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Rooftop PV or Hybrid Systems and Retrofitted Low-E Coated Windows for Energywise and Self-Sustainable School Buildings in Bangladesh

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Abstract: The electricity crisis is a common issue in Bangladesh; however, recently the electricity scenario has been getting worse due to various reasons including power generation and distribution all over the country. Meanwhile, the large number of people requires a huge amount of energy which is not possible to be met by the national grid due to the limited power generation from different plants. Among all renewable energy sources, the solar photovoltaics (PV) system is the best choice as a generation source, either off-grid or with a grid-tied connection, to reduce the pressure on the national grid. In Bangladesh, there are more than 175,000 schools, and it is possible to generate a huge amount of renewable (solar) power to supply all the schools by using rooftop PV systems. We propose a new approach that combines solar energy harvesting and savings to make the schools self-sufficient and energywise. We performed a Hybrid Optimization Model for Multiple Energy Resources (HOMER) pro simulation and find that it was possible to generate approximately 200 megawatts (MW) of power. We conducted a feasibility study on generating power from rooftop PV systems on school buildings and reduced the power consumption using retrofitted thin-film-coated glass by around 16–20% per day depending on the school size, which can help the national power grid system by either making all the schools off-grid or grid-connected to supply power to the national grid. In addition, we perform a HelioScope simulation to investigate the maximum upscaling of PV sizing for the rooftops of school buildings in Bangladesh to realize how to make each school a mini solar power station in the future. The HelioScope simulation performance showed that it was possible to generate approximately 96,993 kWh per year from one school building.

Keywords: HOMER pro software; low-E coatings; rooftop PV; retrofitted glass; school building; thin film

1. Introduction

Manpower is the most valuable asset for any country, especially for one with a denser population like Bangladesh, where natural resources are not abundant. Education is the primary key factor to harvest the power of the population. Education is established as a fundamental right for all. Therefore, a continuous and uninterruptible sustainable power source should be ensured to create a congenial and smart classroom environment for the sake of ensuring a high-quality and productive education for all to build up the nation for the upcoming challenging world. Besides the lighting and mechanical ventilation system, to run a multimedia classroom, an uninterruptible and reliable power source should be confirmed [1–4]. Bangladesh is still running behind in terms of the power generation that is required for the country. According to the latest data from the Bangladesh Power Development Board (BPDB), Bangladesh has the capacity to generate 22,348 MW of electricity. Of that, around 52% is from gas-based plants, 27% from furnace-oil-based plants, 5.86% from diesel-based plants, 8.03% from coal-powered plants, 1% from hydro, 0.5% from other renewable energies, and 5.27% is imported [5]. However, the government has been focusing more on renewable energy generation for the nation and a Renewable Energy Policy (REP) has been established. As a part of that, the first solar power plant has been established in Sutiakhali in Mymensingh and the government has planned to set up another 50 MW solar power plant in Khulna, aiming to mitigate the existing power crisis by enhancing the generation of renewable energy in the private sector as well [6,7]. According to the published article titled "The best source for us is solar energy", solar power projects require a lot of space, and we are limited to using agricultural land to establish any large-scale solar farm. However, in Bangladesh, fallow or uncultivated land is more common in the northern regions, riverside pastures, and sea estuaries. Therefore, plans are being made to set up large-scale solar power projects in these regions [8]. Moreover, rooftop solar power has a huge potential in Bangladesh under net metering, as reported by several research groups [9–13]. For example, Kabir, et al. conducted research work to identify and calculate bright rooftops of Dhaka Megacity using the Quickbird Scene 2006 and found that the solar PV systems on bright rooftops with 75-watt PV modules could generate nearly 1000 MW of electricity through stand-alone PV systems. However, this electricity generation can be substantially higher depending on the installation of PV modules with high capacity and efficiency [14]. Meanwhile, the government of Bangladesh planned to use the rooftops of all educational institutions to generate solar power for the grid. The nation has more than 150,000 primary schools, more than 25,000 secondary schools, and hundreds of colleges and universities. If all these buildings can be brought under a solar power scheme, renewables generation would experience a manifold increase [15]. However, according to the report published in Ref. [16], across the country, 92,513 schools were selected to install rooftop PV power systems after the declaration made by the government in 2015, but unfortunately, there was no follow-up progress on a practical implementation. Several research works have been conducted to find the feasibility of generating electricity using rooftop PV systems in educational institution buildings [17–19] and commercial industrial buildings [20] and their impact on the electricity supply in Bangladesh. Furthermore, there are reports available online about off-grid solar-based floating schools in Bangladesh [21]. A significant number of practical-based research works have been conducted worldwide which reflect the state of the art of current PV technologies and their prospects for facing the global climate challenges as well [22–24]. However, we believe that the generation of power from PV systems only can increase the total energy production but not enough to achieve the country's sustainable development goal to meet global challenges. There should be some smart and innovative additions to power production to face sustainable challenges. Besides the power generation from rooftop solar systems in educational institutes, power consumption minimization can provide increments of power savings to make buildings self-sufficient and off-grid or less dependent on the national grid. To reduce energy consumption, there are many approaches that have been prescribed by researchers and architects including modifying building construction materials such as building-integrated photovoltaics (BIPV) [25,26], coloured building-integrated photovoltaics (CBIPV), glazing windows, solar windows [27–31], and thin-film-coated low-emissivity (low-E) glass [32]. However, most of these materials can be implemented only for newly proposed buildings. In this article, we emphasize a combination of rooftop solar systems and retrofittable low-E-type thin-film-coated glass/windows for existing and new school buildings in Bangladesh to make them energywise and self-sustainable.

The heat is transferred by the method of the Sun's direct transmission, re-radiation, conduction, and convection on the glass of the building windows. Thermal control is important to save electricity. Modern window glass is advanced nowadays and offers a high visibility together with many additional features including resisting heat transfer (reduced heating (IR radiation above 750 nanometres) during summer and low heat leakage during winter), protection against UV radiation (300 to 380 nanometres), and shatter-proof properties. Low-E coatings enable thermal insulation through the control of the transmission of visible light, while blocking some components of the solar spectrum [33,34]. In winter times, these low-E coatings reflect long-wavelength (IR) radiated heat, generated internally, back into the room (thus reducing heat loss). On hot days, they block solar UV and IR radiation (thus resulting in lower solar heat gain coefficients and energy needed for cooling). Therefore, low-E glass enables energy savings during the day and night times in both summer and winter conditions, through the reduction of heat transmission (e.g., in summer into a building) and heat loss (in winter to the outside of the building). Typically, low-E coatings on glass can be used in a variety of ways including single-glazing, laminated glass, or double-glazed windows. Low-E glass products are ideal for commercial glazing as they can reduce the cooling energy costs of buildings. Different coating combinations on clear and tinted glass or with combinations of tinted PVB interlayers in laminated glass, give an array of colour and performance features [35]. Combining low-E thin-film coating and lamination results in shatter-proof (security) energy-efficient glass panels that enable significant energy savings and lower CO_2 (carbon dioxide) emissions [36]. Unlike conventional double-glazed panels, the laminated low-E glass panels or only the coated glass can be retrofitted into the existing windows of buildings.

