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TECHNO-ECONOMIC ANALYSIS OF OFF-GRID AND GRID-CONNECTED SOLAR PV SYSTEMS FOR AN UNIVERSITY BUILDING

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Abstract

To meet daily energy demands, the world depletes all natural resources, especially fossil fuels, resulting in rapid depletion of natural fuel reserves and irreversible environmental damage. In today's world, there is an urgent need to replace fossil fuel-derived energy with renewable energy. Solar energy, as an inexhaustible and abundant renewable energy source, is gaining popularity worldwide, including in Bangladesh, due to its geographical location and climate. The current research project aims to design photovoltaic (PV) energy systems, including grid-connected and off-grid systems, and estimate their viability for an academic building at a regional university. The solar PV system was designed with the help of software called PVsyst V 6.77, and the financial analysis was done with RETScreen-4 and Microsoft Excel. The study has found that both the off-grid and grid-connected systems are profitable and feasible to implement as a replacement for grid energy. However, the high initial investment is the only drawback. The grid-connected PV system without batteries is found to be the most cost-effective option when considering the internal rate of return (IRR) of 32.90%, the net present value (NPV) of ~16,548,800 BDT, annual life cycle savings ~1,706,400 BDT, and the emission savings of about 93.9 tons CO_2 eq.

Keywords: Renewable Energy, Solar Energy, PV System, Economic Feasibility, Net Present Value.

1. Introduction

As a developing country in South Asia, Bangladesh with a large population has a high energy demand to maintain its citizens' standard of living. Mitigating the existing energy crisis is a great concern for its government. Throughout the world, fossil fuel is the main source of energy with a contribution of 79.68% of total energy consumed whereas Bangladesh consumes 73.8% of total energy [1]. Electric energy is the most vital form of energy in Bangladesh. It gets most of its electric energy from fossil fuels where the largest share is from natural gas about 44.28% of total energy and the share of electricity from heavy fuel oil (HFO), captive power plants, coal, high-speed diesel (HSD), imported electricity, and renewable energy are 24.38%, 10.94%, 6.91%, 5.24%, 4.53% and 3.71%, respectively [2]. However, fossil fuel is not inexhaustible. The lifetime of the world reserves of coal, natural gas, and oil are estimated to be 132, 50, and 50 years, respectively [3, 4]. Moreover, these sources of energy are not free from harmful emissions. Sustainable development that does not jeopardize the environment is a pressing issue in Bangladesh as well.

With limited fossil fuels, Bangladesh faces a significant challenge in maintaining socioeconomic development and meeting rising electricity demand while reducing harmful emissions for an environmentally friendly environment. Renewable energy sources like solar, wind, biomass, and hydropower can be likely substitutes to address the global and Bangladeshi energy crises. In Bangladesh, the current percentage of renewable energy to total energy generation is only 3.71%, with solar energy accounting for the majority of all renewable energy (2.8%) [2]. In contrast, the goal was to generate 10% of total electricity generation from renewable energy sources by 2021 [5]. Although solar energy is unlimited, only a very small portion of the electricity in our nation is currently generated by solar energy.

[6]. The fact is that solar energy outweigh all other fossil and renewable-based energy sources. One of the most promising and expanding industries for renewable energy is the direct use of solar energy harvested using photovoltaic (PV) panels to generate power [7]. Furthermore, Si-based solar panel prices have dropped so quickly that they currently account for about <30% of the price of a fully-constructed solar PV system [8]. Recently, for a range of uses, including solar-powered boats, wheelchairs, mobile-network base stations, etc., sustainable solar energy solutions have been investigated [8, 9]. The critical issue is to increase the share of total fossil-fuel-based power generated by solar energy, which will result in lower CO_2 emissions.

