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Greenhouse Gas Emission Reduction through Electricity Generation from Solar Photovoltaic Systems: A Study in Dhaka

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ABSTRACT: Though best provided with electricity, Dhaka, the capital city of Bangladesh, often experiences power outages while lacking at least 500 MW of electrical power. Given a massive shortage of electricity both in Dhaka and the country and the use of fossil fuels in power generation, the present study examines the potential of rooftop solar photovoltaics (SPVs) for electricity generation in the Dhaka Metropolitan Area (DMA) and the consequent greenhouse gas (GHG) emission reduction. It has been found that the roof area of DMA is 62 km^2. Considering 50% of this area (31 km^2), the application of SPVs can generate 9,454 GWh of electricity yearly or 25.8 GWh per day. Such generation can reduce GHG emissions by 4.3 MtCO^{2}e/year, which is 26.7% of the NDC target from the power sector. The results of this study support the wide-scale application of rooftop SPVs throughout DMA.

Keywords: Solar Photovoltaic Systems; Roof-top Application; Electricity Generation; Greenhouse Gas Emission; Dhaka

INTRODUCTION

The world is rapidly shifting toward renewable energy sources. Non-renewable energy sources are finite; hence, nations around the world are developing renewable energy technologies and the renewable energy sector as an alternative environment-friendly power source. Burning hydrocarbon fuels generates GHGs in the atmosphere that causes the greenhouse effect, where radiant heat is trapped by the atmosphere, resulting in a gradual increase in the average temperature (Fraas, 2014). Climate change has been alarming, and the concern surrounding it is growing daily, giving another reason to shift to renewable energy. Bangladesh is significantly affected by climate change, suffering from climate-related disasters, and it is also a signatory to UNFCCC; therefore, it must play its role in reducing greenhouse gas (GHG) emissions. According to the NDC (nationally determined contributions) targets, to achieve the conditional scenario, Bangladesh will have to reduce its GHG emissions by 36 MtCO$_2$e (15%) from BAU (business as usual) levels by 2030. This can be seen in Table 1. From the power sector, the reduction must be 16 MtCO$_2$e (18%) in the conditional scenario (INDC, 2015). Renewable energy can play a role in achieving the NDC targets.

Table 1: NDC Projected Emissions Reduction by 2030

Sector	Base Year (2011) (MtCO$_2$e)	BAU Scenario (2030) (MtCO$_2$e)	BAU Change from 2011 to 2030		Unconditional Contribution Scenario (2030) (MtCO$_2$e)	Change vs BAU		Conditional Contribution Scenario (2030) (MtCO$_2$e)	Change vs BAU	
			Percent	Amount (MtCO$_2$e)		Percent	Amount (MtCO$_2$e)		Percent	Amount (MtCO$_2$e)
Power	21	91	336%	70	86	-5%	-5	75	-18%	-16
Transport	17	37	118%	20	33	-9%	-4	28	-24%	-9
Industry (Energy)	26	106	300%	80	102	-4%	-4	95	-10%	-11
TOTAL	64	234	264%	170	222	-5%	-12	198	-15%	-36

Source: Based on INDC, 2015

Bangladesh has a great potential for renewable energy; its location has an exceptionally high potential for solar energy, receiving 4 – 6.5 kWh/m^2 daily solar radiation intake (Amin, Islam, Kamal, and Mithila, 2016). Grid-