In this study, power generation from roof-top PV panels on school buildings and a reduction of power consumption using retrofitted thin-film-coated glass is discussed from an economic point of view. This article is organized into two main subsections: one is the modelling of power generation using HOMER pro simulation software and the other is the presentation of low-E-type coated glass features that can help reduce a building's energy consumption.

2. Motivation for This Research Work

The present world's power consumption is mostly generated from fossil fuels. Among all users, the residential and commercial consumers in the building sector consume one-fifth of the world's total delivered energy [37–39]. In order to reduce carbon dioxide (CO_2) emissions as well as to achieve an improved green globe, using renewable energy sources is a well-known alternative. However, using only renewable energy sources will not be the best solution for a fossil-fuel-free sustainable green world. A combination of simultaneous energy-generation and energy-saving approaches can help to redesign the pathways to build a new sustainable world. The principal objective of this research article was to investigate the feasibility of installing rooftop PV systems and replacing the existing window glass panels with retrofitted, coated window glass panels, as well as to reduce the initial capital cost, the cost of energy, and greenhouse gas emissions to establish a smart building infrastructure for the educational institutes in Bangladesh. Figure 1 shows the schematic diagram of the proposed PV system in conjunction with an example of retrofittable coated window glass and the power collection and distribution process for a typical school building in Bangladesh.

With the help of the simulation tool HOMER pro [44], this study reveals that by using rooftop PV systems, sufficient power can be generated per day, which can reduce the pressure on the national grid. On the other hand, in remote areas where a grid connection is not available but the establishment cost remains the same, renewable energy can act as the lighthouse of society and ensure these areas get connected to the global world. Section 3 describes in detail the simulation that was performed by using HOMER pro software considering the school size and energy demand. The simulation results confirm the adequate generation of electricity from the roof of the school building without any additional horizontal land space required for the educational institutes. This research work will lead the opportunity to establish and build capabilities to conduct cutting-edge intelligent and smart energy system research, simulation, and building toward a more specialized research capability in smart building infrastructures. To the best of our knowledge, we can expect that this research will contribute to becoming energywise and self-sustainable, based on renewable energy generation, and can encourage industry experts and small business entrepreneurs as well. In addition, significant innovations are also expected in PV technologies due to the incremental demand for energy savings towards obtaining net-zero facilities in the future.

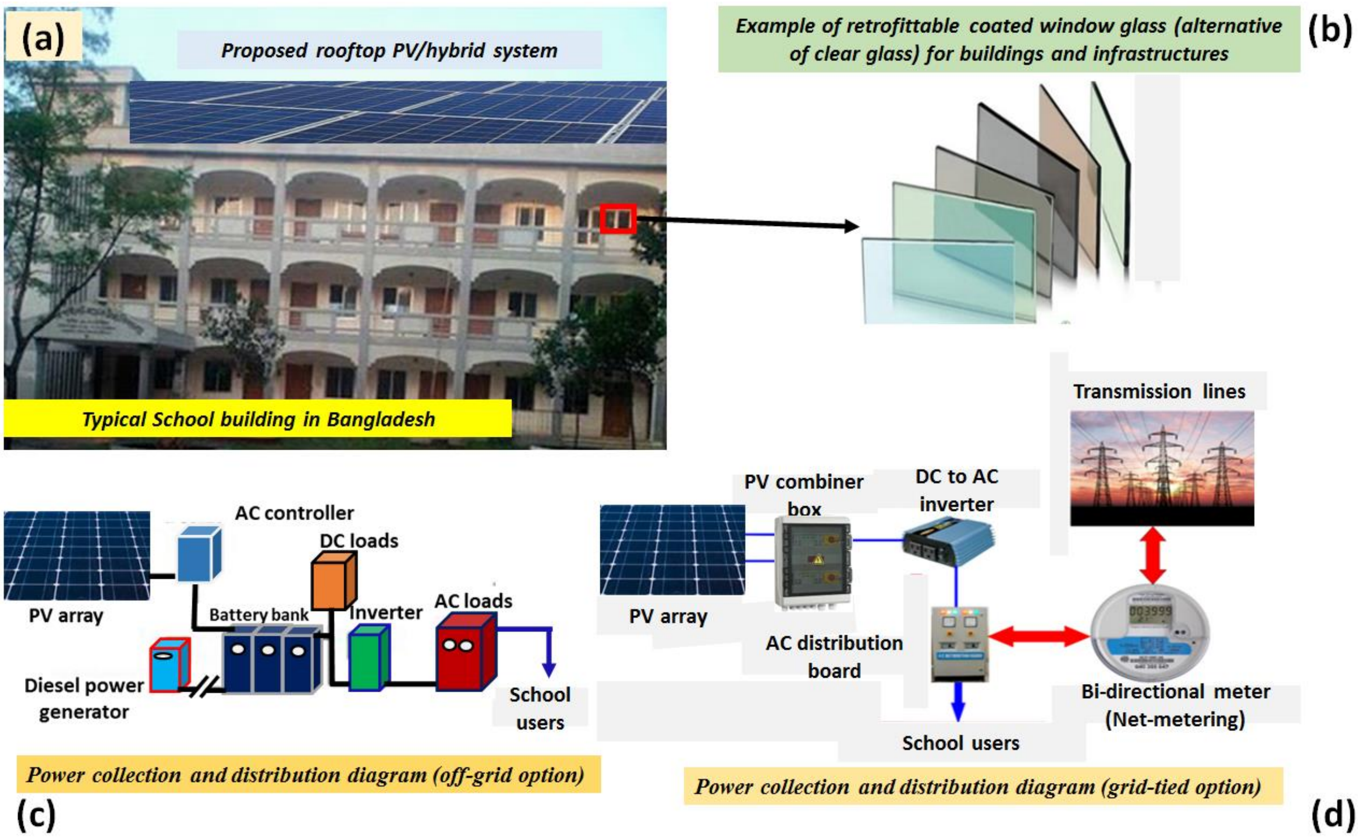

Figure 1. Schematic diagram of the proposed energywise and self-sustainable school building in Bangladesh; rooftop PV/hybrid system (**a**), the example of available retrofittable coated window glass on the local and international market (**b**), and the power collection and distribution diagram (both off-grid and grid-tied) (**c**,**d**) [40–43].