Due to the geographical location of Bangladesh, between 20.30-26.38° north latitude and between 88.04-92.44° east longitudes, it has a great potential to harvest solar energy [10, 11]. Implementing off-grid PV systems for the population that is not connected to the grid electricity is the best solution for increasing the share of renewable energy. Furthermore, sourcing a university's energy needs from renewable sources is essential to cutting back on the use of fossil fuels. Shahjalal University of Science and Technology (SUST), which is situated in the Bangladeshi city of Sylhet, is a green campus with hills and a variety of tourist attractions. In Sylhet, the average annual worldwide solar insolation for the years 1988 to 1998 was reported to be 4.54 kW/m^2/day [12]. In addition, as part of our experimental work, a 4.81 kWh/m^2/day annual average solar irradiance at a 25° tilting plane during 2018-2019 was also reported for the city of Sylhet [13].

A few number of research work [14-16] has been reported worldwide on the designing of a PV system for University Campuses towards their energy independence. So far, no published research carried out in Bangladesh has been found on designing PV installations for any local Universities. It is worth investigating the technological and economic feasibility of replacing the existing fossil fuel-based energy system (grid-electricity) with solar energy for Shahjalal University of Science and Technology, Sylhet, Bangladesh.

2. Methodology

One of the four four-story academic buildings at Shahjalal University of Science and Technology in Sylhet has been chosen for this study. The building has a total floor area of about 1800 m^2 being used as lecture rooms, seminar rooms, different laboratories, library space, and office rooms. Data has been collected visiting different areas of the selected building to determine the total energy consumption for a variety of electrical appliances. In this research, air-conditioners and other heavy-duty machines have been excluded to lower down the total energy consumption of the selected building. The total number of existing electrical appliances (Fan, Light, Projector, Printer, and PC) for academic building 'C' of SUST has been manually counted. Several rational assumptions have been made to calculate the total amount of energy consumed daily in the selected academic building.

The assumptions considered are:

- A calendar year has been divided into one cold and warm weather where November to February is assumed as the cold weather period and March to October is considered the moderately hot or hot weather period. All fans are assumed to remain unused during the cold weather only.
- The total number of holidays including the weekends has been calculated and is shown in Table 1.
- AC and other heavy-duty machines including laboratory equipment have been excluded for lowering down the power consumption requirement.
- Average durations of lectures, laboratory demonstrations, and office openings have been considered as 6 hours, 3 hours, and 9 hours, respectively.

Table 1. Total number of working days, holidays, and weekends in a typical academic year.

Weather	Total days	Holidays including weekends	Working days
Hot/mildly hot weather (March-October)	245	120	125
Cold weather (November-February)	120	49	71
Total days	365	169	196

PVsyst V 6.77 [17] has been used for technical analysis (PV system sizing & simulation) and RETScreen-4 [18] for the financial feasibility (Cost analysis, financial analysis, emission analysis). The sizing of a

PV system to determine the number of solar panels, batteries, inverters, etc. were detailed in a couple of previous work [19, 20]. Net Present Value (NPV) for existing energy systems and PV systems during the Project Life Cycle has been calculated by using the equation given below:

$$Present\ Value\ of\ cashflow$$
$$= Annual\ cost\left(\frac{1+e}{(1+d)(1+i)}\right)^{n}$$

NPV= Sum of present value for whole project life – Initial Investment

Where the project life, N = 25 years, n is the number of years, fuel escalation rate, e = 5.7%, inflation rate, i = 5.5% and discount rate d = 10%. These numerical values are considered on the basis of relevant reports published by the World Bank [1] and Bangladesh Bank [21].

3. Results and Discussions

3.1 Energy analysis and designing PV systems

A schematic diagram of a grid-connected PV system with batteries is displayed in Fig. 1. The figure shows the main components of a typical PV solar system, namely, a solar panel, charge controller, battery, inverter, net meter, etc. Calculating the total energy consumption is necessary before designing a PV system for the selected academic building.

