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# Current Scenario of Solar Energy Applications in Bangladesh: Techno-Economic Perspective, Policy Implementation, and Possibility of the Integration of Artificial Intelligence

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**Abstract:** Bangladesh is blessed with abundant solar resources. Solar power is considered the most desirable energy source to mitigate the high energy demand of this densely populated country. Although various articles deal with solar energy applications in Bangladesh, no detailed review can be found in the literature. Therefore, in this study, we report on the current scenario of renewable energy in Bangladesh and the most significant potential of solar energy's contribution among multiple renewable energy resources in mitigating energy demand. One main objective of this analysis was to outline the overall view of solar energy applications in Bangladesh to date, as well as the ongoing development of such projects. The technical and theoretical solar energy potential and the technologies available to harvest solar energy were also investigated. A detailed techno-economic design of solar power applications for the garment industry was also simulated to determine the potential of solar energy for this specific scenario. Additionally, renewable energy policies applied in Bangladesh to date are discussed comprehensively, with an emphasis on various ongoing projects undertaken by the government. Moreover, we elaborate global insight into solar power applications and compare Bangladesh's current solar power scenario with that of other regions worldwide. Furthermore, the potential of artificial intelligence to accelerate solar energy enhancement is delineated comprehensively. Therefore, in this study, we determined the national scenarios of solar power implementation in Bangladesh and projected the most promising approaches for large-scale solar energy applications using artificial intelligence approaches.

**Keywords:** solar energy; Bangladesh; techno-economic analysis; artificial intelligence



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## 1. Introduction

Energy is the ultimate indicator to evaluate a nation economically and socially [1–3]. To eradicate poverty or to bring about sustainable development for future generations, it is necessary to ensure the availability of energy resources at all stages of society [4,5]. Global energy demand has been rapidly increasing, putting a strain on existing resources such as coal and oil. Global energy consumption decreased by 4.5% in 2020 before increasing by 5% in 2021. The use of energy in Russia rose by 9% in 2021, followed by 5.2% in China, 4.7% in India, 4.7% in the United States, and 4.5% in the European Union (EU) [6]. Demand for oil products and natural gas also showed growth in 2021. Due to the easing of lockdowns and increase in mobility, demand for oil products increased by 5% in 2021, and global natural gas consumption increased by 4.8% in the same year [6]. The United States and China were the most significant contributors to this increase in oil consumption. Because of the economic recovery and high gas prices in Western countries, coal consumption has also increased significantly. Global coal consumption increased by 5.7%, and the United States was the leading contributor to this sector. These resources have been extensively used to produce electricity [7]. According to the IEA, 60% of electricity produced globally is generated using fossil fuels [8]. Fossil fuels release a large amount of $CO_2$ and other pollutants into the atmosphere. Industrial activities and fossil fuel combustion for transportation or electricity generation have also released a large amount of $CO_2$, contributing to an increase in the greenhouse effect. These greenhouse gas emissions can increase the Earth's temperature and lead to climate instability [9], with dramatic consequences for the future of humanity, especially in underdeveloped rural areas, where people are affected by droughts and floods [10,11]. The current energy crisis, the unavailability of fossil fuels, and greenhouse gas emissions from these limited resources have made people think about finding suitable alternatives. Over the last decade, the enthusiasm for utilization of renewable energy has been renewed. The term 'renewable energy' is applied to all energy sources that will not be exhausted or change significantly in millions of years [12]. In 2021, the total amount of renewable electricity produced exceeded 8000 TWh, an all-time high, which is 500 TWh higher than in 2020 [8]. Moreover, most of this electricity is produced by solar and wind resources. Solar power provided 5% of the world's electricity by the end of 2021. Table 1 shows the leading countries in terms of production of solar power in 2021 [13].

**Table 1.** Solar energy capacity by the leading solar-power-implementing countries [13].

| Country | Capacity (MW) |
|---|---|
| China | 306,973 |
| United States | 95,209 |
| Japan | 74,191 |
| Germany | 58,461 |
| India | 49,684 |
| Italy | 22,698 |
| Australia | 19,076 |
| South Korea | 18,161 |
| Vietnam | 16,660 |
| Spain | 15,952 |

In Bangladesh, primary energy consumption was reported to be 1.57 quadrillion British thermal units (Btu) in 2019. Bangladesh's primary energy consumption increased significantly between 2000 and 2019, from 0.51 to 1.57 quadrillion Btu, with an annual rate of increase that peaked in 2015 at 10.65% before declining to 0.86% in 2019 [14]. Natural gas demand in Bangladesh has also increased in the power generation sector, and almost 65% of the total production is supplied to power plants [15], placing massive pressure on natural gas reserves. The current natural gas reserve is 7.25 trillion cubic feet (Tcf), which is expected to be depleted in a decade [16]. Additionally, there is an immense gap between demand and generation. In 2019, the maximum production was 12,893 MW, while the demand was 14,796 MW [17]. This large gap between demand and production is a barrier to the country's economic development. The government of Bangladesh has taken a few initiatives to mitigate the country's dependency on petroleum products and adopt sustainable power sources. Several private and public organizations are working hand in hand to generate electricity from renewable sources.

Due to the favorable geographical location and direct sunlight year-round, research on solar energy implementation in Bangladesh is highly lucrative. Different power industries have developed efficient solar panels and commercialized them on a pilot or large scale in Bangladesh. Besides experimental and case studies on solar panels [18–20], several prospective/review studies have reported on solar energy targets and constraints. A previous study on the solar home system in Bangladesh reported on the general prospective and feasibility of solar panel installation for home applications, as well as possible constraints [21]. Another study presented a general survey of solar energy projects and targets for upcoming projects [22]. A review study on solar energy implementation presented the solar energy scenario, investigating different projects and their feasibility [23]. Although a general perspective on solar energy implementation and feasibility in Bangladesh has been explored, no review study has been conducted on the correlation of past and current scenarios of solar energy, comprehensive mapping, in-depth techno-economic perspectives, and integration with niche technology implementing artificial intelligence (AI) in the near future. Therefore, the aim of this review study is to showcase the progress and latest developments with respect to solar energy implementation by various projects run by government/non-government organizations in Bangladesh, as well as a detailed techno-economic analysis and investigation of the pioneering concept of AI integration with solar systems to elevate solar panel technology. The novelty of this study lies on the in-depth analysis of the techno-economic prospective of solar energy implementation based on the current energy scenario in Bangladesh and integration of Al technology in the overall process to elevate technological advancement in this sector.

### 1.1. Energy Scenario of Bangladesh

An electrical power system has three major components, i.e., generation, transmission, and distribution. In the generation subsector, electricity is produced from primary fuel. The transmission network carries power produced by the generation subsector to the major load centers, and finally, the distribution system interfaces with the end clients, for example, retail clients. As an economically viable utility-scale electricity storage system is yet to be developed, demand created in the distribution system must be met instantaneously by producing power at power generation stations and transmitted through the transmission network, which bridges generation and distribution. The journey of modern power utilities in Bangladesh started in 1962 with the creation of WAPDA and the installation of the 80 MW Karnafuli Hydropower plant. Established on 1 May 1972, BPDB began with a production capacity of 200 MW. Since then, the generation capacity has expanded, and in 2022, the total installed capacity (by fuel type) increased to 22,612 MW (as of August 2022), although the maximum power generation was only 13,525 MW (up to January 2022) [24]. Of the total net generation, the private sector generated the most energy (47.39%), followed by the public sector (40.02%) and joint venture (4.10%). The remaining energy (8.50%) is imported from foreign countries [24]. Figure 1 depicts the installed capacity by fuel type [25]. As shown in Figure 1, it is clear that Bangladesh is heavily dependent on natural gas. As previously stated, 65% of natural gas in Bangladesh is used to generate electricity. However, this amount was reduced to 42% in 2022 due to the gas shortage, as presented in Figure 2 [26].

