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An Assessment of Solar Micro-Grid System in the Islands of Bangladesh for Sustainable Energy Access

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ABSTRACT

The isolated islands in the northern Bay of Bengal face difficulties accessing electricity from the central grid and use fossil fuel-based generators, which causes health risks, environmental damage, and high expenses. So, this study aims to replace these fossil fuel-based power sources with Solar Photovoltaic (SPV) microgrids to provide continuous power to remote islands and contribute to reducing emissions. A specific location on the island of Manpura is selected for the SPV plant installation, considering land availability and vulnerability to erosion. Solar power density and other technical parameters such as Direct Normal Irradiation, Global Horizontal Irradiation, Diffuse Horizontal Irradiation, Global Tilted Irradiation, the optimum tilt angle of Photovoltaic (PV) modules, air temperature, and terrain elevation are analyzed using some prominent online analytical tools named "Global Solar Atlas (GSA)", "Photovoltaic Geographical Information System (PVGIS)" etc. Based on these datasets, a 10kW ground-mounted PV system using monocrystalline silicon solar panels is designed for off-grid operation. The developed system can generate 14.808 MWh of energy per year. This design's environmental and social impacts are critically analyzed considering the Sustainable Development Goals (SDGs). Compared with conventional energy sources, the results show that the 10kW microgrid SPV system can reduce CO2 emissions by 284 tons. Financial analysis shows the recovery period of the investment based on electricity production at around 8.8 years, making solar PV microgrids a viable option for remote areas like Manpura Island.

Keywords:
Solar Energy, SPV, Renewable Energy, Micro-grid Powerplant, Global Solar Atlas

1. Introduction

Renewable energy-based microgrid systems have the potential to greatly contribute to offering affordable, eco-friendly, and dependable electricity supply to individuals residing in rural areas and isolated islands [1]. Conventional power plants have detrimental effects on the environment as a

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result of burning fossil fuels. They also have byproducts like coal ash and fly ash, which are hazardous substances that pose significant risks to human health. Managing and disposing of coal ash is a global environmental concern [2]. In recent years, using renewable energy sources to solve the electricity problems of remote areas has become a hot research topic in renewable energy system applications [3]. The microgrid system has advantages, mainly for providing the decentralization of energy generation that, based on the electricity demand, can be used well in each location based on the topographical position and distribution of renewable resources [4].

Renewable energy sources have been implemented in various places in the world to address such issues [5]. In particular, several efforts have been made to integrate renewable energy sources in isolated microgrids to reduce dependency on fossil fuels and mitigate the environmental impact of conventional power generation [6]. Abirham *et al.* [7] developed a liquid piston-type thermally driven pump concept with superior performance compared to the literature. The system can pump enough water for biogas production, with 87-93% available for agricultural purposes. The results suggest that 87-93% of the pumped water would be available for agricultural purposes, while only 6-13% would need to be fed to the biogas digester. Another study by Kang and Jung [8] compared off-grid and on-grid energy systems in North Pyongan, focusing on the most cost-effective option. The hybrid energy system (HES) of solar photovoltaic, wind turbines, lead-acid batteries, and diesel generators is the most cost-effective option for the selected location, with a breakeven grid-extension distance of 9.69 km to 20.57 km. The study suggests that deploying a HES could improve the electrification rate in remote and rural areas in North Korea.

Hidalgo-Leon *et al.* [9] examined the technical, economic, operational, and environmental feasibility of four off-grid hybrid power systems for Ecuador's Cerrito de los Morreños community. The simulations used Homer Pro software and a 15-year planning horizon, showing that a diesel/photovoltaic/battery configuration with energy efficiency had the best performance. Meanwhile, Syafii *et al.* [10] explored the economic feasibility of a hybrid microgrid power system in Sumatra, Indonesia. The study simulated and analyzed the system using Homer Pro software. The most economical configuration was photovoltaic (PV), diesel generation, and batteries in Mandeh and Lagundri Island. The optimal configuration was obtained with 86 kW from the Wind Turbine in Lagundri and 67 kW from the Wind Turbine in Mentawai.