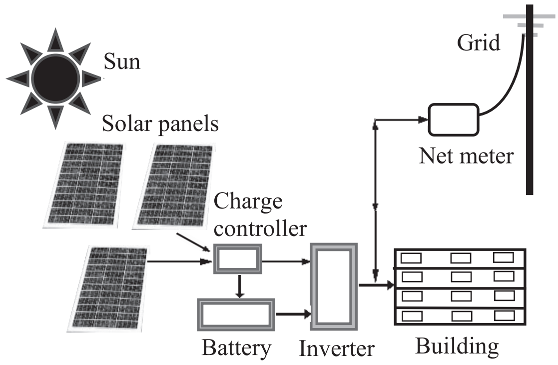

Fig. 1: Schematic diagram of a grid-connected solar PV system.

The total number of existing electrical appliances such as lights, fans, personal computers (PCs), printers, projectors, and photocopiers and their corresponding energy consumption has been shown in Table 2. The total power consumption of all electrical appliances with their individual power ratings is found to be 105.830 kW as shown in the table. The table also shows that the total energy consumption is expected to be 557.108 kWh per day which is considered as a peak energy demand for the off-grid system. The off-grid system ideally does not get energy from the grid. On the other hand, for the grid-connected PV systems, the average energy demand calculated for the duration of a year is considered as the system can use electric energy from the electric grid when it is necessary. The total energy consumption per year is calculated assuming cold weather from November to February, hot weather for the rest of the months in a year, and the number of days the university is open as shown in Table 1. Neglecting the minimal energy consumption during the holidays and weekends, the total energy consumption per year is found to be 100.27 MWh. Consequently, the average energy consumption per day is estimated to be 274.72 kW for the grid-connected PV system.

Table 2. Daily energy consumption of the selected academic building for different electric appliances.

Appliances	Space type	Quantity	Power /unit W	Daily Consumption (kWh)
Fluorescent tube	Class	116	36	25.1
	Lab	195	36	21.1
	Office	207	36	67.1
Energy saving lamps	25 W	108	25	24.3
	13 W	14	13	2.2
Fan	Class	112	60	40.3
	Lab	90	60	16.2
	Office	128	60	69.1
PC	Lab	173	150	77.9
	Office	92	150	124.2
Projector (Hitachi)	Class/ Lab	15	300	27.0
Printer (HP)	Office	49	250	36.8
Photocopier (Canon)	Office	8	1000	16.0
Refrigerator	Office	4	500	10.0
Hot/Moderately hot weather			Total	557.1
Cold weather (excluding fans)				431.5

A maximum power point tracking (MPTT) charge controller of a capacity of 5.76 kW was initially selected to facilitate the sizing of the panel and battery.

The charge controller has an input DC voltage ranging from 250-500 V and the output voltage of the MPTT charge controller is 48 V. The number of PV panels has been determined assuming the efficiency of the overall components as 80%, and the average sunshine hour for the year-round in Sylhet as 4.9 hours/day (PVsyst database). In this research work, the PV module is taken with a rated current of 8.85A and a rated voltage of 31.64V. The PVsyst V 6.77 was run to find the number of panels for the generation of total peak energy of 274.72 kW per day. The number of the selected PV panels in parallel was found to have a range of 19-38 and the number of panels in series ranges 8-16. The optimal output has been taken where 27 panels and 12 panels are considered to be in parallel and in series, respectively. The total number of panels is found to be as their product that is 324 panels. To estimate the number of batteries, the number of autonomy day was considered as 1 day, the depth of its discharge as 80%, and the capacity of 12 V battery is 250 Ah. From the software, the total number of batteries was found to be 136 where 34 in parallel and 4 in series (output voltage 48V).

Considering the current of the charge controllers as 120A, a short circuit current of each panels as 9.24A and a safety factor of 1.245, the PV system is capable of producing 81.2 kW per hour at the standard operating conditions. Therefore, a string inverter of 100 kW has been selected for the PV system. The total number of inverter has also been found as 4 and 2 for the off-grid and the grid-connected PV systems, respectively. The different components selected for the PV system are shown in Table 3 with their model, capacity and price of each unit in BDT.

Table 3. Different components of the PV systems with their specifications and unit prices [22].