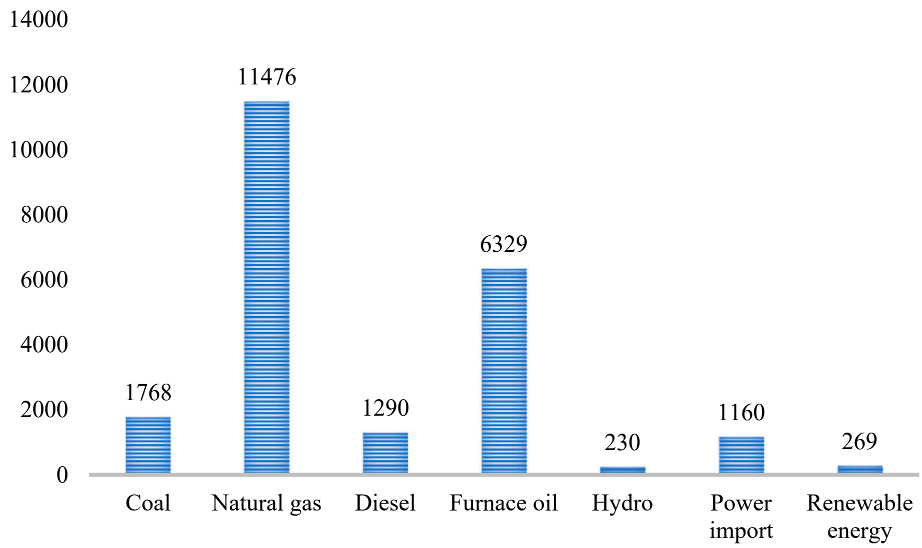


**Figure 1.** Electricity generation scenario of Bangladesh in 2022 (MW) [25].

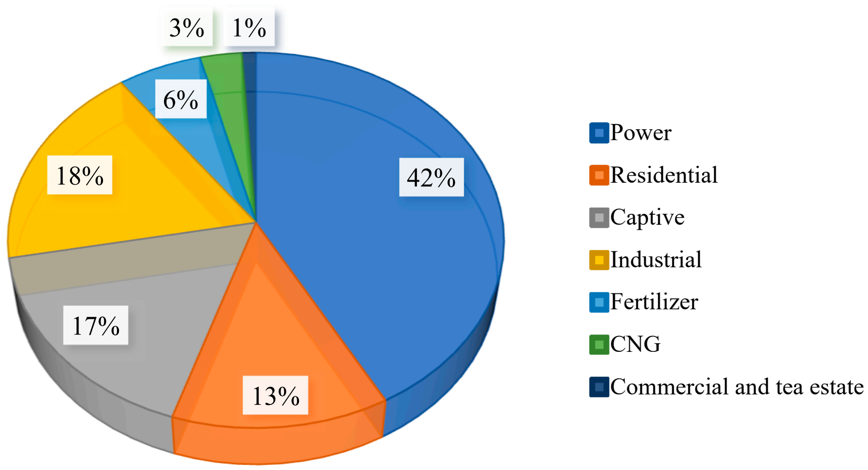


**Figure 2.** Employment of natural gas in various segments of Bangladesh [26].

Bangladesh's power division has been affected by gas accessibility issues and the push for strong economic growth. There is currently a gap due to fuel shortages, resulting in frequent power cuts [27]. Furthermore, faults in the transmission system also act as a barrier to supplying energy to people [28]. Total system losses in transmission and distribution of electricity were reduced to 9.54% in 2021–22 (up to January 2022) from 14.73% in 2010–11 [24]. Although much improvement has been made in reducing this loss, there is still much room for improvement. Energy demand is also increasing at an alarming rate in Bangladesh. The energy demand in Bangladesh is expected to reach 33,708 MW by 2030 [25]. To overcome this challenge, Bangladesh is now investing in renewable energy.

### *1.2. Current Status of Renewable Energy Implementation in Bangladesh*

Bangladesh has been blessed with abundant biomass resources. Biomass resources are not only used for cooking purposes but also for electricity generation. Solar energy also represents an attractive solution to meet energy needs due to the country's geographical location, which enables the proper utilization of solar resources. Therefore, solar energy has become popular in off-grid and hill tract areas. Like solar and biomass, wind and hydropower are not widespread in the country. Flat surfaces and a lack of available (water) heads have restricted hydropower development in this country [29]. Owing to inadequate information, wind power cannot be assessed successfully [30]. Table 2 shows the present status of sustainable power capacity from various sources in Bangladesh.

**Table 2.** Current status of installed renewable energy capacity (MW) from different sources in Bangladesh [31].

| Technology | Off-Grid (MW) | On-Grid (MW) | Total (MW) |
|---|---|---|---|
| Solar | 356.35 | 359.16 | 715.51 |
| Wind | 2 | 0.9 | 2.9 |
| Hydro | - | 230 | 230 |
| Biogas to Electricity | 0.69 | - | 0.69 |
| Biomass to Electricity | 0.40 | - | 0.40 |
| Total | 359.44 | 590.06 | 949.5 |

Bangladesh was not able to accomplish the goal of "5% of the power from sustainable sources" by 2015, as the share of non-conventional sources of power generation was 3.5%. The availability of natural gas and its low electricity cost is the main reason for this. However, the administration is trying very hard to accomplish the next goal of "10% of power generation from inexhaustible sources by 2020" [32]. To accomplish this objective, the government of Bangladesh (GoB) is searching for alternatives that could be ideal as sustainable power sources. The government recently initiated the "500 MW Solar Power Mission" to advance the utilization of sustainable power sources to fulfill the expanding power needs presented in Tables 3 and 4 [33]. The government has also aimed to produce 4190 MW of electricity from different sustainable energy sources, as shown in Table 5 [22]. Tables 3 and 4 show the expected solar projects completed by the private and public sectors. Table 5 lists the government's yearly goals to produce electricity from different renewable energy sources.

**Table 3.** Expected projects to be implemented by the private sector as part of the 500 MW solar program [33].

| Project | Capacity (MW) |
|---|---|
| Solar Mini Grid | 25 |
| Solar Irrigation Pump | 150 |
| Solar Rooftop (residential, commercial, and industrial) | 30 |
| Solar Park | 135 |
| Total | 340 MW |

**Table 4.** Expected projects to be implemented by the public sector as part of the 500 MW solar program [33].

| Project | Capacity (MW) |
|---|---|
| Solar electrification at religious establishments | 12 |
| Solar electrification in health centers | 50 |
| Solar electrification at union e-centers | 7 |
| Solar electrification in remote educational institutions | 40 |
| Solar electrification at remote railway stations | 10 |
| Solar PV systems in government and semi-government offices | 41 |
| Total | 160 |

**Table 5.** Government's yearly plan to generate electricity from renewable energy [22].

| Year | Solar | Wind | Hydro | Biomass | Biogas | Others (Tidal, Wave) | Total |
|---|---|---|---|---|---|---|---|
| Until 2018 | 350 | 2.9 | 230 | 0 | 1.08 | 0 | 583.98 |
| 2019 | 84 | 0 | 0 | 0 | 1 | 0 | 85 |
| 2020 | 100 | 38 | 0 | 0 | 2 | 0 | 140 |
| 2021 | 120 | 80 | 0 | 15 | 3 | 0 | 218 |
| 2022 | 150 | 120 | 0 | 15 | 4 | 0 | 289 |
| 2023 | 165 | 170 | 0 | 15 | 4 | 0 | 354 |
| 2024 | 165 | 170 | 0 | 15 | 4 | 0 | 354 |
| 2025 | 165 | 170 | 0 | 15 | 4 | 2 | 356 |
| 2026 | 165 | 170 | 0 | 15 | 4 | 4 | 358 |
| 2027 | 165 | 170 | 0 | 15 | 4 | 6 | 360 |
| 2028 | 165 | 170 | 0 | 15 | 4 | 8 | 362 |
| 2029 | 165 | 170 | 0 | 15 | 5 | 10 | 365 |
| 2030 | 165 | 170 | 0 | 15 | 5 | 10 | 365 |
| Total | 2124 | 1600.9 | 230 | 150 | 45.08 | 40 | 4189.98 |

## 2. Methodology

A methodology built on an extensive literature review across multiple data sources was employed to find helpful content. Two main types of content were searched to prepare this review study: (i) websites and databases, such as Scopus, Web of Science, PubMed, IEEE Explore, and ResearchGate, were accessed for the literature search; and (ii) data gathered from numerous technical papers and documentation on Bangladesh's energy scenarios, policies, and guidelines served as the second information source. Based on the collected data and information related to solar energy implementation, in this study, we determined past and current energy scenarios, as well as the current status of solar energy implementation for various applications, conducted a techno-economic analysis, and verified the feasibility of the integration of AI in existing solar systems to upgrade the overall solar technology.

### *2.1. Techno-Economic Analysis*

In this study, we present a techno-economic analysis of a garment building in Dhaka, Bangladesh, to demonstrate the economic benefit of solar energy. Annual energy consumption data are collected and presented in Figure 3 [34]. The annual energy demand of the garment building is 3596 kWh/day.

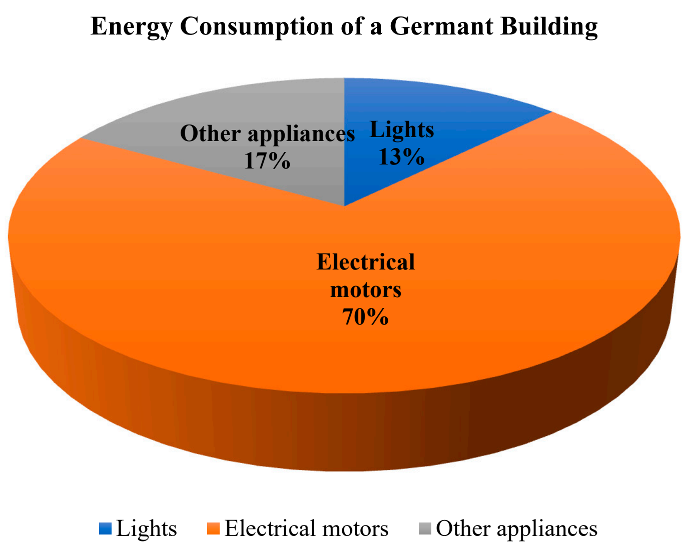


**Figure 3.** Energy consumption data of a garment building in Dhaka [34].

#### 2.1.1. Panel Generation Factor (PGF)

PGF is a pivotal element in determining the size of the PV power plants based on the total peak rating, differing depending on the location [35,36]. PGF can be calculated as described in [37]. For Dhaka, the average daily solar radiation is 4.65 kWh/m$^2$. According to the equation presented in [37], the value of PGF is 4.65.