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connected solar photovoltaics (SPVs) in Bangladesh have been calculated to have a technical potential of 50,174 MW (Mondal and Denich, 2010). According to the Renewable Energy Policy 2008, 10% of Bangladesh's power demand must be met through renewable energy sources by 2020. However, renewable energy accounts for only 2.73% of the total power generation (BPDB, 2019). Bangladesh is also a member of IRENA (International Renewable Energy Agency), an inter-governmental agency for renewable energy (S. Islam & Khan, 2017). Natural gas is the predominant fuel used in the country, but natural gas reserves may be depleted in 15-20 years (Hossain et al. 2017). Bangladesh has targeted 100% electricity access by 2021 (REN 21, 2018), but 10% of the population still does not have access to electricity (HCU, 2020). The capital of Bangladesh, Dhaka, is the economic hub. It is best supplied with electricity compared to the rest of the country yet still experiences load shedding. Load shedding has the most significant economic impact in Dhaka and causes dissatisfaction among the people. Therefore, Dhaka will benefit from an additional renewable power source, which will consequently reduce greenhouse gas emissions. Dhaka has a severe shortage of land and has high-density buildings. Renewable technologies like windmills, ground-mounted SPVs, etc., take up ground space; on the other hand, rooftop SPVs and other BIPVs do not occupy additional ground space, and they benefit from high-density buildings that provide more area for installation. Therefore, rooftop SPVs and other BIPVs are especially suited to Dhaka City compared to other renewable technologies. SPVs are user-friendly as they do not have moving parts and require minimal maintenance effort. No noise or other pollution is produced while it operates; hence, SPVs can be installed near or on residential buildings. Furthermore, Dhaka has a very good GHI of 4.20 kWh/m^2/day (Kabir et al. 2010) and an annual GHI of 1,536 kWh/m^2/day (SWERA, 2007). The seasonal variation in GHI can be seen in Figure 1; Dhaka receives the best radiation during April and May but also receives good radiation throughout the year. Dhaka also has an average of 7.55 bright sunshine hours daily (Ahiduzzaman and Islam, 2011). Solar energy now has the highest potential compared to other renewables (Islam et al. 2014). Solar photovoltaic technology has the highest potential among solar power systems (Hosenuzzaman et al. 2015). Among solar technologies, solar home system (SHS) is expanding rapidly in rural Bangladesh with great success (Baky et al. 2017). Distribution of 645,000 SHS throughout the country by IDCOL (Infrastructure Development Company Limited) as of 2010 has contributed to the reduction of about 22,000 tCO_2 emissions per annum (Kabir and Uddin, 2015). Rooftop SPVs, on the other hand, are yet to be widely explored. Considering the suitability and benefits, this paper attempts to determine the electricity generation potential from rooftop SPV applications in Dhaka and the consequent reduction in greenhouse gas emissions.

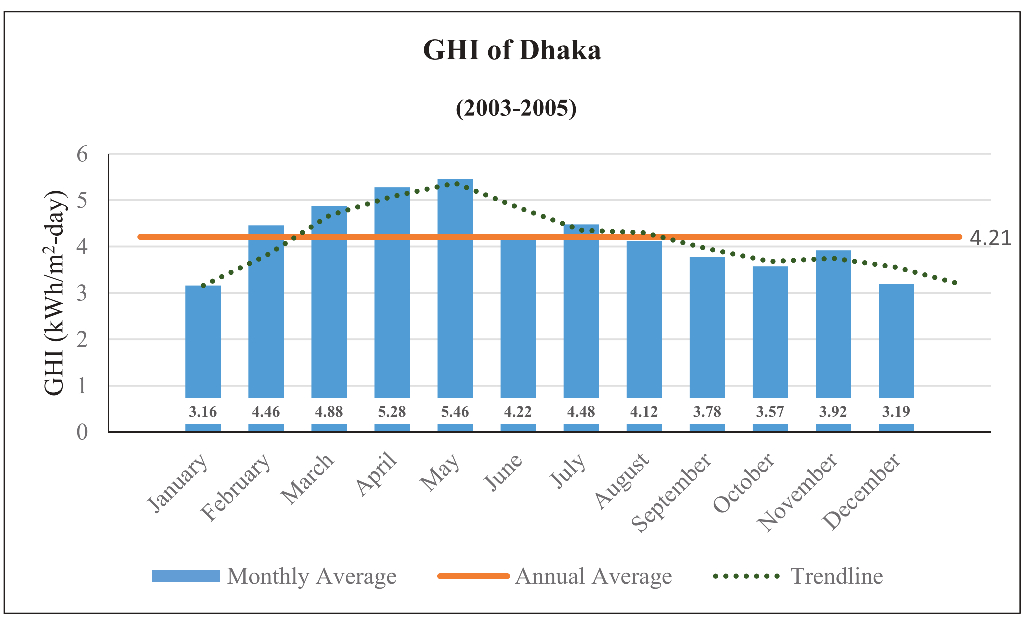

Figure 1: Monthly Average GHI of Dhaka

Source: Based on SWERA (SWERA, 2007)

MATERIALS AND METHODS

The study area is the Dhaka Metropolitan Area (DMA). The study area is 300 km^2 and is shown in Figure 2.