Garg *et al.* [11] evaluated the performance of a grid-connected microgrid system that employs photovoltaic arrays, wind energy generating units, and battery energy storage systems. The results show that the PV-BESS utility grid system is an optimal solution for renewable energy penetration, making it sustainable and improving reliability in rural areas. Another study conducted in Pakistan focused on the optimal operation planning of a hybrid microgrid powerplant for grid-connected and grid-islanded modes, which serves as a solution for rural electrification [12]. Similarly, a feasibility study was conducted in Iran to assess the suitability of a hybrid energy system for supplying electrical energy to a hotel located on Kish Island. The study considered the integration of PV, wind, diesel generators, and battery backup to meet the hotel's electricity demands [13].

In Bangladesh, the southern islands face unique challenges in terms of energy access. The islands often have high household density or are located in informal settlements, limiting open land availability for installing traditional centralized solar PV systems [14]. Manpura is a small island off the coast of Bangladesh. The island is located in the northern Bay of Bengal, in the Meghna River's estuary, which is 80 kilometers from the district center of Bhola [15]. Due to its isolated position, supplying electricity here from the central grid is very challenging and expensive. The BPDB's West Zone Power Distribution Company Ltd's local office is responsible for delivering electricity to this island. Until 2017, the only source of electricity was through generators provided by BPDB and private generators, which ran for six hours a day [16]. These generators are run by fossil fuels and produce noise and air pollution. Moreover, the emission of harmful gasses like Carbon monoxide (CO), Carbon dioxide (CO_2), and Nitrous oxide (NO) pose severe health risks. According to a report from the U.S. Consumer Product Safety Commission (CPSC), deaths from CO poisoning from generator emissions are on the rise [17].

Extending the national grid to the distant island in the Meghna River's estuary via submarine cable would cost roughly 400 crore BDT [18]. However, Manpura Island is very permissible for solar PV (Photovoltaic) technologies, and it has around 1481.1 kWh/kWp of specific photovoltaic power output. A 281kW solar mini-grid PV plant is already operating at South Sakuchia, Manpura [19]. So, this assessment aims to design a 10kW Solar PV Plant for a particular area of Manpura that is not connected to the grid. By implementing Solar PV microgrids, the use of generators in the locality will be reduced. Also, Bangladesh was quite realistic in its goal to the U.N. climate body to unconditionally eliminate 5% of its estimated emissions by 2030 [20]. So, this project will become an essential part of the country's energy infrastructure and may become even more ambitious in tackling climate change.

2. Site Overview

Manpura Island is approximately 373 square kilometers in size and has a population of around 1,25,000 people [15]. It is mostly flat and covered with tropical vegetation. It has many ideal spots for solar energy production due to its location, which receives plenty of sunshine throughout the year.

2.1 Project Location

Evaluating essential factors in the decision-making process can help simplify the location selection process for utility-scale solar PV energy systems by using Multicriteria Decision-Making (MCDM) techniques [21]. For this assessment, a location in Char Jatin, Manpura Island, is considered. It has an abundance of land area, making it suitable for the installation of large solar panels. As Manpura Island faces the threat of erosion, a location in the middle of the island is searched to avoid this threat [22]. Figure 1 (data extracted from https://solargis.com/maps-and-gis-data) illustrates the DNI map of the selected location for the plant.