#### 2.1.2. Total Energy Required

The total energy required from PV modules will is the daily energy demand of the garment building plus system losses, which are generally considered to be 30%. The total energy is calculated by multiplying energy demand by the system loss compensation factor. Accordingly, the energy demand of the garment factory is 4674.905 kWh/day.

#### 2.1.3. Watt Peak Rating for PV Modules

The total watt peak rating for PV modules is calculated to identify system sizing, which depends on the energy required from modules and the panel generation factor [38]. It can be determined by dividing the energy required by modules by the PGF.

#### 2.1.4. Number of Modules

The total number of modules required for the proposed plant depends on the peak rating of the modules, which is based on temperature variations at the location, and can be calculated by dividing the total watt peak rating by the PV module peak-rated output. PV module specifications are presented in Table 6.

**Table 6.** Characteristics of PV modules [36].

| Parameter | Value |
|---|---|
| Maximum Power | 215 Watt |
| Maximum Power Voltage | 42 Volt |
| Maximum Power Current | 5.13 Amp |
| Open-Circuit Voltage | 51.6 Volt |
| Short-Circuit Current | 5.61 Amp |

#### 2.1.5. Inverter Rating

The size of the inverter needed for the plant depends upon the peak watt requirement, which is 1005 kW in the case of the considered garment factory. The inverter must be large enough to handle the peak requirement in watts. The inverter should be able to handle 25–30% more than the total watt requirement [39] and can be determined according to Equation (1).

$$\text{Inverter size} = \text{Peak watt requirement} \times 1.3 \quad (1)$$

#### 2.1.6. Inverter Sizing

A cost-effective Solectria PVI 82 kW Grid Tied Inverter 480 VAC PVI-82 kW (Solectria) with a cost of USD 36,306 was selected for the system, with 82 kW rated power and a max open-circuit voltage of 600 VDC integrated with PV maximum power point tracking (MPPT) [40]. The number of inverters required for the SPV plant depends on the inverter size and can be determined according to Equation (2).

$$\text{Number of inverters} = \frac{\text{Inverter size}}{\text{Rated power of an inverter}} \quad (2)$$

#### 2.1.7. Battery Sizing

Batteries are required to store the excess electricity generated in the PV panel. The total number of cells required depends on the capacity of each battery. In the present analysis, a J185E-AC 12V (Trojan, United States) deep cycle battery with a cost of USD 205.5 was used [40]. Detailed specifications of the battery are provided in Table 7.

**Table 7.** Battery specifications [39,40].

| Nominal Voltage | 48 Volt |
|---|---|
| Depth of Discharge | 40% |
| Battery Efficiency | 90% |
| Lifetime | 4 years |
| Battery Capacity | 175 Ah |

The number of batteries and their capacity can be calculated according to Equations (3) and (4), respectively.

$$\text{No. of Batteries} = \frac{\text{Battery Capacity Required}}{\textit{Single Battery Capacity}} \quad (3)$$

$$\text{Batter Capacity Required (Ah)} = \frac{\text{Days of Autonomy} \times \text{Total Watt} - \text{hour required}}{\text{Nominal Battery Voltage} \times \text{ Battery Efficiency} \times (1 - \text{DOD})} \quad (4)$$

2.1.8. Module Circuit

The module circuit represents the number of modules to be connected in series, i.e., the size of an array and voltage input to the inverter, as well as the total number of arrays in the solar field.

The size of an array depends on the inverter's maximum $V_{oc}$; the $V_{oc}$ of the module can be calculated according to Equations (5)–(7) [40].

$$\text{Size of an array} = \frac{\text{Maximum Open} - \text{Circuit Voltage of Inverter}}{\text{Open Circuit Voltage of each PV Module}} \quad (5)$$

$$\text{The maximum voltage input to the inverter} = \text{ No. of Modules in Series} \times \text{Maximum voltage from a module} \quad (6)$$

$$\text{Total No. of Arrays in the solar field} = \frac{\text{No. of Modules}}{\text{No. of Modules in an Array}} \quad (7)$$

2.1.9. Land Requirement

- The number of PV modules required = 4674;
- Dimensions of one PV module = 1.57 m × 0.798 m;
- Total width of each PV array = 12 × 0.798 = 9.576 m;
- Length of one PV module = 1.57 m;
- Number of arrays in the PV field = 390.

Number of arrays in a row = 12;
Width of the solar field = 12 × 9.576 = 114.912 m;
Number of rows in the solar field = 33;
Pitch distance between two arrays (including the module length of 1.57 m) = 3 m;
Length of the solar field = 33 × 3 + 1.57 m = 100.57 m;
Land required for PV field = 100.57 × 114.912 = 11,556.7 $m^2$ = 2.85 acres (1 acre = 4047 $m^2$).

2.1.10. Overall Techno-Economic Assessment

Energy Payback Time (EPBT)

The energy payback time (EPBT) of the plant can be defined as the duration required to recuperate the total energy expenditure. Total embodied energy is the summation of energy consumed in materials, manufacturing, transport, installation, and management. EPBT is determined by Equations (8) and (9).

$$\text{Energy Payback Time (EPBT)} = \frac{\text{Total Embodied Energy of Modules}}{\text{Annual electricity generated from the plant}} \quad (8)$$

$$\text{EPBT} = \frac{(\text{Em} + \text{Emf} + \text{Et} + \text{Ei} + \text{Emg})}{\text{Eg}} \quad (9)$$

The value for the total energy consumed in materials, manufacturing, transport, installation, and management for each $m^2$ area of the module was proposed in [41].

Therefore, (Em + Emf + Et + Ei + Emg) = 1516.59 kWh/$m^2$ of module,

$$\begin{aligned}\text{The total area of modules} &= \text{No. of Modules} \times \text{Length} \times \text{Width of Modules} \\ &= 4674 \times 1.57 \times 0.798 = 5855.87\ \text{m}^2\end{aligned} \quad (10)$$

Total embodied energy = 5855.87 × 1516.59 = 8880.95 MWh;
Number of sunny days = 300;
Annual electricity generated (Eg) = 3596 × 300 = 1078.8 MWh/year;
Electricity production factor (EPF).

The electricity production factor (EPF) is defined as the ratio of the annual energy output to the input energy, and it predicts the overall performance of the PV module. EPF can be calculated according to Equation (11).

$$\text{EPF} = \frac{\text{Eg}}{(\text{Emg} + \text{Emgf} + \text{Et} + \text{Ei} + \text{Emg})} \quad (11)$$

Capital Utilization Factor (CUF)

The proportion of the actual energy produced by an SPV plant over a year to the comparable energy output at that plant's rated capacity in the same period is known as the capacity utilization factor (CUF). The energy generation for an SPV project depends on solar radiation and the number of bright, sunny days. The capital utilization factor (CUF) is determined by Equation (12).

$$\text{Capacity utilization factor (CUF)} = \frac{\text{Annual energy Generated for each kW peak capacity}}{8760\ \text{h}} \quad (12)$$

## *2.2. Financial Assessment*

### 2.2.1. Cost of PV Modules and Inverters

The cost of each PV module = USD 528.9 [42]. The total cost of all modules can be determined by Equation (13).

$$\text{Total Cost of all modules} = number\ of\ modules \times \text{cost of each PV module} \quad (13)$$

A Solectria PVI 82 kW Grid Tied Inverter 480 VAC PVI-82 kW (Solectria) was considered for the inverter in this study. The cost of one inverter is USD 36,300 [39]. Total cost of inverters can be measured by Equation (14).

$$\text{Total Cost of Inverters} = number\ of\ inverters \times \text{cost of each inverter} \quad (14)$$

### 2.2.2. Cost of Batteries

Batteries store energy produced by a given generating source; when this source is unavailable, this energy can be used by the load. Including storage in any energy-generating system increases the availability of energy. A Trojan J185E-AC 12 V deep cycle battery with a cost of USD 205.5 (atbatt.com) was used in this study. The battery life was considered five years, as no frequent use of batteries is expected, and an annual maintenance contract will improve the battery's life. The replacement cost was considered every five years, considering the applicable discount rate. The total cost of batteries can be measured by Equation (15).

$$\text{Total Cost of batteries} = number\ of\ batteries \times \text{cost of each battery} \quad (15)$$

### 2.2.3. Miscellaneous Cost

Miscellaneous costs, which consist of operation and maintenance, installation, and electrical items (such as cables), total nearly USD 0.13/Wp [36]. Thus, the total miscellaneous cost of the proposed plant = 0.13 × 1005 × 1000 = USD 130,650. An economic analysis of solar PV is presented in Table 8.

**Table 8.** Financial assessment of solar PV plants.

| | Cost Type | Cost (USD) |
|---|---|---|
| 1 | Module cost | 2,472,078.6 |
| 2 | Battery cost | 1127,646 |
| 3 | Inverter cost | 580,800 |
| 4 | Miscellaneous cost | 130,650 |
| 5 | Total cost without land cost | 4.311 million |

The LCOE is the lifetime cost of an electricity plant, divided by the amount of electricity it is expected to generate over its lifetime. LCOE is an important parameter, as it is the minimum price at which energy must be sold for an energy project to break even. It indicates whether a project will be profitable or not.

