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Research Article

Environmental and techno-economic feasibility study of photovoltaic systems in Northern Bangladesh

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ABSTRACT

The feasibility study for the photovoltaic solar systems in Rajshahi, Bogura, and Sirajganj regarding Bangladesh, comprehensively addresses financial, technical, and environmental factors to attract both the national and international investors. The objective of the analysis is to evaluate photovoltaic (PV) solar systems in northern cities of the Bangladesh; Rajshahi, Bogura, and Sirajganj to minimize the effect of the global warming caused by burning of the fossil fuels as well as to improve region's sustainable development, which was hampered by the factory pollution. To analyze study and the verify its techno-economic and environmental sustainability, RETScreen Expert and Homer software is utilized. Sensitivity analysis emphasizes importance of the considering the diesel prices, inverter efficiency, and interest rates, as these factors significantly impact cost of energy (COE). Among these zones, Rajshahi attitudes out with lowest total emissions and the carbon dioxide levels, making it the furthermost favorable option for the reducing pollution and advancing the sustainable technology in this region.

Introduction

Bangladesh is the developing country that is the almost entirely electrified at this time. Approximately 100% of the Bangladesh's population has access to the electricity from both the renewable and the non-renewable sources. (BPDB, 2021). Electricity demand is constantly increasing due to a rapidly growing population and economic growth. There is always a large gap between electricity supply and demand. In 2041, Bangladesh's total power demand is expected to be around 50,000 megawatts (BER, 2022). To meet this demand, fossil fuels such as coal, gas, and oil are used to generate electricity. To generate electricity (Sarkar et al., 2015), only a limited amount of fossil fuel resources is available. As a result, the storage of fossil fuels has reached an alarming level. The use of fossil fuels has negative effects on the atmosphere and environment. As a result, the demand for alternative energy resources to generate electricity has increased.

Many researchers have examined various renewable energy sources (Rashwan et al., 2017; Hasan and Habib, 2025; Habib and Asgar, 2025), particularly solar energy, to produce environmentally friendly, sustainable electricity. To go for sustainable (Habib et al., 2020a), techno-economic (Noman et al., 2023), and environmentally friendly electricity (Habib et al., 2022), several strategies; decision-making processes (Habib et al., 2020b and Mondal et al., 2009), optimization, etc., are presumed (Habib, 2023) Islam

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et al. (2022a) suggested multiple optimal fusions to minimize grid dependency and identified the optimum combination of hybrid energy systems comprising nonrenewable and renewable energy for Nilphamari, Bangladesh. Islam et al. (2022b) designed a model using PVsyst software to evaluate and develop a solar photovoltaic rooftop system with a grid-connected system in Bangladesh. Mondol et al. (2009) assessed a 500 kW grid-connected photovoltaic (PV) solar system in southern Bangladesh. Rahman et al. (2018) discussed a hybrid optimization model for obtaining continuous power. Nikita et al. (2016) surveyed several areas in the northwestern region of Bangladesh to assess the viability of PV-based solar electricity generation. Khandelwal and Shrivastava (2017) assessed performance of the 600kW grid-connected photovoltaic system for the Rajasthan village, India. Mehmood et al. (2014) settled the model of the 5kW solar PV stand-alone system to meet the Pakistan's household power demand, for the considering the payback periods, the net present value (NPV), the internal rate of return (IRR), and the greenhouse gas emissions. In the evolutionary game setting, Habib et al. (2022) scrutinized cost-benefit subsidy regarding power generator system, considering rapid growth of global economy and industry. Thevenard et al. (2000) estimated probable potential of the renewable energy system by the providing the initial estimate of size of solar array, pump, or battery. Mirzahosseini and Taheri (2012) projected new electricity tariffs based on the solar photovoltaic power plant's environmental, technical, and economic viability. Mukherjee and Razzak (2017) assessed a 100 kW grid-connected photovoltaic solar system, which has the potential to reduce greenhouse gas emissions by approximately 166 tons per year. Tahera et al. (2019) designed a project to assess the payback period and feasibility of a local grid-connected PV solar project for the residential hall at Bangladesh University of Engineering and Technology. Uddin et al. (2016) surveyed the cost and probable performance of a wind power plant on the Chittagong coastline in Bangladesh. Khan et al. (2009) analyzed the financial and technical information of a photovoltaic system with a small solar grid in the Rangamati district of Bangladesh. Rashid and Habib (2018) presented a Boost converter for solar power control by simulating the system and observing the control mechanism for power-point tracking in Simulink/MATLAB. Habib (2022a) used statistical methods to assess the characteristics of wind speed data from Rangpur, Bangladesh, from 2016 to 2020. The techno-economic feasibility study aimed to optimize the PV-Wind-Hydro hybrid power system in Fukuoka, Japan, as discussed in Habib et al. (2024).

Financial parameters, feasibility analysis, sensitivity analysis, and risk analysis issues were considered on the application of photovoltaic solar energy; Owolabi et al. (2019) established a strategy map for PV solar energy according to Sambo (2009), the investors of the solar energy to make investments in the technology of green energy, such as photovoltaic solar energy, from the underutilization and plentiful of photovoltaic energy in the northern part of Nigeria. This study is only for Nigeria, but almost no similar research has been conducted in the northern part of Bangladesh. So, this research focuses on the northern part; Rajshahi, Bogura, and Sirajganj of Bangladesh, to assess the system.

This paper examines photovoltaic solar systems for producing electricity in the northern regions of Bangladesh: Rajshahi, Bogura, and Sirajganj. This study assesses cost, feasibility, sensitivity, risk, and performance analyses for the RETScreen Expert and Homer software.

The remainder of this paper is organized as follows: Section 2 presents details about the site location. Section 3 establishes the design parameters for a photovoltaic solar system. Section 4 presents results from RETScreen and includes a detailed discussion. Section 5 outlines the materials and methods used for HOMER. Section 6 showcases results and discussion from HOMER. Finally, Section 7 draws the conclusions.

Site location

Bangladesh is almost entirely surrounded by India in the south-subtropics and tropics of Asia, with the only other neighbors being Myanmar to southwest and the Bay of Bengal to the south. The geographical position of Bangladesh extends between latitude: 20°34' to

26°38' and longitude: 88°01' to 92°41' (Bangladesh-An-Introduction). The solar angle of Bangladesh ranges from 40 to 90 degrees due to its location (Mengen et al., 2018). This representsthe study area: Rajshahi (latitude 24.4°, and longitude 88.6°), Bogura(latitude 24.8°, and longitude 89.4°), and Sirajganj (latitude 24.5°, and longitude 89.7°) of Bangladesh.