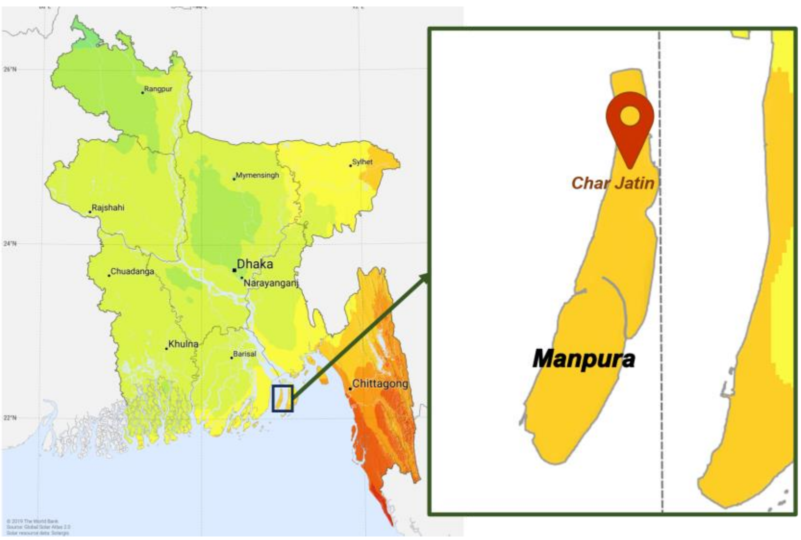


Fig. 1. Selected location for the plant

2.2 Load Demand

In this study, the number of units of appliances is taken into consideration, including 24 houses, four shops, a madrasa, a mosque, and a power plant office. Every home comes equipped with a television, a wall outlet, three lights, and two fans. There is a fan and a light in every store. Six fans, six lights, and a computer are installed in the madrasa. Four fans, four lights, and a pump are present in the mosque. A computer, a lamp, a charging station, and a fan are all present in the workspace. Among every two houses, 1 house has a refrigerator, and among all the four shops one has a refrigerator. A daily load curve is plotted in Figure 2 depending on these hypothetical data. The curve shows the total consumed load per hour for a day. The maximum amount of consumed load was observed at the 20th hour (8 p.m.), with a value of 9580W in the summer and 5380W in the winter. The total daily consumption of the locality is 140060W for summer and 74600W for winter.

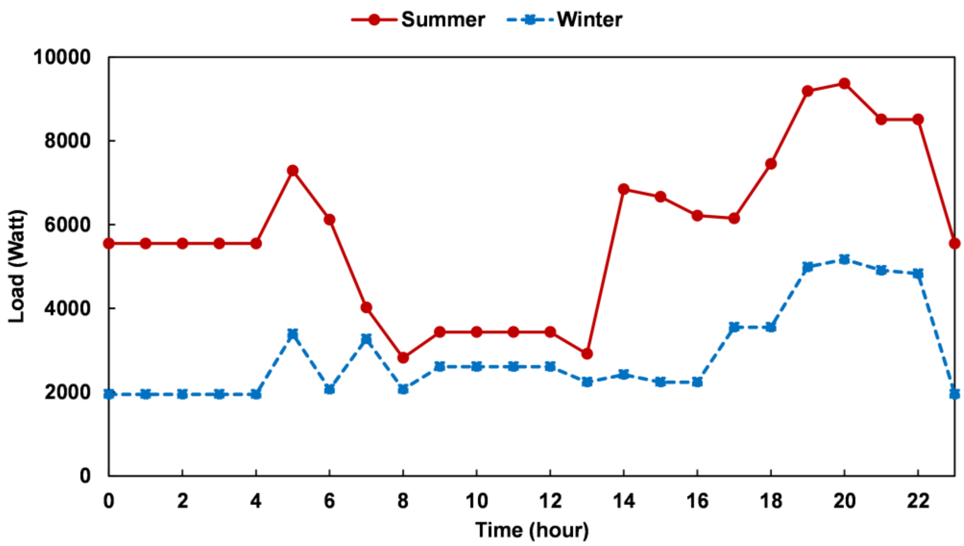


Fig. 2. Load Curve of the selected locality in Char Jatin, Manpura

3. Resource Assessment

After finalizing the site for the solar PV plant, the solar resource availability of the location was assessed to check its suitability for the required demand. A preliminary assessment of the photovoltaic electricity production for Char Jatin, Manpura Upazilla, Bhola District, Bangladesh is done using data from the web platform Global Solar Atlas. Table 1 (data extracted from https://globalsolaratlas.info/map) Shows the solar map data of the Char Jatin, Manpura availed from GSA for every year.

Table 1
Map data of Char Jatin, Manpura site (per year)

Properties	Abbreviation	Value	Unit
Direct normal irradiation	DNI	1169.6	kWh/m^2
Global horizontal irradiation	GHI	1733.3	kWh/m^2
Diffuse horizontal irradiation	DIF	913.6	kWh/m^2
Global tilted irradiation at the optimum angle	GTI_{opta}	1855.7	kWh/m^2
The optimum tilt of PV modules	OPTA	24 / 180	-
Air temperature	TEMP	26.1	°C
Terrain elevation	ELE	3	m

The Sunpath diagram is shown in Figure 3 (data extracted from https://globalsolaratlas.info/map) by plotting solar elevation angles and solar azimuth angles of a typical meteorological year for every hour of the day. In June, maximum solar elevation (90^o) is found at noon, and the azimuth direction is north. In December, the noontime solar elevation angle is half of that.

