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Design and Techno-economic Analysis of a Grid-connected Solar Photovoltaic System in Bangladesh

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***Abstract*— Growing energy demand has exacerbated the issue of energy security and causes us to necessitate the utilization of renewable resources. The best alternative for promoting electricity generation in Bangladesh with renewable energy is solar photovoltaic technology and grid-connected solar photovoltaic (PV) systems are increasingly being popular considering solar potential and the recent cost of PV modules. This study proposes a grid-connected system using solar PV with a net metering strategy using Hybrid Optimization of Multiple Electric Renewables model. Outcomes reveal combining 420 kW PV with a 405-kW converter and connecting to the utility grid is the least cost and ecologically healthy configuration of the system. Electricity generation cost is estimated to be 0.0725 dollars per kilowatt-hour with a payback period of 6.4 years based on the system's 20-year lifespan. Also, compared to the existing grid and the electricity generation of diesel, the optimized system with a renewable fraction of 31.10%, provides a reduction in carbon dioxide emissions respectively of 191 tons and 1,028 tons each year.**

Keywords—Grid-connected solar system; Solar photovoltaic array; HOMER model; Life-cycle cost; Cost of energy; Emissions

I. INTRODUCTION

Electricity plays the leading role in our daily lives in homework, industry, transport, agriculture, and so on. The Gross Domestic Product (GDP) yearly growth rate represents any country's socio-economic development. Gross domestic product is heavily influenced by a country's long period energy supply surety, particularly its direct links to the country's energy market [1]. Electricity is one secondary type of energy that is created by the energy transition. It can be produced in a variety of ways, including the combustion of gas, oil or coal and some renewable energy (solar, hydro, wind, tidal, and nuclear energy) resources. Renewable sources of energy are long considered clean energy creation as a replacement of fuels burning because they can display nil environmental harm. For the past few years, energy consumption has grown in every discipline of life globally. It is extrapolated almost from 2010 to 2030 to increase by 33% [2]. Bangladesh has many potentials in renewable resources such as; Solar, Hydro, Biogas, Biomass, Wind those can help to attain success of the government announcement in February 2000 of a vision and policy statement outlining its plans to supply energy to the whole country in stages through 2020 [3]. Already, the Bangladesh government provides electricity to 85.6% of the total people in 2020 [4]. There are already 583.5 GW of operating PV systems around the world., accounting for a significant share of the 2563.8 GW total installed renewables capacity [5]. In Bangladesh, total solar energy production is 500 MW, which contributes to 39.5% of total renewable energy[6]. However, about 3.3% of Bangladesh's total generation of electricity is from renewable energy, which is still on the rise, as the government has established the objective of generating 5% of renewable energy supplies by 2015 and 10% by 2020 and a series of renewables programs has been initiated to attain this objective [7].

To meet this development goal, net power demand is expected to reach 61 GW by 2041. Bangladesh now has 20,383 MW installed capacity with total power demand of about 20,000 MW during peak hour, however the maximum peak generation is 12,738 MW with a growth rate of only 1.26 percent, and electricity generation per capita is expected to be 510 kilowatt-hours [8]. In comparison to all other forms of energy, Fig. 1 indicates that Bangladesh relies heavily on fossil fuels to generate power. According to estimates, the country's fossil energy reserves will be depleted within the next decade. For this reason, Bangladesh must deploy alternative energy generating to meet the growing demand. This green power strategy can minimize present dependencies on nonrenewable resources, as well as different imported fuels [1]. This report recommends solar as an alternate power source to address this energy crisis. Because, from 2010 the cost of power generated by solar photovoltaic plants dropped dramatically. Even though the cost of electricity from non-renewable source was estimated to range from 0.05 to 0.17 dollars per kWh in 2017, depending on fuel and country, the global total average cost of electricity from the utility-scale solar systems has decreased since 2010, to 0.10 dollars per kWh for new ventures deployed in 2017, and it is continuing to fall [9].

