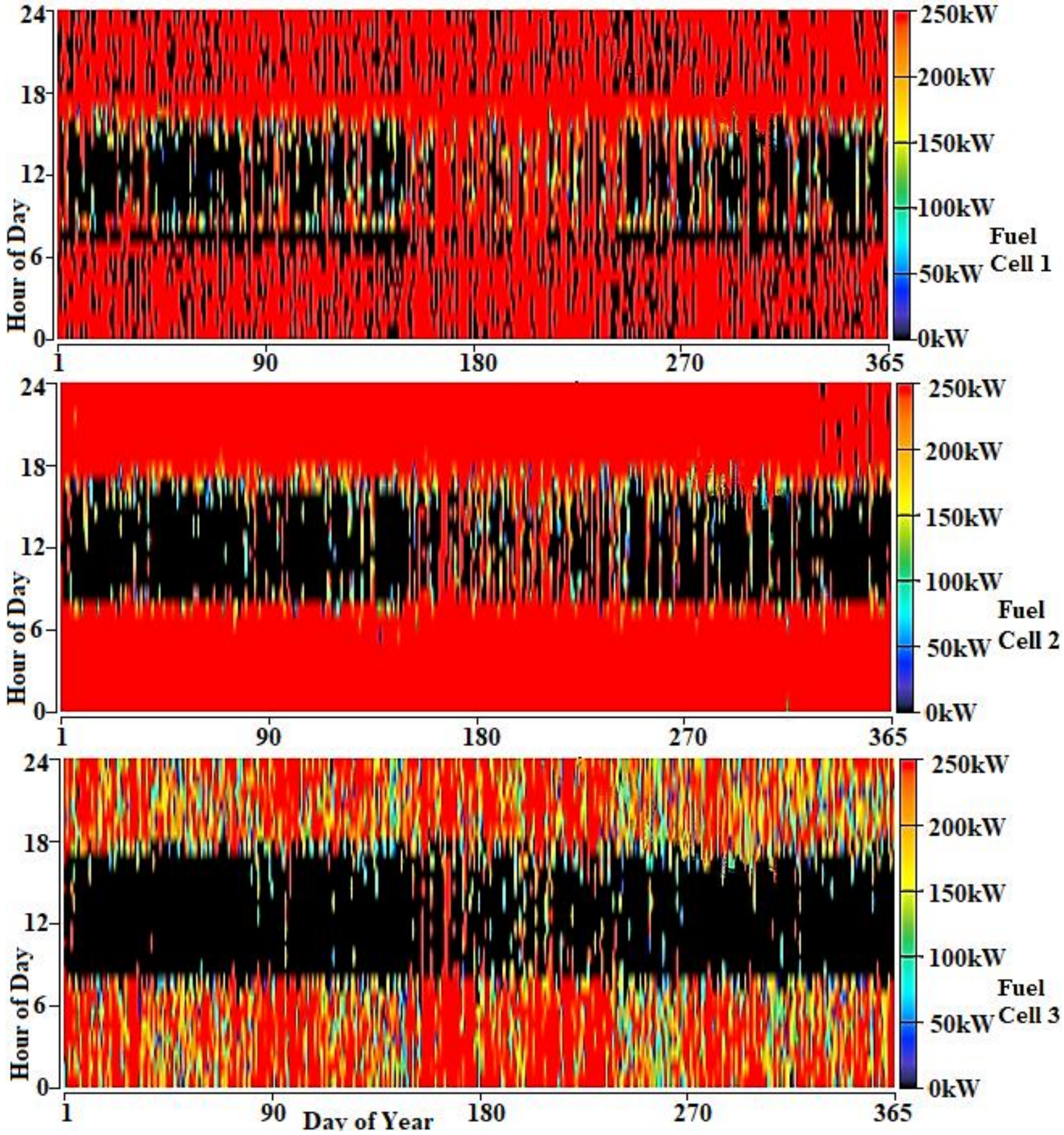

Fig.5 Fuel Cells power output in a year.