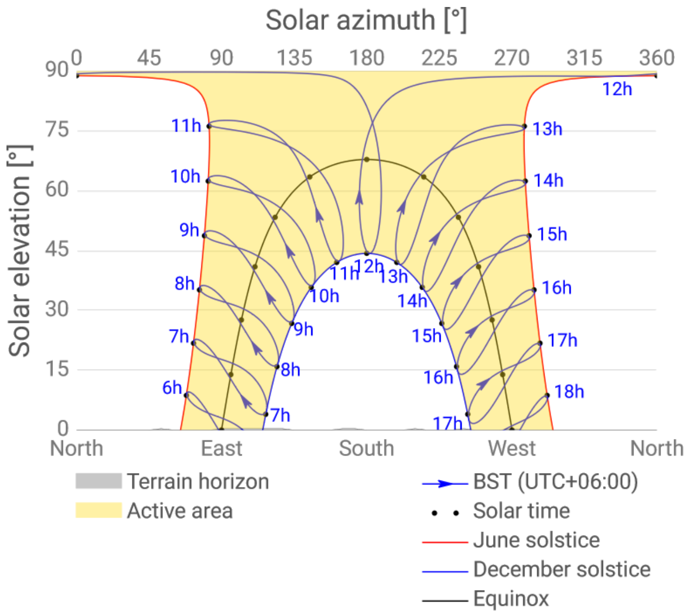


Fig. 3. Sunpath and Azimuth Diagram of the location from GSA

A ground-mounted large-scale PV system configuration was used to acquire data from the GSA web platform. Data from the GSA states that from a 10kW SPV system made of crystalline silicon solar panels, a total of 14.808 MWh of energy will be produced in a typical meteorological year, and the average is 41 kWh per day. Figure 4 (data extracted from https://globalsolaratlas.info/map) shows the amount of energy generated monthly from a 10kW system. The maximum power output was found to be about 1.5 MWh in March. In monsoon months, the power output is relatively lower, with the lowest being in June.

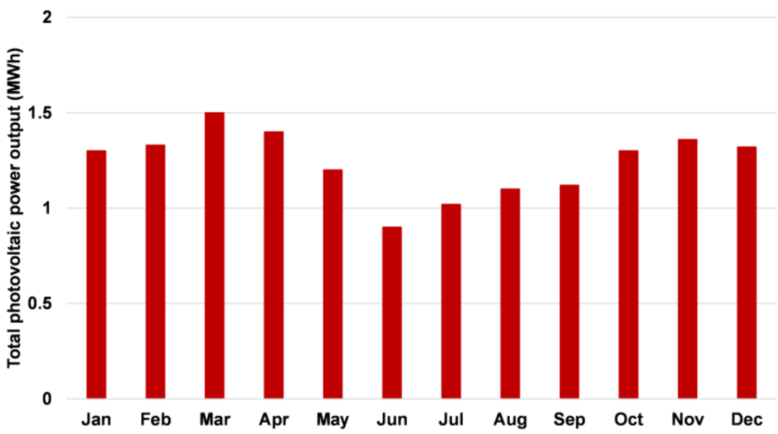


Fig. 4. Monthly averages of total photovoltaic power output

Figure 5 (data extracted from https://globalsolaratlas.info/map) shows the average hourly profile of the total photovoltaic power output in kWh. The figure shows how many units of energy are found per hour, considering the system runs at full capacity. For example, no units will be produced in