Design parameters of the PV system

This section discusses the project parameters, technical parameters and methodology of the PV system being measured for the installation of a photovoltaic solar project in the northern region of Bangladesh, specifically Rajshahi, Bogura, and Sirajganj. This includes the PV solar system, the power generation factor, the demand for electricity, the required energy from the PV module size, the inverter size, the battery size, and the capacity factor (Chande et al., 2014). This project is planned for the 100MW solar photovoltaic system.

Panel generating factor

The size of the photovoltaic solar cells is well-defined by the panel generation factor (PGF), which is based on total wattage rating and varies with the solar intensity and length of sunshine [How to Design Solar PV System, 2025]. The PGF for the Bangladesh is calculated as the 2.8, using following formula (Design Solar PV System, 2022).

The Panel Generation Factor = (Solar irradiance × Sunshine hour)/Standard test conditions irradiance (1)

The average solar irradiance = 215 W/m^2 (Owolabi et al., 2019), average sunshine hours = 13 hours (Chande et al., 2014) and standard test conditions irradiance = 1000 W/m^2 (Khan et al., 2015).

Energy of PV modules

The required energy of PV components is calculated using the following formula (Design Solar PV System, 2022) . The total daily electricity demand of the three villages in Rajshahi, Bogura, and Sirajganj, is considered 300 households (an average of 8 people per household) (Standard Test Conditions, 2022). The daily electricity demand in Godagari, Rajshahi, is 35270 kWh/d, in Kahaloo, Bogura, is approximately 31250 kWh/d, and Sadar, Sirajgonj, is approximately 29210 kWh/d. The total daily electricity demand for the three locations is considered 95730 kWh.

The energy loss of the system = 1.3 (Design Solar PV System, 2022).

Energy of PV modules = the requirement of peak energy × energy loss of the system (2)

Energy of PV modules = 95,730×1.3 = 124,449 kWh/d.

Total peak watt rating of PV modules

The total peak watt rating is determined using the following equation (Design Solar PV System, 2022).

Total peak watt rating = Solar PV energy required/ Panel generation factor (3)

Total peak watt standing = (124,449)/2.8 = 44,446.07 kW

PV modules

The mono-silicon China Sunergy CSUN200-72M PV module, with an output power rating of 200W, is chosen for the proposed power plant and photovoltaic solar cell. The technical details of the mono-silicon China Sunergy CSUN200-72M are demonstrated in Table 1.

Required number of PV modules

The following equation computes the total number of PV modules required in the power plant (Design Solar PV System, 2022).

Required number of the PV modules = Total watt peak rating / PV module peak rated output (4)

Required number of PV modules = 44,446.07 / 200 = 222,230.35 ~ 222,231 modules

The size of the inverter

The following formula is used to determine the inverter size.

Inverter size = the requirement of peak energy × safety factor (Design Solar PV System, 2022) (5)

The size of inverter =124,449 kWh × 1.3 = 161783.7 kW

Battery sizing

The following equation determines the battery's size (Design Solar PV System, 2022).

Battery sizing = (Daily power consumption × Days of autonomy) / (Battery efficiency × Depth of discharge × Battery nominal Voltage) (6)

Battery sizing = (124,449 kW × 3) / (0.85 × 0.6 × 12) = 61004.41 Ah

Daily power consumption = 124,449 kW, days of autonomy = 3, the efficiency of battery = 85%, depth of the discharge = 60%, and battery nominal voltage = 12V (Design Solar PV System, 2022).

Capacity factor

The following formula is used to calculate capacity (Lee et al., 2012).

CF= (Annual kilowatt hours produced per kilowatt AC peak capacity (kWh/kWp))/(8760 h in a year)

The required energy to be produced by the plant = 124,449 kWh/d. Annual energy to be generated from the plant = 124,449 kWh × 365 = 45,423,885 kWh

Peak capacity demand of PV plant=105 kWp CF= (45,423,885/100,000,000)/8760 = 5.18%--

Table 1. Detail of mono-silicon China Sunergy CSUN200-72M.

Parameters	Values
Maximum Power (P_{max})	200 W
Positive Power Tolerance	0-3%
Open Circuit Voltage (V_{OC})	45.3 V
Short Circuit Current (I_{sc})	5.72 A
Maximum Power Voltage (V_{mpp})	37.6 V
Maximum Power Current (I_{mpp})	5.32 A
Module Efficiency	15.67 %
Voltage Temperature Coefficient	−0.307 %/K
Current Temperature Coefficient	+0.039 %/K
Power Temperature Coefficient	−0.423 %/K

Results and Discussion

The financial and environmental parameters, the energy product, and the greenhouse gas (GHG) emissions are used to evaluate the optimization issues of this proposed photovoltaic solar system. The RETScreen expert software produced the result; climate data for the named position, parametric parcels of China surnergy solar PV module, photovoltaic solar energy overview per position, financial input variables, financial output variables, gross GHG emissions, and periodic GHG emissions profit for the three location are represented respectively in Tables 2, 3, 4, 5, 6, 7, and 8. A thorough feasibility study reveals the specialized, profitable, environmental, and risk/sensitivity outcomes.

Technical viability

The ability of any solar photovoltaic module to generate electricity is affected by solar radiation per location as well as the quantity of pure sunny days (Khandelwal and Shrivastava, 2017), the annual electricity exported to the national grid from the capacity utilization factor (CUF) and the panel (Mehmood et al., 2014). As shown in Table 2, the Rajshahi district has the highest monthly average solar radiation of 4.87 kWh/m^2/d and Sirajganj and Bogura districts have the lowest monthly average solar radiation of 4.74 kWh/m^2/d. The properties of the China Sunergy mono-si-CSUN200-72M PV module were determined using the RETScreen Expert software and are shown in Table 3. The mono-silicon China Sunergy CSUN200-72M solar PV module has a 15.67% efficiency. Table 4 displays the overview of photovoltaic solar energy for a specific location. Rajshahi district has the largest annual electricity export to the national grid of 140,155 MWh and the highest capacity factor of 16%. Sirajganj district has the lowest annual electricity export to the national grid of 136,969 MWh and the lowest capacity factor at 15.6%. Bogura district has a capacity factor of 15.7% and an annual energy export to the grid of 137,481 MWh. Fig. 1 shows the monthly variation in daily solar radiation at three locations. The Rajshahi district has the highest daily sun radiation of 6.43 kWh/m^2/d in April, and the Bogura district has the lowest daily solar radiation of 3.91 kWh/m^2/d in September.