Parts	Model	Capacity	Price/unit (BDT)
Charge controller	Studer VarioString VS-120 (MPPT)	5.76 kW	91,300
Panel	PLM-280M-60 (Mono)	280 W	6,275
Battery	NP12_250 (AG, Lead)	250 Ah	22,410
Inverter	Huawei inverter SUN2000-100KTL	100 kW	588,000

3.2 Cost Analysis

The costs of a stand-alone PV system include component costs, installation and replacement costs, and operation and maintenance (O & M) costs. The requirements of different components for the PV systems are shown in Table 4.

Table 4. Required quantity of different components.

Items	Off-grid	Grid-tied with battery	Grid-tied without battery
PV module	720	368	368
Battery	228	116	-
Charge Controller	35	18	-
Inverter	4	2	2

The component costs are shown in Fig. 2, where installation and operation and maintenance (O&M) costs are assumed to be 10% and 2% of the PV cost, respectively. All costs are entered into the RETScreen-4 software for both off-grid and grid-connected PV systems.

3.3 Financial Analysis

Financial analysis is a process of assessing the performance and suitability of finance-related activities such as businesses, projects, budgets, and other finance-related entities. It is used to determine whether a company is stable, solvent, or profitable enough to justify a financial investment. The income statement, balance sheet, and cash flow statement are the most important documents to be utilized. In the present study, the RETScreen-4 software generates the project costs or savings/incomes shown in Fig. 3 after taking into account all costs, required energy, and current energy prices for the considered projects. It should be noted that a grid-connected PV system cannot export more than 50% of total power consumption [23]. The figure also shows that the initial cost of a grid-connected (no battery) PV system is the lowest. Except

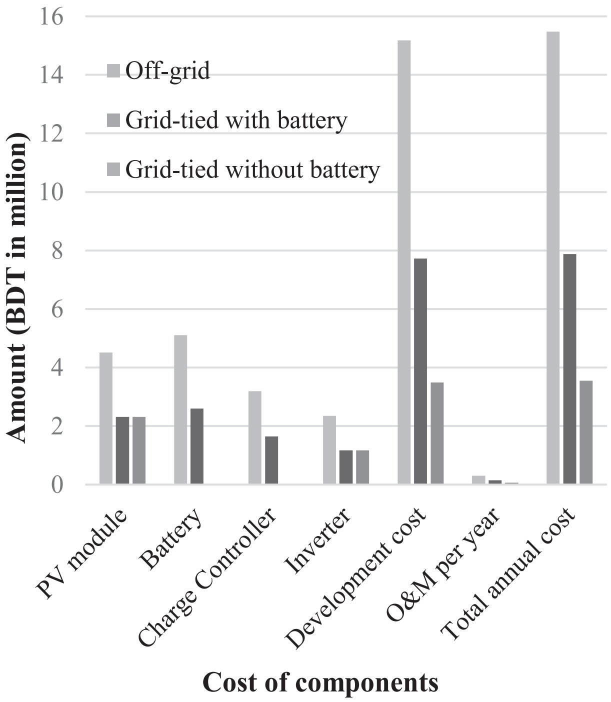

Fig. 2: Various costs for the solar PV systems.

for the panel, this system has no replacement costs and can save a total of 1,267,466 BDT per year, making it more profitable than the other solar PV systems.

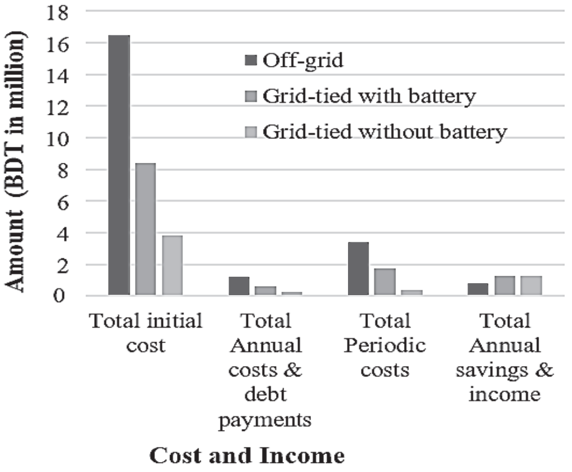

Fig. 3: Costs and incomes for the PV systems.