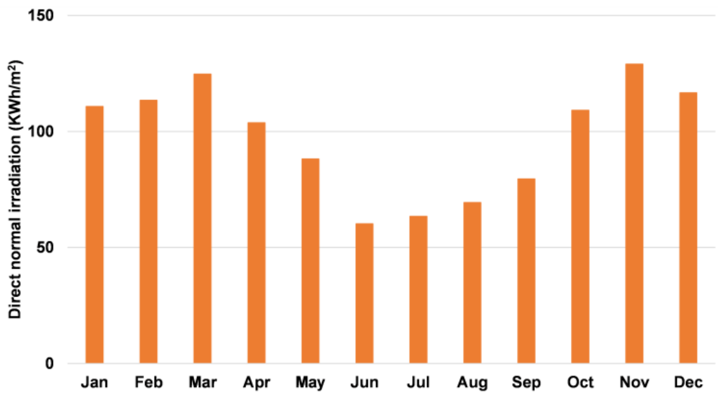
February from 6 a.m. to 7 a.m. From 7 a.m. to 8 a.m., only 1 unit of energy will be produced; from 10 a.m. to 11 a.m., 6 units of energy will be produced, and so on.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				0	0	0	0	0				
6 - 7	0	0	0	1	1	1	0	0	0	0	0	0
7 - 8	1	1	2	2	2	1	1	1	1	2	2	1
8 - 9	3	3	3	4	3	2	2	2	3	3	4	3
9 - 10	4	5	5	5	4	3	3	3	4	5	5	5
10 - 11	6	6	6	6	5	4	4	4	5	6	6	6
11 - 12	6	7	7	6	5	4	4	5	5	6	7	7
12 - 13	7	7	7	6	5	4	4	5	5	6	6	6
13 - 14	6	7	7	6	5	4	4	5	5	5	6	6
14 - 15	5	5	5	5	4	3	4	4	4	4	4	5
15 - 16	3	4	4	3	3	3	3	3	3	3	3	3
16 - 17	1	2	2	2	2	1	2	2	1	1	1	1
17 - 18	0	0	0	0	1	1	1	1	0	0		0
18 - 19				0	0	0	0	0				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	43	47	49	46	40	32	32	35	37	41	45	42

Fig. 5. Average hourly profile of total photovoltaic power output in kWh

Figure 6 (data extracted from https://globalsolaratlas.info/map) shows the monthly averages and average hourly profiles of DNI values in Char Jatin, Manpura Island. The average annual global tilted irradiation is 1855.7 kWh/m^2 and 5.084 kWh/m^2 daily. The monthly average DNI received is lowest in June, and highest in November, and average hourly profiles show the maximum amount of DNI that will be received between November and March.

(a)



(b)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				1	2	4	4					
6 - 7		3	16	50	60	45	39	33	44	42	35	2
7 - 8	99	126	158	169	143	87	74	79	121	213	259	140
8 - 9	254	289	291	275	226	142	125	131	183	311	407	304
9 - 10	365	411	405	368	303	195	179	206	260	396	506	419
10 - 11	448	503	492	431	355	233	234	259	316	444	564	506
11 - 12	501	556	538	453	371	248	255	289	340	458	581	544
12 - 13	516	564	544	450	362	246	267	298	347	457	567	542
13 - 14	494	540	522	427	342	243	265	299	350	440	526	509
14 - 15	431	476	464	366	289	225	238	272	327	385	455	428
15 - 16	331	378	358	282	226	181	191	211	239	278	338	312
16 - 17	151	226	230	183	150	124	133	140	145	138	98	88
17 - 18	4	27	47	43	56	57	68	47	19	6		
18 - 19						1	6					
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	3594	4098	4065	3498	2885	2031	2078	2264	2692	3568	4335	3793

Fig. 6. Direct Normal Irradiation (a) Monthly average, and (b) Average hourly profile in Wh/m^2

4. Design and Optimization

This study proposes a 10kW solar PV system, which is a micro-grid powerplant, with a capacity between 10kW and 100kW [23]. The system is designed to be off-grid due to the geographical location of Manpura Island. When an on-grid system fails, all areas the central system covers are left without power, whereas an off-grid system remains operational [20]. Thus, a decentralized off-grid system is more efficient for a remote location like Char Jatin.

4.1 System Design

The system was designed to get the maximum possible output at affordable prices. So, all components and the plant design were done keeping these in mind and also keeping in mind the climate condition of Manpura island. An off-grid system's power sources can be either AC or DC coupled based on the size of the system. DC-coupled power sources were opted for because they are more efficient than AC-coupled systems for microgrid systems [24]. This system has 5 major components: solar panels, a charge controller, battery storage, a power inverter, and a supply box. 22 units of 455W Monocrystalline Silicon cell-based Solar panels are mounted on a 5-by-5 grid. The output of the solar panels is then transferred to the six 24V 600A lithium polymer batteries units via 130 meters of DC Solar cables. An MPPT solar charge controller is placed between the panels and batteries to ensure efficient charging and avoid overcharging. DC power from the batteries is then passed through another 30 meters of DC solar wires to a 10KW multi-mode Inverter which converts DC input into AC power output. This AC output is transferred via transmission lines to consumers and can be controlled by the circuit switch box. The detailed schematic diagram of the powerplant can be seen in Figure 7.

