

Research Article

Design and Economic Analysis of a Rooftop Photovoltaic Power Generation System for an Educational Institution in Bangladesh

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Received: 10 November 2025; **Revised:** 16 January 2026; **Accepted:** 26 January 2026

Abstract: The increasing energy demand driven by population growth and urbanization in Bangladesh is primarily met through imported fossil fuels, which raises economic and environmental concerns. Rooftop Photovoltaic (PV) systems provide a sustainable solution to ensure a reliable power supply and reduce disruptions to academic activities caused by frequent power outages. This study offers the design and cost analysis of a rooftop PV power system for Bangladesh's Dhaka High School, with the goal of addressing the school's energy difficulties caused by frequent power outages. The system, which consists of a 4.8 kWp monocrystalline silicon PV array, is intended to meet the school's annual electricity demand of 17,547 kWh. The economic study shows that the installation cost is \$ 14,550, which may be reduced to \$ 11,640 with a 20% subsidy, lowering energy production costs from \$ 0.829/kWh to \$ 0.66/kWh. The system has a payback period of 8.5 years and an Return on Investment (ROI) of 86%. The study indicates the viability of incorporating renewable energy solutions into schools, resulting in long-term cost savings and environmental benefits. The findings emphasize the system's potential to reduce reliance on fossil fuels and promote sustainability, serving as a model for other educational institutions in Bangladesh and similar countries.

Keywords: energy sustainability, rooftop photovoltaic system, solar energy, economic analysis

1. Introduction

Bangladesh is witnessing an increasing energy demand attributed to its burgeoning population and swift urbanization. The nation significantly depends on imported fossil fuels, resulting in elevated energy expenses and environmental deterioration [1]. Solar energy has evolved as a feasible alternative, particularly advantageous for Bangladesh due to its geographic position and ample solar radiation year-round. Rooftop Photovoltaic (PV) systems are a viable solution for educational establishments that experience frequent power outages. These outages impede academic activities, obstruct productivity, and affect the learning environment [2]. Rooftop photovoltaic systems can deliver consistent energy, enhance operating efficiency, and contribute to climate change mitigation. Moreover, they diminish energy consumption from the grid and mitigate stress on transmission circuits [3]. In addition, PV systems contribute to the reduction of energy consumption from the grid, as well as the relief of transmission circuits.

Photovoltaic technologies are primarily categorized into crystalline silicon and thin-film cells. Crystalline silicon, encompassing mono-crystalline, poly-crystalline, and ribbon silicon, is the most prevalent choice due to its reliability

and superior efficiency (often 11%-15%) [4]. These modules generate direct current at conventional voltages and are commonly utilized for independent applications such as school rooftops, particularly in regions with unreliable grid connectivity. Conversely, thin-film technologies, including Cd-Te, Copper Indium Selenide (CIS), a-Si, and thin-film silicon, exhibit reduced efficiency and are not favored for standalone systems owing to their worse conversion rates [5].

Following the exploration of the different types of PV technologies, there remains a major challenge in many parts of the world, particularly in the countryside areas where infrastructure is limited. Rural electrification in India is progressing, though many states still have electrification rates below 80%. A survey by Grameen Vidyut Abhiyanta (GVA) reported that 18,452 villages still require electrification, with 3,430 remaining un-electrified [6]. The government is working to electrify 2,395 villages, with 2,293 already in progress. Electricity is crucial in rural areas for lighting, water pumping, and domestic activities, with average daily consumption in rural households being 892 W. Small-scale solar PV systems are proposed as a feasible solution to meet this demand [7].

Meanwhile, renewable energy has become a central focus of European Union (EU) policy [8]. Bulgari set a target to achieve a 20% share of Renewable Power Sources (RPS) in its energy mix by 2020. The nation implemented preferential pricing to promote photovoltaic projects, resulting in a substantial expansion of photovoltaic capacity. A technical investigation indicated that Bulgaria's RPS capacity must remain below 600 MW to ensure the quality of power system management [9]. This restriction exempts photovoltaic installations under 200 kW, which may be incorporated into industrial facilities or rooftops. The increasing disparity between installed and required power poses difficulties in the effective management of the power system [10].

Worldwide, solar photovoltaic systems are expanding swiftly thanks to their capacity to capture enough sunlight. Technological innovations have markedly decreased the expense of solar photovoltaic systems, facilitating extensive use. As of the conclusion of 2021, the worldwide installed capacity attained 843 Gigawatt (GW), with estimates predicting 1,630 GW by 2030. Saudi Arabia intends to produce 40 GW from solar photovoltaic sources. Nevertheless, adoption rates have remained low, with merely 3,000 residential solar PV applications submitted by 2018, despite advantageous rules [11].

Rooftop photovoltaic systems encounter many obstacles, including elevated upfront expenses for modules and installation, shade, and unfavorable roof orientation. These factors frequently undermine system efficiency, diminishing energy output. The absence of efficient energy storage solutions intensifies the problem, as dependence on the grid constrains performance during power outages or nighttime. Moreover, various legislation and incentives across areas impede the extensive implementation of rooftop photovoltaic systems. Addressing these challenges is crucial for maximizing the potential of rooftop solar energy [12].

This paper focuses on the design and economic analysis of a rooftop PV power generation system at Dhaka High School in Bangladesh. The objective is to illustrate the technological feasibility and economic viability of utilizing solar energy to fulfill the energy requirements of educational institutions. The site's physical attributes and solar energy potential are assessed. The school's energy use is assessed to determine the necessary capacity of the photovoltaic system. The photovoltaic array is configured with suitable solar panels and battery storage to fulfill load demands. The electrical configuration encompasses Maximum Power Point Tracking (MPPT) modeling, series and parallel arrangements of photovoltaic modules, switch cabinets, protection systems, and grounding mechanisms. The economic viability of the system is evaluated using a cost-benefit analysis, taking into account prospective subsidies and returns on investment.