Based on the photovoltaic solar system's technological viability, the values are attained as yearly electricity exported to the national grid as well as capacity factors for each of Rajshahi, Bogura, and

Table 2. Climate data of the selected location.

Location	Bogura	Sirajganj	Rajshahi
Latitude	24.8	24.5	24.4
Longitude	89.4	89.7	88.6
Elevation	25	20	22
Heating design temperature (℃)	14	14	13.9
Cooling design temperature (℃)	31.7	31.7	32
Earth temperature amplitude (℃)	15	15	16.9
The monthly average solar radiation kWh/m^2/d)	4.74	4.74	4.87

Sirajganj in Bangladesh. Therefore, it is technically feasible to construct and operate photovoltaic solar power plants in Rajshahi, Bogura, and Sirajganj using the suggested system.

Table 3. Parametric properties of China surnergy solar module.

Property	Value
PV technology type	mono-Si
Power capacity	100,000 kW
Manufacturer	China Surnergy
Model	mono-Si-CSUN200-72M
Number of units	500,000
Efficiency	15.67%
Nominal operating temperature	45 ℃
Temperature coefficient	0.4%/ ℃
Solar collector area	638162 m^2

Economic sustainability

The development of a solar photovoltaic plant requires careful economic analysis. An economic analysis of a solar photovoltaic project establishes its economic

Table 4. Photovoltaic solar energy overview per location.

Locations	Capacity factor	Annual energy exported	Annual electricity exported revenue
Bogura	15.7%	137,481MWh	$ 13,748,101
Sirajganj	15.6%	136,969MWh	$ 13,696,915
Rajshahi	16%	140,155MWh	$ 14,015,512

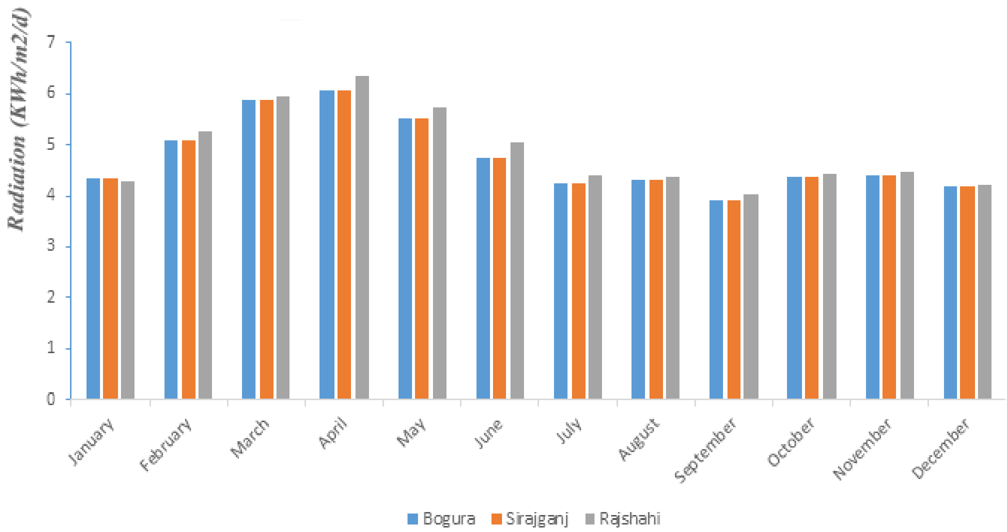


Fig. 1. Monthly variance in daily solar radiation for three different places.

viability and sustainability. As shown in Table 5, the economic analysis worksheet for the software includes financial factors such as escalation rate, fuel, debt term, debt ratio, debt interest rate, electricity export rate, and inflation rate. The software directly obtains the default configuration for the input parameters. Based on the entered inputs, the RETScreen software estimated Net Present Value (NPV), the Internal Rate of Return (IRR), annual life savings, and other economic factors, as shown in Table 6. According to the Table 6, the project in northern cities of Bangladesh; Rajshahi, Bogura, and Sirajganj has a positive net present value (NPV), making it profitable and economically viable (Islam et al., 2022a). In Table 6, the COE (Energy production cost ($/kWh)) for Bogura, Rajshahi and Sirajganj are 0.097$, 0.095$, and 0.097$, respectively.

The period of time required for the planned project to recover its initial cost is called the payback period. Fig. 2 shows the payback period for the northern region Bangladesh, including Rajshahi, Bogura, and Sirajganj. The suggested system's payback duration; simple payback period, and equity payback period were computed based on its 20-year lifespan. Rajshahi district has the lowest payback period at 8.7 years, whereas Bogura district has the greatest payback period of 8.9 years. The district of Bogura and Sirajganj has an 8.9-year payback time. The financial viability of solar PV systems is unaffected by the break-even year. Rajshahi district has the shortest equity payback period at 6.4 years, while Bogura and Sirajganj district has the longest at 6.8 years.

Table 5. Financial input parameters by RETScreen Expert.

Financial parameters	Value
Escalation rate fuel	2%
Inflation rate	2%
Discount rate	9%
Reinvestment rate	9%
Project Life	20
Debt ratio	70%
Debt interest rate	7%
Debt term	15 yr.
Debt payment	$9222748/yr.
Electricity export rate	$0.095/kWh
Electricity export escalation rate	2%
Initial cost	$120,000,000
O & M cost	$1,000,000
Total annual cost	$10,222,748

Table 6. Financial output variables.

Financial viability	Bogura	Sirajganj	Rajshahi
Internal rate of return (%)	17.1	16.9	17.8
Net Present Value (NPV) ($)	32,409,498	31,838,147	35,394,398
Annual life cycle savings ($)	3,550,346	3,487,757	3,877,332
Benefit-cost (B-C) ratio	1.9	1.9	2
Debt service charge	1.5	1.5	1.5
Energy production cost ($/kWh)	0.097	0.097	0.095

Fig. 3 shows the total cash flow of the proposed project after 20 years in three locations in Bangladeshi: Rajshahi, Bogura, and Sirajganj. The project's highest profit is $160,073,300 in Rajshahi district, and its lowest is $151,908,097 in Sirajganj district. In addition, the project profit in the Bogura district is $153,219,926.

Emission reduction assessment

The RETScreen software was used to determine the gross annual greenhouse gas emission reductions of

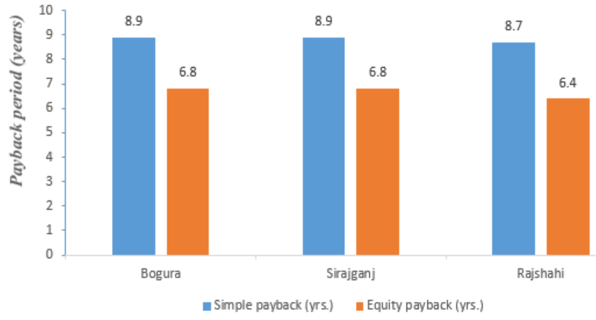


Fig. 2. The payback period for the three locations of proposed project.