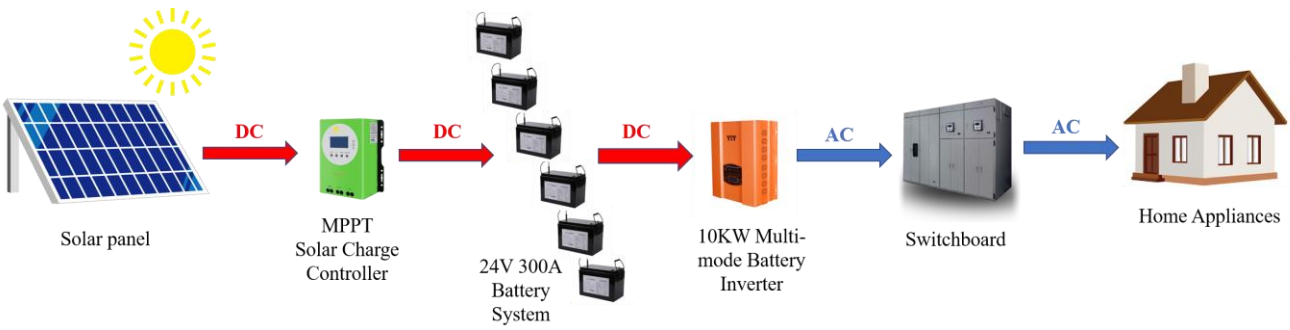


Fig. 7. Schematic diagram of the 10kW ground-mounted Solar PV Powerplant

4.2 Performance Analysis

Performance analysis of the designed off-grid 10kW solar PV system for Char Jatin, Manpura was done using the Photovoltaic Geographical Information System (PVGIS) web application. After giving the latitude and longitude of the location in PVGIS, an off-grid system was selected. Then all necessary inputs were provided based on the design. The total daily consumption calculated for summer was considered when simulating. Considering the default value, the battery discharge cutoff limit was set at 40%. The stimulation output showed that there'd be 100 days with an empty battery and almost 103kW of energy missing, which is not desired. However, the daily consumption input was given for summer, which is the maximum consumption. In winter, consumption is reduced to almost half. Then, average daily consumption would be much lower and show better results.

Moreover, it was found that on more than 80% of the days' the battery will remain at around 40% of capacity. But on none of the days does the battery percentage remain more than 60%.

Figure 8 (data extracted from https://re.jrc.ec.europa.eu/pvg_tools/en/) shows the average monthly energy output of the preliminary design of the 10kW off-grid solar PV powerplant. Lower energy production is seen in the monsoon months, and maximum output is achieved during spring. The maximum daily average energy output is about 44.56 kWh in March.

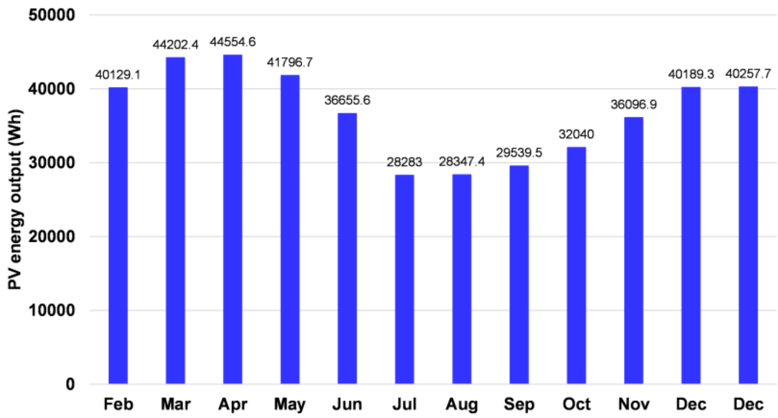


Fig. 8. The power production estimate for the 10kW off-grid PV system

4.3 Optimization

After analyzing the performance of the 10kW ground-mounted solar PV plant, further analysis was done to optimize its performance. Optimization of the azimuth angle and tilt angle was done using the web application PVGIS to enhance the output results further. System inputs were given in the grid-connected PV tab to optimize the slope angle and azimuth angle, as the optimization option is not available for off-grid PV systems. A system loss of 14% is considered for the optimization simulation. The simulated results show the optimum tilt angle of the panels to be 27° and the optimum azimuth angle to be 7° (south to west).