2. Methodology

2.1 Theory of photovoltaic cell technology

PV technology converts solar energy into electricity through the photoelectric effect. When solar radiation strikes a PV cell, it excites electrons, creating electron-hole pairs in a semiconductor material. The electric field at a p-n junction separates these charge carriers, generating Direct Current (DC) flow [13].

$$(Y) = \frac{hc}{y} \quad (1)$$

where Y is the photon energy in Joules, h is Planck's constant (6.626×10^{-34} J·s), c is the light speed in a vacuum (3×10^8 m/s), and y is wavelength of incident light in meters. On a clear day, around 4.4×10^{17} photons per second strike each square centimeter of Earth's surface, offering significant energy potential [14]. The output of a PV cell depends on factors like solar irradiance, time of day, and panel orientation. Silicon-based PV cells typically produce 0.5-0.6 volts under open-circuit conditions [15]. Photovoltaic cells convert sunlight into electricity by generating electron-hole pairs in the semiconductor material. The internal electric field at the p-n junction separates these charges and produces direct current [16].

The conversion of sunlight into electrical energy occurs when photons are absorbed by the semiconductor material, generating electron-hole pairs. Under the influence of an electric field at the p-n junction, free electrons migrate towards the n-type semiconductor, and holes move towards the p-type semiconductor [17]. This separation of charge carriers creates a flow of electrons from the n-type to the p-type semiconductor, thereby generating an electric current [18].

The surface of PV cells, which are formed of semiconductor materials like silicon, is exposed to photons (light-related particles). When sunlight reaches the semiconductor material of the PV cell, it is stimulated to emit electrons, creating electron-hole pairs. Stated otherwise, it results in the displacement of some of the material's electrons from their typical locations, leaving "holes" where the electrons once were. The excited electrons, which are now free to move throughout the semiconductor, create an electric current. The PV cells are joined in an array to produce a more significant amount of electricity. As seen in Figure 1, this current passes through the PV cells and is collected as direct current electricity. The PV cells are connected in an array to generate a more substantial amount of electricity.

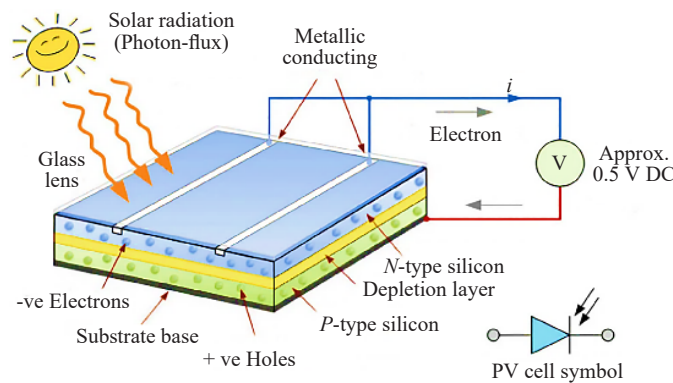


Figure 1. Conversion of light energy to electrical energy

The electrical equivalent circuit of a solar cell includes a current source Photo current (I_{ph}), a diode, and two resistors (series resistance and shunt resistance). When exposed to light, the solar cell generates current (Light generated current), part of which powers a load [19]. The current source models the generated current, the diode represents the p-n junction's behavior, and the resistors account for the solar cell's internal resistance. This circuit is used to predict the solar cell's performance under varying operating conditions [20].

The solar cell current is given below.

$$I = I_{ph} - I_0 \left(\exp \left(\frac{q(V + IR_s)}{nKT} \right) - 1 \right) - \frac{(V + IR_s)}{R_{sh}} \quad (2)$$

The Current-Voltage ($I-V$) and Power-Voltage ($P-V$) characteristics are critical for evaluating solar cell performance. These curves illustrate the variation in current and power concerning voltage, with the maximum power output occurring at the Maximum Power Point (MPP) [21].

$$P_{\max} = V_{\text{mp}} \times I_{\text{mp}} \quad (3)$$

The Fill Factor (FF), as a key performance metric, is expressed as

$$FF = \frac{V_{\text{mp}} \times I_{\text{mp}}}{V_{\text{oc}} \times I_{\text{sc}}} \quad (4)$$

Figure 2 shows the I - V and P - V characteristics of a monocrystalline Silicon (c-Si) p-n junction solar cell under standard test conditions and illustrates the relationship between voltage, current, and power in a PV solar cell, highlighting key performance characteristics. The I - V curve shows how current decreases as voltage increases, reflecting the typical behavior of solar cells. The P - V curve represents power output as the product of current and voltage. Initially, power increases with voltage until a certain point, after which it begins to decline. The MPP, identified on the P - V curve, indicates the voltage (V_{mp}) and current (I_{mp}) values at which maximum power output (P_{max}) occurs. The area under the P - V curve, represented by the product of V_{mp} and I_{mp} , quantifies the maximum energy generated by the solar panel. Additionally, the figure highlights the Open Circuit Voltage (V_{oc}) and Short Circuit Current (I_{sc}), which define the operational limits of the solar cell and are critical for evaluating its efficiency and performance.

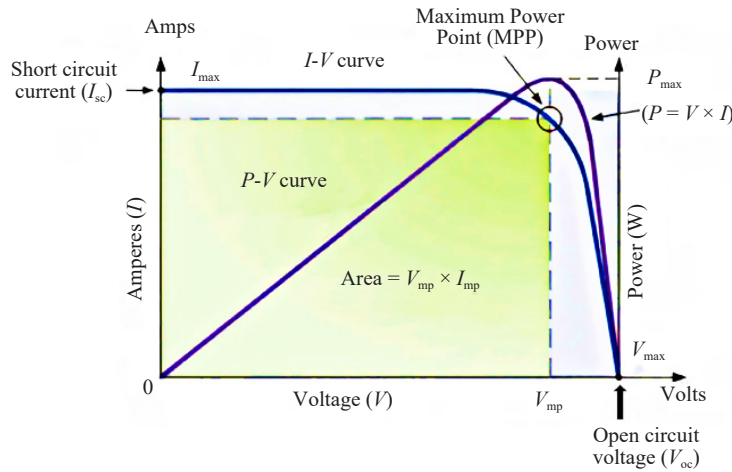


Figure 2. I/V and P/V characteristics curve of a solar cell

2.2 Electrical load estimation

The most critical factor in selecting a PV plant site is insolation, as it directly impacts energy generation [22]. Other considerations include temperature, land topography, shading, land size, and economic factors like land cost and access. Institutional and social aspects, such as population density and land use policies, must also be evaluated to ensure long-term project viability [23]. The second step in designing a photovoltaic system is to estimate the electrical load of the system. This involves listing all the daily loads and estimating the total energy required by consumers in watt-hours per day using equation.