3. Simulation and Optimization of Load Consumption, Power Generation, and Cost Analyses

3.1. Load Consumption without Considering the Effect of Coated Glass

3.1.1. High School

A school requires continuous electricity during school hours (at least 6 h of nonstop electricity). Lights, fans, and computers are essential for schools and there are different types of rooms according to the student ratio. Table 1 shows the power rating and components for different types of rooms in a high school. High schools are comparatively larger than primary schools. We considered a typical high school in Bangladesh as a base case. In this school, there was a total of 41 rooms, including the teachers' and head teacher's room and four bathrooms for students and teachers.

Table 1. Power rating and components for different types of classrooms in a high school.

Component Name	Power Rating (W)	No. of Rooms (Different Types) for a Typical High School				
		Small (2 Rooms)	Small (8 Rooms)	Medium (26 Rooms)	Large (3 Rooms)	Toilet (4 Rooms)
Computer	200			5		
LED Light	10	2	3	4	6	1
Fan	30	4	3	4	6	

The daily power consumption for a typical high school was calculated as follows:

$$(154 \text{ lights} \times 10\text{ W} + 154 \text{ fans} \times 30\text{ W} + 5 \text{ computers} \times 200\text{ W}) \times 6\text{ h} = 42.96\text{ kWh per day}$$

Assuming that there are four Fridays in a month (Friday is the public holiday and all educational institutes remain closed; we can consider no use of electricity on Fridays), the monthly consumption was

$$26 \text{ days} \times 42.96\text{ kWh} = 1116.96\text{ kWh per month.}$$

The high school's load consumption in the winter season was:

$$(154 \text{ lights} \times 10\text{ W} + 5 \text{ computers} \times 200\text{ W}) \times 6\text{ h} = 15.9\text{ kWh per day.}$$

In the winter season, the average power consumption was about 413.4 kWh per month, whereas the rest of the year's power consumption was about 1117 kWh per month. Figure 2 represents the calculated load and the average power consumption differences monthly and yearly for a typical high school compared to a plot of the used power consumption data for the year 2021 of a subdistrict-level government high school in Bangladesh.

In Bangladesh, the summer season generally lasts from March to October of the year and the summer vacations were not accounted for in the simulation and calculation in this work. Moreover, in Bangladesh, most schools (except some private organizations) do not use any modern technology to reduce the heat in the summer. Therefore, in the simulation, we used average values. However, to get a better understanding of the monthly load consumption for a high school, we plotted it in Figure 2c by using the real power consumption data for a comparatively big high school. This school contained more than 1700 students and had more rooms than what was considered in the load consumption calculation. In addition, the school's operating hours were longer as this school ran a 3 h morning shift for the students in kindy to year five. Note that the power consumption in May and June was comparatively lower than that of the months July to September as was expected during the COVID-19 pandemic in the country, due to not operating the education program face to face.

3.1.2. Primary School

According to Fourth Primary Education Development Program guidelines, the base infrastructure of primary schools in Bangladesh is dependent on the population of the area and the student-classroom ratio is 40:1. In the most common cases, primary schools have either six rooms or nine rooms, one common toilet for teachers, and two separate toilets for male and female students. The required components are lights (10 W) and fans (30 W).

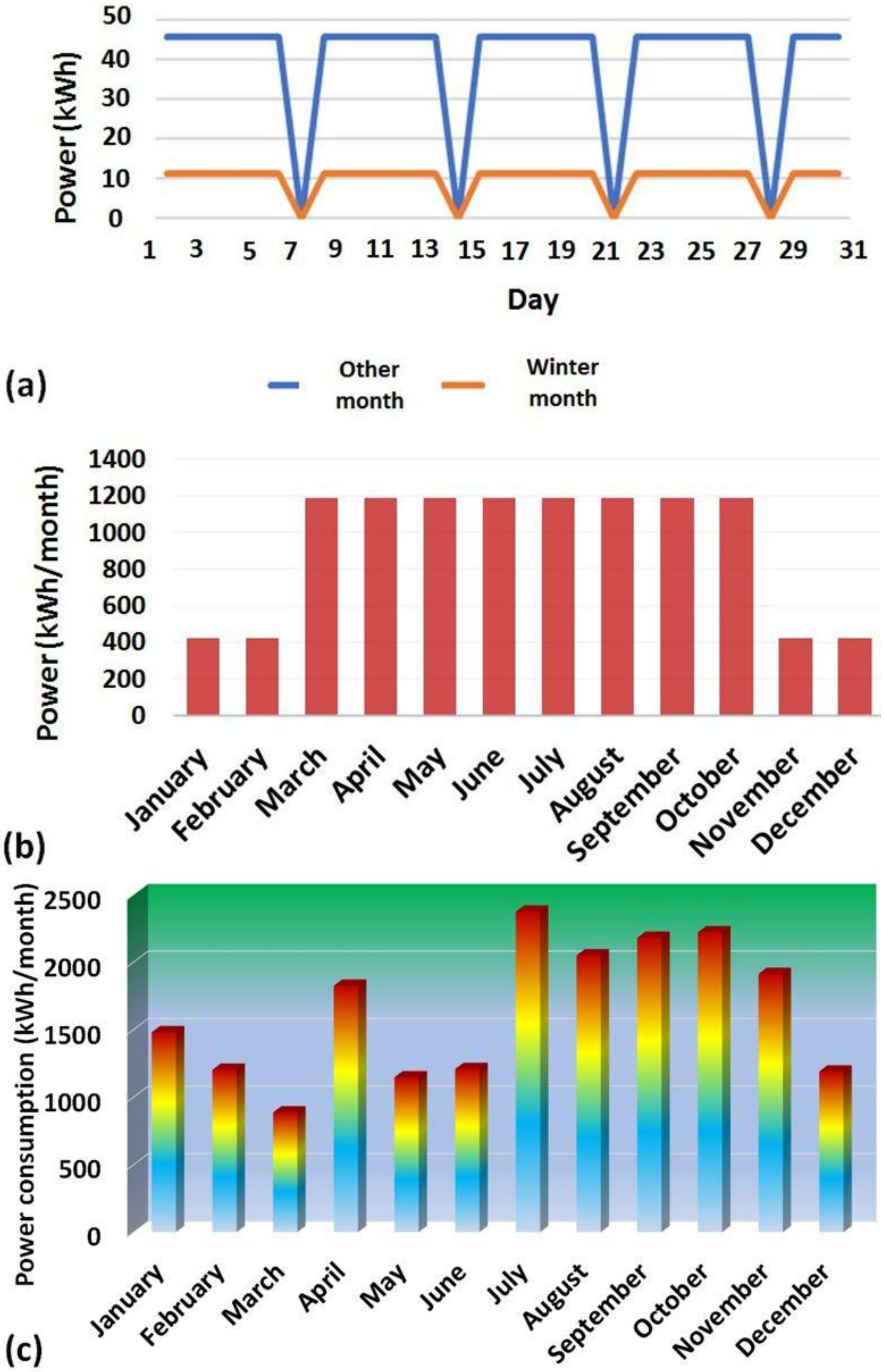

Figure 2. Calculated load and average power consumption differences monthly (**a**) and yearly (**b**) for a typical high school. A plot of the used power consumption data for the year 2021 of a subdistrict-level government high school (**c**). The data were by courtesy of Mr. Mohammad Kawsar Alam (Assistant teacher, Nabinagar Government Pilot High School, Nabinagar, Brahmanbaria, Bangladesh).