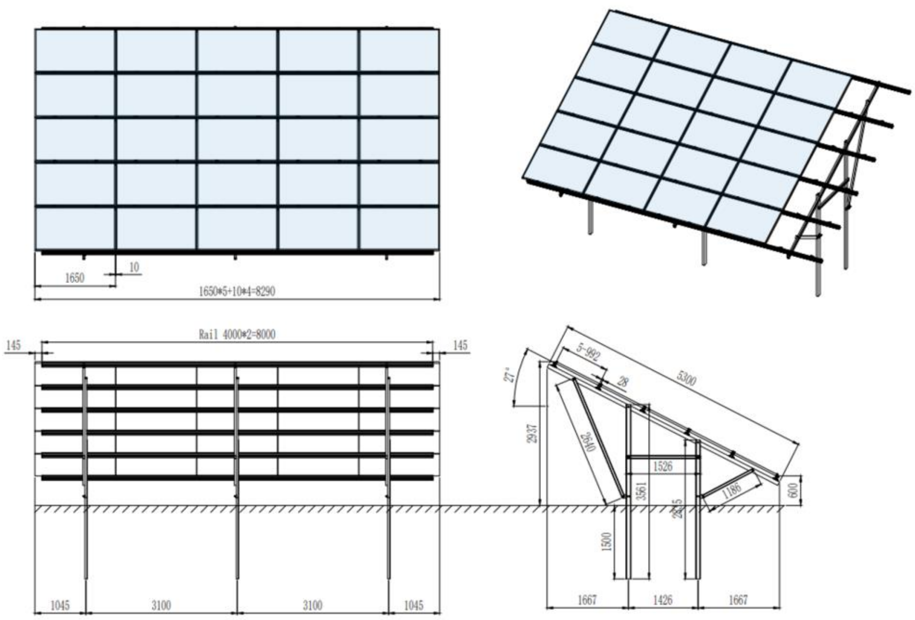


Fig. 9. 2D drawing of the panel mounting design (all dimensions are in mm)

With the optimized azimuth and tilt angle, the mounting system is designed for the 10kW micro-grid Solar PV plant using AutoCAD software. A solar pile ground mounting system using Galvanized steel is opted for, with a ground screw foundation. The system is designed considering the following details: 25 units of solar panels with a 5×5 landscape panel layout plan with dimensions 1650mm×992mm×40mm. The design also considered a location wind of 20km/h with no snow load [25] and a 0.6m ground clearance [26]. Figure 9 shows the 2D drawing of the final panel mounting design.

5. Result Assessment

Given the optimized azimuth and tilt angle values as inputs in the off-grid PV performance section of PVGIS, the energy output results of Figure 10 were generated. For this stimulation, the daily consumption value was taken as the average of the maximum consumption values of summer and winter from the demand analysis.

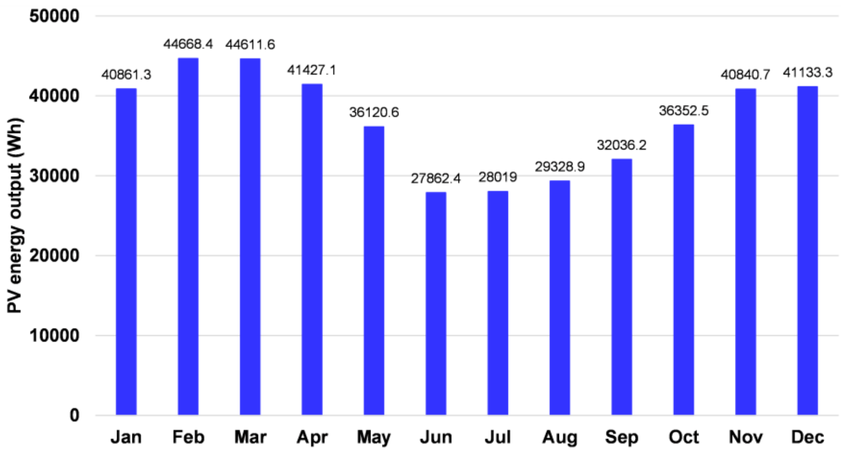


Fig. 10. Stimulation results for PV energy output of the optimized system

With these optimizations, the value of average missing energy decreases to 70.46 kW, and the maximum monthly energy output also increases to 44.67 kW. The battery charge rate is also found to be better distributed after optimization. Up to 80% of the charge remains in the batteries, though only for a short percentage of days. So, slightly better results are obtained with the optimization of azimuth and tilt angles.