## 3. Solar Resources in All Divisions of Bangladesh

Bangladesh has the potential to generate electricity from solar resources due to its geographical location. An ongoing report directed by the Renewable Energy Research Centre found that Bangladesh receives the most extreme solar radiation during spring (March–April), with the lowest levels in December–January [43]. The average national solar radiation ranges from 4 to 6.5 kWh/m$^2$/day [22]. There are eight divisions in Bangladesh: Dhaka, Chattogram, Barisal, Khulna, Sylhet, Rajshahi, Rangpur, and Mymensingh. Figure 4 shows the solar radiation data from the eight districts of Bangladesh [22].

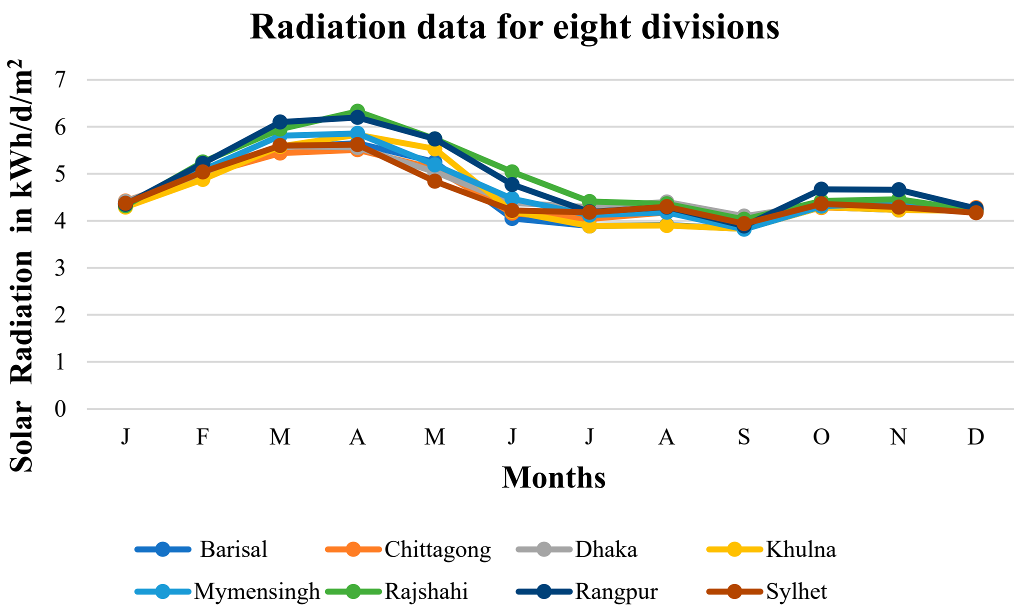


**Figure 4.** Solar radiation data for the eight divisions Bangladesh [22].

### 3.1. Theoretical Potential

Theoretical potential was simulated based on land area data and solar radiation. Figure 5 shows a solar map of Bangladesh, demonstrating that solar radiation is in range of of 4–5 kWh/m$^2$/day in approximately 94% of Bangladesh [44]. Approximately 6.5 h of daylight is available throughout the day, and the national average solar radiation is 0.2 kW/m$^2$ per year [44]. Accordingly, the nation's yearly theoretical solar energy capacity is 70,000 terawatt-hours (TWh), surpassing the current power production by 1500 times [30,32]. However, various snags, for example, geological zone, land use, and atmosphere, have become an integral factor in improving solar energy, and some advancements concerning solar PV technologies are likewise restricted in this nation.

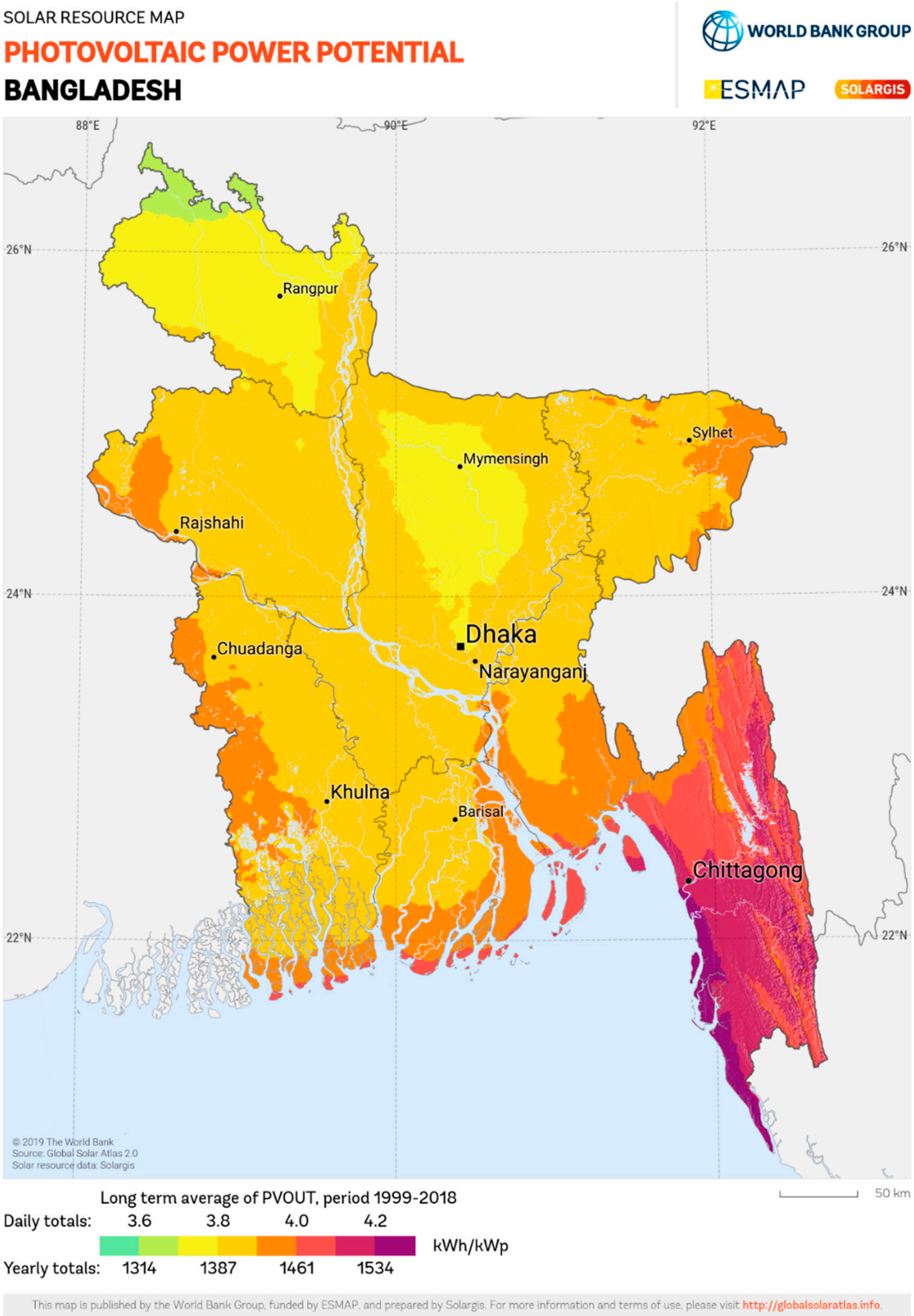


**Figure 5.** Solar map of Bangladesh [45].

### 3.2. Technical Potential

The mean yearly power density of solar radiation is 100–300 W/m$^2$. As a result, an area of 3 to 10 km$^2$ is needed to produce an average electricity output of 100 MW, which is approximately 10% of a sizable coal or nuclear power plant, with a solar PV efficiency of 10% [46]. The main advantage of sun-oriented innovations is that these advances do not cause noise or pollution. Therefore, the search for appropriate areas for sun-oriented projects includes unused land and reasonable housetops. An examination found that housetops cover 3.2% of the total land area of Bangladesh [47]. Another investigation suggested that to lessen or tackle the interest in the power issue of 3000 kWh/capita/year, 6.8% of the entire country's land is required for power production from sunlight-based solutions [48]. Approximately 7.86% of land in Dhaka city can be used for PV-based generation, and it is accepted that considering the accessibility of the grid, 1.7% of the land area of the entire nation is appropriate for PV-based power generation [49]. Therefore, the technical potential of a grid-connected solar power plant is assessed to be 50,000 MW [50]. It was previously determined that four million houses can benefit from SHS in the future [51]. This capacity can increase up to 200 MW if a PV panel of 50 Wp is considered for each family unit [44]. The financial feasibility of SHS in Bangladesh was assessed in [44], and the techno-monetary viability of a hybrid system was investigated in [32]. CSP is another promising innovation that can be used to reap the benefits of solar power; among the eight divisions of Bangladesh, Rajshahi was found to be the most reasonable area for the use of this innovation [33], which can provide Bangladesh with approximately 100 MW of power, as presented in Table 9, which illustrates the solar energy potential of Bangladesh.