Daily power consumption for a primary school with six rooms (small building):

$$20 \text{ lights} \times 10\text{ W} + 18 \text{ fans} \times 30\text{ W} = 200\text{ W} + 540\text{ W} = 740\text{ W},$$
$$\text{or } 740\text{ W} \times 7\text{ h} = 5.18\text{ kWh per day}$$

For large buildings (9 rooms):

$$27 \text{ lights} \times 10\text{ W} + 24 \text{ fans} \times 30\text{ W} = 270\text{ W} + 720\text{ W} = 990\text{ W, or}$$
$$990\text{ W} \times 7\text{ h} = 6.93\text{ kWh per day}$$

Winter season load consumption for primary schools:

Small buildings need 1.4 kWh per day and 36.4 kWh per month
Large buildings need 1.89 kWh per day and 49.14 kWh per month

Figure 3 shows the differences in power consumption in a year for two types of primary schools. In the winter season, the load consumption was comparatively low because in the winter season, the load consumption components were lights and computers. In the winter season, the monthly power consumption was 36.4 kWh per month for small buildings and 49.4 for large buildings. On the other hand, in the summer season (April to September), the load consumption was high. It was 134.68 kWh per month for a small building and 180.18 kWh per month for a large building. Note that in the yearly load consumption calculation, we neglected the other school vacation periods because in Bangladesh, during school vacation periods such as the end of the year or just after the middle year exams, classrooms may remain closed but other official activities are still in operation.

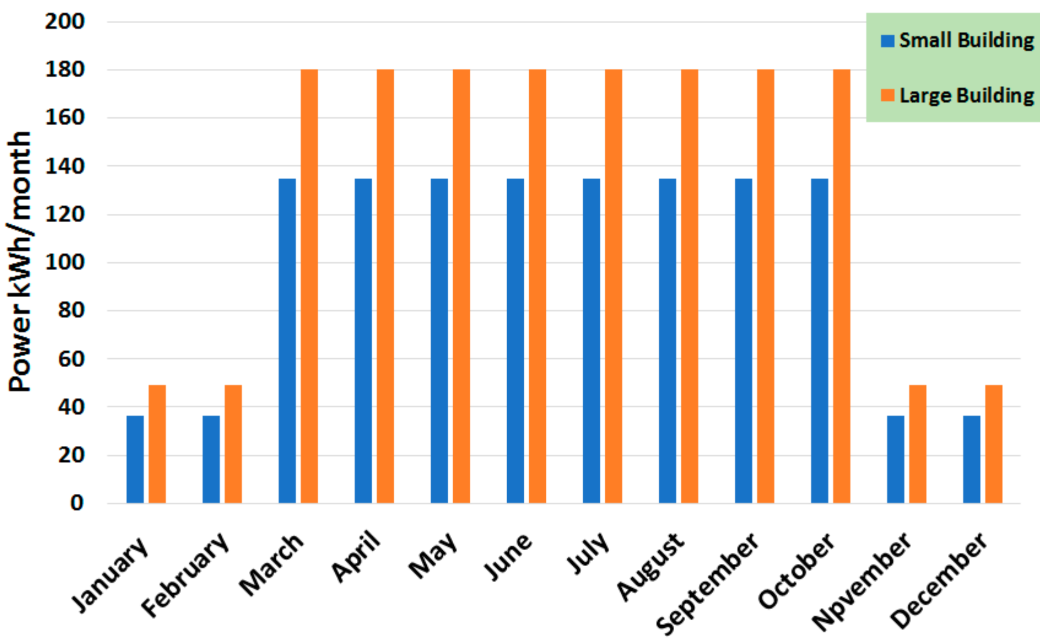

Figure 3. Yearly power consumption differences for two types of primary schools.

The load consumption calculation was performed based on the used components and their power ratings. A significant study was conducted to investigate the feasibility of rooftop solar system installation at academic buildings in Bangladesh [17,18], which was reliable and most relevant for future similar types of work.

3.2. Load Consumption Considering the Effect of Coated Glass

Thin-film coating is effective to reflect about 71% of IR heat of a building. Since primary and secondary school buildings in Bangladesh are not fully glass covered, 71% of IR heat reflection is not acceptable. However, the assumption was made that a reduction of about 5 °C of room temperature could be obtained, especially by using a coating technology. In Bangladesh, the school operating hours are mostly between 9 a.m. to 5 p.m. During the first hour and last hour of school, the outside temperature is quite low compared to other times of the day. Based on this, we assumed the number hours using fans was reduced to 4.5 h. Then, the high school power consumption can be calculated as follows:

$$(154 \text{ lights} \times 10 \text{ W} \times 6 \text{ h}) + 154 \text{ fans} \times 30 \text{ W} \times 4.5 \text{ h} + 5 \text{ computers} \times 200 \text{ W} \times 6 \text{ h})$$
$$= (9240 + 20{,}790 + 6000) \text{ watt per day}$$
$$= 36.030 \text{ kWh per day (before coating the glass, the consumption was 42.96 kWh)}$$

From the above calculation, we can say that by using a thin-film-coated glass, we can reduce power consumption by around 6.93 kW per day (16%) during the summer season, whilst in the case of a small primary school (6 rooms, standard building), the power consumption is summarised in Table 2.

Table 2. Summary of load consumption for a typical small primary school building while the effect of a thin-film coating is considered.

Component Name	Power Rating (W)	Number of Lights	Operation Hours	Total (kW)
Light	10	20	7	1.400
Fan	30	18	5	2.700
			Total consumption	4.100

From the above calculation, we can say that around 1.080 kW of power can be saved per day (without considering the coating, the power consumption is 5.180 kW per day). For a big primary school (with nine rooms), the power consumption is tabulated in Table 3.

Table 3. Summary of load consumption for a typical big primary school building while the effect of a thin-film coating is considered.

Component Name	Power Rating (W)	Number of Lights	Operation Hours	Total (kW)
Light	10	27	7	1.890
Fan	30	24	5	3.600
			Total consumption	5.4790

It can be seen that around 1.44 kW of power can be saved per day which is around 20% of the power consumption without considering the coating (6.93 kW/day).