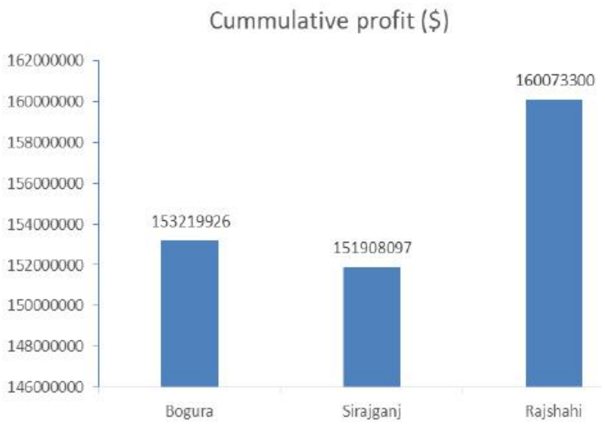


Fig. 3. The total cash flow for the project after 20 years.

the selected locations. The GHG emission reduction is obtained by excluding the determined emission of the proposed case from the determined emission of the baseline case, as shown in Table 7. The GHG emission reduction for the selected locations is illustrated in Fig. 4. Sirajganj district has the lowest GHG emission of 77184.4 tCO2, equivalent to 7,099 hectares of forest absorbing carbon. Rajshahi district has the highest GHG emission of 78979.7 tCO2, which corresponds to 7,264.1 hectares of forest absorbing carbon. Bogura district emits 77472.8 tCO2, which corresponds to 7,125.5 hectares of carbon-absorbing forest.

The software calculated the GHG-emissions-reduction revenue for three locations in Bangladesh: Rajshahi, Bogura, and Sirajganj, as shown in Table 8. Any investor is encouraged to profit from selling GHG emissions reductions rather than carbon trading. The estimated credit rate for GHG emissions

Table 7. Annual GHG emission of the three locations.

Location	Based case (tCO_2)	Proposed case (tCO_2)	Gross annual GHG emission reduction (tCO_2)
Bogura	83304.1	5831.3	77472.8
Sirajganj	82994.0	5809.6	77184.4
Rajshahi	84924.4	5944.7	78979.7

Table 8. Annual GHG emissions revenue for the three locations.

Location	Bogura	Sirajganj	Rajshahi
Net GHG reduction (tCO_2/yr.)	77,473	77,184	78,980
Net GHG reduction for 20 yrs. (tCO_2/yr.)	1,549,457	1,543,688	1,579,595
GHG reduction credit rate ($/($tCO_2$/yr.)	10	10	10
GHG reduction revenue ($)	774,728	771,844	789,797
GHG reduction credit duration (yr.)	15	15	15
Net GHG reduction for 15 yrs. (tCO_2/yr.)	1,162,092	1,157,766	1,184,696

reduction is $10 for a 15-year lifespan with a 2% annual escalation rate. Rajshahi district has the highest net GHG emissions reduction of 1,579,595 tCO2/year, while Sirajganj district has the lowest net GHG emissions reduction of 1,543,688 tCO2/year. Sirajganj has a net GHG emissions reduction of 1,549,457 tCO2/year. This is because Rajshahi district emits the most GHG emissions among the other districts.

Sensitivity analysis

RETScreen software creates the sensitivity analysis worksheet. The sensitivity analysis worksheet reduces uncertainty by comparing two input variables to the calculated financial parameters, as shown in Fig. 5.

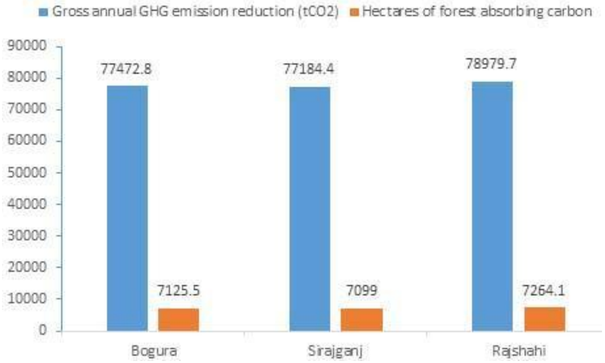
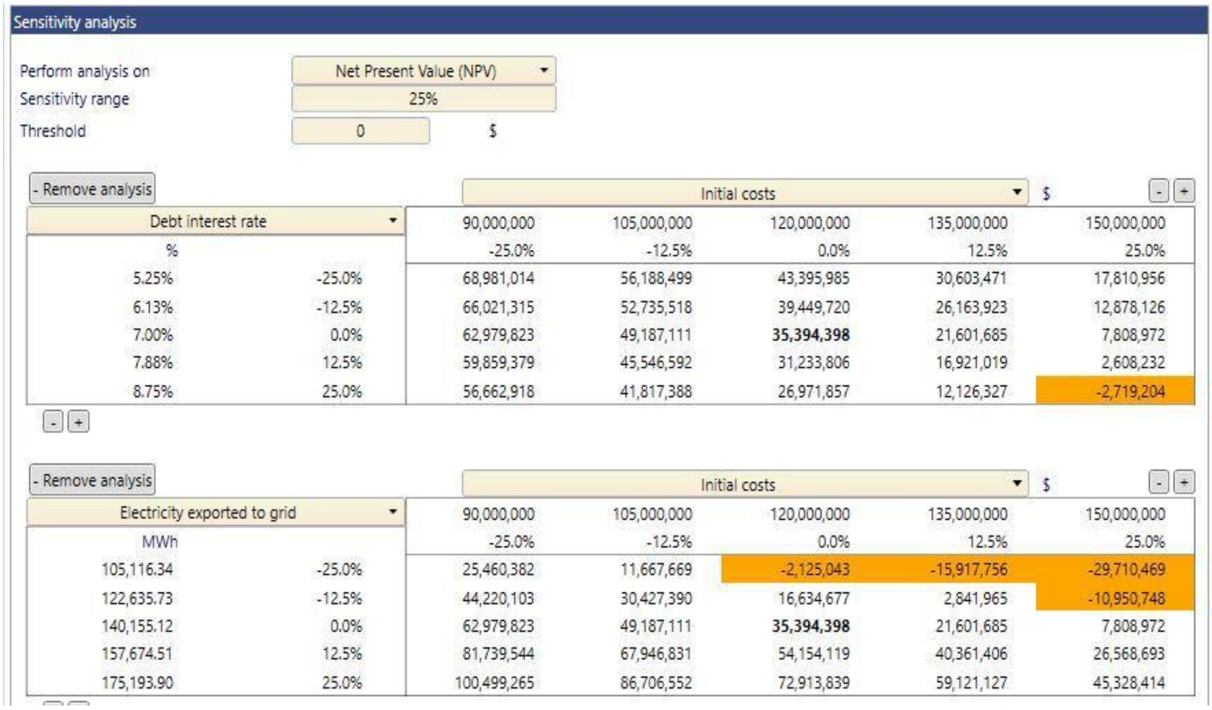


Fig. 4. Gross annual GHG emission and the corresponding hectares of forest absorbing carbon.