$$E_T (\text{Wh}) = P_1 N_1 H_1 + P_2 N_2 H_2 + \dots + P_n N_n H_n \quad (5)$$

where P is the power consumed by the load in watts, N is the quantity of load used, and H is the number of hours the load is used. For Alternating Current (AC) systems, the total Direct Current (DC) watt-hours per day can be calculated using the equation (6) as

$$TDC_{\text{whrs/Day}} = \frac{E_t (\text{Wh})}{\text{Efficiency of inverter}}. \quad (6)$$

To calculate the required total energy consumed in Ampere-hours (Ah), the following formula is used.

$$E_T (\text{Ah}) = \frac{E_T (\text{Wh})}{V_{\text{Nom.Sys}}} e^{i\theta}. \quad (7)$$

2.3 Size of PV array

Before deciding which module (s) to use, it is essential to compare them based on their performance, physical size, and cost. This comparison will help identify the best option that meets the specific requirements of the project or application. To determine the required number of modules, first calculate the necessary current and voltage. Based on the system voltage and the specifications of the modules, establish the appropriate series and parallel connections to fulfill the design requirements [24]. Total solar array current is expressed as

$$I_{\text{MP}} (\text{AMP}) = \frac{E_T (\text{Ah})}{\text{Sun}_{\text{PD}}}. \quad (8)$$

The final module count is determined by multiplying the number of modules in series by the number of modules in parallel. In any stand-alone PV system that powers AC loads, Power Conditioning Units (PCUs) are critical components [25]. The PCU choice affects system performance and economics, with the PCU being the third-largest cost component after the array and battery. The following equation is used to determine the required capacity of the inverter.

$$P_{\text{inv}} (\text{VA}) = \frac{P_L}{(F_p I_{\text{Eff}})} \quad (9)$$

where P_L is the energy consumed by the load, F_p is the power factor, and I_{Eff} is the efficiency of the inverter, which is around 0.95.

2.4 Components of PV systems

Charge controllers are essential in standalone PV systems to regulate the flow of electricity from solar panels to batteries [26], preventing overcharging and protecting battery health. The main types include three parts. The first part is Pulse Width Modulation (PWM) Controllers. These controllers regulate voltage by rapidly switching the connection between the panel and battery on and off. They are affordable and widely used but offer moderate efficiency [27]. The second part is MPPT Controllers. These are more advanced and efficient than PWM controllers. MPPT technology continuously tracks the optimal voltage and current to maximize power output and convert excess voltage into additional charging current [28]. The third part is Shunt Controllers. These divert excess energy away from the battery once it is fully charged. While simple and reliable, they are less efficient compared to PWM and MPPT types [29].

Table 1 presents a comparison of different types of charge controllers used in PV systems, focusing on the PWM, MPPT, and Shunt controllers. Each controller type is evaluated based on its advantages and disadvantages. The PWM controller is noted for being simple and cost-effective, but it is less efficient than the MPPT controller. On the other hand, the MPPT controller offers higher efficiency and faster charging, though it comes at a higher cost compared to PWM. The Shunt controller is recognized for its simplicity and reliability, but is less efficient than both PWM and MPPT controllers. This comparison helps in understanding the trade-offs between cost, efficiency, and reliability when selecting charge controllers for PV systems.

Table 1. Comparison of different types of charge controllers used in PV systems

Charge controller type	Advantage	Disadvantage
PWM	Simple, cost-effective	Not as efficient as MPPT
MPPT	More efficient, faster charging	More expensive than PWM
Shunt	Simple, reliable	Not as efficient as PWM or MPPT

2.5 IRR method

The Internal Rate of Return (IRR) is the rate at which the Net Present Value (NPV) of a project is equal to zero. The IRR decision rule states that all independent projects with an IRR greater than the cost of capital should be accepted [30]. When choosing among mutually exclusive projects, the project with the highest IRR should be selected. The IRR can be calculated using the equation shown below by a trial-and-error method.

Entrepreneurs generally prefer photovoltaic projects with higher IRR. A project with an IRR less than the commercial rate of interest is not considered a good investment. However, households may find photovoltaic systems beneficial even if the IRR is less than the bank interest rate due to social factors. If the IRR of a project is equal to or greater than the required rate of return for the organization, the project is considered acceptable [31]. The equal risk is as follows

$$NPV = \sum \left(CF_t / (1 + IRR)^t \right) - C_0 = 0 \quad (10)$$

where CF_t is cash flow at time t , IRR is internal rate of return, C_0 is initial investment.

2.6 NPV method

The Net Present Value (NPV) method involves summing up the net cash flows discounted back to the present time. This approach is considered the most logical and commonly used method for investment decisions, particularly for long-term investments. NPV is obtained by deducting the present value of the project's cash outflows from the present value of the project's cash inflows. A positive NPV value suggests that the project may be viable. The essential concept of the present value method is that a Taka today is worth more than the same amount of money tomorrow, as the Taka today can be invested to start earning interest immediately. Therefore, the present value of a delayed payoff is calculated by multiplying the payoff by a discount factor, which is less than one. Suppose C_1 represents the anticipated payoff after one year. In that case, the Present Value (PV) is calculated as the discount factor multiplied by C_1 [32]. The discount factor is calculated as the reciprocal of 1 plus a rate of return, r . The rate of return r represents the reward that investors demand for accepting a delayed payment. To calculate the present value, expected future payoffs are discounted using the rate of return offered by comparable investment options [33]. This rate is often referred to as the discount rate, hurdle rate, or opportunity cost of capital. The present value formula is as following.

$$PV = \frac{AFV}{(1 + r)^n} \quad (11)$$

where Annual Future Value (AFV) is the future value, r is the discount rate, and n is the number of periods.