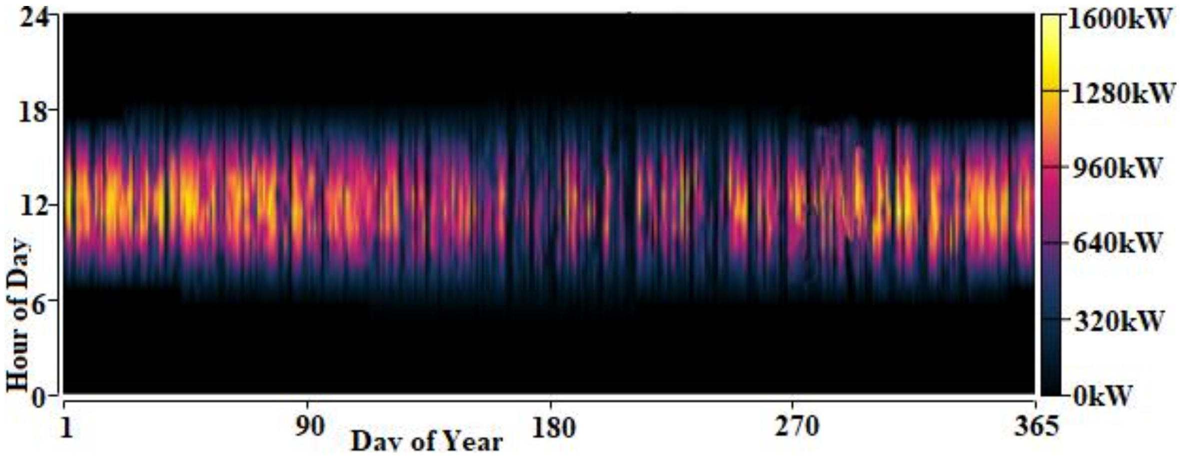

Fig. 6 Power output in a year by PV panels.

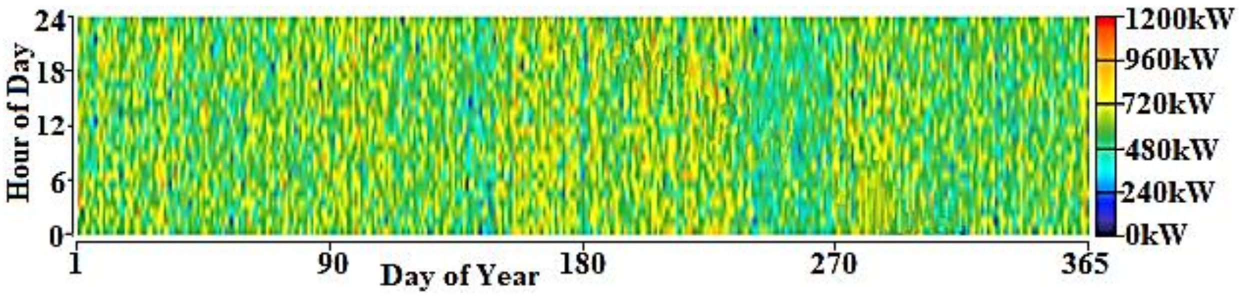

Fig.7 Converter output in a year.

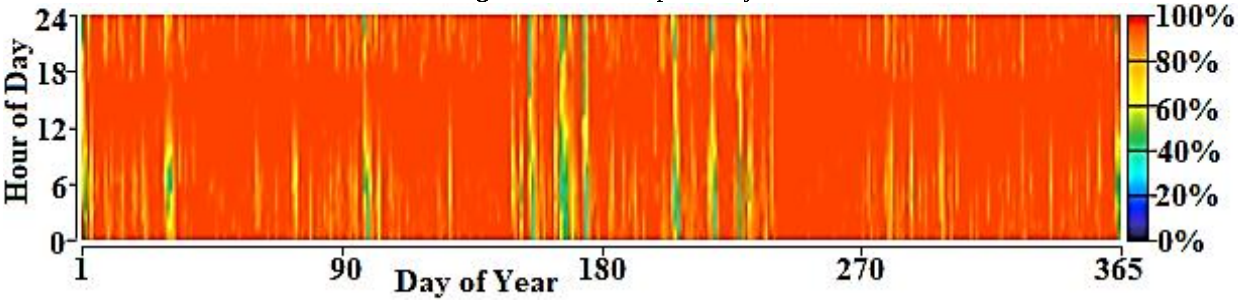

Fig.8 State of charge of battery in a year.