3.3. HOMER Pro Simulation, Components, and Obtained Outcomes

3.3.1. Solar Irradiance and Clearness Index

The solar irradiance and clearness index were taken from the HOMER pro software database. Figure 4 presents the solar irradiance and clearness index for Bangladesh that was considered during the simulation process.

Solar irradiance data are important for solar-energy-based system utilization. It provides information on how much of the sun's energy strikes a location on the earth's surface during a particular period. The clearness index is the ratio of global extraterrestrial irradiance on a horizontal plane. The clearness index is defined as a time-dependent random binary variable (zero and one). If the sun is covered by clouds, it is close to zero otherwise, it is close to one. It can be seen (Figure 4) that the clearness index is high in November, but solar irradiance is low because of the winter season. Generally, November to February is the winter season in Bangladesh. In the winter season, the night is longer than the day, and the sky is often foggy in the morning, and sometimes foggy weather persists for several days in a row. April to June is the summer season though in March, the weather gets hotter, and the sky becomes cloudy. In March, April, and May, solar irradiance is also comparatively higher.

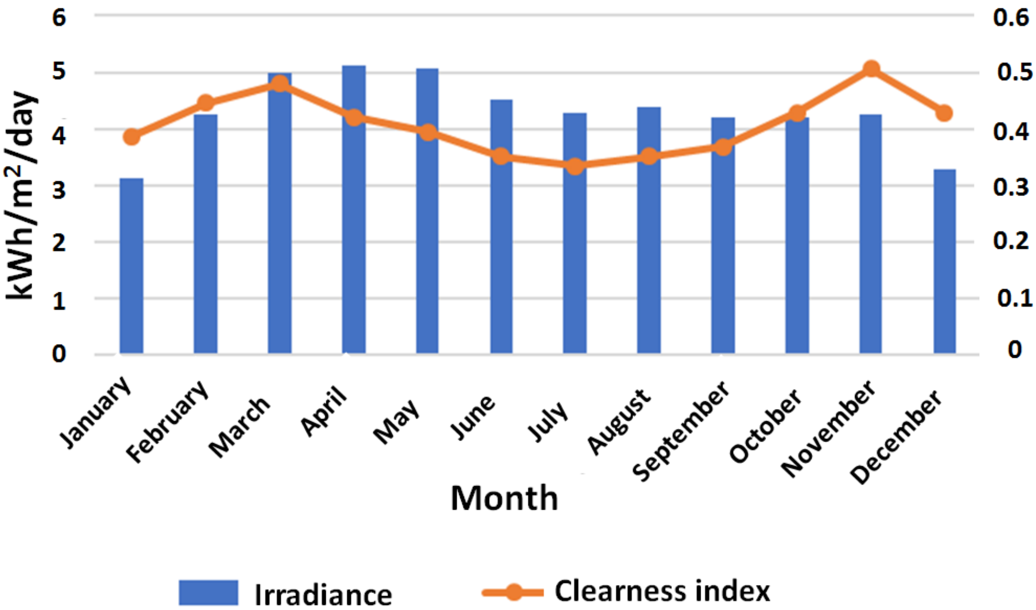

Figure 4. The average solar radiation and clearness index for a year.

3.3.2. Solar PV Module

We used generic flat-plate PV modules in this research as they are efficient for generating adequate power with minimum maintenance. The additional details about the PV module are available in the following datasheet which is very useful to understand the type and characterizing of a PV module [45]. The PV panels were oriented toward the south. The optimum tilt angle was calculated by adding 15 degrees to the latitude during winter and subtracting 15 degrees from the latitude during summer. The estimated primary cost of a PV module was USD 1283.46 including instalment cost and the replacement cost was USD 1283.46 considering a lifetime of about 25 years.

3.3.3. Battery

Batteries are often used in PV systems for storing energy produced by the PV array during the daytime and supplying it to electrical loads as needed. After all, batteries are also needed in tracker systems to operate at the maximum power point to provide electrical loads with stable voltages (3). Lead acid batteries were considered to be used in the proposed work. The installation cost for the battery was USD 300/battery [46]. The technical parameters for the battery are listed in Table 4.

3.3.4. Converter

A converter is mainly used to convert electrical power from alternating current (AC) to direct current (DC) or direct current (DC) to alternating current (AC). A large institute or off-grid system requires external power sources, such as a generator, which runs on diesel. In that case, the power generation system becomes a hybrid power generation system that has different signals such as DC and AC. The PV module produces DC, and a diesel generator produces AC; to synchronize these signals for charging along with supplying power to the load, a converter is needed for any hybrid power system. The estimated installation cost of a converter was USD 300/kW and the replacement cost was USD 300/kW [46]. Table 5 summarised the specification of the converter considered during the simulation process.

Table 4. Properties and the variables of the battery system.

Variable	Unit	Values
Nominal voltage	V	12
Nominal capacity	kWh	1
Maximum capacity	Ah	83.4
Capacity ratio	-	0.403
Rate constant	1/hr	0.827
Round trip efficiency	%	80
Maximum charge current	A	16.7
Maximum discharge current	A	24.3
Maximum charge rate	A/Ah	1
Lifetime	Years	10
Throughput	kWh	800
Initial state of charge	%	100
Minimum state of charge	%	20

Table 5. Parameters of proposed inverter and rectifier.

Variable		Unit	Values
Inverter	Lifetime	Year	15
	Efficiency	%	95
Rectifier	Capacity of inverter	%	100
	Efficiency	%	95

3.3.5. Generator

Due to the weather conditions, a PV system alone cannot deliver the required power; therefore, a battery backup diesel generator is an effective power source. Generators generate power from fossil fuels such as diesel. They turn chemical energy into electricity. The initial capital cost of a generator was estimated to be USD 500/kW with an operational and maintenance cost of USD 0.030/operational hour [46]. In the Bangladesh market, the current value of diesel is USD 0.759/litter. The specifications of the generator are given in Table 6.

Table 6. Specifications of the diesel generator.

Variable	Unit	Values
Fuel curve intercept	L/hr	0.838
Fuel curve slope	L/hr/kW	0.236
Lifetime	Hours	

In this work, we categorized different types of schools which can be run by PV/hybrid power generation systems and performed a cost analysis for the schools that can run on fully off-grid systems. The optimization of the economic parameter for each type of source was evaluated by Homer pro software as given in Table 7. The obtained result showed that the operation and maintenance (O&M) costs were low for a primary school as it could be run fully by a solar-based power system, while for a high school, a huge off-grid system was required as a backup due to a higher usage of power for a comparatively large number of students than that of primary schools. The obtained results indicated the requirements of PV panels and other components, e.g., generator, battery, etc., were completely dependent on the size of the school. Only the big schools (high schools or senior high schools) consumed comparatively more power and required to have an alternative option for power generation besides the PV modules. Conversely, only PV panels (maximum 6.6 kW) with proper energy-saving units were enough to run the small and medium schools, once designed to be fully off-grid. However, it was possible to install bigger PV modules on each school building's rooftop depending on the available funding for the schools. In addition, the schools could also be connected to the national grid when grid connections were available (note that some remote areas of Bangladesh are still not connected to the national electricity supply) and could be beneficiaries of the national grid. The results also revealed that a hybrid power generation system (which contained an average size of solar module of around 15.4 kW and other components) could run a high school where the installation cost could be paid back within less than 6.5 years.