For an investment of one year duration,

$$\text{Present Value (PAV)} = \text{Discount factor} \times C_1, \quad (12)$$

$$\text{Discount factor} = \frac{1}{(1+r)}, \quad (13)$$

$$(NPV) = PV - \text{Required investment} = C_0 + C_1/(1+r). \quad (14)$$

For an investment of two years duration,

$$NPV = C_0 + C_1/(1+r_1) + C_2/(1+r_2)^2. \quad (15)$$

The economic analysis of the PV system is conducted using Renewable Energy Technology Screening Tool (RETScreen) software, which enables a detailed financial assessment through multiple integrated Excel-based modules.

3. Results and discussion

3.1 Design and analysis of a standalone PV system

Table 2. Design parameters of the PV system

Project location	Rooftop of a sub-sub-sub-sub-district-level high school in Dhaka
Load type	Mainly fan, light, and computer load during the load shed period
Average daily insolation/Sunshine hour	4.5 kWh/day/m ²
Rooftop area	4,253 sq.meters
System nominal voltage	230 VAC or 12/24 V DC
Type of battery	Nickel-cadmium
Battery maximum Depth of Discharge (DOD)	80-90%
Battery efficiency	70-80%
Battery life	15-20 years
Inverter efficiency	95 ~ 97%
PV module type	Mono-Si
PV array controller	Fixed
Slope of the PV array	23°
Azimuth of PV array	0 degree
Typical financial figures for the analysis	\$ 10,000-15,000
Energy cost escalation rate	5%
Inflation rate	7%
Discount rate	5%
Project life	20 years

The design parameters and important assumptions for the analysis and feasibility study of a standalone solar power system are outlined in this section, and a high-quality monocrystalline-Si PV array feeds into the mini-grid via a charge

controller or inverter. Some key assumptions for the technical and financial analysis are presented in Table 2. To reduce I^2R loss, the wire size should be as large as possible, and the cumulative loss should be no more than 5%. Soiling factor and battery Coulombic efficiency should be considered to ensure the panel receives solar insolation and to overcome resistance created by gas formation during charging.

To enable greater clarity and reproducibility of the design process, the statistics in Table 2 should be complemented by the assumptions or rationale that underpin them. First, the panel size should be adjusted by 5% to allow for temperature rises and the impact of meteorological circumstances. This modification is necessary to account for anticipated losses in solar panel efficiency caused by increased temperatures, which can have a major impact on overall system performance. In addition to temperature, several other parameters must be considered when sizing PV panels, including as wiring loss, soiling factors, battery Coulombic efficiency, and the temperature factor. These components ensure that the system is built to work optimally in real-world situations, especially in a place like Bangladesh.

Moreover, in battery design, it is crucial to account for autonomy during intervals of insufficient sunlight. This approach adheres to a normal practice of designing for three consecutive days without sunlight, ensuring that the battery can sustain the system during prolonged overcast or rainy conditions, which are common in Bangladesh. This will provide a dependable electricity supply during load-shedding or other interruptions.

The standard financial metrics incorporated in the research, including the energy cost escalation rate, inflation rate, discount rate, and project lifespan, are derived from local market conditions and prevailing financial trends. These assumptions are crucial for assessing the project's financial viability. The unit pricing for construction items is obtained from local market prices and online sources, which are utilized to estimate development expenses. The model autonomously refreshes essential financial metrics, including Net Present Value (NPV) and Internal Rate of Return (IRR), in accordance with the input parameters, facilitating real-time modifications and representing the latest data.

3.2 PV array sizing worksheet

To calculate the required solar panel capacity for a daily electricity consumption during the winter season, the total daily electricity consumption was first assessed. The average total daily electricity consumption is 66.465 kWh/day, based on yearly data. During the winter season, the daily electricity consumption is assumed to be 10.41 kWh/day for 6 hours of the day. The remaining daily consumption, for the rest of the day, is considered to be 2.46 kWh/day, which was calculated by dividing 1,462.23 kWh/month by 22 days and 24 hours. Thus, the total daily electricity consumption during the winter season is 12.87 kWh/day, combining the 10.41 kWh/day during peak hours and the 2.46 kWh/day for the remaining period.

Next, the daily solar electricity generation is estimated at 0.75 kWh/m²/day, based on an average solar irradiance of 5 kWh/m²/day and a solar panel efficiency of 15%. To meet the high school's electricity needs, the required solar panel area is calculated by dividing the total daily electricity consumption (12.87 kWh/day) by the daily solar electricity generation (0.75 kWh/m²/day). This results in an area of 17.16 m² of solar panels. To determine the required solar panel system's capacity in watts, the area is multiplied by the solar irradiance per square meter (1,000 W/m²), and then divided by the number of sunlight hours per day (5 hours). The resulting required capacity is 3,432 Wp. Therefore, a solar panel system with a capacity of at least 3,432 Wp is necessary to cover the high school's electricity consumption during the winter season.

To determine the number of solar panels required for the system, it is essential to consider the specifications of the selected solar panels. Each solar panel has a maximum power output of 300 watts, a voltage rating of 36 volts, and a current rating of 8.33 amperes. The daily energy requirement is 1,462.23 kWh, which, when divided by 30 days, gives a daily consumption of 48.74 kWh. To calculate the total power required per hour, we divide the daily power requirement by 24 hours, resulting in 2.03 kW of power required per hour. Each solar panel generates 1.5 kWh per day, based on an average of 5 hours of sunlight and a power output of 300 W. To meet the daily power requirement of 2.03 kW, calculated the number of panels needed in parallel: 2.03 kW divided by 1.5 kWh per panel results in 1.35 panels, which we rounded up to 2 panels. After that, determine the number of solar panels to be connected in series. Since the panel voltage is 36 V and the current rating is 8.33 A, we can connect up to 8 panels in series without exceeding the maximum current rating of the charge controller. Therefore, to meet the power requirement, we need 16 panels in total, arranged in 2 parallel strings of 8 panels each, with each string consisting of 8 panels connected in series. This configuration ensures that the system meets the required daily power generation while adhering to the technical specifications of the panels.