Bangladesh lies between 20.30° to 26.38° North latitude and 88.04° to 92.44° East longitudes, which is optimum place to use sun power and the radiation is 4 to 6.5 kWh/m^2/day [10]. Consequently, Bangladesh has a significant solar PV power generation option for making sustainable energy generation by solar PV system. According to International Renewable Energy Agency statistics, grid-connected solar capacity reached 580.1 GW globally and 3.4 GW of off-grid capacity in 2019. With grid-connection facility, Bangladesh's installed PV capacity has exceeded 370 MW [11].

In this study, an improved and cost-effective technique to synchronize the PV array output with the utility grid using a net-metering scheme is proposed using HOMER (Hybrid Optimization Model for Electric Renewables) software at Younus Khan Scholars' Garden, Ashulia, Dhaka. The study's goals are to introduce the technology as a more cost-effective and ecologically friendly replacement to the present grid-only and diesel-generator systems, with the goal of reducing pollution by lowering greenhouse gas emissions and saving money for the Younus Khan Scholars' Garden.

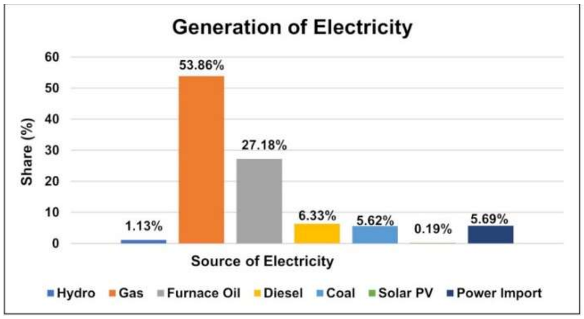

Fig. 1. Electricity generation in Bangladesh by fuel type.

A. *Literature Review*

In Bangladesh, extensive research has been conducted on grid-connected solar PV system applications. N.K. Das and J. Chakrabartty propose an energy scenario and evaluate Bangladesh's energy mix [12]. The potential for renewable and solar energy in Bangladesh was investigated and presented in Ref. [6]. Global Solar Atlas 2.4 produced solar resource maps for Bangladesh in December 2020 [10]. According to the study, Bangladesh's yearly average solar radiation is calculated of 4.59 kWh/m^2/day, with minimum of 4.33 kWh/m^2/day in September and highest of 4.95 kWh/m^2/day in April.

In Bangladesh, a study of grid-connected solar system was conducted without any techno-economic assumptions [13]. An improved configuration has less energy cost of $ 0.24/kWh and emits 30% less CO_2 than the battery-based system [14]. According to another study in Bangladesh's southeastern region, the grid-connected system has cost of producing one unit of power is USD 0.20 [15]. Another study found that a grid-connected PV system with a USD 0.200/kWh generating cost could meet Bangladesh's electricity demand [16]. Another study used the HOMER model to propose a grid integrated system with PV and battery storage for 800-household rural residential region in Bangladesh [17]. According to the analysis, the suggested system's levelized cost of electricity (COE) is USD 0.24/kWh. Similarly, the HOMER model was used to depict a hybrid conjugation with an electricity cost of USD 0.0995/kWh [18]. Iqra and Abdul Razaque, compared off-grid with grid-tied solar systems using HOMER [19]. In furthermore, a hybrid system analysis of a small town in Bangladesh revealed that generation cost is 0.47 USD/kWh, with a 10% annual capacity shortage [20]. In India, Amit and Ashutosh presented an optimization study of grid-connected hybrid systems using HOMER, which resulted in lower levelized COE and emissions [21]. In rural Pakistan, Fahad Ali used HOMER software to examine techno-economics of grid-connected hybrid systems, and the cost of electricity is currently lower than off-grid systems [22]. Also, Samir & Lin used HOMER optimization to find economical and environment friendly hybrid system in Egypt [23]. Finally, Chouki and Maamar present a hybrid grid-connected system of low levelized cost of electricity with minimal carbon dioxide emissions for a university building in the UAE [24].