5.1 Emission Analysis

No technology on this planet is one hundred percent clean. Even the cleanest source of energy has lots of side effects. Solar energy is also no exception. The materials used in solar PV modules have to be mined and processed. Manufacturing solar panels also releases CO_2 as the shaping of Silicon requires a high amount of heating [27]. There's also a carbon footprint for shipping materials and components. However, the overall lifetime emission of solar PV plants is much less than that of fossil fuel-based sources.

The estimated CO_2 emission by a diesel generator is between 0.8-0.93 kg/kWh [28]. Whereas, CO_2 emissions from the three conventional fuels, coal, natural gas, and petroleum, are 2.23, 0.91, and 2.13 pounds per kilowatt of energy production respectively [29]. The NREL report states that for each kilowatt of energy produced using solar PV, 40g of CO_2 is released into the atmosphere [30].

When compared with all conventional sources, this value seems pretty frugal. Figure 11 compares the amount of CO_2 produced by the 10kW solar PV microgrid with four other 10kW conventional power plants. The 10kW solar PV microgrid produces 14.95 tonnes of CO_2 in its 25-year lifetime whereas other conventional sources produce a few thousand times more CO_2 in the same lifetime. The plot clearly shows that Solar PV is a far better option for GHG emissions and would reduce emissions by literally hundreds of tonnes.

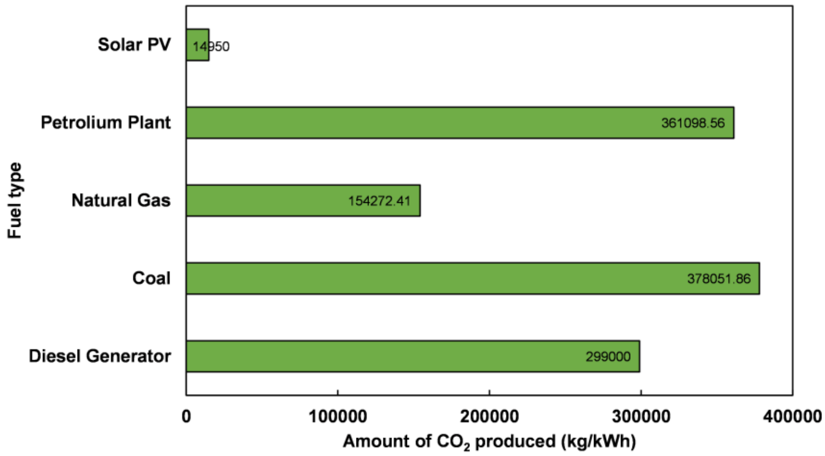


Fig. 11. Comparison of life cycle CO_2 emissions of the 10kW SPV microgrid with conventional fuels for a 25-year lifetime

5.2 Financial Analysis

In Table 2 all the data are taken considering the project life of 25 years. Most of the data are taken from the PV performance tool report of PVGIS for this system. The production cost of electricity and the payback period have been calculated concerning the total investment cost and considering a 2% maintenance cost per year. So, the total investment cost can be revoked within 8.8 years of operation.

Table 2
Financial Parameters of the Project

Parameter	Value
Project life (years)	25
Investment Cost (Taka)	9,58,752
Yearly electricity production (kWh)	14,950
The production cost of electricity (Taka/kWh)	2.6
Price of electricity (Taka/kWh)	7.3
Expected Revenue during the project life (Taka)	7,67,002
Simple payback period (years)	8.8

6. Conclusions

Solar energy is one of the most promising renewable energy sources that has gotten a lot of press in recent years. From the previous discussion, it is conceivable to construct a 10 kW PV system at Manpura Island. The primary goal of this initiative was to provide electricity to those who may only have access to electricity for a maximum of 5 hours every day. The solar power generation unit works more efficiently without hampering nature like the conventional ones, specifically the diesel generators operating on this island. The SPV system's electricity price is also less than that of conventional systems in the locality. This effort may provide light to all of the homes that were previously dark at night. These types of projects will also create some work opportunities for rural people. This work can be performed without generating a single gram of CO_2 or any other harmful particle into the Earth's atmosphere.

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