3.3 Controller sizing worksheet

To calculate the parameters of the charge controller, it is essential to determine the maximum current and voltage of the solar panel array, as well as the battery bank voltage and capacity. From the previous calculations, we know that the solar panel array will have a maximum current of 37.44 A and a maximum voltage of 120 V. We also know that the battery bank voltage is 24 V and its capacity is 400 Ah. To properly size the charge controller, we need to ensure that it can handle the maximum current and voltage of the solar panel array and that it can properly charge the battery bank. The first step is to calculate the maximum power of the solar panel array, which is simply the product of the maximum current and voltage.

$$P_{\max} = V_{\max} = 37.44 \text{ A} \times 120 \text{ V} = 4,492.8 \text{ W}. \quad (16)$$

Subsequently, it is necessary to determine the maximum current that the charge controller is capable of handling, which is equal to the maximum current of the solar panel array $I_{cc} = I_{\max} = 37.44 \text{ A}$. To properly charge the battery bank, we need to ensure that the charge controller can deliver a current equal to at least 5% of the battery capacity, or 20 A in this case. Since the charge controller needs to handle a higher current than this, we can choose a charge controller with a maximum charging current of 60 A to ensure that it can handle the load.

Finally, it is essential to ensure that the charge controller is capable of handling the maximum voltage of the solar panel array. Since the array has a maximum voltage of 120 V, we can choose a charge controller with a maximum input voltage of at least 150 V to provide a safety margin. Therefore, the Maximum charging current is 60 A and the Maximum input voltage is 150 V.

3.4 Battery sizing worksheet

The daily energy consumption, autonomy period, and battery capacity requirements for the off-grid solar system were calculated. The daily energy consumption was found to be 66.465 kWh (or 66,465 Wh). To ensure a reliable energy supply without recharging, the system's autonomy period was set to 3 days, a typical value for off-grid solar systems. Therefore, the total energy consumption during the autonomy period was calculated by multiplying the daily energy consumption by the number of autonomy days: $66.465 \text{ kWh} \times 3 = 199.395 \text{ kWh}$.

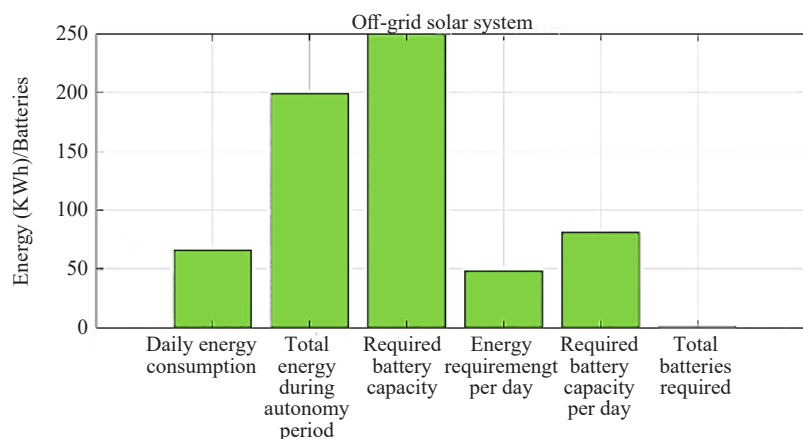


Figure 3. Energy and battery requirements for an off-grid solar system

Next, the required battery capacity was determined by accounting for battery efficiency, which was assumed to be 80% for a Ni-Cd battery. The formula used to calculate the required battery capacity was as follows: Required battery capacity = Total energy consumption during autonomy period/Battery efficiency. This gave a required capacity of $199.395 \text{ kWh}/0.8 = 249.244 \text{ kWh}$. To calculate the number of batteries required, the energy requirement for one day

was first calculated by dividing the monthly energy requirement (1,462.23 kWh) by 30 days, yielding a daily energy requirement of 48.74 kWh. The battery capacity needed to meet this requirement was then calculated by dividing the energy requirement by the battery voltage, assuming a 50% Depth of Discharge (DOD). Using the formula, Battery capacity = Energy requirement/(Battery voltage × DOD), found the battery capacity to be 48.74 kWh/(1.2 V × 0.5) = 81.23 kWh.

Figure 3 illustrates the energy and battery requirements for an off-grid solar system. The chart presents key parameters such as daily energy consumption, total energy needed during the autonomy period, required battery capacity, daily energy requirement, required battery capacity per day, and the total number of batteries required. The data highlights the importance of accurately estimating energy needs to ensure sufficient battery storage and system reliability for off-grid applications.

Finally, the total number of batteries required was determined by dividing the battery capacity by the rated capacity of a single battery. The rated capacity of each battery was assumed to be 1.2 V × 100 Ah, and the number of batteries required was calculated as follows: Total number of batteries = Battery capacity/Single battery capacity = 81.23 kWh/(1.2 V × 100 Ah) = 42 batteries. Therefore, a total of 42 batteries is needed to meet the energy demands of the system.

3.5 Inverter and system wire sizing worksheet

The design of the system’s wiring and components was carefully calculated to ensure optimal performance. The maximum current in the system, which occurs when the battery is charging, was determined as the sum of the current from the solar panels and the current from the AC charger, yielding a total maximum current of 16.64 A. Assuming a maximum allowable voltage drop of 3%, the maximum voltage drop was calculated to be 1.44 V.

The following formula is used to calculate the wire gauge.

$$\text{Wire gauge} = \frac{2 \times (\text{Length} \times I_{\max} \times 0.017)}{V_{\max \text{ drop}}} \quad (17)$$

For the wiring from the solar panels to the charge controller, with a wire length of 10 meters, and 5 meters from the charge controller to the battery, the required wire gauge was found to be 4.1 American Wire Gauge (AWG). For the wiring from the charge controller to the battery, with a wire length of 5 meters, the required wire gauge was calculated to be 5.9 AWG. Regarding the battery bank, a total voltage of 48 V and a capacity of 400 Ah were required. Given that Ni-Cd batteries have a nominal voltage of 1.2 V, the total number of batteries required was 40. To preserve battery life, the depth of discharge was limited to 50%, reducing the usable battery capacity to 200 Ah. The charge controller’s maximum charge current was set to 10% of the battery’s rated capacity, resulting in a maximum charge current of 40 A. Finally, to convert the DC power from the battery to AC power for the loads, an inverter was selected with a continuous output of at least 4 kW and a peak output of at least 8 kW to handle any transient loads.