The sensitivity analysis is performed only for the photovoltaic solar system in the Rajshahi district because it offers superior technological, economic, and environmental analyses compared to the other regions. The proposed project's net present value (NPV) was subjected to a sensitivity study. Fig. 5 shows the sensitivity analysis worksheet, varying the initial cost in contradiction of the debt interest rate by ±25% for scenario 1 (Fig. 5) and the initial cost in contradiction of the electricity exported to the grid by ±25% for scenario 2 (Fig. 5).

The initial cost in Scenario 1 is calculated to be $120,000,000 with a ±25% discount. The initial costs will be $150,000,000 and $90,000,000, respectively. The original debt interest rate is 7%, but after a ±25% increase, the debt interest rate is 8.75% and 5.25%, respectively. The NPV value and the debt interest rate for the initial cost combination are recalculated while all other parameters remain constant. The software uses orange to identify NPV values less than zero. The project will not be financially profitable with a 25% increase in the starting cost and a 25% decrease in the debt interest rate, since the NPV would be -$2,719,204. If the debt interest rate is raised by 25% while the initial cost is decreased by 25%, the solar PV system project becomes economically viable because the net present value is $ 68,981,014, which is significantly greater than zero. This indicates that the net present value (NPV) is more responsive to the initial cost than the project's debt interest rate. Also, in Scenario 2, the initial cost is measured in terms of electricity exported to the national grid, as shown in Fig. 5.

The proposed project will be economically profitable if the preliminary cost is reduced while increasing the



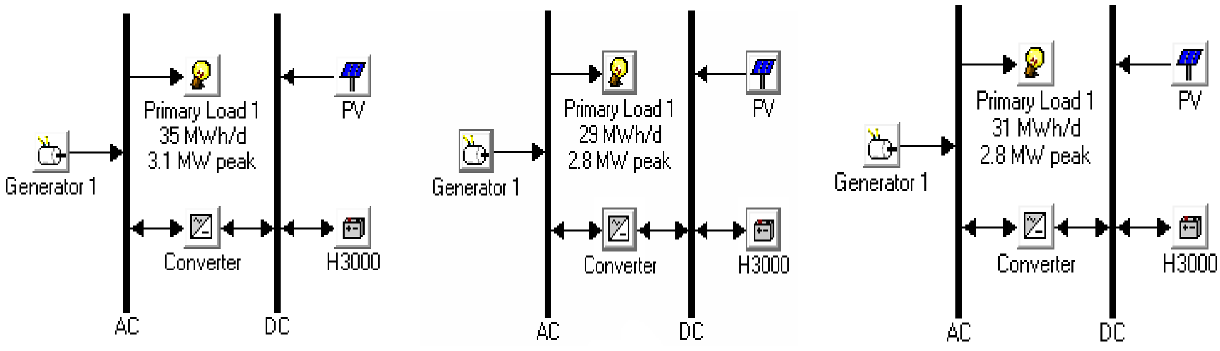
Sensitivity analysis

Perform analysis on: Net Present Value (NPV)
Sensitivity range: 25%
Threshold: 0 $

Debt interest rate (%)		90,000,000 (-25.0%)	105,000,000 (-12.5%)	120,000,000 (0.0%)	135,000,000 (12.5%)	150,000,000 (25.0%)
5.25%	-25.0%	68,981,014	56,188,499	43,395,985	30,603,471	17,810,956
6.13%	-12.5%	66,021,315	52,735,518	39,449,720	26,163,923	12,878,126
7.00%	0.0%	62,979,823	49,187,111	**35,394,398**	21,601,685	7,808,972
7.88%	12.5%	59,859,379	45,546,592	31,233,806	16,921,019	2,608,232
8.75%	25.0%	56,662,918	41,817,388	26,971,857	12,126,327	-2,719,204

Electricity exported to grid (MWh)		90,000,000 (-25.0%)	105,000,000 (-12.5%)	120,000,000 (0.0%)	135,000,000 (12.5%)	150,000,000 (25.0%)
105,116.34	-25.0%	25,460,382	11,667,669	-2,125,043	-15,917,756	-29,710,469
122,635.73	-12.5%	44,220,103	30,427,390	16,634,677	2,841,965	-10,950,748
140,155.12	0.0%	62,979,823	49,187,111	**35,394,398**	21,601,685	7,808,972
157,674.51	12.5%	81,739,544	67,946,831	54,154,119	40,361,406	26,568,693
175,193.90	25.0%	100,499,265	86,706,552	72,913,839	59,121,127	45,328,414

Fig. 5. Sensitivity analysis outcome of the photovoltaic solar project in Rajshahi.



a) Rajshahi **b) Bogura** **c) Sirajganj**

Fig. 6. Configuration of the proposed hybrid system at a) Rajshahi, b) Bogura, and c) Sirajganj, Bangladesh.

value of the electrical energy exported to the national grid. In both scenarios, the initial cost has a greater impact on net present value (NPV) than the debt interest rate and the quantity of electrical energy exported to the national grid.

HOMER simulation methods with materials

This section is essential for researchers seeking to comprehend the study's methodology and for those aiming to extend or confirm its results.

The Configuration of HOMER Simulation

The HOMER software package integrates the simulation, the optimization, and the sensitivity analysis to the accurately assess energy balance across the various seasons. By the modeling energy production and the consumption dynamically, HOMER detects the viable solutions throughout the system's lifecycle. It also computes the levelized cost of energy (LCOE) to evaluate economic viability of energy systems. The next section details the calculation method for Net Present Cost (NPC) as

follows:

$$NPC = I + \sum_{i=1}^{n} (C_y)[\frac{1}{(1+d)^i}]$$

I is for initial investment, n is the life span of project, C_y is yearly cost (including O (Operation)) & M (Maintenance) and replacement), and d is discount rate. The levelized cost of energy is expressed as:

$$COE = \frac{NPC}{\sum_{i=1}^{n}(E_y)[\frac{1}{(1+d)^i}]}$$

E_y is the yearly electricity served.