Table 7. Optimized combination of PV, generator, and battery for a hybrid system: operational and maintenance cost analysis.

School Types	PV (kW)	Generator (kW)	Battery (No.)	Converter (kW)	NPC (USD)	Initial Capital (USD)	O&M (USD/Year)	LCOE (USD)	Payback Period (Year)
High school	15.4	14	34	10.7	66,204	40,250	2008	0.352	6.4
Primary school (Medium)	6.6	0	16	1.91	20,679	13,893	524.89	0.6328	NA
Primary school (small)	4.37	0	13	1.47	12,592	8407	323.75	0.5155	NA

Note that when performing the simulation for our manuscript, the world economy was in a stable condition, but the current world has been going through inflation due to the COVID-19 interruption, which is pushing up the costs for everything including components, transportation, and installation. The price of energy is also getting higher, so readers may keep the feedback time the same or closer to that found in the simulation.

We considered a diesel generator as an extra power source for the high school. Keeping in mind that a diesel generator emits carbon dioxide and creates noise, the use of diesel generators can be minimized based on the available bright roof area in a school for a larger number of installed PV panels or by being connected to the national grid. Figure 5 shows the various quantities of gas emissions from different types of energy generation systems, where it can be seen that using a hybrid power generation system (i.e., a combination of PV, generator, and battery), it is possible to have lower gas emissions for the off-grid system.

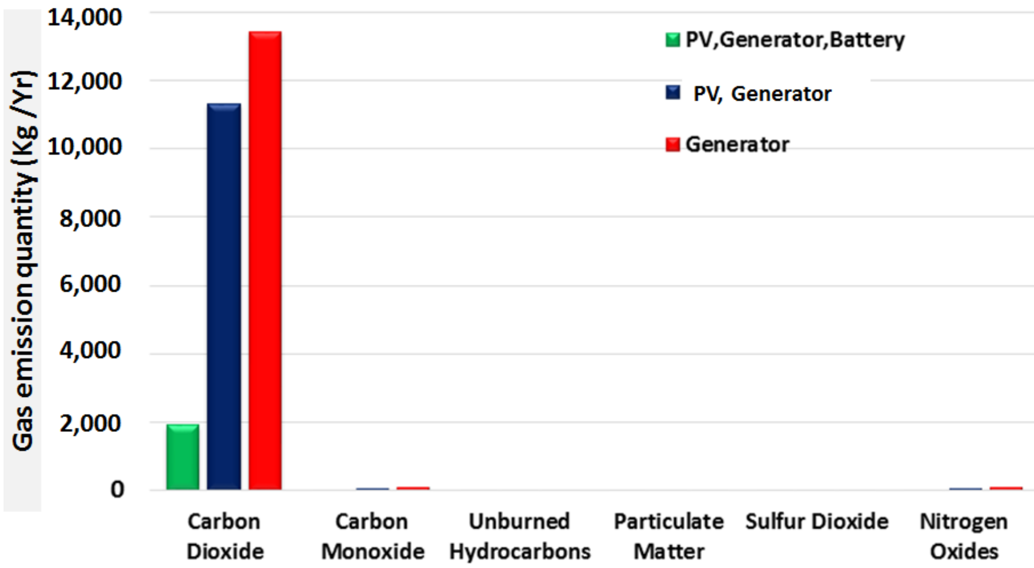

Figure 5. Comparison of gas emissions for different power generation systems for a possible off-grid system.

3.4. *Retrofitted Low-E Coated Windows Features and Energy Savings*

Thin-film coatings, mainly the low-emissivity (low-E)-type coatings can reduce heating-related, cooling-related, or both (limited cases) electric energy usage in buildings. Highly durable optical coatings for various applications, including energy-efficient glass window products are available worldwide [25,35,36,47]. There is a huge market for thin-film-coated glass and glazing window products, especially in Europe, America, Australia, and Middle Eastern countries [48–53]. Even the growth of urbanization, changing tastes, and building patterns have increased the use of different types of glass in Bangladesh forcing the country's industries to produce various types of energy-efficient float glass and glass sheets to meet the local demand [54].

The net-zero energy building (NZEB) concept has also brought the demand for thin-film-coated glass and windows in highlight, besides the various modern and sustainable building materials such as building-integrated photovoltaic (BIPV) products. In developed countries, nowadays, most high-rise buildings and other modern infrastructures use more thin-film-coated glass panels and modern glazing windows to save energy towards achieving the smart-city concept [55,56]. Even spectrally selective thin-film-coated glass panels are also used in many greenhouse projects for agriculture, as the properties (transmittance, reflectance, and absorption) of thin-film coatings can be tailored according to the plant's growth requirement [57–61]. The energy-saving potential of advanced coated glass products was illustrated by Nur-E-Alam et al. [34], in terms of performing solar heat filtration through a simple generic thin-film coating on the glass. They demonstrated without constructing any type of double-glazing system, a simple single-pane window constructed using a metal–dielectric composite (MDC)-based coating that could significantly reduce the radiant heat transmission into the internal spaces of buildings. The integration of the standardized solar radiation spectrum presumed to be normally incident onto the coated glass resulted in only about 29% of solar IR heat entering the internal building spaces through the thin-film-coated glass. Figure 6 represents the schematics of the spectra and energy distribution of sunlight together with the possible features when the incident sunlight passes through clear glass and a thin-film-coated glass, and a comparison of the transmission spectra of clear glass and a laboratory-demonstrated thin-film coating.