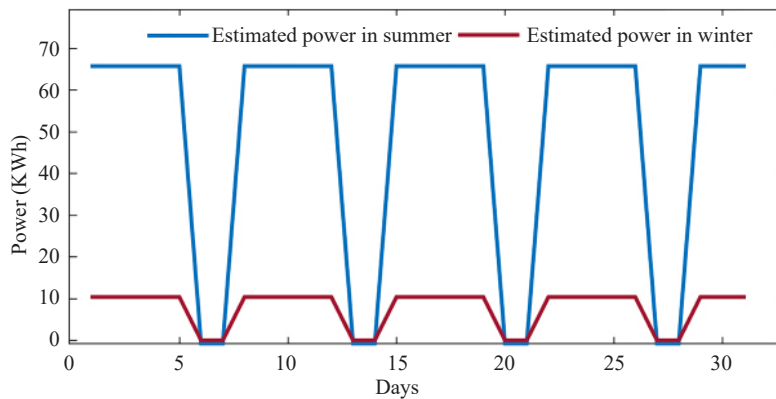


Figure 4. Average power consumption summer vs. winter

Figure 4 illustrates the estimated power consumption over 30 days for both summer and winter seasons. The y-axis displays the power in kilowatt-hours (kWh), and the x-axis shows the days of the month. There are two different power trends displayed. The red line represents the estimated power consumption in the winter, which is continuously lower with fewer fluctuations, and the blue line represents the estimated power consumption in the summer, which varies between higher peaks and lower troughs. According to the figure, power demand fluctuates more in the summer than it does in the winter, possibly as a result of seasonal variations in energy consumption. The ratio of global extraterrestrial irradiance on a horizontal plane is known as the clearness index. It is a time-varying binary variable that takes on values of zero or one. When the sun is obscured by clouds, the clearness index is low, and when it is not, the clearness index is high. Although the clearness index is high in November, the solar irradiance is low due to the winter season.

Figure 5 shows the monthly data on solar power generation and consumption. The x-axis displays the months of the year, and the y-axis displays the energy in kilowatt-hours (kWh). The purple bars represent the average amount of electricity generated by the solar system each month, and the yellow bars represent the average amount of power used. The graph illustrates the seasonal differences in solar power generation and consumption, with the former occurring more frequently during the warmer months, particularly spring and summer, than the latter. This comparison provides a complete picture of the balance between energy production and consumption for the year.

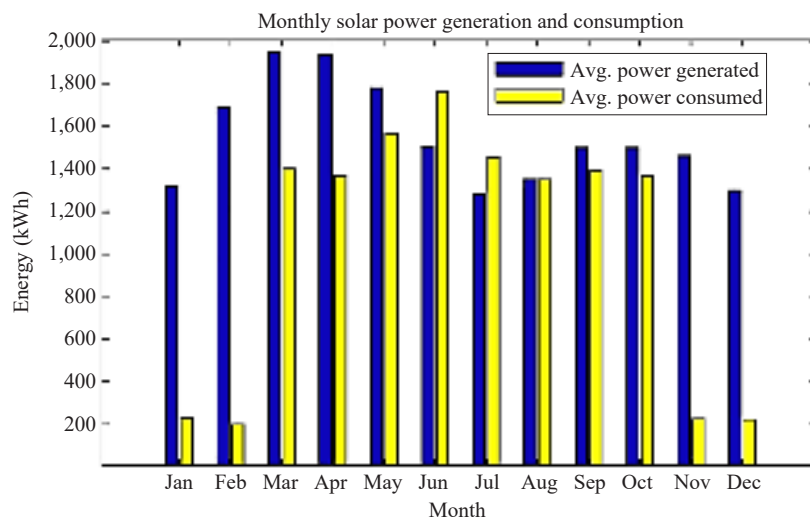


Figure 5. Power generated vs. consumed in Dhaka High School

In Bangladesh, the winter season lasts from November to February, and the nights are longer than the days. The sky is frequently foggy in the morning, and foggy conditions can persist for several consecutive days. The summer season, on the other hand, lasts from April to June, although in March, the weather becomes hotter and the sky becomes cloudy. Solar irradiance is also relatively high in March, April, and May.

3.6 Payback period

The Payback Period (PP) measures how long it takes to recover the initial investment of a standalone PV system. It is calculated using the formula $PP = I / (R - E)$, where I is the initial investment, R is the annual revenue from energy savings, and E is the annual maintenance expense. For a project to be considered viable, the PP must be shorter than the system's operational life (N years). Although this method is simple and highlights quicker returns as more favorable, it has significant limitations. It overlooks long-term costs such as battery replacements and does not account for the time value of money or inflation, thus providing an incomplete financial assessment.

3.7 Economic analysis of the PV system

The local cost values for the PV system are calculated using a combination of market surveys, vendor quotations, and estimates, reflecting current pricing for major components such as solar panels, inverters, and batteries. These prices were acquired from local suppliers and online sources to verify that they truly reflect market realities in Bangladesh. Battery replacement, panel cleaning, and inverter maintenance are all costs associated with Operation and Maintenance (O & M), which are required to ensure system efficiency and dependability. Battery replacement is normally required every 5-7 years, while frequent cleaning and inverter checks are required to ensure peak performance. Finally, the paper compares the proposed system to other similar case studies from Bangladeshi schools and institutions, demonstrating that the projected payback periods, Return on Investment (ROI), and energy costs are consistent with those of other successfully implemented PV systems, thereby proving its feasibility in this context.