Almost all of the studies cited above looked at PV, PV-diesel, PV-wind-diesel, PV-diesel-battery, PV-diesel-hydro and hybrid systems and concluded that renewable systems are most viable. Still, some are also reviewing grid-tied PV systems with a high levelized COE or high carbon dioxide emission. Thus, the studies for Bangladesh are less consistent yet. This research uses surveyed primary energy usage data and updates system component costs for more up-to-date energy system planning and includes a net metering scheme for selling excess electricity. The sensitivity analysis also broadens and deepens the broadness and deepness of the evaluation. The outcome of this study can applicable in any locations at Bangladesh where electrification is available from the grid and solar radiation and can offer insights into other fast-emerging Asian countries.

II. MATERIALS & METHOD

Identifying Younus Khan Scholars' Garden as a good site for on-grid electricity generation, first we used National Aeronautics and Space Administration (NASA) data for solar potential and temperature. From September 2020 to April 2021, primary data was gathered from surveys and end-users' questionnaires. Secondary data was mostly gathered via yearly reports, publications, literature, and online searches from relevant organizations. Then, the collected data is fed to HOMER and used to generate daily load profile for the HOMER model, which was then used to build the system. Finally, the system delivers most cost-effective and ecologically friendly alternative for meeting the area's daily electricity consumption. Furthermore, changes in critical parameters like solar radiation, grid electricity price, and PV array capacity were considered in sensitivity analyses.

A. *Equation of PV Array*

Output from PV arrays mostly depends on array size, derating factor, solar radiation, temperature. Compute that output, HOMER uses this equation below.

$$P_{PV} = C_{PV} f_{PV} (I_T / I_{T,STC})[1 + \beta_P (t_C - t_{C,STC})] \quad (1)$$

Here, C_{PV} is PV array capability (kW), f_{PV} is Derating factor of PV Panel [%], I_T is in the current time step, solar energy strikes the array in kW per m^2, $I_{T,STC}$ is in conventional test conditions, incident radiation kW/m^2, β_P is heat coefficient of energy in %/^{o} C, t_C is current time step's cell temperature in degree Celsius, and $t_{C,STC}$ is temperature of cells under typical circumstances for testing [25°C].

B. *Cost Analysis Procedure by HOMER*

The sum of the C_{PV} and converter costs C_{CONV} is the system cost.

$$C_{System} = C_{PV} + C_{CONV} \quad (2)$$

1. Net present cost: Total installation and operation cost over its lifetime, is determined as:

$$NPC = \frac{A_C}{R_F}(i, P_L) \quad (3)$$

where, A_C, R_F, i, and P_L represent total annualized cost, capital recovery factor, interest rate in percentage, and system lifetime in years, respectively.

2. Annualized cost: The sum of all equipment's annualized costs, capital, operation, maintenance, including replacement and gasoline costs.

$$C_{Annual} = (CCR_F + CO) \quad (4)$$

3. Capital recovery factor: It is a ratio which calculates present value of equal annual cash flows.

$$R_F = (i \times (1+i)^n / ((1+i)^{n-1}) \quad (5)$$

where, n denotes length of time and i denotes yearly real interest rate.

4. Cost of energy: It is the average cost per kilowatt-hour of usable electricity produced by system:

$$COE = A_C / (D_{\text{Pr},(AC)} + D_{\text{Pr},(DC)}) \quad (6)$$

here, $D_{\text{Pr},(AC)}$ denotes primary load of AC and $D_{\text{Pr},(DC)}$ is DC primary load.

C. Study Site and Electrical Load Profile

Younus Khan Scholars' Garden is located at 23.5° North latitude and 90.2° East longitude, which is connected with the utility grid through the REB distributor to meet its energy requirements. Now, a grid-tied solar system is proposed to meet that demand using 2900 m^2 rooftop area of a total 10,000 m^2 area. The climate is subtropical monsoon, with an annual rainfall of 1595 mm here. Bangladesh's rainy season runs from June through September [25]. The load demand was investigated across the site. It has a load of 491 kW for a total of 8240 pieces of equipments. Daily average load demand has also been determined which is depicted in Fig. 2.