Table 5 shows the financial viability performed using RETScreen-4 and Microsoft Excel to determine which option will be viable to implement. Financial viability analysis requires some factors to be considered, such as the 5.5% inflation rate, the 10% discount rate or minimum interest rate [23], and the 5.7% fuel cost escalation rate [1]. If the net present value (NPV) is greater than zero, the project will add value to the farm or investor while also creating wealth for shareholders [24]. If the internal rate of return (IRR) exceeds the Minimum Attractive Rate of Return (MARR), which is set at 10%, the PV project is considered acceptable and viable. Table 5 shows that the off-grid PV system is not acceptable in any way, whereas the other two systems are viable, profitable, and thus acceptable. However, the initial cost of an off-grid PV system is extremely high (Fig. 3). In addition, Table 5 shows that the net present value (NPV) for the PV system is higher during the Project Life Cycle when compared to the existing electricity system. The initial costs of the grid-connected PV systems with and without storage batteries are significantly lower than that of an off-grid system. When compared to the existing grid system, the table also shows that the net present value (NPV) during the Project Life Cycle is lower for the grid-connected PV system with battery and the least for the grid-connected PV system without battery.

RETScreen-4 software was used to calculate the annual and cumulative cash flow. The cumulative cash flow was calculated using a bank loan for 40% of the total project investment at a simple interest rate of 6%. For tax purposes, the first ten years of project income are tax-free. During the remaining project life, a 1% incremental tax has been considered for earnings of every 5 lac taka. In addition, the cumulative cash flow takes into account the price declination of panels and batteries at the same rate of 12% per year. If the income exceeds the expenses, the cash flow is positive; otherwise, it is negative. Income and expenses will be equal at the break-even point. Fig. 4 depicts the cumulative cash flow for the off-grid system simulated using RETScreen-4 software, indicating that this project would not yield a benefit over a 25-year period. Table 5 shows that the project IRR is negative, the net present value (NPV) is -23930957.00 BDT, and the simple payback period is greater than the project life, indicating that this project is unviable. The table also shows that the IRR for the off-grid project is negative < (MARR 10%), indicating that the project is also economically unfeasible.

Fig. 5 depicts the forecasted cumulative cash flow for the grid-connected PV system (with battery) taking into account similar economic factors. According to the Fig. 5 and Table 5, the project with a high IRR (11.32%) has a payback period of 8.78 years and a large positive NPV (5,652,567.00 BDT). The cumulative cash flow for the grid-connected PV system (without battery) is illustrated in Fig. 6. According to the Fig. 6 and Table 5, the payback period for a grid-connected (no battery) PV system is approximately 3.47 years, with a large positive NPV (16,584,800.00 BDT).

Table 5. Financial viability analysis for the PV systems.

Particulars	PV Systems		
	Off-grid	Grid-connected with battery	Grid-connected without battery
After-tax IRR (in %)	Negative	11.32%	32.90%
Simple payback (in year)	Not attained	8.78	3.47
Net present value in BDT	-23,930,957	5,652,567	16,584,800
Annual life cycle savings (in BDT/year)	-1,333,977	475,134	1,706,426

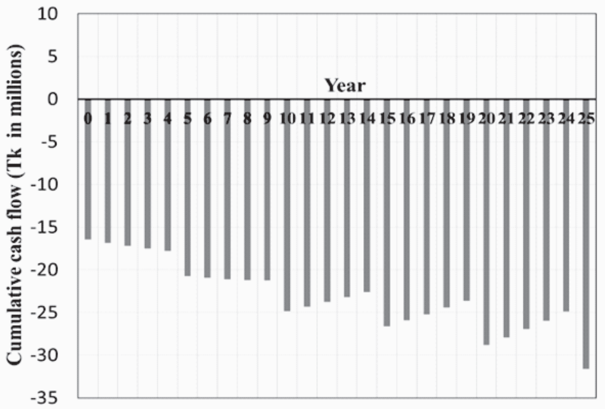

Fig. 4: Cumulative cash flows for the off-grid PV system.