**Table 9.** Solar energy potential of Bangladesh [33].

| Technology | Potential Power (MW) |
|---|---|
| SHS | 234 |
| CSP | 100 |
| Grid-connected PV | 50,174 |

## 4. Application of Solar Technologies in Bangladesh

### *4.1. Solar Home System (SHS)*

SHS is the most feasible and compelling off-grid power system to fulfill the power needs of the rural community. Worldwide, SHS has the highest installment rate. Initially, the SHS project was modeled by PSL but was started by IDCOL. In 2003, the REREDP project was initiated, and subsequently, SHS programs attracted increasing attention. The number of SHS projects installed until September 2019 (up to January) was 4.13 M, with the number expected to increase to 6 M by 2021 [52]. To date, the program has prevented the use of 1.14 million tons of kerosene. To function, SHS requires a 12 V DC power supply and consists of one or more crystalline Si solar PV modules (10–120 Wp with a 20-year warranty), a rechargeable flooded lead–acid battery (12 V dc, 50–130 Ah, DOD 70% at a discharge rate of 10 h with five years of useful life), and a charge controller (with low- and high-voltage detection and 90% efficiency) to control and protect against abnormal conditions among the modules, battery, loads, etc. The loads can be fluorescent lamps (5 W, 45 lum/W), radios, TVs, fans (15 W), etc. Therefore, off-grid solar home system projects play an essential role in the electrification of Bangladesh's remote areas.

### *4.2. Solar Power Plant/Solar Park*

As the energy demand in this country is gradually increasing every year, the government has planned to generate additional energy from nuclear and fossil-fuel-based power plants. However, nuclear power plants and fossil-fuel-based power plants emit toxic waste, which is hazardous to human life and the surroundings. Furthermore, burning fossil fuels is not a sustainable long-term solution to fulfill future energy demands because fossil fuels will run out one day. For this reason, solar power plants represent an alternative solution to fossil-fuel-based power plants in Bangladesh. India has started producing electricity from solar parks and solar power plants, which costs BDT 3.10/kWh or USD 0.038/kWh [53,54]. In Bangladesh, a 3 MW solar park was set up in Jamalpur, and 22 projects are in the planning phase [55]. Table 10 depicts the sizes of solar park projects undertaken by various utilities in Bangladesh.

**Table 10.** Capacities of solar park projects undertaken by various utilities in Bangladesh [55].

| Utility/Institution/Company | Capacity (MW) |
|---|---|
| Bangladesh Power Development Board | 100 |
| Ashuganj Power Company Limited | 100 |
| Electricity Generation Company Bangladesh Limited | 100 |
| Northwest Power Generation Company Limited | 150 |
| Rural Power Company Limited | 200 |
| Coal Power Generation Company Limited | 50 |
| Total | 700 |

### *4.3. Solar Transport (School Boats)*

Bangladesh floods annually during the monsoon season, with floodwaters covering up to one-fifth of the country [56]. Solar school boats play a vital role in promoting education programs among the flood-affected people in Bangladesh. An organization named 'Shidhulai Swanirvar Sangstha (SSS)' designed solar-powered floating schools in the 'Chalanbeel' region in 2002. The aim was to provide education services to affected children and to improve socioeconomic conditions in the area. Another objective of that organization is to provide recharge facilities so that affected people can use their solar lanterns. The length and width of the designed boat are 55 feet and 11 feet, respectively, and the boat can host 30 children and a teacher [57]. The rooftops of the boat were used for PV module installations. The modules provide at least 2 kW of power. By 2013, SSS owned 111 boats and provided services to more than 70,000 children and 90,000 families [58]. These boats also contain libraries, health centers, education centers, etc. More than 200 staff members and 40 boat drivers work in these boats.

### *4.4. Solar PV for Drinking Water and Irrigation Pumps*

People living in the coastal areas of Bangladesh are forced to drink water from ponds, canals, etc., due to saline intrusion. Furthermore, in the event of a flood, people suffer from many waterborne diseases. To address this issue, GIZ executed a program named SED. Under this program, 139 pumps with a capacity to supply 2.18 million liters of pure drinking water daily have been installed [59]. A total of 112 solar pumps have been installed in coastal areas to minimize the crisis of pure drinking water. The UN has also contributed to this sector by supporting 500 water purification units [60]. These units are manufactured by a Swedish firm named 'Water Sprint' and can purify 600 L of water per hour. In 2015, 'Water Sprint' and the 'Yunus Centre' jointly distributed ten purification units across Bangladesh [60].

Agriculture is the most significant labor sector in Bangladesh. Half of the population depends on agriculture for their livelihood [61]. Approximately 1.28 million diesel pumps are in operation across the country. The government must import 1.06 million tons of diesel and spend USD 280 million in annual subsidies to make irrigation more affordable. Moreover, pumps operated via electricity consume a significant amount of energy. Currently, 0.33 million electric pumps are in operation, consuming 1500 MW of electricity [62]. To reduce dependence on diesel, Bangladesh is now considering shifting to solar irrigation. Currently, 2787 solar pumps are in operation around the country [62]. IDCOL has also endorsed solar projects with an aggregate capacity of approximately 7 MW to operate these pumps [63]. Table 11 shows some major irrigation projects undertaken by IDCOL. Multiple suppliers supply these pumps; a list of pump providers can be found in Table 12.

**Table 11.** Major irrigation projects currently in operation [63].

| Location | POs | Water Flow ($m^3$/Day) | Pump Capacity (kW) | Pump Head/Lift (m) |
|---|---|---|---|---|
| Shapahar, Naogaon | GS | 300 | 7.50 | 35.00 |
| Fatiqchari, Chittagong | RCNSL | 128 | 3.50 | 12.80 |
| Sadar, Bogra | NUSRA | 394 | 3.50 | 15.93 |
| Dhamrai, Dhaka | NUSRA | 381 | 7.50 | 17.30 |
| Kaharole, Dinajpur | NUSRA | 430 | 3.50 | 12.20 |
| Shailkupa, Jhenaidah | NUSRA | 430 | 7.50 | 15.30 |
| Kumarkhali, Kushtia | NUSRA | 383 | 7.50 | 17.60 |
| Sadar, Thakurgaon | 4SL | 468 | 3.50 | 12.50 |
| Ranisongkoil, Thakurgaon | 4SL | 468 | 3.50 | 12.20 |
| Baliadangi, Thakurgaon | 4SL | 468 | 3.50 | 12.20 |
| Birgonj, Dinajpur | 4SL | 504 | 5.50 | 13.60 |
| Sadar, Panchagar | 4SL | 504 | 5.50 | 12.60 |
| Autuary, Panchagar | 4SL | 504 | 5.50 | 12.60 |
| Debiganj, Panchagar | 4SL | 504 | 5.50 | 12.60 |
| Tetulia, Panchagar | 4SL | 504 | 5.50 | 12.60 |
| Pirganj, Thakurgaon | 4SL | 504 | 5.50 | 13.20 |
| Haripur, Thakurgaon | 4SL | 504 | 5.50 | 13.30 |
| Gabtali, Bogra | GHEL | 420 | 3.50 | 13.10 |
| Dhunat, Bogra | GHEL | 443 | 3.50 | 12.40 |
| Sonatola, Bogra | GHEL | 420 | 3.50 | 13.00 |
| Pirganj, Rangpur | AVA | 664 | 7.50 | 14.85 |
| Birol, Dinajpur | AVA | 679 | 7.50 | 17.46 |
| BoroBalia, Sadar, Thakurgaon | AVA | 613 | 5.50 | 12.46 |
| Ghagrapara, Sadar, Panchagarh | AVA | 594 | 7.50 | 12.61 |
| Sadullahpur, Gaibandha | AVA | 588 | 7.50 | 13.46 |
| Badarganj, Rangpur | GRAM | 373 | 4.00 | 10.25 |
| Badarganj, Rangpur | GRAM | 373 | 4.00 | 9.71 |
| Badarganj, Rangpur | GRAM | 373 | 4.00 | 10.91 |
| Badarganj, Rangpur | GRAM | 373 | 4.00 | 10.71 |
| Badarganj, Rangpur | GRAM | 373 | 4.00 | 10.71 |
| Chowgacha, Jessore | ARS-BD | 709 | 7.50 | 12.71 |
| Chowgacha, Jessore | ARS-BD | 709 | 7.50 | 12.71 |
| Chowgacha, Jessore | ARS-BD | 709 | 7.50 | 12.71 |
| Chowgacha, Jessore | ARS-BD | 709 | 7.50 | 12.71 |
| Chowgacha, Jessore | ARS-BD | 709 | 7.50 | 12.71 |
| Chowgacha, Jessore | ARS-BD | 740 | 7.50 | 16.01 |
| Chowgacha, Jessore | ARS-BD | 740 | 7.50 | 16.01 |
| Shibganj, Bogra | GHEL | 350 | 3.50 | 16.50 |
| Sherpur, Bogra | GHEL | 350 | 3.50 | 16.10 |
| Shajahanpur, Bogra | GHEL | 350 | 3.50 | 16.50 |
| Chirirbandor, Dinajpur | RREL | 645 | 11.00 | 14.57 |
| Parbotipur, Dinajpur | RREL | 576 | 11.00 | 18.71 |
| Boda, Panchagar | RREL | 594 | 7.50 | 12.51 |
| Mithapukur, Rangpur | RREL | 666 | 7.50 | 14.47 |