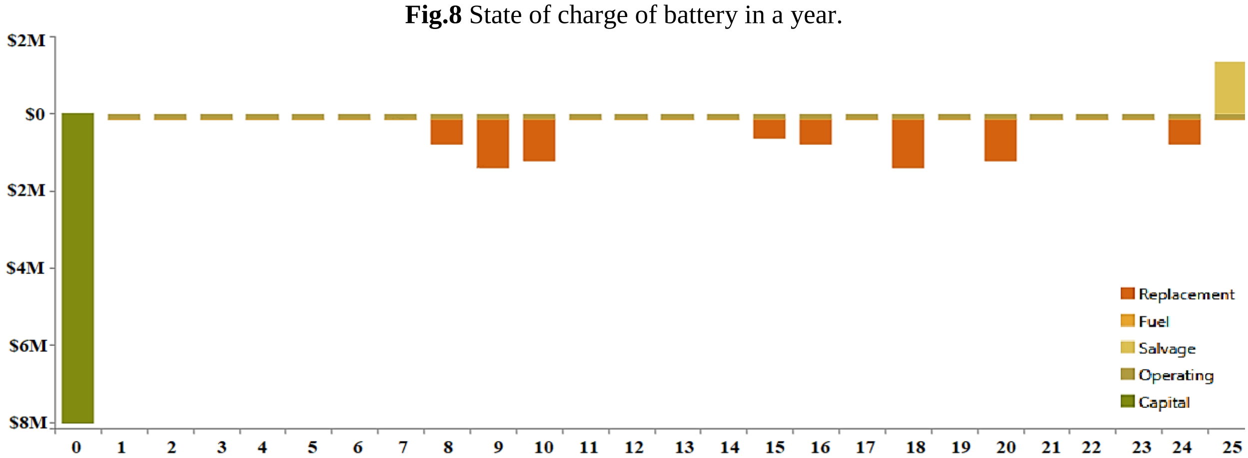

Fig.9 Cash flow in 25 years by cost type.

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 °C).

7.1.3. Comparative electrical production

Total energy produced by this system is 6,247,228 kWh/year while average demand is 5,512,129 kWh/year. Energy generated by PV panels is 2,161,610 kWh/year. So, renewable energy fraction is 34.8%.

Table 2 Comparative production and consumption.

Components	Energy/year (kWh/yr)	Percentage(%)
Fuel Cell 1 output	1,399,213	22.4
Fuel Cell 2 output	1,548,280	24.8
Fuel Cell 3 output	1,138,124	18.2
PV output	2,161,610	34.6
Total Production	6,247,228	100
Average demand	5,512,129	-
Excess energy	403,433	6.46

Table 3 Annualized Costs by components

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
Generic 1kWh Lead Acid	40,726.64	86,714.05	35,840.00	0.00	22,594.03	140,686.67
Generic 250kW Fuel Cell 1	28,408.65	49,970.76	29,005.00	11,165.72	2,613.59	115,936.55
Generic 250kW Fuel Cell 2	28,408.65	75,778.63	32,240.00	12,355.28	20,383.38	128,399.18
Generic 250kW Fuel Cell 3	28,408.65	50,039.11	28,290.00	9,082.23	4,491.70	111,328.30
Generic flat plate PV	161,290.85	0.00	14,193.81	0.00	0.00	175,484.66
System Converter	18,556.00	19,750.19	0.00	0.00	6,862.91	31,443.28
System	305,799.45	282,252.74	139,568.81	32,603.23	56,945.60	703,278.64

7.1.4. Performance of battery and converter

Batteries are used to store excess electricity and utilized this energy during shortage. Annual throughput of 3,584 kWh Lead Acid batteries is186,052 kWh/yr and expected life time is 10 years. Minimum state of charge is setto 40% and bus voltage is 12 V. A converter is used in this proposed project to convert dc power to acas all loads are ac type. Size of converter is 1,633 kW with capacity factor 38.5%. Maximum and mean output is found 1,168 kW and 629 kW respectively.

7.2. Environmental impact

This hybrid system reduces notable amount of emissions due to use of significant fraction of renewable energy technology. It decreases the consumption of fossil fuel. So, it is a more environment friendly power generating system. The emission of different gases is determined by simulation which shown in Table 4.

Table 4 Emission of pollutants.