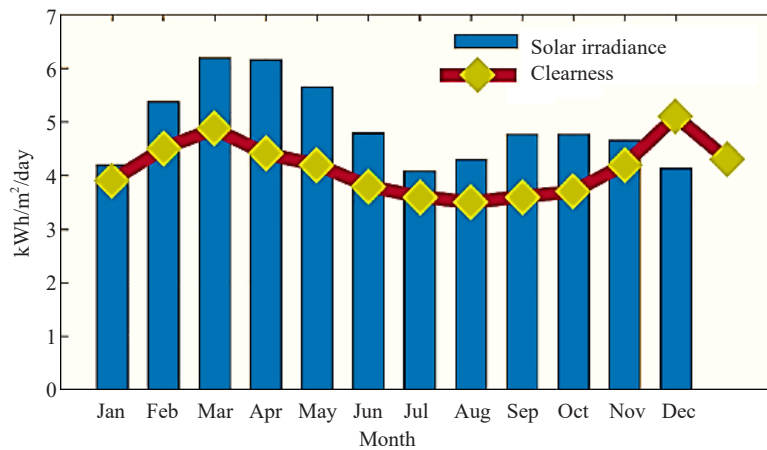


Figure 6. Solar irradiance levels and clearness index

Table 3. Production costs in the present economic analysis

Initial cost	USD	Taka
Photovoltaic (3,432 Wp)	4,900	539,000
Module support structure	250	27,500
Other equipment	300	33,000
Storage battery	8,400	924,000
Transportation cost	200	22,000
Training and commissioning cost	150	16,500
Charge controller	150	16,500
Contingencies	200	22,000
Total initial investment	14,550	1,600,500
O & M cost/year	50	5,500
Controller replacement after 10 years	150	16,500
Battery replacement after 5 years	8,000	880,000

The clearness index and the monthly variation in sun irradiance levels are displayed in Figure 6. The clearness index is shown by the red line with yellow diamond markers, and the solar irradiance, expressed in kWh/m²/day, is represented by the blue bars. There is a clear seasonal pattern to solar irradiance, with higher values recorded during the spring and summer. The clearness index, on the other hand, shows an upward tendency from the start of the year and peaks in the latter months. This chart illustrates how air conditions and solar irradiation vary throughout the year. The detailed costs of different devices in the PV power system are presented in Table 3.

Solar generation is at its peak in March and April, followed by a gradual decline through the year, while consumption remains relatively stable throughout the months. This analysis can guide optimization strategies for energy management based on solar power availability and demand fluctuations.

Figure 7 illustrates the monthly comparison between solar power generation and average power consumption, with the x-axis representing the months of the year and the y-axis depicting energy in kilowatt-hours (kWh). The blue bars correspond to solar power generation, while the red circles indicate the average power consumption. Solar generation is at its peak in March and April, followed by a gradual decline through the year, while consumption remains relatively stable throughout the months.

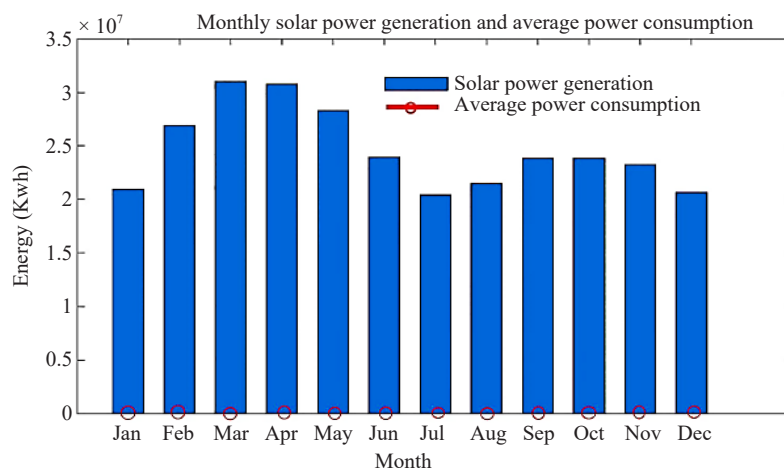


Figure 7. Average consumption vs. monthly solar generation

Table 4. Comparison between Dhaka High School & grid tied system

Aspect	Dhaka High School (4.8 kWp)	5 kW grid-tied system	5 kW off-grid system
Capacity	4.8 kWp	5 kW	5 kW
Annual energy output	17,547 kWh/year	7,000-8,000 kWh/year	7,000-8,000 kWh/year
Initial cost (USD)	\$ 14,550 (without subsidy)	\$ 6,000-\$ 10,000	\$ 8,000-\$ 15,000
Cost with subsidy (USD)	\$ 11,640	N/A	N/A
Cost per kWh	\$ 0.829/kWh	\$ 0.75-\$ 1.25/kWh	\$ 1.00-\$ 1.50/kWh
Grid connection	No grid connection needed	Requires grid connection	No grid connection
Additional components	Inverter and mounting	Inverter and wiring	Inverter, battery, wiring
Installation complexity	Moderate	Relatively simple	High due to battery integration

Table 4 shows the comparison between the Dhaka High School & grid tied system. The photovoltaic system at

Dhaka High School delivers a markedly superior yearly energy production compared to standard 5 kW systems, owing to its optimal design tailored to the school’s specific energy requirements. The cost per kWh is competitive at USD \$ 0.829/kWh without subsidy, decreasing to USD \$ 0.66/kWh with a 20% subsidy, which is advantageous compared to grid-tied 5 kW systems. Nonetheless, off-grid solutions generally incur elevated prices per kWh owing to the increased intricacy of batteries and storage elements. In terms of installation, grid-tied 5 kW systems exhibit reduced starting costs and facilitate easier installation when a grid connection is accessible. Conversely, off-grid systems are costlier and more intricate, resulting in elevated installation expenses and increased cost per kilowatt-hour. The Dhaka High School system is more efficient and cost-effective owing to its customized design.