**Table 12.** List of pump providers [63].

| Name of the Supplier | Equipment Brand Pump | Controller |
|---|---|---|
| Rahimafrooz Renewable Energy Ltd. (RREL) | Lorentz | Lorentz |
| Energypac Electronics Ltd. (EEL) | Grundfos | Grundfos |
| Electro Solar Power Ltd. (ESPL) | Schenzhen Solartech Co. Ltd. | Shenzhen SolartechCo. Ltd. |
| JSF Technology Pvt Ltd. (JSF) | Duke Plasto Technique Pvt Ltd. | Hermes Technologies Pvt Ltd. |
| Sherpa Power Engineering Ltd. (Sherpa) | (Sherpa) | (Sherpa) |
| Samaj Unnayon Palli Sangtha | Sherpa | Sherpa |
| Greentek Ltd. (GTL) | Sherpa | Sherpa |
| UDDIPAN Energy Ltd. (UEL) | Franklin Electric | Schneider Electric |
| Navana Renewable Energy Co. Ltd. (NREL) | Grundfos | ABB |
| Greenergy Solutions Ltd. (GSL) | HCP | Vacon |
| Solar E Technology (Solar E) | Hebei prime pump | Setec |
| Solargao Ltd. (Solargao) | HCP, Pedrollo, Lorentz | Schneider Electric, Lorentz |
| Bangla Trac Engineering Ltd. (BTEL) | Grundfos | Schneider Electric |
| Karben Solar Energy Ltd. (Karben) | Grundfos | Grundfos |
| Sunkoji Power Development Ltd. (Sunkoji) | Grundfos | Grundfos |
| MAKS Renewable Energy Company Ltd. (MAKS) | Lorentz | Lorentz |

### *4.5. Solar Cookers and Solar Aeration*

A solar cooker is a device whereby solar radiation is used to cook food. Three different types of solar cookers are available: (i) box, (ii) panel, and (iii) parabolic reflector. Research has been ongoing to develop and modify these types of solar cookers. The development and implementation of solar cookers are still in their primary stages in Bangladesh. The Institute of Fuel Research and Development (IFRD) has successfully tested and experimented with various stoves. Two-axis parabolic solar cookers have also been tested by KUET [64]. A study reported that box-type solar cookers are preferable under the climatic conditions of Bangladesh, also reporting that solar cookers can be functional for 294 days a year [64]. Another study recommended that the government provide appropriate subsidies and that industry introduce change agents to motivate rural people to adopt this technology to efficiently address barriers to its adoption in Bangladesh [65].

Aeration is the artificial process of making close contact between air and water. This process is used in water treatment plants to improve water quality. Generally, aeration systems consist of an aerator and a power source. There are different types of aeration systems available. However, where grid connection is not possible and costly, solar and wind energy sources can come in handy. A study developed by Prasetyaningsari et al. reported that solar aeration could be adequate for places not connected to the grid [66]. Based on this study, Chowdhury et al. developed a model using optimization software named Homer for an off-grid site in Bangladesh called Godagori in Rajshahi. This study suggested that the cost of electricity is high solar aeration systems because renewable energy technologies lack penetration in local markets [67].

### *4.6. Ongoing Projects*

The GoB launched a 500 MW solar power mission to mitigate dependency on fossil fuels and to achieve the goal 10% of power generation from sustainable sources by 2020. Solar mini grids are a promising solution for coping with the energy crisis. IDCOL, jointly with BPDB, has undertaken several projects, as depicted in Table 13. IDCOL also plans to install 50 mini grids by 2025, as presented in Table 14. To mitigate the dependency on diesel generators in the agricultural sector, IDCOL also has a plan to install 50,000 pumps by 2025, as presented in Table 15. IDCOL has approved approximately 1429 pumps, of which 1186 are in operation, with a capacity of 26.59 MW [52]. To make the country self-sufficient in terms of photovoltaic manufacturing, IDCOL has funded two photovoltaic assembly plants with a total capacity of 10 MW. Moreover, BPDB has focused on grid-tied solar power plants, and two power plants with a capacity of 3 MW and 8 MW are under construction in

Jamalpur and Rangamati, respectively [52]. IDCOL recently funded a PPL solar rooftop project with a capacity of 723 kW. This solar plant is located in Gazipur, Dhaka. IDCOL also intends to generate 1000 MW of electricity from the rooftop solar project. It is estimated that the textile industry's rooftops can produce 400 MW and that it is possible to create 4000 MW of electricity from industrial and commercial rooftops [52].

**Table 13.** Mini-grid projects under consideration in Bangladesh [52].

| Project Location | Capacity (kWp) | Project Status |
|---|---|---|
| Enam Nahar, Sandwip, Chittagong<br>Kutubdia, Cox's Bazar | 100<br>100 | Operational<br>Operational |
| Bagha, Rajshahi | 141 | Operational |
| Paratoli, Raipura, Narshingdi | 141 | Operational |
| Narayanpur, Nageshwari, Kurigram | 158 | Operational |
| Godagari, Rajshahi | 149 | Operational |
| Monpura, Bhola | 177 | Operational |
| Nooner Tek, Sonargao, Narayangonj | 168 | Under construction |
| Rupsha Char, Sadar, Sirajganj | 130 | Under construction |
| Chilmari, Daulatpur, Kushtia | 188 | Under construction |
| Munmiar Char, Islampur, Jamalpur | 162 | Under construction |
| Baghutia char, Doulatpur, Manikganj | 228 | Under construction |
| Nijhum island, Hatiya, Noakhali | 200 | Under construction |
| North Channel Union, Sadar, Faridpur | 162 | Under construction |
| Char Kajal, Patuakhali | 100 | Under construction |
| Char Biswas, Patuakhali | 100 | Under construction |
| Ghaschapru, Belkuchi, Sirajganj | 218.4 | Under construction |
| Poschim Shalipur, Char Bhadrashan, Faridpur | 156 | Under construction |

**Table 14.** Number of solar mini grids to be installed by 2025 [52].

| Year | No. of Solar Mini-Grid Plants |
|---|---|
| 2018 | 08 |
| 2019 | 12 |
| 2020 | 15 |
| 2021 | 20 |
| 2022 | 25 |
| 2023 | 30 |
| 2024 | 40 |
| 2025 | 50 |

**Table 15.** Number of solar irrigation pumps to be installed by 2025 [52].

| Year | No. of Solar Irrigation Pumps |
|---|---|
| 2018 | 500 |
| 2019 | 1000 |
| 2020 | 2000 |
| 2021 | 3000 |
| 2022 | 5000 |
| 2023 | 8000 |
| 2024 | 14,000 |
| 2025 | 16,500 |

## 5. Renewable Energy Policy Implementation in Bangladesh, Techno-Economic Analysis, and Future Prospective of AI Technology Integration with Solar Systems

The Bangladesh government founded SREDA in 2014 to take advantage of the country's substantial renewable energy potential. The GoB has also found a way to expand global collaboration and is one of IRENA's initiating agencies. To accomplish the goal of 10% of power generation from sustainable sources by 2020, the Legislature of Bangladesh has undertaken a few policies, which are discussed below [68].

### *5.1. Resources, Technology, and Program Development*

In this subsection, we address the policies undertaken by the government regarding different renewable energy technologies and their development.

- SEDA, which is related to the Power Division of the MPEMR, will decide the needs for sustainable power source innovation, advancement, and program execution.
- SEDA will provide infrastructural and technological facilities to expand and develop the market for renewable energy electricity in Bangladesh.
- All affiliated government and private utilities will undertake renewable energy expansion programs for applications throughout the country.
- Power utilities will purchase the energy produced by both public and private companies from renewable sources through corporate compliance.
- Existing transmission and distribution lines may be used to supply electricity to consumers through corporate compliance between sponsors and owners of transmission and distribution lines. The owners will apply a wheeling charge to sponsors, and BERC and MPEMR will determine the amount of the charge.
- In addition to power generation, a sustainable power source for sunlight-based heating and biogas or different methods such as cooking will be created.
- SEDA will energize the advancement of human assets, as well as nearby generation of sustainable power source equipment and help to set up a quality control lab to test sustainable power source equipment.
- The generation and utilization of biofuel might be empowered on a restricted scale without endangering the current yield.

### *5.2. Speculation and Monetary Impetuses*

In this subsection, we discuss the economic policies undertaken by the GoB to promote the advancement of renewable energy technologies in Bangladesh. Such policies are listed below.