Pollutant	Emissions (kg/yr)
Carbon dioxide	1,664,869
Carbon monoxide	172
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	0
Nitrogen oxides	17.2

7.3. Economic analysis

Project life time is expected as 25 years. Cash flow in 25 years by cost type is presented in fig.9 and annualized costs by components are shown in Table 3. Different types of costs like replacement cost, fuel cost,salvage cost, operating cost, and capital cost are shown in fig.9. Price of natural gas in Bangladesh is 0.04$/m^3 and inflation rate is 6.04%. Fuel cost offuel cell generators is 32,603.23$/yr. From this simulation, the operating and net present cost is 397,479.20$/yr and 18,566,840.00$

respectively andcost of electricity is found 0.1276$/kWh. This indicates a feasible system.HOMER finds the optimal system by determining the lowest possible initial capital costs, operating costs, net present costs, and cost of per unit electricity.

8. Conclusion

To meet ever increasingper capita electricity demand of Bangladesh, integration of renewable energy technology is essential. This proposed hybrid power generation system can be a perfect long term solutionto meet the energy demandin many remote localities like Kutubdiaisland. Cost of electricity found from this simulation is $0.1276/kWh which is acceptable. Both cost of electricity and environmental pollutions are lower than the proposed project in [8], as natural gas is used instead of diesel and fraction of renewable energy is increased.

REFERENCES

[1] Dhaka Tribune.Available online: https://www.dhakatribune.com/bangladesh/2018/03/18/developing-bangladesh-new-identity-2/.

[2] Bangladesh Power Development Board (BPDB). Annual Report 2016–2017, BPDB, Dhaka. Available online: http://www.bpdb.gov.bd/bpdb_new/index.php/site/annual_reports/e445-c332-c830-6930-2bf2-2651-a538-fa23-852b-02bb.

[3] Power & Energy Sector Master Plan (PSMP 2016) Final Report. Available online: http://open_jicareport.jica.go.jp/pdf/12269742.pdf.

[4] Renewable Energy Policy of Bangladesh, Power Division, Ministry of Power Energy and Mineral Resources, Government of the People’s Republic of Bangladesh. 18 December 2008. Available online: http://www.iea.org/media/pams/bangladesh/Bangladesh_RenewableEnergyPolicy_2008.pdf.

[5] Sk. Suzauddin Yusuf, Md. Shariful Islam, Robiul Islam Rubel,Md. Abu ShaidSujon,RafiqulAlam Beg, Construction, and Performance Test of a Portable Solar Photovoltaic Water Pumping System for Irrigation and Household Water Supply, *International Conference on Mechanical, Industrial and Materials Engineering 2017* (ICMIME2017), Paper ID: ET-83 (2017).

[6] Sanjoy Kumar Nandi, Mohammad NasirulHoque, HimangshuRanjan Ghosh, Swapan Kumar Roy, Potential of Wind and Solar Electricity Generation in Bangladesh, *International Scholarly Research Network ISRN Renewable Energy*, Volume 2012, Article ID 401761 (2012).

[7] World Bank. Lighting Up Rural Communities in Bangladesh. January 2015. Available online:http://www.worldbank.org/en/news/feature/2014/01/15/lighting-up-rural-communities-in-bangladesh.

[8] Sk. Suzauddin Yusuf, NirendraNathMustafi, Design and simulation of an Optimal Mini-Grid Solar-Diesel Hybrid Power Generation system in a remote Bangladesh. *International Journal of Smart Grids, ijSmartGrid*, [S.l.], v. 2, n. 1, March, p. 27-33, mar. 2018. ISSN 2602-439X (2018).

[9] Offroad Bangladesh. Available online: http://offroadbangladesh.com/places/kutubdia-island/2/.

[10] Kutubdia Upazila, BANGLAPEDIA. Available online: http://en.banglapedia.org/index.php?title=Kutubdia_Upazila.

[11] Md. TanjilSarker, Md. Anisur Rahman, Prf. Dr. Zahid Hasan Mahmud, Electricity Demand Load Forecasting for a Remote Area of Bangladesh, *International Journal of Scientific & Engineering Research*, Volume 8, Issue 1, January-2017 265-277 (2017).

[12] Mini Grids. Available online:https://energypedia.info/wiki/Mini_Grids.

[13] HOMER ENERGY. Available online: https://www.homerenergy.com/.

[14] Wind turbine system. Available online: http://www.level.org.nz/energy/renewable-electricitygeneration/wind-turbine-systems/.