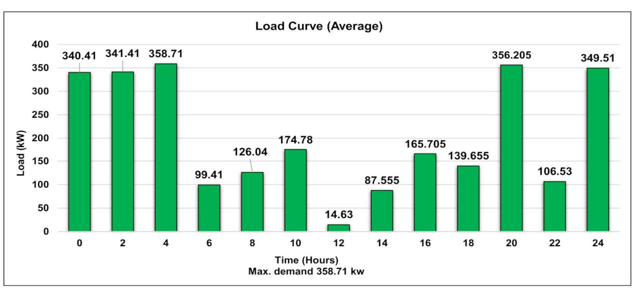

Fig. 2. Average electrical load curve of Younus Khan Scholars' Garden.

D. Input Parameters of Proposed Grid-connected System

HOMER carries out optimization and determines the technical feasibility and life cycle costs in each hour of the year of a certain system configuration as well as multiple optimizations under a variety of input assumptions to assess the impacts of changes in input variables [26]. Investigated load profile is changed in the HOMER model by defining average everyday demand profile of 10% daily, 15% hourly random variability. As a result, the annual peak load has increased to 718.68 kilowatt, and initial demand has increased at 4945 kilowatt-hour per day. Figure 3 depicts the proposed system configuration which uses a blockchain technique to connect to grid. Fig. 4 display overall hourly load profile. Solar and temperature resources data was acquired from the NASA database of the study area are presented in Table 1.

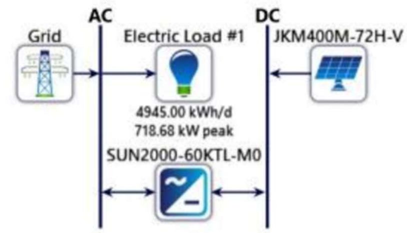

Fig. 3. Configuration of proposed system.

Fig. 4. Hourly load profile by HOMER.

TABLE I. SOLAR RADIATION (KWH/M²/DAY) AND TEMPERATURE (°C/DAY) AT ASHULIA.

Month	Solar Radiation (kWh/m^2/day)	Clear ness Index	Temperature (°C/day)
January	4.36	0.632	19.74
February	4.92	0.616	23
March	5.59	0.599	26.45
April	5.76	0.552	27.15
May	5.3	0.481	27.65
June	4.53	0.405	27.95
July	4.23	0.382	27.66
August	4.29	0.404	27.61
September	4.02	0.415	27.01
October	4.32	0.517	25.48
November	4.28	0.601	22.5
December	4.21	0.644	20.2
Annual average	**4.65**	**0.521**	**25.20**

E. Technical and Economic Input Parameters

PV modules produce DC electricity, which an inverter converts to AC, which subsequently feeds into the grid and supplies the AC load through net-metering strategy. Because the grid works as infinity storage in a net-metering grid-tied solar PV system, we designed this system without battery storage [27].

1. Photovoltaic modules

The PV array's output is proportional to the amount of solar energy received. Like, a panel generates 80 percent of its rated output if solar radiation is 0.80 kW/m^2 [28]. This simulation includes PV module having 19.88% efficiency and 25 years lifetime. Here temperature effect and a derating factor of 88% is accounted. Solar PV's capital and substitution expenses are considered as $920/kilowatt and operation and maintenance cost are $0.55/year.

2. Power Converter

The simulation model includes power converter with a 98.6% efficiency and a 15-year lifetime, with capital and substitution costs of $75/kW and operating and maintenance (O&M) costs of $1.60 per year. The converter is used in inverter mode as the grid is to be fed in an alternating way.

3. Grid

In this study power costs are considered as $0.107/kwh for purchasing and $0.165/kWh for sale back to the grid [29].