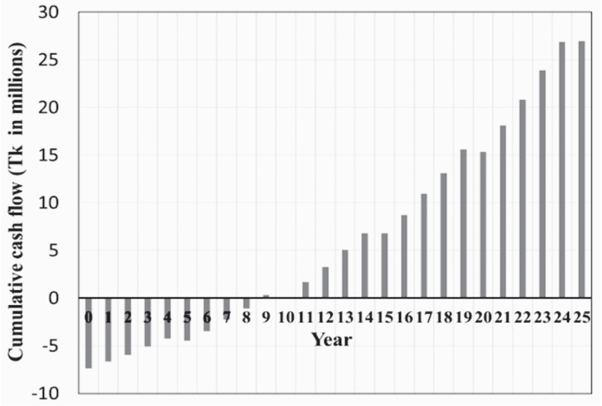

Fig. 5: Cumulative cash flows for the grid-connected (with battery) PV system.

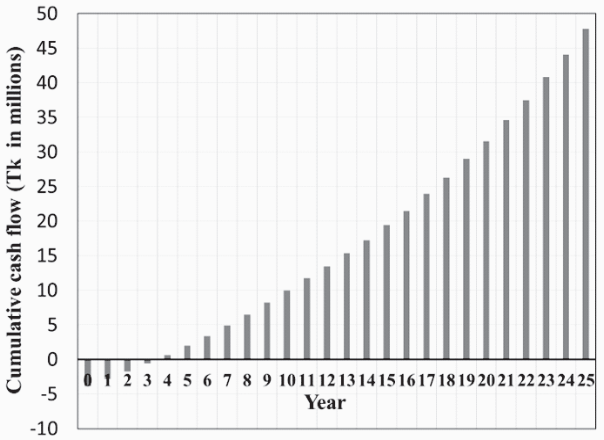

Fig. 6: Cumulative cash flows for the grid-connected (without battery) PV system.

3.4 Emission Study

Implementing a solar PV system to replace grid-electricity generated from fossil fuels will eventually help to reduce CO_2 emissions. Natural gas is used to generate the majority of grid electricity in Bangladesh. To determine the reduction of greenhouse gas emissions, CO_2 emissions from natural gas, coal, hydropower, and petroleum oils were considered in this study. CO_2 emissions from natural gas, petroleum, coal, and hydropower generation are reported to be 490, 783, 820, and 27 g CO_2eq./kWh, respectively [25, 26]. On the other hand, a solar PV system using Si-based PV modules generates 1 kWh of power while emitting 45 g CO_2eq. [27, 28]. In Bangladesh, natural gas, petroleum, coal, solar photovoltaic energy, and hydropower each contribute 44.3%, 45.1%, 6.9%, 2.8%, and 0.9% of the total electricity generated, respectively [2]. As a result, a total of 628.2 g CO_2eq. of gas are released to produce 1 kWh of power. In contrast, installing a PV system to produce 1 kWh of power results in a total decrease of CO_2 gas emissions of 583.2 g CO_2eq. The off-gird system required to generate 100 MWh of electricity annually for the chosen academic building will prevent the release of 58.32 tons of CO_2 eq. In contrast, the grid-connected PV system with an annual capacity of 161 MWh can prevent the emission of 93.9 tons of CO_2 equivalent. The location of Sylhet, the energy mix of electricity generation [2], and the peak output of the PV system of 275 kW are taken into account when using the RETScreen-4 software to estimate a reduction in greenhouse gas emissions of roughly 96.9 tons of CO_2eq. This finding is fairly consistent with our estimated value.