Typically, low-E coatings are of two types, passive coatings that are mostly designed for solar heat gain and others that reflect the solar-infrared radiation, known as solar-control low-E coatings, that are designed to obtain a low solar heat gain coefficient (SHGC). The coatings with SHGC less than 0.35 are considered ideal for window glazing applications. A liquid-type coating (SketchNanoGard, SNG) was established and investigated by Umberto Berardi [62] intended for use in in situ window retrofit. The author described the energy-efficiency improvement possibilities for different kinds of windows in Canada using this SNG coating. Another research group reported on the economic benefits of low-E coatings by comparing the annual cost for cooling and heating in buildings in Chicago and Miami, with buildings having noncoated glass windows. They reported that as a significant reduction of the solar IR heat occurred through the coated windows, the heating and cooling costs of the buildings were significantly reduced [63]. However, there should be a question in the case of implementation of these types of energy-saving coatings or coated glass in already established school buildings. If the buildings are in construction, it is easy to design the windows using modern coated glass that requires special framing as well. In old or already-established buildings, the window glass can be replaced using retrofitted coated glass including laminated low-E coated glass, spray-coated glass, and coated polycarbonate sheer onto the existing windows depending on the institutional budget. There is a significant amount of research work that has been conducted worldwide to find the feasibility of replacing clear glass windows with modern glazing/coated low-E-type windows in terms of an economic point of view [58,64–66]. However, in the case of Bangladesh, one thing should be considered regarding the coated glass: dust. If single-panel coated glass is used, removing the dust from the windows can damage the coatings on the glass and it can change the optical properties and visual appearance of the buildings. In this case, using a laminated low-E coated glass would be a wise idea, where the coatings are protected between two glass panels. Thin-film coatings when combined with lamination, enable the development of energy-efficient glass panels of an adequate security level, which can be retrofitted into existing buildings and homes while maintaining the glass thickness below 6.4 mm (for retrofitting).

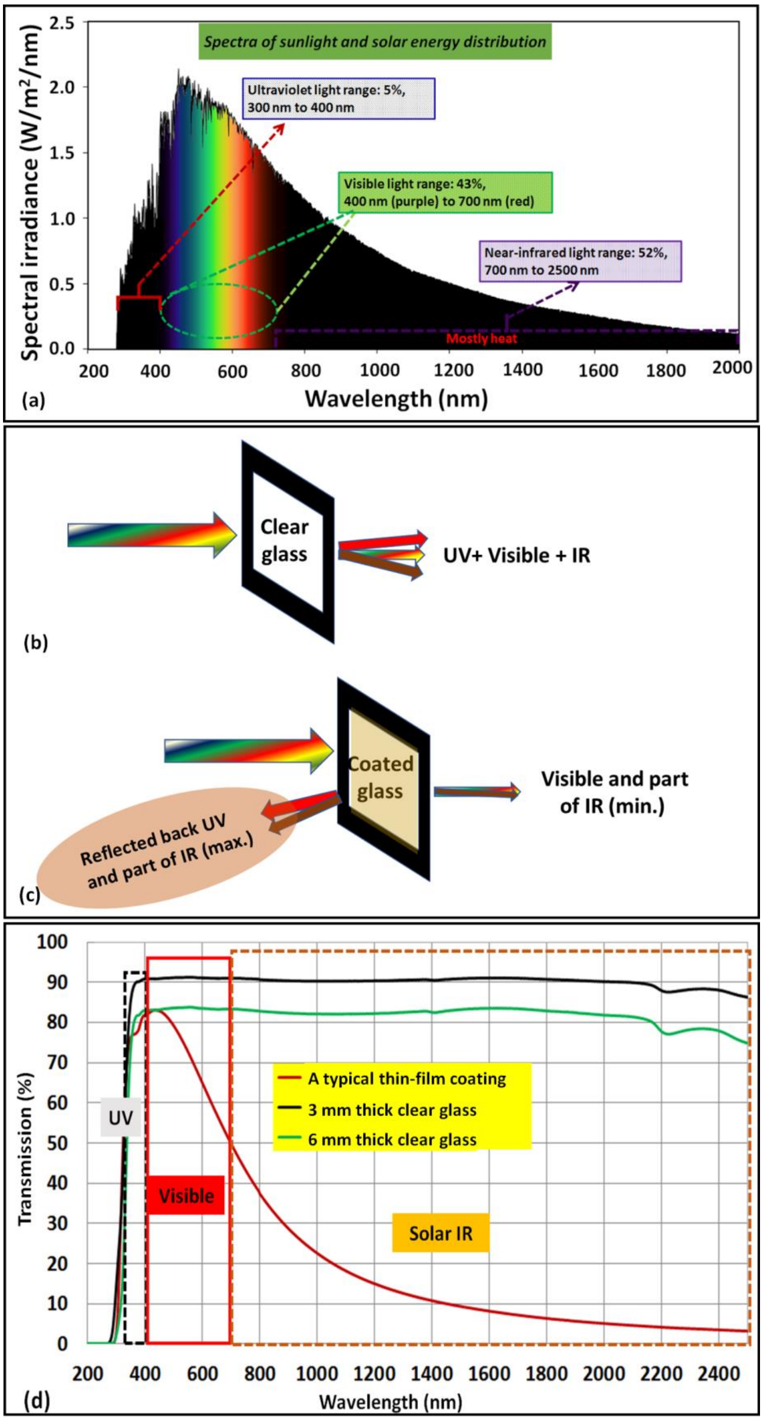

Figure 6. The spectra of sunlight and solar energy distribution (**a**), the features of sunlight spectra before and after passing through a clear glass and low-E thin-film-coated glass (**b**,**c**), and the measured transmission spectra of a laboratory-demonstrated typical thin-film coating compared with 3 and 6 mm clear glass panels (**d**). It can be seen that the thin-film coating significantly filters the solar IR spectrum while clear glass transmits most of the IR spectrum.

4. Discussion

The very recent electricity crisis in Bangladesh confirms more production of power is required, as well as economizing the power consumption all over the country. Bangladesh has been facing severe power cuts for the last couple of months and it could continue for another couple of months. However, the power-cuts have spurred the current power-handling policies, and it seems that it is time for considering innovative approaches and new policies as well. The shortage has brought back load shedding, shutting down part of the grid to prevent the failure of the system, which had become a thing of the past, in both cities and rural areas. Government and power board authorities are advising the public to be energywise and to reduce power consumption on many occasions, which is very difficult to follow. According to the scholars and authorities of Bangladesh, the main issue of this current critical condition is not only the shortage of natural resources, but power transmission and distribution is also a major issue for Bangladesh's power sector [67–69]. Haque et al. made a detailed study of the power crisis and possible solutions in Bangladesh. They reported misuse, system loss, and corruption in the power sector as the main issues in the power crisis in Bangladesh. To resolve the power crisis, they proposed several suggestions including the control of misuse and corruption in the power sector, control of the load demand by using compact fluorescent lamps (CFL), the transformation of holidays, proper load management, independent power producers (IPP), and reducing transmission loss. However, the proper utilization of renewable energy was focused on as the best choice for solving the power crisis in Bangladesh due to its low cost and lesser risk [70]. Since August 2017, after the first introduction of solar power to the national grid in Bangladesh, many solar minigrids are now being built in the country to provide electricity to off-grid areas (especially for those areas that do not have electricity from the national grid). Despite the high price of solar power, people of those remote areas are enjoying 24 h of electricity with solar power lighting, which brought happiness to the villagers as they could be connected to not only the country but also the world using the internet. At present, many large solar power projects are planned or under implementation. By 2024, over 1000 MW of solar power will be added to our national grid, which will continue to grow.