The outline of rooftops as polygon features, in the form of a data layer, was extracted from OpenStreetMap (OSM) and can be called the footprints of rooftops. This data is from January 2023. The layer was extracted using OSM's JOSM software (Java OpenStreetMap Editor). The boundary of the Dhaka Metropolitan Area cropped this layer. The shapefile for the DMA boundary was extracted from ArcGIS Hub data. In this way, the rooftop polygon shapes were obtained for DMA. This new layer was examined and processed in ArcGIS Pro software to remove any errors and inaccuracies. Then, the cumulative area from all the rooftop polygon shapes was calculated using the same software. This gives the total roof area present in the Dhaka Metropolitan Area.

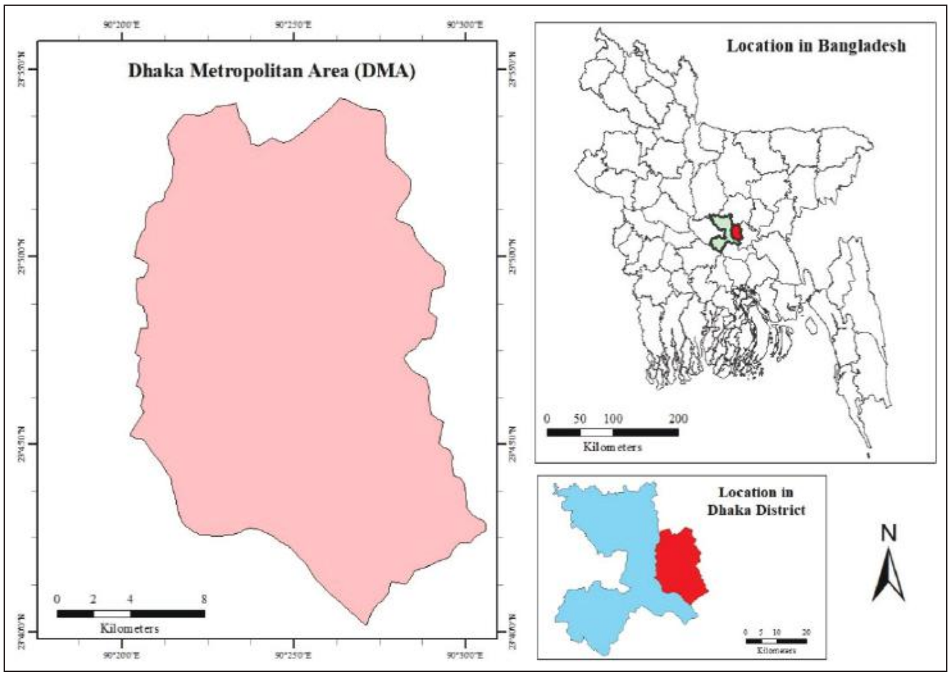

Figure 2: Study Area

From the total roof area of DMA, the electricity that could be potentially generated by installing solar PVs on 50% of the roof area throughout Dhaka was calculated. For this calculation, some equations were formulated. The equations were utilized along with the global horizontal irradiance (GHI) value of 4.20 kWh/m^2/day (Kabir et al. 2010) daily and 1536 kWh/m^2/day (SWERA, 2007) annually. The average annual tilt factor is 1.097 for a PV tilted at 23.73^{0} in Dhaka (Ghosh et al. 2010).

From the amount of electricity generated by installing SPVs on the rooftops of Dhaka, the amount of GHG emissions that can be avoided by generating that amount of electricity from SPVs rather than from conventional fuel sources is calculated. For this calculation, an equation was formulated, which was used along with emission factors obtained from SWERA (SWERA, 2007) and AR5 global warming potential (GWP) values for the 100-year time horizon obtained from IPCC (IPCC, 2014).