A nominal discount rate of 8% and a 6% inflation rate were applied in this simulation with both load-following and cycle-charging dispatch strategy [30]. The capacity shortage penalty is not taken into account throughout the planned project's 20-year lifespan. The maximum renewable portion was also determined to be 100%.

III. Results & Discussion

This part displays the HOMER model's optimization results, feasibility evaluation and sensitivity results also.

A. Optimized Outcome

The overall optimization outcomes are given in Fig. 5 based on the system's NPC and optimized model by category are in Fig. 6.

HOMER findings demonstrate that PV-Grid-Converter configuration, where PV array capacity is 420 kilowatt and a converter capacity is 405 kilowatts with cycle-charging strategy, is the most cost-effective setup. It has a USD 1.83 million total NPC and a COE of USD 0.0725/kWh, with 31.1% renewable energy penetration. It is not only less expensive, but it also emits fewer CO_2 (953 tons/year) into the atmosphere. The payback period of the system is only 6.4 years, which means approximately 13.5 years of pure income over the system's 20-year lifespan. As a result, it can be regarded as the most reliable, cost-effective, and environmentally friendly system arrangement.

Architecture				Cost				System	
JKM400M-72H-V (kW)	Grid (kW)	SUN2000-60KTL-M0 (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
420	999,999	405	LF	$0.0725	$1.83M	$111,146	$416,747	31.1	0
420	999,999	405	CC	$0.0725	$1.83M	$111,146	$416,747	31.1	0
400	999,999	405	LF	$0.0741	$1.85M	$114,266	$398,347	30.0	0
400	999,999	405	CC	$0.0741	$1.85M	$114,266	$398,347	30.0	0
350	999,999	405	LF	$0.0785	$1.91M	$122,105	$352,347	27.0	0
350	999,999	405	CC	$0.0785	$1.91M	$122,105	$352,347	27.0	0
	999,999		LF	$0.107	$2.24M	$175,748	$0.00	0	0
	999,999		CC	$0.107	$2.24M	$175,748	$0.00	0	0

Fig. 5. Overall optimized result by HOMER.

Architecture				Cost				System	
JKM400M-72H-V (kW)	Grid (kW)	SUN2000-60KTL-M0 (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
420	999,999	405	LF	$0.0725	$1.83M	$111,146	$416,747	31.1	0
420	999,999	405	CC	$0.0725	$1.83M	$111,146	$416,747	31.1	0
400	999,999	405	LF	$0.0741	$1.85M	$114,266	$398,347	30.0	0
400	999,999	405	CC	$0.0741	$1.85M	$114,266	$398,347	30.0	0

Fig. 6. Categorized optimized result by HOMER.

The existing grid-only configuration has NPC of 2.24 million dollars and COE of 0.107 dollar/kWh. From economic and environmental standpoint, this system is less practical because the overall NPC and COE is somewhat higher and because it emits CO_2 of 1144 tons per year with 0% renewable penetration.

The system with diesel generator only, which requires a 760-kW diesel generator with price of diesel 0.77 dollar per liter with annual diesel usage for diesel generator systems is 6,86,578 liters. It gives worst performance, with COE of 0.53 dollar/kilowatt-hour, net present cost of 15.8 million dollars, and CO_2 emissions of 1981 tons per year, which is much greater than the grid-tied PV system.

In the system with diesel generator only COE and NPC are 0.46 dollars per kilowatt-hour and 14 million dollars respectively and of a grid-only system are 0.035dollars/kilowatt-hour and 0.41 million dollars higher than that of the solar PV system. With renewable penetration rates of 0%, diesel generator and grid-only systems produce 1028 tons and 191 tons of CO_2 per year more than PV-Grid-Converter systems. As a result, grid-only and diesel generator systems are no longer economically viable or environmentally beneficial due to rising COE and CO_2 emissions.