4. Conclusion

The goal of this study is to determine whether a photovoltaic (PV) system for generating power for a typical facility at a public university in Bangladesh is both environmentally friendly and economically feasible. In order to develop the off-grid and grid-connected PV systems, the daily energy requirements for the academic building were found to be 547.108 kW (peak) and 274.720 kW (average), respectively. 720 panels with a 280 W power output, 228 batteries with a 250 Ah capacity each, 35 charge controllers (120 Ah), and 4 inverters (50 kW) make up the off-grid independent PV system. The same standards must be met by 368 panels and 2 inverters for both grid-connected PV systems. It has been determined that the development expenses of off-grid, grid-connected with battery, and without battery PV systems are 15,174,980 BDT, 7,728,160 BDT, and 3,485,200 BDT, respectively. The grid-connected PV system with battery has an NPV of 5,652,567 BDT, while the system without a battery has an NPV of 475,134 BDT. They each can save 16,584,800 BDT and 1,706,426 BDT on a yearly basis. The off-grid solution appears to have a significantly higher straightforward payback than the project's lifespan. However, for the grid-connected PV systems with and without batteries, the simple payback periods are 8.78 years and 3.47 years, respectively. When compared to an off-grid PV system, which emits 58.32 tons less CO_2 annually, both grid-connected PV systems can reduce emissions by a total of 93.9 tons. Although both grid-connected PV systems are technically and financially possible, the grid-connected PV system without battery is the most advantageous choice when taking into account the net present value (NPV), emission and yearly life cycle savings, equity payback duration, and internal rate of return (IRR).

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References:

1. World Bank (2019). Fossil fuel energy consumption (% of total), https://data.worldbank.org/indicator.

2. Sustainable & Renewable Energy Development Authority (SREDA) (2022). Bangladesh. http://www.renewableenergy.gov.bd.

3. British Petroleum (2019). BP Statistical Review of World Energy 2019 https://www.bp.com/content/dam/bp/business-sites/en/global/ corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

4. Ritchie, H., Roser, M. & Rosado, P. (2021). Fossil Fuels. Our World in Data 2021. Available online: https://ourworldindata.org/fossil-fuels.

5. Bhuiyan, M.R.A., Mamur, H. & Begum, J. (2021). A brief review on renewable and sustainable energy resources in Bangladesh, Cleaner Engineering and Technology, 4, 100208, https://doi.org/10.1016/j.clet.2021.100208. Bhuiyan, M.R.A., Mamur, H. & Begum, J. (2021). A brief review on renewable and sustainable energy resources in Bangladesh, Cleaner Engineering and Technology, 4, 100208, https://doi.org/10.1016/j.clet.2021.100208.

6. Lewis, N. S. (2007), Toward Cost-Effective Solar Energy Use, Science 315 (5813), 798-801.

7. Sampaio, P.G.V. & González, M.O.A. (2017). Photovolatic solar energy: conceptual framework. Renewable and Sustainable Energy Reviews, 74, 590-601.

8. Lewis, N. S. (2016). Research opportunities to advance solar energy utilization, Science 351 (6271), 353-aad1920-9.

9. Tercan, Ş.H., Eid, B., Heidenreich, M. et al. (2021). Financial and Technical Analyses of Solar Boats as A Means of Sustainable Transportation, Sustainable Production and Consumption, 25, 404-412, https://doi.org/10.1016/j.spc.2020.11.014.

10. Masud, M.H., Nuruzzaman, M., Ahamed, R. et al. (2020). Renewable energy in Bangladesh: current situation and future prospect, International Journal of Sustainable Energy, 39(2), 132-175, https://doi.org/10.1080/14786451.2019.1659270.

11. Baky, M.A.H., Rahman, M.M. & Islam, A.K.M.S. (2017). Development of renewable energy sector in Bangladesh: Current status and future potentials, Renewable and Sustainable Energy Reviews, 73, 1184-1197.