RESULTS AND DISCUSSION

Electricity Generation through the Solar Photovoltaic System

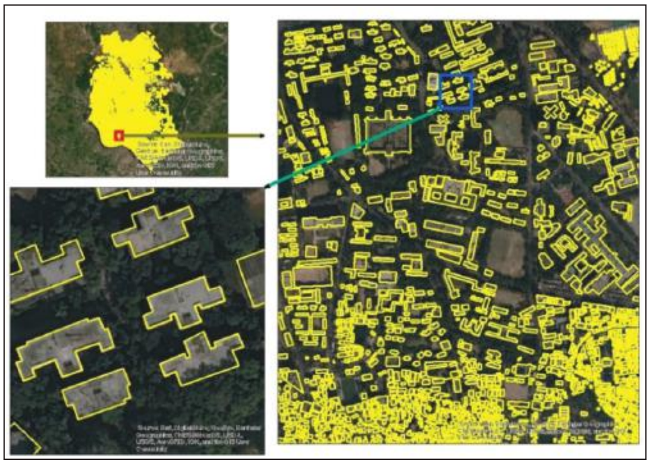

Figure 3: Rooftop Footprints with Satellite Base Map for a Subset in DMA

The roof area of DMA was found to be 62 km^2, which is 20.5% of the 300 km^2 DMA. Figure 3 shows the rooftop footprints over a satellite base map in a subset of the study area. The equations used to calculate the potential electricity generation are given below. For grid-connected solar modules,

$$E_G = N \times M \times G \times \eta_p \times \eta_i \times 10^{-6} \quad (1)$$

$$EY_G = N \times M \times G_Y \times \eta_p \times \eta_i \times 10^{-6} \quad (2)$$

$$N = A/M_g \quad (3)$$

$$A = 0.5 \times a \quad (4)$$

$$M_g = L_g \times W_g \quad (5)$$

$$L_g = L\cos\theta \quad (6)$$

$$W_g = W \quad (7)$$

$$M = L \times W \quad (8)$$

Here,

E_G = Potential grid-connected electricity generation in 1 day (GWh)

EY_G = Potential grid-connected electricity generation in 1 year (GWh)

a = Roof area (m^2)

A = Roof area suitable for SPV installation (m^2)

M = Area of 1 module (m^2)

L = Length of the module (m)

W = Width of a module (m)

M_g = Ground area required for 1 module (m^2)

L_g = Length of the ground area required for 1 module (m)

W_g = Width of the ground area required for 1 module (m)

N = Number of modules that can be installed

G = Solar irradiation (kWh/m^2-day)

G_Y = Annual solar irradiation (kWh/m^2-day)

η_i = Inverter efficiency

η_p = Solar module efficiency

θ = Tilt angle (^{o})

For a tilted module, as shown in Figure 4,

$$G = GHI \times F_\theta \quad (9)$$

$$G_Y = GHI_Y \times F_\theta \quad (10)$$

Here,

GHI = Global horizontal irradiance (kWh/m^2-day)
GHI_Y=Annual global horizontal irradiance (kWh/m^2-day)
F_θ = Tilt factor at angle θ

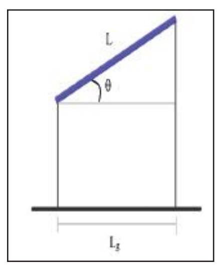

Figure 4: Side View of a Tilted Solar Module

For off-grid solar modules, battery efficiency must be taken into account.

$$E_{OG} = N \times M \times G \times \eta_p \times \eta_i \times \eta_b \times 10^{-6} \quad (11)$$

$$EY_{OG} = N \times M \times G_Y \times \eta_p \times \eta_i \times \eta_b \times 10^{-6} \quad (12)$$

Here

E_{OG} = Potential off-grid electricity generation in 1 day (GWh)

EY_{OG} = Potential grid-connected electricity generation in 1 year (GWh)

η_b = Battery efficiency

Table 2: Potential Electricity Generation from Tilted SPVs with a Capacity of 325Wp

Roof Area (m^2)	Suitable Roof Area (m^2)	Area per Module (m^2)		Number of Modules	Solar irradiation ($kWh/m^2/day$)		Daily off-grid generation (GWh)	Daily grid-connected generation (GWh)	Annual off-grid generation (GWh)	Annual grid-connected generation (GWh)
a	A	M_g	M	N	G	G_Y	E_{OG}	E_G	EY_{OG}	EY_G
6.25×10^7	3.12×10^7	1.77	1.94	1.77×10^7	4.61	1,685	20.7	25.8	7,563	9,454