We believe that it is the right time to be innovative in both the generation and consumption of power. Our proposed concept will be very much effective and will reduce the huge pressure from the national grid once those thousands of educational buildings become independent and self-sustainable. Our study revealed that power generation from PV panels had a good match with the load demand of school hours. As a result, a minimum storage device was required to meet the electricity demand. It also revealed that the excess power generated from the system could be exported for neighbouring household demands. For example, the average-sized PV panel takes up an area of 17.6 square feet and produces 265 watts under direct sunlight, which is equivalent to over 15 watts per square foot [71]. If 90% of all school buildings (175,000 [15]) could be brought under the rooftop PV system, then the total number of effective buildings would be 157,500. From each building, if a 100-square-feet area could be used for PV panels, the total area of PV panels would be 157,500 × 100 = 15,750,000 square feet, which would result in a possible power output of 15,750,000 × 15 = 236,250,000 watts = 236.25 MW, four times bigger than that of a recently established solar farm in Bangladesh. However, this number will differ depending on solar irradiation, climate condition, and shading factors. From the simulation, it can be noted that the average solar size was quite enough to generate the required power to run the schools. However, this will be confirmed upon completion of future feasibility studies to use the maximum roof area of school buildings to install PV panels to make each school a mini solar power station. For example, the Bangladesh government has funded each school to build a new model building (up to three storied) and those buildings have a minimum roof area of around 94 feet × 34 feet = 3196 sq. feet, which are available to install solar panels for a possible maximum energy generation. In addition, by using the HelioScope simulation tools [72], we calculated the rooftop's available space and panel sizing for the rooftop of the north block of the Udayan school, Dhaka which has a usable roof area of around 9500 square feet. Figure 7 shows the images of the rooftop space of the north block of the Udayan school and HelioScope simulated PV sizing.

In the simulation, 157 solar panels named CAT430 were used with a capacity of 430 watts each. To get the highest efficiency, HelioScope suggested using two optimum converters with a size of 24.10 kW. The possible total power output from the rooftop was

96,993 kW per year, which is equivalent to 266 kW per day. Table 8 summarises the details of upscaling the PV sizing and possible power output.

However, a further study is required to find the feasibility of collecting and saving the produced electricity from the PV systems either directly to the grid or stored in external storage facilities. There are several useful reports found in the literature about the challenges and possibilities of collecting power from PV systems [73–77], which can help us to continue our research work upon getting enough research funds. Hence, together with this generation of power, if the building windows are replaced by energy-efficient coated glass, this can help the buildings to reduce their energy consumption by up to one-third, especially in summer, and the saved energy can be provided to other sectors to mitigate their demand. On the one hand, the price of low-E coated glass is comparatively higher than that of normal clear or coloured glass products, but low-E coated glass will pay back in terms of saving energy costs, while normal clear glass will do nothing. On the other hand, the government is going to implement two days off for all educational institutes, which will take 104 days of minimum (almost zero) use of power in a year. Other than that, in Bangladesh, all educational institutes also get various festival holidays including all government public holidays. Thus, the maximum generated power on those holidays can be supplied to the national grid where the grid connections are available. For off-grid-connected school buildings, a huge amount of electricity can be saved for rainy, cloudy, and foggy days when solar power generation will be minimum.

Figure 7. Images of rooftop space of the north block of the Udayan school, Dhaka (**a**) and the PV sizing obtained using the HelioScope simulation tools (**b**).

Table 8. Summary of upscaling the PV sizing and possible power output obtained from Helioscope simulation performance.

Area of the Rooftop (Sq. Ft.)	Number of Panel	Capacity (W)	Power Production (kW/Year)	Grid Supply (kW/Year)	Max. Output kW/h	No. of Converter	Size of Converter (kW)
9448	157	430	96,993	311	47.9	2	24.10

Our new approach to establishing energywise and self-sustainable school buildings using rooftop PV or hybrid systems in conjunction with retrofittable low-E coated windows can be an excellent way of providing intellectual and innovative solutions for the efficient, cost-effective, and environmentally sustainable development of Bangladesh's energy and power infrastructure, which aligns with the vision and mission of Bangladesh Energy and Power Research Council (BEPRC) as well [78]. This new approach can attract intellectuals of national and international research and commercial organizations and can also assist entrepreneurs to develop application-specific technologies. For the first track development of this new idea, government renewable energy policy and subsidies to small entrepreneurs, schools, and private companies will be helpful; however, it may require the renewable energy policy to be rigorously revised. The present policy and incentives for grid-tied PV power generation for IPPs have been studied to address economic barriers to grid-tied ground-mounted PV power generation and several new proposals have been suggested [79].

5. Conclusions

The simulation results confirmed an adequate generation of electricity was possible from the roof of school buildings without any additional horizontal land space required for the educational institutes. We demonstrated a combined approach of solar energy harvesting and savings, which is a small forward step to meet the purpose of the country's green energy and low carbon emission goal for a sustainable future. The HOMER pro simulation results confirmed that it was possible to run an educational institute in Bangladesh by using its own site-generated power by installing only a rooftop PV system or a hybrid system (i.e., the combination of a PV system and a diesel generator) with a battery backup in case of a lack of sun availability such as on rainy days or the during rainy season. The battery backup (i.e., storage system) would help to provide the required energy during the rainy season and on cloudy days, while the retrofitted coated glass would serve as a heat protector during the summer days and would save the energy for a longer lifetime. The simulation results indicated that a hybrid power generation system could sufficiently run a high school where the installation cost could be paid back within less than 6.5 years. We calculated that by considering most of the schools and assuming a minimum area of the buildings' rooftops (only 100 sq. ft.), it was possible to generate more than 200 MW of power, which is four times bigger than that of a recently established solar farm in Sutiakhali in the Mymensingh district. However, the utilization of larger rooftop space in a school building could lead to generating up to 266 kW per day. This huge amount of power production together with the energywise building concept could be a big relief for the national power grid system with either all schools being off-grid or grid-connected to supply the national grid. This approach would reduce the pressure on the national grid and the schools could save the electricity cost, hence it would create a sustainable green environment at schools in Bangladesh and could be a model for any other countries. A further research study is required to investigate the feasibility related to the progress of solar electrification for school buildings and make them save power without compromising comfort inside the buildings. Our research work is an ongoing project; however, based on the possibilities and funding opportunities, we hope to continue our work further to make a pilot project to implement our proposed ideas to realize our work and collect real-life data for future reporting elsewhere.

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