B. Production of Electricity

The grid-tied solar PV system's monthly average electricity generation is shown in Fig. 7. According to the findings, the PV array and grid provide 31.4% and 68.6% of total electricity generation respectively, with no capacity shortage and 0.0077% of surplus electricity.

HOMER also determines how much electricity that can be bought from grid or given to the utility. Fig. 8 shows net operation and energy bills annually. The figure illustrates electricity is occasionally sold by the grid during daytime because of significant solar PV production. Seasonal factors led energy sold to the grid to be slightly lower from April to October, according to the study.

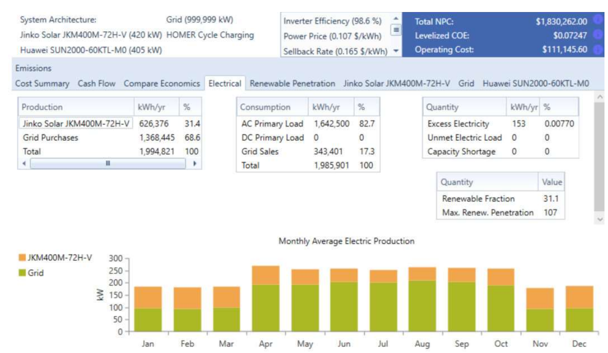

Fig. 7. Monthly electric production from the system.

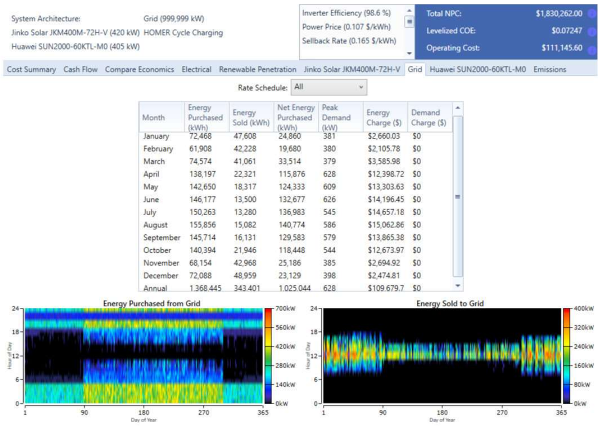

Fig. 8. Annual grid operation and energy bill of Younus Khan Scholars' Garden.

C. Sensitivity Results

Sensitivity results for fluctuations of solar radiation and energy prices are shown in Fig. 9 with a constant 420 kW PV capacity. NPC and levelized COE have both decreased significantly demonstrated for all energy prices in the scaled average solar radiation and higher electricity prices for all average fixed scaled radiation in the NPC and levelized COE have increased. Figure shows that with solar radiation ranging from 4-5 kWh/m^2/day and levelized COE of 0.072 dollar/kWh to 0.103 dollar/kWh, systems with PV-Grid-Converter become attractive for any grid purchase price.

Also, the sensitivities for varying PV capacity with converter sizes are shown in Fig. 10, where solar irradiance being constant at 4.65 kilowatt-hour per square in a day. In this situation, increasing PV capacity for any converter size reduces NPC and levelized COE significantly, whereas increasing converter size for any PV capacity increases NPC significantly as well as levelized COE. The figure shows that with any converter size, PV capacity range of 300-420 kW, and COE of 0.072 dollars per kilowatt-hour to 0.085 dollars per kilowatt-hour, system with PV-Grid-Converter becomes the most cost-effective and ideal system.

However, a grid-tied solar system with 420 kW PV capacity and 405 kW converter size emerges financially feasible for all grid pricing and solar irradiance of 4.65 kWh/m^2/day for Younus Khan Scholars' Garden in Ashulia, Dhaka.

D. Emission Analysis

The grid-connected solar PV system is far more environmentally friendly than the present grid-only and diesel generator system. Because solar PV provides a substantial amount of energy, the rate of fuel combustion can be reduced which results in, greenhouse gases released rate into the atmosphere will be reduced. The emissions of three alternative system configurations for Younus Khan Scholars' Garden are displayed in Table 2. which indicates that integrating renewable energy sources with grid reduces greenhouse gas emissions on an annual basis. So, though the proposed grid-tied solar PV system involves some fuel combustion in the energy generation process, it is a cleaner and environmentally beneficial technology.