Configuration of the proposed system

The proposed system configuration is shown in Fig.6 and includes a PV source, diesel generator, a converter, and loads. Detailed specifications for each component are provided below.

PV array

The PV array is a crucial component of the energy system, representing the interconnected setup of individual PV modules. The HOMER software evaluates the power output of the PV array using the following equation: $P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S}$

Where, f_{PV} is the PV derating factor, Y_{PV} represents the rated capacity of the PV array (KW), I_T introduces the global solar radiation (beam plus diffuse) incident on the surface of the PV array (KW/m^2), and I_S is the standard radiation rate (KW/m^2). Various PV panel sizes, ranging from 0 kW to 4000 kW, were considered for optimization across all sites.

Diesel Generator

To improve system reliability, a 24 kW diesel generator, costing $10,058, has been incorporated into the energy scheme to provide backup power during periods when renewable sources fall short (Standard Test Conditions (STC) of a Photovoltaic Panel, 2022). This generator consumes 5000 liters of fuel annually and has a lifespan of 15,000 operational hours. The optimization process assesses the range of the diesel generator sizes from the 0 kW to the 500 kW to the guarantee the continuous power supply.

Converter

The converter, which includes both the rectifier and the inverter, is the essential to energy system, dynamically acclimates to the operation of PV system. It efficiently converts the AC to the DC during active the PV power generation and contraries the process for the grid or the off-grid usage. The 2 kW unit, costing $651 and boasting 90% efficiency over the 15-year lifespan, is available in the sizes ranging from the 0 to the 250 kW. This versatility confirms the optimal energy conversion and the system performance (Fig. 7). The converter plays the critical role in the optimizing energy utilization and the ensuring grid compatibility, highlighting its significance in overall system.

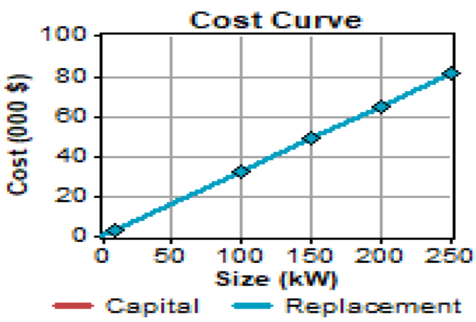


Fig. 7. Cost curve of the converter.

Estimation of the Electrical Loads

The primary load, recognized as electric load, shows total energy demand that the system must meet (Chandel et al., 2014). The daily load demand at Godagari, Rajshahi, is 35 MWh/d, the Kahaloo, Bogura, is the approximately 31 MWh/d, and the Sadar, Sirajgonj, is the approximately 29 MWh/d, which is consistent with the RETScreen.

Resource assessment

The HOMER model shows the crucial role in the study by the enabling of the evaluation of the various energy resource combinations, including the solar energy, to determine most effective system configuration. By systematically evaluating resources as the solar irradiance and reliability of the existing power infrastructure, HOMER classifies the economically viable and the sustainable energy mix that meets demand.

Economics and constraints

The study projects the 25-year lifespan, reflecting the focus on the long-term sustainability and the economic viability. The conservative annual interest rate of 15% is applied in financial analysis to account for time value of the money and the investment risks. Importantly, the system is designed with flexibility, permitting up to the 10% annual capacity shortage, which is acceptable within renewable energy framework.

Results and the discussion by HOMER

The study explores the environmental and the techno-economic feasibility of the implementing photovoltaic (PV) systems in northern areas of the Bangladesh, specifically the Rajshahi, the Bogura, and the Sirajganj. Utilizing the HOMER software, the analysis estimates the various aspects of the PV system performance, including the cost-effectiveness and the environmental impact.

Cost of energy (COE) by HOMER

The simulation in the study goes the beyond merely identifying the optimal solutions by the providing the in-depth sensitivity and the optimization analysis. It clarifies how the various factors influence proposed system's design outcomes. The results, detailed in Table 9, are the crucial for the supporting optimization cases, with discount rate emerging as the significant factor in system's analysis. The simulation proposals valuable insights into dynamics between the factors such as discount rate and the PV capacity, which greatly affect system's reliability and the cost-effectiveness. In the evaluating different power system combinations with the HOMER, focus is on the economic and the operational characteristics. Among hybrid options, PV-diesel-converter combination is the notable for its versatility, integrating both conventional and non-conventional energy resources. With the calculated cost of the energy (COE) of the $0.329 per kWh for Rajshahi, the $0.351 for Bogura, and the $0.440 for Sirajganj, this configuration displays competitive the affordability and the efficiency. By combining the photovoltaic energy with reliability of the diesel generator and the converter, these configurations proposal the well-balanced approach that boosts their cost-effectiveness. Moreover, systems with the higher proportions of the renewable energy sources, including the PV, are mainly attractive for the environmental sustainability. So, the HOMER simulation results the demonstrate that the PV-diesel-converter combination is the versatile and the efficient solution for the studied areas. Rajshahi's lower COE highpoints its cost-effectiveness, while the ability to the incorporate various energy resources ensures system reliability and the operational flexibility. The findings highlight importance of the considering both the economic and the environmental factors in design and optimization of the energy systems.

Sensitivity analysis

The sensitivity analysis showed the using the HOMER software, as showed in Fig. 8 (a) for the Rajshahi, (b) for the Bogura, and (c) for the Sirajganj, emphases on the diesel price as the important parameter. With the assumed the inverter efficiency of 90% and the interest rate of 15%, the analysis utilizes how the varying diesel prices affect levelized cost of energy (COE) for the hybrid system, which comprises the PV panels, the

Table 9. Cost of energy of the different options with respect to (a) Rajshahi, (b) Bogura, and (c) Sirajganj.