12. Islam M.R., Islam M.Ra. & Beg, M.R.A. (2008). Renewable energy resources and technologies practice in Bangladesh, Renewable and Sustainable Energy Reviews 12(2), 299-343.

13. Hasan, M. M., Malek, A.B.M.A. & Talukder, M.I.A. et al. (2021). Solar irradiance measurement in Sylhet and performance evaluation of photovoltaic (PV) modules in outdoor conditions. Journal of Engineering Research, Innovation and Education, 3(1), 5-12.

14. Iqbal, S., Jan, M.U. & Anis-Ur-Rehman, R. et al. (2022). Feasibility Study and Deployment of Solar Photovoltaic System to Enhance Energy Economics of King Abdullah Campus, University of Azad Jammu and Kashmir Muzaffarabad, AJK Pakistan. IEEE Access, 10, 5440-5455, https://doi.org/10.1109/ACCESS.2022.3140723.

15. Kumar, R., Rajoria, C.S. & Sharma, A. et al. (2021). Design and simulation of standalone solar PV system using PVsyst Software: A case study. Materials Today: Proceedings, 46, 5322-5328. https://doi.org/10.1016/j.matpr.2020.08.785.

16. Hasapis, D., Savvakis, N. & Tsoutos T. et al., (2017). Design of large scale presuming in Universities: The solar energy vision of the TUC campus, Energy and Buildings, 141, 39-55.

17 Mermoud, A. (1994). PVSYST: a user-friendly software for PV-systems simulation, The Twelfth European Photovoltaic solar energy conference, 1703-1706, Amsterdam, Netherlands.

18. Thevenard, D., Leng, G., & Martel, S. (2000). The RETScreen model for assessing potential PV projects, Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference-2000, 1626-1629, Anchorage, AK, USA.

19. Verma, J.K., & Dondapati, R.S. (2017). Techno-economic sizing analysis of solar PV system for domestic refrigerators, Energy Procedia, 109, 286-292.

20. Hasan, M. M., Hasan, M. R., Biswas, R., Malek, A. A., & Parvej, M. M. (2019). Design and Feasibility Analysis of a Solar PV System for Street Lighting in a University Campus, International Journal of Science and Engineering Applications, 8(9), 432-437.

21. Bangladesh Bank. 2017, Financial Stability Report,https://www.bb.org.bd/pub/annual/fsr/final_stability_report2017.pdf (Accessed on 01 September, 2021).

22. Alibaba.com, An e-commerce online platform, https://www.alibaba.com/ (Accessed on November 05, 2021).

23. Chowdhury, S.A. Khan, M.Z.R. (2020). The Net Metering Guideline of Bangladesh-Potential and Way Forward, 11th International Conference on Electrical and Computer Engineering (ICECE), 435-438, Dhaka, Bangladesh, https://doi.org/10.1109/ICECE51571.2020.9393148.

24. Magni, C.A. (2009). Investment decisions, net present value and bounded rationality, Quantitative Finance, 9, 967-979, https://doi.org/10.1080/14697680902849338.

25. Gouw, J.A. de, Parrish, D.D. & Frost, G.J. *et al.* (2014). Reduced Emissions of CO2, NOx and SO2 from U.S. Power Plants Due to the Switch from Coal to Natural Gas with Combined Cycle Technology, Earth's Future, 2, 75-82, https://doi.org/10.1002/2014EF000196.

26. Dones, R., Heck, T. & Hirschberg, S. (2003). Greenhouse Gas Emissions from Energy Systems, Comparison and Overview. Encyclopedia of Energy, 3, 27-40 https://doi.org/10.1016/B0-12-176480-X/00397-1.

27. Nugent, D. & Sovacool, B.K. (2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey, Energy Policy, 65, 229-244, https://doi.org/10.1016/j.enpol.2013.10.048.

28. Fthenakis, V.M., Kim, H.C. & Alsema, E.A. (2008). Emissions from photovoltaic life cycles. Environmental Science & Technology, 42, 2168-2174.