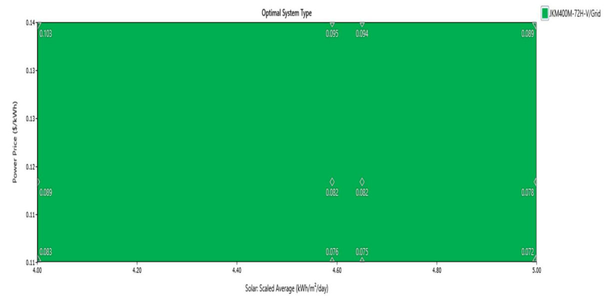

Fig. 9. Optimal systems for average solar radiations and power prices at 420 kW PV.

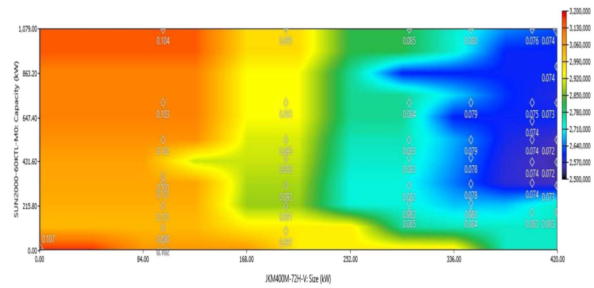

Fig. 10. Optimal systems for PV and converter capacity at 4.65 kWh/m^2/day solar radiation.

TABLE II. EMISSIONS OF DIFFERENT MODELS.

Components	**Amount (kg/yr.) (Grid-only system)**	**Amount (kg/yr.) (Grid-tied system)**	**Amount (kg/yr.) (Diesel generator system)**
CO_2	1,038,060	864,857	1,797,196
CO	0	0	11,329
Hydrocarbons	0	0	494
Particulate Matter	0	0	68.7
SO_2	4,500	3,750	4,401
NO_x	2,201	1,834	10,642

IV. Conclusion

The design and financial estimation for grid-connected solar system to meet electric demand of commercial building are presented in this paper. According to the research, the chosen study location, which receives a significant global solar radiation on an annual basis of 4.65 kWh/m^2/day, is a strong option for the implementation of a grid-tied solar system. As per the simulation results, the most cost-effective, technically sound, and stable grid-tied system for Younus Khan Scholars' Garden, would be a 420-kW solar PV array and a 405-kW converter. In addition, the energy audit determined a daily peak demand of 719 kW and a daily energy usage of 4945 kWh.

The analysis also shows that all areas in Bangladesh, is a suitable candidate for the deployment of one of the grid-tied solar photovoltaic systems for the favorable solar radiation and grid disruption throughout the country. This analysis also indicates that, as compared to using solely diesel generators and grid-only systems for power generation, adopting this grid-tied system would lower energy generating costs and boost grid volume by using renewable sources. Also, the proposed system will minimize greenhouse gas emissions, reduce reliance on imported fuel and natural gas, and improve system dependability as well as affordability.

The proposed system's energy cost is 0.0725 dollars/kWh, net present cost is 1.83 million dollars and the initial cost of capital is USD 416,747. With a renewable fraction of 31.1%, the system has 343,401 kWh/year of surplus energy. The payback period for the systems' life of 20 years is only 6.4 years. The proposed grid-tied solar PV system also emits fewer greenhouse gases, CO_2 of 953 tons, SO_2 of 4.13 tons, and 2 tons of NO_X into the atmosphere per year.

Although grid-connected solar PV systems have substantial installation costs, they are highly profitable and environmentally friendly in the long run. With their increased reliability and service quality, grid-connected solar Photovoltaic systems can play a major part in Bangladesh's electrification.

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