PV (kW)	Label (kW)	H3000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
300...	3000		3000	$ 5,633,750	3,324,830	$ 27,125,942	0.329	0.87	0.00	2,918,423	5,144
300...	3000	1	3000	$ 5,662,272	3,324,446	$ 27,151,984	0.329	0.87	0.00	2,917,958	5,143
	3000			$ 1,257,250	6,031,272	$ 40,244,284	0.488	0.00	0.00	5,339,616	8,759
	3000	1	5	$ 1,287,400	6,031,471	$ 40,275,724	0.488	0.00	0.00	5,339,618	8,759

a) Rajshahi

PV (kW)	Label (kW)	H3000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
300...	3000		3000	$ 5,633,750	3,094,244	$ 25,635,400	0.351	0.89	0.00	2,692,532	5,091
300...	3000	1	3000	$ 5,662,272	3,093,305	$ 25,657,856	0.351	0.89	0.00	2,691,602	5,089
	3000			$ 1,257,250	5,704,492	$ 38,131,936	0.522	0.00	0.00	5,012,836	8,759
	3000	1	5	$ 1,287,400	5,704,690	$ 38,163,360	0.522	0.00	0.00	5,012,836	8,759

b) Bogura

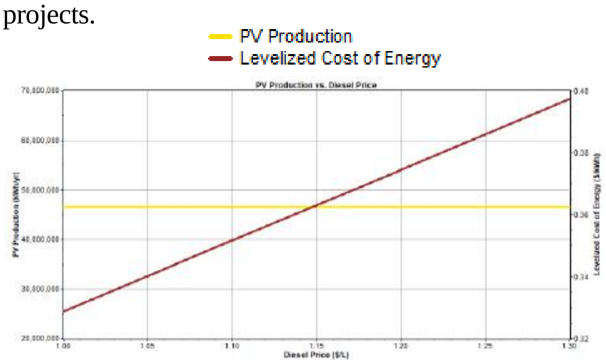
PV (kW)	Label (kW)	H3000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
300...	3000		3000	$ 5,633,750	3,828,930	$ 31,949,706	0.440	0.89	0.00	2,633,217	5,076
300...	3000	1	3000	$ 5,662,272	3,829,115	$ 31,979,498	0.440	0.89	0.00	2,633,217	5,076
	3000			$ 1,257,250	7,071,614	$ 49,859,936	0.687	0.00	0.00	4,906,646	8,759
	3000	1	5	$ 1,287,400	7,071,828	$ 49,891,560	0.687	0.00	0.00	4,906,646	8,759

c) Sirajganj

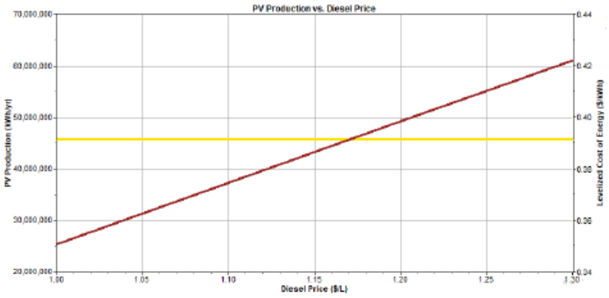
diesel generator, the battery,the power electronics, and the converter, while allowing for the maximum annual capacity shortage of 10%. As depicted in figure, levelized COE is plotted against the diesel prices ranging from the $1 to the $1.30 per liter. The results display the clear trend: as the diesel prices upsurge, the COE for hybrid option also increases. This trend highpoints system's sensitivity to the fluctuations in the diesel prices and the economic viability. The increase in the diesel prices raises cost of the energy production, emphasizing critical need to the account for such variables in planning and the decision-making processes for the energy projects. This sensitivity analysis emphasizes importance of the considering fuel price volatility and its possible impact on the overall system costs.

The sensitivity analysis conducted using the HOMER software, shown in the Fig. 9 (a) for the Rajshahi, (b) for the Bogura, and (c) for the Sirajganj, efforts on the inverter efficiency as primary parameter. With the presumed interest rate of 15%, the analysis assesses how varying the inverter efficiency moves levelized cost of energy (COE) for hybrid system, which includes the PV panels, the diesel generator, the battery, the power electronics, and the converter, while allowing for the maximum annual capacity shortage of the 10%. The figure shows the COE plotted against different the inverter efficiency values ranging from the 70% to the 90%. The results reveal that the higher inverter efficiency leads to lower COE, indicating the lower energy production costs. This tendency highlights sensitivity of hybrid system's economic viability to change in the inverter efficiency, highlighting significance of the accounting for the factors in planning and the decision-making processes for the energy projects.

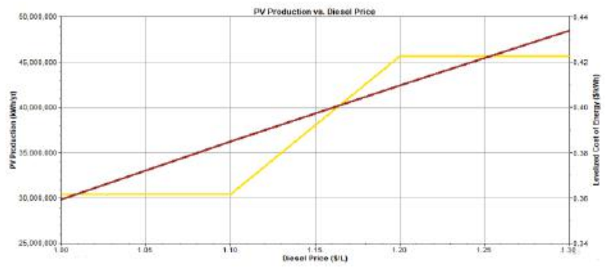
The sensitivity analysis conducted by the using HOMER software, exposed in Fig. 10 (a) for the Rajshahi, (b) for the Bogura, and (c) for the Sirajganj, emphases on the interest rate as important parameter. With the presumed inverter efficiency of the 90%, the analysis explores how the varying interest rates influence levelized cost of energy (COE) for hybrid system, which includes the PV panels, the diesel generator, the battery, the power electronics, and the converter, while allowing for the maximum annual capacity shortage of the 10%. The figure depicts COE plotted against the interest rate values ranging from the 13% to the 15%. The results show that the increasing interest rates generally lead to the rise in COE, though in the several cases, energy production costs may decrease. This trend underlines sensitivity of hybrid system's economic viability to change in the interest rates, the highlighting the critical need to consider these factors in planning and decision-making for the energy projects.



a) Rajshahi

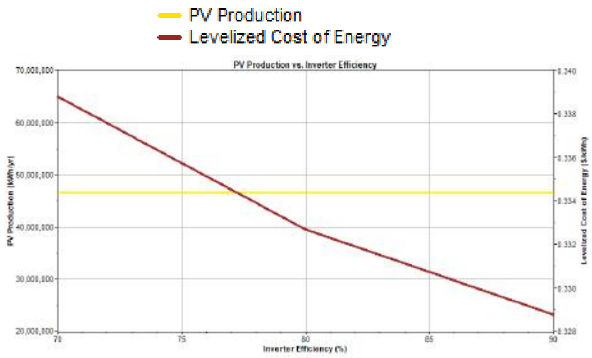


b) Bogura

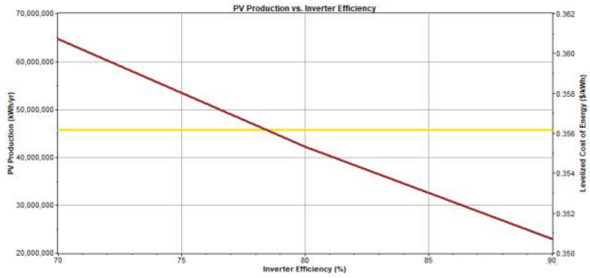


c) Sirajganj

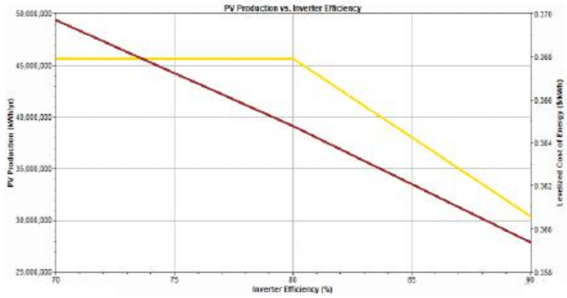
Fig. 8. The sensitivity analysis is driven for (a) the Rajshahi, (b) the Bogura, and (c) the Sirajganj focuses on relationship between PV production, diesel price, and levelized cost of energy (COE).