- ➢ Existing sustainable power source financing offices will be extended so that all public and private contributors will receive the necessary information and support.
- ➢ All the equipment and raw materials exempt from the 15% VAT to promote renewable sources.
- ➢ A small-scale microcredit network will be set up to financially support rural areas to purchase sustainable power source equipment.
- ➢ Investment in sustainable energy projects will be handled by MPEMR, whereas SEDA, jointly with other local government offices, will work on developing sustainable energy programs.
- ➢ SEDA will provide endowments to utilities for the establishment of sunlight, wind, biomass, and other sustainable/clean energy projects.
- ➢ Sustainable power source venture speculators will be exempt from providing corporate salary charges for 5 years. This will be applied from the period of the announcement of this agreement in the official journal and is expected to be broadened intermittently.
- ➢ An incentive fee of 10% or more will be considered to promote electricity generation from sustainable sources. This fee will be higher than the maximum price of a utility buying electricity from private generators.
- ➢ The utilization of power and gas will be lowered to advance solar-based water heating, with additional advances considered subsequently.

- The loan scheme will be updated and strengthened for fruitful usage of sustainable power sources.

*5.3. Administrative Approach*

In this subsection, we discuss the managerial policies undertaken by the GoB to promote renewable energy development in Bangladesh. Such policies are listed below.

- BERC will provide power generation licenses to sustainable power source projects with a plant capacity of 5 MW or more if they want to sell electricity.
- MPEMR and SEDA, together with BERC, will establish an administrative structure empowering power generation from sustainable power sources.
- BERC will favor an energy levy in consultation with MPEMR or SEDA according to the agreement of the BERC Demonstration 2003 if the limit of sustainable power source projects is 5 MW or more. Power wholesalers may offer "green energy" taxes, which give customers a chance to participate in cofinancing through their power charges.

Despite being an environmentally friendly technology, if the disposal of solar technology is not carried out properly, it could harm the environment once it has reached the end of its useful life [69]. It has been estimated that 33,205.36 tons of PV waste will be generated in Bangladesh once solar technology reaches its end of life [69,70]. Lead, cadmium, and tin are heavy metals generally found in solar panels, and their open dumping can damage the environment [71]. Hazardous waste is produced when certain heavy metals are present. A polycrystalline PV cell has a hazardous material content of 0.15 g/W [72]. Therefore, 33,205.36 tons of PV cell waste of would result in 62.26 tons of hazardous materials. Hence, it is necessary to ensure proper management of this waste. However, in Bangladesh, there is a lack of appropriate laws addressing expired PV panels as e-waste. Although there are some rules and policies regarding e-waste (National 3R Strategy for Waste Management (2010), E-waste management rules (2017), National Environment Policy—Bangladesh (2018)), none considers end-of-life cycle PV panels as e-waste [70]. Therefore, the development of appropriate policies and rules regarding this matter are necessary.

*5.4. Overall Outcome of Techno-Economic Analysis*

The number of PV modules required to meet the garment industry's demand is 4674. A total of 2.85 acres of land are required to set up these PV modules. The number of inverters required is calculated to be 16, and the optimum inverter size is 1310 kW. The number of batteries needed to store the excess energy is calculated to be 793, and the required battery capacity is 138,735 Ah. EPBT, EPF, and CUF are found to be 8.232 years, 0.1213, and 0.1225, respectively. Financial analysis clearly shows that USD 4.3 million is required to set up a plant (without land cost). The cost of PV modules is higher than that of inverters and batteries. LCOE is calculated to be USD 0.091/kWh. Khatri designed a solar PV plant for a girls' hostel (GARGI) at MNIT University, Jaipur city, and found that the LCOE of the proposed plant was USD 0.12/kWh [39]. Chandel et al. also designed a solar PV plant for a garment zone and found that the LCOE of the designed plant was INR 14.94/kWh [36].

*5.5. Possibility of Artificial Intelligence (AI) Integration in the Solar Energy System*

With the industrial revolution and population increase, Bangladesh's energy demand is increasing rapidly, but resources are limited to fulfill this demand. In the previous section, we broadly emphasized the potential of solar energy, atmospheric conditions, geology, environmental conditions, and ongoing projects in Bangladesh. However, the current plan may not assure the fulfillment of energy demand for this developing country. It must incorporate the ongoing project with artificial intelligence (AI) techniques to tackle future energy demands and challenges in which atmospheric, geology, and environmental conditions are used as input features, considering the energy policy as a constraint. Artificial intelligence (AI) is a technique whereby a computer can explicitly learn from examples (big data) and is broadly used to support a sustainable energy system by forecasting, optimization, decision making, policy making, and system recognition [73–75]. AI can now play a more significant role in modeling, analyzing, and predicting both the weather and the performance of renewables compared to traditional computer methods [76]. Additionally, in combination with satellite imagery, AI can detect and predict cloud characteristics, track aerosol, and utilize numerical weather data to create an efficient solar energy system [77,78]. Modern technology (using appropriate sensors) can be employed to measure several weather and environmental variables on a large scale. A sustainable energy system can be developed by employing machine learning (ML) and AI techniques. Various algorithms have been applied to predict solar resources and model solar energy systems, as summarized in Table 16.

The number of applications of machine learning and artificial neural networks in the solar cell field has increased rapidly over time [79,80]. Future energy challenges are expected to be diminished with the use of AI techniques, especially in developing countries such as Bangladesh, where energy demand proliferates with the increasing population and the industrial revolution. In addition to increasing efficiency, AI-based solar systems are expected to reduce the effects of climate change by limiting carbon emissions. AI can play a role in modeling, analyzing, and predicting solar energy factors such as radiation, temperature, wind, etc. An AI-based solar system is much more efficient than traditional computer models. AI can incorporate satellite images to detect and predict cloud characteristics and track aerosol to improve models of solar systems. AI-based solar energy systems not only increase the efficiency of renewable energy projects but can also reduce the effects of climate change and carbon pollution. AI-based solar systems promote a low-carbon electricity system. Conventional solar models cannot tackle energy challenges in developing countries such as Bangladesh, where energy demand is increasing rapidly with the industrial revolution and a rapidly growing population.

### 5.5.1. Machine Learning in Solar Energy Systems

Machine learning is an emerging technique and can be used to increase the sustainability of energy systems. Machine learning, artificial neural networks, fuzzy logic, genetic algorithms, and hybrid systems can be successfully applied in the solar and renewable energy sector [81–84]. Figure 6 shows a simple framework of a machine learning system applied to a renewable energy system. The model must be trained on feature data related to solar energy to enforce machine learning algorithms such as linear regression, logistic regression, decision tree, and support vector machine [85]. Based on the data, next, it is necessary to develop a learning algorithm, followed by hypothesis development. Then, the hypothesis is tested using the test data. If the interpretation passes the test, the desired output is yielded. Otherwise, the hypothesis must be updated, followed by accuracy checking with the test data.

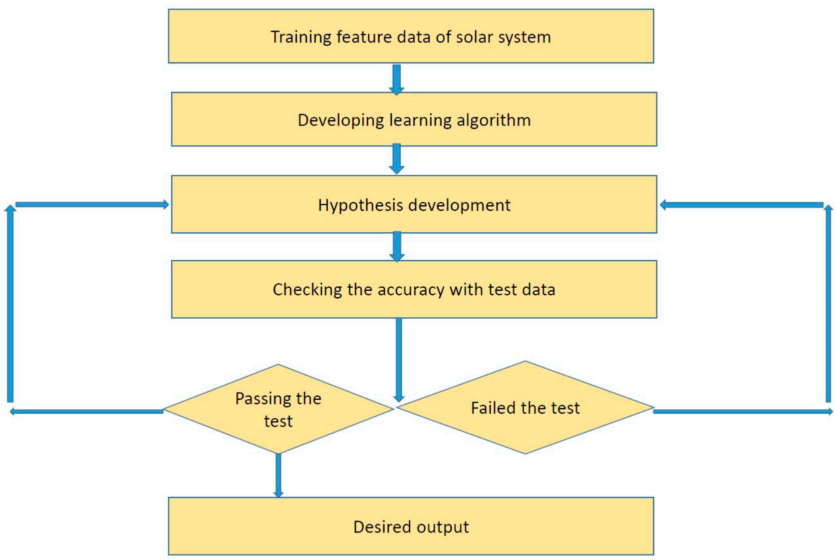


**Figure 6.** Simple framework of a machine learning approach for solar and renewable energy systems [84].

5.5.2. Artificial Neural Networks (ANN) in Solar Energy Systems

Artificial neural networks can be used in the renewable energy sector to predict and optimize the effects of several factors on solar energy, such as solar radiation and temperature [86,87]. Prediction and future trends of these meteorological parameters are essential in designing renewable energy systems, primarily because the efficiency of energy systems largely depends on them. Such predictions can help policymakers make decisions, ultimately making renewable energy systems more sustainable. Along with a plethora of positive factors, the ANN approach has shortcomings, such as limited theory to assist the ANN (theory related to ANN is increasing with time), the requirement of an evenly spaced dataset, and limited options to rationalize the solution. However, these flaws have limited opportunities to influence the results of ANNs. The ANN approach for predicting features such as temperature and solar radiation is discussed below.