Implementing the proposed rooftop Photovoltaic (PV) power generation system at Dhaka High School may be financially feasible, although it could encounter practical challenges. A significant issue is the substantial initial expenditure required for the procurement and installation of components such as solar panels, inverters, and batteries. The requirement for upfront funding may provide a significant challenge, particularly for financially constrained schools. The system’s efficacy is significantly influenced by factors such as shadowing, seasonal variations in sun irradiation, and dust accumulation, which can diminish its overall efficiency and energy production. In Bangladesh, solar power generation may be further constrained during the monsoon season and overcast weather, potentially resulting in energy shortages. The system’s longevity is contingent upon its maintenance and reliability. Photovoltaic systems require minimal maintenance; nonetheless, components such as batteries and inverters necessitate periodic inspection and replacement. Batteries often require replacement every 5 to 7 years, thereby incurring additional expenses. The system’s battery storage and inverter capacity dictate its ability to operate during power outages or extended durations of insufficient sunlight. This capacity may not consistently suffice to maintain a continuous power supply. Furthermore, if the system is linked to the grid, its integration may pose challenges from both technical and regulatory perspectives. To maintain grid stability and synchronization with the national grid, significant modifications to the infrastructure may be required, resulting in increased complexity and costs.

3.8 Summary of calculations and key parameters

Dhaka High School consumes 66.465 kWh of energy daily, with 12.87 kWh/day utilized during the winter, encompassing both peak and non-peak hours. The system requires 249.244 kWh of battery power to operate for three days. This indicates a requirement of 42 batteries, each possessing a voltage of 1.2 V and a capacity of 100 Ah. A photovoltaic system with a capacity of 3,432 Wp is required during the winter season. To fulfill the energy requirements, 16 solar panels (300 W each) must be put in two parallel arrays of 8 panels each in Table 5.

Table 5. Summary of daily load, battery sizing, and PV array sizing

Parameter	Value	Calculation method
Total daily consumption (Annual)	66.465 kWh/day	Based on yearly consumption data.
Winter consumption (Peak)	10.41 kWh/day (6 hours)	Estimated for the peak hours in winter season.
Winter consumption (Non-peak)	2.46 kWh/day (rest of day)	Average daily consumption during non-peak hours.
Total winter consumption	12.87 kWh/day	Sum of peak and non-peak consumption in winter.
Required battery capacity	249.244 kWh	Total energy during autonomy period (3 days)/battery efficiency.
Number of batteries	42	Based on required battery capacity and specifications (1.2 V × 100 Ah).
PV system capacity	3,432 Wp	Required capacity for winter season, based on energy consumption and panel output efficiency (15%).
Panel configuration	16 panels (8 in series × 2 parallel)	Based on the daily consumption, panel capacity (300 W), and sunlight hours per day (5 hours).

3.9 Effect of discount rate

The project's economic viability is influenced by the discount rate; when the rate exceeds 8.5%, the NPV turns negative, making the project unfeasible. The total project cost is \$ 14,550, and the electricity production cost is \$ 0.829 per kilowatt-hour. With a 20% subsidy, the overall investment decreases to \$ 11,640, resulting in a reduction of the power production cost to \$ 0.66 per kilowatt-hour, as shown in the Figure 8.

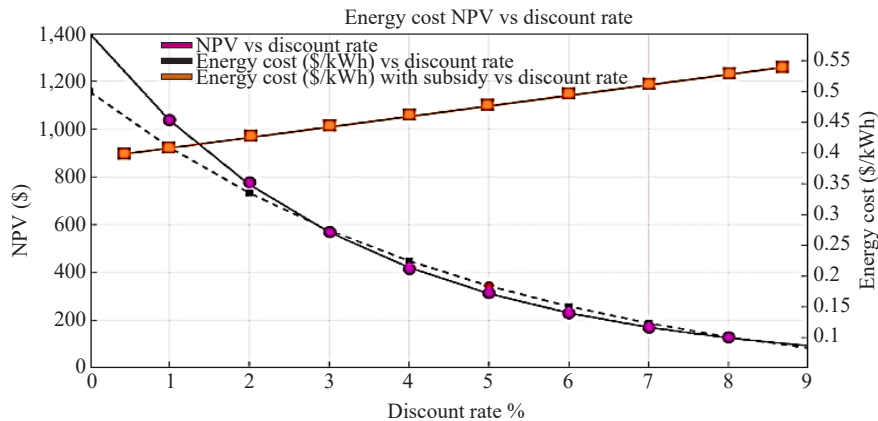


Figure 8. Effect of discount on NPV and energy production cost

4. Conclusion

The design and cost analysis of the PV system at Dhaka High School indicates that solar energy could assist Bangladesh in addressing its energy challenges, particularly in educational institutions that frequently experience power outages. This study demonstrates the feasibility of utilizing renewable energy to satisfy the school's energy requirements. It also serves as a model for other schools nationwide. The photovoltaic system comprises a 4.8 kWp monocrystalline silicon array, sufficient to meet the school's annual electricity requirements. This indicates that the school is less dependent on conventional fossil sources for energy. The research indicates that such technologies are beneficial for the economy over the long term, with a payback period of 8.5 years and a ROI of 86%. The findings indicate that despite the substantial initial investment in photovoltaic systems, the resultant savings and environmental advantages render them a viable choice for energy sustainability in Bangladesh. Future studies may explore the integration of rooftop solar systems with grid-connected or hybrid systems, thereby improving flexibility and energy security. Hybrid systems utilizing solar energy in conjunction with battery storage or backup generators can enhance power supply stability during periods of insufficient sunlight or elevated demand. Further investigation into the integration of these solutions into the grid and the establishment of regulatory frameworks could facilitate their application in diverse sectors, hence promoting the adoption of renewable energy among the populace in Bangladesh.

CRedit authorship contribution statement

Mingbo Niu: conceptualization, resources, methodology, writing-original draft. Razikul Hasan Milon: investigation, formal analysis, validation, writing-original draft. Md Imran Hossain: writing-review & editing. Guoxing Li: funding acquisition, data curation, supervision, writing-review & editing, project administration.

Acknowledgements

Financial support from Xi'an Science and Technology Plan Projects (24GXFW0095) is gratefully appreciated.

Conflicts of interest

The authors declare no competing financial interest.

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