a) Rajshahi

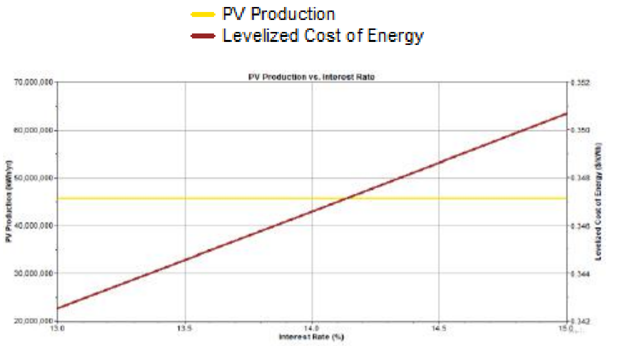


b) Bogura

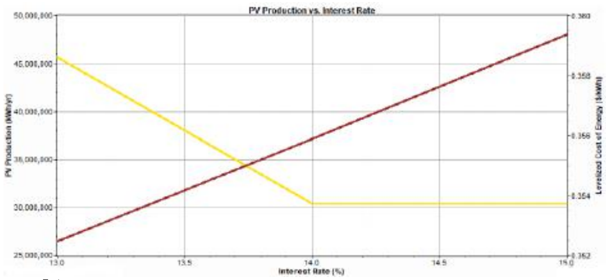


c) Sirajganj

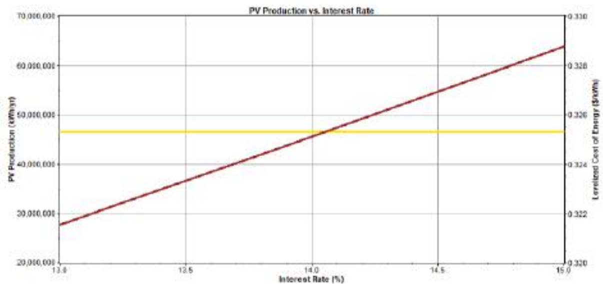
Fig. 9. The sensitivity analysis is conducted for (a) Rajshahi, (b) Bogura, and (c) Sirajganj focuses on the relationship between PV production, inverter efficiency, and levelized cost of energy (COE).



a) Rajshahi



b) Bogura



c) Sirajganj

Fig. 10. The sensitivity analysis is conducted for (a) Rajshahi, (b) Bogura, and (c) Sirajganj emphases on the relationship between PV production, interest rate, and levelized cost of energy (COE).

Table 10. The emission analysis is driven for (a) Rajshahi, (b) Bogura, and (c) Sirajganj.

Rajshahi	
Pollutant	**Emissions (kg/yr)**
carbon dioxide	768943
carbon monoxide	18967
sulfur dioxide	15431
Nitrogen oxides	169242

Bogura	
Pollutant	**Emissions (kg/yr)**
carbon dioxide	7087875
carbonmonoxide	17495
sulfur dioxide	14234
Nitrogen oxides	156113

Sirajganj	
Pollutant	**Emissions (kg/yr)**
carbon dioxide	6934126
carbon monoxide	17116
sulfur dioxide	13925
Nitrogen oxides	152727

emissions. Here's a breakdown: the Rajshahi has lowest carbon dioxide emissions, while the Bogura and the Sirajganj have the much higher emissions. Sirajganj has the lowest carbon monoxide emissions, followed closely by the Bogura. Sirajganj has the lowest sulfur dioxide emissions. Sirajganj has the lowest nitrogen oxides emissions. Regarding the overall emissions comparison: the Rajshahi has the lowest total emissions, and the Bogura has the highest. Based on the providing data, Rajshahi is the better option owing to its lower overall pollution levels. It has the lowest carbon dioxide and total emissions, suggesting a lower environmental impact than the Bogura and the Sirajganj.

Conclusion

The viability study for applying the photovoltaic solar system in the Rajshahi, the Bogura, and the Sirajganj, Bangladesh, addresses financial, technical, and environmental issues. Its aim is to attract both the national and the international investors by highlighting potential for the clean energy in the Bangladesh. The study considered the effect of sensitivity, risk, technical, financial, and environmental factors. This was established to the develop the photovoltaic solar energy strategy that will attract the PV solar energy investors from the national and the international administrations to fund Bangladesh's abundant and underutilized the clean energy. This will reduce overall warming and the advance the region's sustainable technological development.

RETScreen Expert software responses the lower energy production costs for Bogura, Sirajganj, and Rajshahi ($0.097, ($0.097, and $0.095 per kWh), HOMER's calculations display the higher costs of energy (COE) for these regions, with $0.329 per kWh for the Rajshahi, $0.351 for the Bogura, and $0.440 for the Sirajganj. Despite the discrepancies, HOMER's results reveal that the hybrid configurations are still competitively affordable and the efficient, reflecting the robust energy solution for the regions.

The sensitivity analysis discloses that rising diesel prices pointedly increase levelized cost of energy (COE), emphasizing the need to account for the fuel price volatility in the energy planning. Higher inverter efficiency reduces COE, representing its importance in the improving economic viability. Conversely, increasing the interest rates generally raise COE, highlighting the impact of the financial factors on project costs. These findings highlight the need to carefully consider the fuel prices, the inverter performance, and the interest rates in development and the decision-making processes for the hybrid energy systems.

Based on the emissions data, Rajshahi is the best option for pollution levels, as it has the lowest total emissions and the lowest carbon dioxide emissions. Sirajganj, while having the lowest emissions of carbon monoxide, sulfur dioxide, and nitrogen oxides, still falls behind Rajshahi in overall emissions. As a result, the effects of global warming will be greatly reduced.

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Authors contribution

All authors contributed equally to the conception, design, data collection, analysis, and writing of the manuscript.

Conflict of interest

There is no conflict of interest.

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