5.5.3. ANN for Solar Radiation Estimation

Solar radiation is an essential feature in designing solar energy systems [88]. Information about future solar radiation is necessary to develop sustainable and efficient solar energy systems. Several researchers have used the ANN approach to estimate daily solar radiation. The aim is to describe a simple method to develop ANN to predict solar radiation [89,90]. Solar radiation is predicted in the form of hourly, daily, monthly, or maximum solar radiation. For the development of an ANN, the input variables used to predict and measure solar radiation are humidity, cloud cover, sunshine duration, temperature, latitude, longitude, altitude, low diffuse radiation, low-beam radiation, daily precipitation, and length of the day [84]. The backpropagation algorithm can be adapted to train the dataset of input variables. The training dataset goes through several hidden layers and ultimately produces the desired output, as shown in Figure 7.

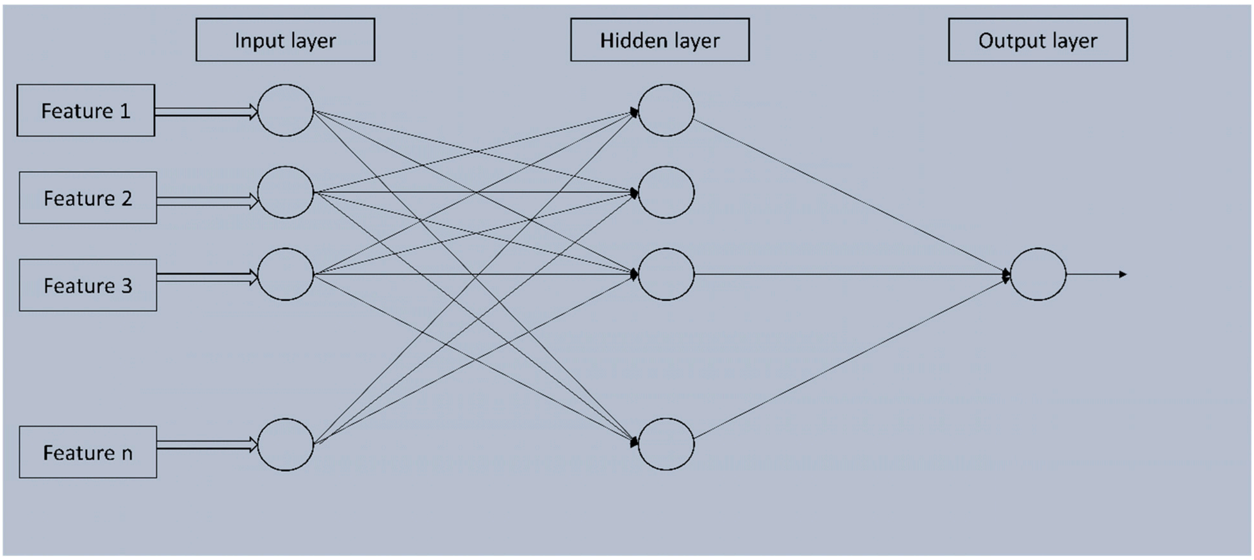


**Figure 7.** ANN network used for prediction with 1—n neurons in the input layers [74].

5.5.4. ANN for the Estimation of Daily Minimum and Maximum Temperature

Besides the solar energy sector, maximum and minimum temperature prediction is widely used in other sectors. However, conventional methods, such as physical model development using radiation law, have several limitations, such as the complexity of predicting the temperature of the regime and limited practical applications [91,92]. This approach has motivated researchers to use ANNs for temperature prediction in solar energy systems. It is necessary to input the variables related to a temperature, such as visibility, cloud amount, weather conditions, dry and wet bulb temperature, and atmospheric pressure, to develop an ANN model for maximum and minimum temperature prediction.

The relevant weather data related to Bangladesh's solar and renewable energy system are available from Bangladesh Meteorological Department. The ANN model is trained by a backpropagation algorithm, which produces the desired output, as shown in Figure 7.

**Table 16.** Commonly used AI algorithm to predict and design solar energy resources and systems.

| Algorithm/Method | Application | References |
|---|---|---|
| ANN | Solar radiation prediction | [89,90,93,94] |
| ANN | Predicting daily temperature | [95–97] |
| BPNN | Predicting solar radiation | [98–101] |
| BPNN | Predicting daily temperature | [102] |
| ANN | Performance assessment of a solar water heating system | [103–105] |
| GA | Solar collector design | [106–108] |
| GA | Solar tracking | [109,110] |
| GA | Solar radiation prediction | [111,112] |

Besides this, AI can help determine the proper power scheduling optimization method [113], design power planning and sharing control method [114,115], and design new energy vehicles where solar energy is used [116].

## 6. Conclusions

The renewable energy utilization scenario in Bangladesh has been increasing at a rocketing rate due to financial investments by government/non-governmental organizations. With an abridgment forecasted to develop at 7–8% per year, the quest for other energy sources is expected to intensify. Bangladesh ought to understand the tremendous capability of sustainable power sources. This target is achievable, and it can not only provide green energy but also business opportunities to many unemployed individuals. Consequently, the demand for installed power capacity has increased, and the grid-connected renewable scheme has experienced dramatic growth in the past year. This study represents an attempt to examine the development of solar photovoltaic energy in Bangladesh. We also reviewed modern applications and government policies. The potential application of AI to mitigate the energy crisis was also studied in this research. The realistic application of Al technology and its impact on efficiency, as well as the feasibility, challenges, and limitations of Al integration ins solar systems should be further investigated in future studies.

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## Nomenclature

| | |
|---|---|
| ADALINE | Adaptive linear neuron |
| ANFIS | Adaptive neuro-fuzzy inference system |
| ANN | Artificial neural network |
| AI | Artificial intelligence |
| APSCL | Ashuganj Power Station Company Limited |
| ARS-BD | Association for Rural Society—Bangladesh |
| AVA | Association of Village Adventure |
| BAEC | Bangladesh Atomic Energy Commission |
| BPNN | Backpropagation neural network |
| BMDF | Bangladesh Municipal Development Fund |

| | |
|---|---|
| BPRE | Bangladesh Policy of Renewable Energy |
| BTEL | Bangla Trac Engineering Ltd. |
| BPDB | Bangladesh Power Development Board |
| BPRE | Bangladesh Policy of Renewable Energy |
| BERC | Bangladesh Energy Regulatory Commission |
| BUET | Bangladesh University of Engineering & Technology |
| BIPV | Building-integrated photovoltaic |
| CES | Conventional energy source |
| CSP | Concentrated solar power |
| DOD | Depth of discharge |
| DUET | Dhaka University of Engineering & Technology |
| EGCB | Electricity Generation Company of Bangladesh |
| ESPL | Electro Solar Power Ltd. |
| EEL | Energypac Electronics Ltd. |
| GA | Genetic algorithm |
| GoB | Government of Bangladesh |
| GHEL | Green Housing & Energy Limited |
| GRAM | Global Resource Augmentation and Management Limited |
| GSL | Green Energy Solutions Ltd. |
| GTL | Greentek Ltd. |
| IDCOL | Infrastructural Development Company Limited |
| IRENA | International Renewable Energy Agency |
| JU | Jahangirnagar University |
| JSF | JSF Technology Private Ltd. |
| Karben | Karben Solar Energy Ltd. |
| KUET | Khulna University of Engineering and Technologies |
| LGED | Local government engineering department |
| LOE | Levelized cost of energy |
| M | Million |
| MPEMR | Ministry of Power, Energy and Mineral Resources |
| MIST | Military Institute of Science and Technology |
| Mtoe | Million tons of oil equivalent |
| MAKS | MAKS Renewable Energy Company Limited |
| NB | Naïve Bayes |
| NBR | National Board of Revenue, Bangladesh |
| NUSRA | Network for Universal Services and Rural Advancement |
| NREL | Navana Renewable Energy Co. Limited |
| NWPGCL | North West Power Generation Company Limited |
| PBS | Palli Bidyut Samity |
| PPL | Paragon Poultry Limited |
| PO | Partner organization |
| PGCB | Power Grid Company Bangladesh |
| PSL | Prokaushali Sangsad Limited |
| PV | Photovoltaic |
| RETs | Renewable energy technologies |
| REREDP | Rural Electrification and Renewable Energy Development Project |
| RPCL | Rural Power Company Limited |
| RCNSL | Rural Communication Network and Service Ltd. |
| RREL | Rahimafrooz Renewable Energy Limited |
| RBFNN | Radial basis function neural network |
| 4SL | Survior's Sancred Solar System Limited |
| Sunkoji | Sunkoji Power Development Limited |
| Solargao | Solargao Limited |
| Solar E | Solar E-technology |
| Sherpa | Sherpa Power Engineering Ltd. |
| SEDA | Socioeconomic development alliance |
| SREDA | Sustainable and Renewable Energy Development Authority |

| | |
|---|---|
| SED | Solar energy development |
| SHS | Solar home system |
| SVM | Support vector machine |
| toe | Tons of oil equivalent |
| UEL | UDDIPAN Energy Ltd. |
| WAPDA | Water and Power Development Authority |
| WZPDCL | West Zone Power Distribution Company Limited |
| WNN | Wavelet neural network |
| WT | Weight |
| Em | Primary energy demand to produce materials comprising PV systems |
| Emf | Primary energy demand to manufacture PV systems |
| Et | Primary energy demand to transport materials used during the life cycle |
| Ei | Primary energy demand to install the system |
| Emg | Primary energy demand for end-of-life management |
| Eg | Annual electricity generation in primary energy terms |

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