For the calculation in Table 2, a 325 Wp solar module of 16.7% efficiency is considered, paired with a 98.1% efficient inverter and 80% efficient battery if off-grid. The module has 1956 × 992 mm dimensions and is tilted at an angle of 23.73°. The potential electricity generation can be calculated with such conditions as in Table 2. A study (Ghosh et al., 2010) has shown that at the conventional tilt angle of 23.73°, the average annual tilt factor in Dhaka is 1.097. As such, it has been calculated in this study that the tilted solar irradiation will be 4.606 $kWh/m^2/day$ and 1685 $kWh/m^2/day$ for daily and annual, respectively. This has been calculated from the GHI value of 4.20 $kWh/m^2/day$ (Kabir et al., 2010) and the yearly GHI of 1536 $kWh/m^2/day$ from SWERA (SWERA, 2007). In Table 2, it has been calculated that 20.7 GWh of daily and 7,563 GWh of yearly off-grid electricity can be generated. In the case of grid-connected electricity generation, 25.8 GWh of daily and 9,454 GWh of annual generation is possible. In August 2020, DESCO had energy sales of 493.013 MkWh (DESCO, 2020), and the grid-connected 325Wp SPV electricity generation (E_G) can provide 157% of that. Therefore, the SPV application has an electricity generation potential that significantly exceeds the electric energy consumption in the DESCO region. Hence, in terms of the amount of electricity that can be generated, the SPV application shows excellent potential to be a feasible option that has the potential not just to supplement Dhaka's power but may as well be able to be the predominant source of energy.

Greenhouse Gas Emission Reduction

Equation 13 calculates the emissions that can be decreased by SPV-based electricity generation instead of generating the same amount of electricity using conventional fuels. Whether grid-connected or off-grid electricity can be considered; this study will consider grid-connected electricity generation. This study will evaluate the natural gas emission factor because it is the predominant fuel. Therefore, by generating electricity using SPVs instead of natural gas, the emissions that can be abated are calculated in Table 3. In Table 3, the calculation is done for the application of tilted grid-connected 325Wp modules, where EY_G was estimated to be 9,454 GWh.

$$AE = EF \times EY_G \quad (13)$$

Here,

AE = Abated Emissions ($tCO_2e/year$)

EF = Emission Factor (tCO_2e/MWh)

EY_G = Electricity Generation in 1 year from SPVs (MWh)

Table 3: Abated Emissions by 325Wp Application of SPV

Emission Type	Emission Factor for Natural Gas, **EF**	Abated Emissions (tonnes)	Global Warming Potential, GWP	Abated Emissions (tCO_2e/year), **AE**	Abated Emissions ($MtCO_2e$/year)
GHG	0.452 tCO_2e/MWh			4.27×10^6	4.27
C_O2	56.1 kg/GJ	1.60×10^6	1	1.89×10^6	1.90
CH_4	3×10^{-3} kg/GJ	101.3	28	2.83×10^3	2.84×10^{-3}
N_2O	1×10^{-3} kg/GJ	33.8	265	8.95×10^3	8.94×10^{-3}

Source for Emission Factors: SWERA in (SWERA, 2007)*; Source for GWPs:* (IPCC, 2014)

As shown in Table 3, it has been calculated that it is possible to reduce greenhouse gas emissions by 4.3 $MtCO_2e$ each year. This includes a reduction of 1,894,581tCO_2e of carbon dioxide, 2,835 tCO_2e of methane, and 8,946 tCO_2e of nitrous oxide. This is 26.7% of the NDC requirement of the 16 $MtCO_2e$ reduction in GHG emissions from the power sector in the conditional scenario, as shown in Figure 5. Therefore, rooftop SPV application in DMA can significantly contribute to meeting Bangladesh's NDC target. It should be noted that the replaced fuel was considered to be natural gas, the predominant source in Bangladesh. If other sources like coal, which have higher emission factors, were considered, then the greenhouse gas emission reduction would be much higher. Replacing conventional fossil-fuelled energy sources with renewable energy sources like SPVs will not only reduce greenhouse gas emissions. Still, it will also mitigate the production of other pollutants like suspended particulate matter (SPM).

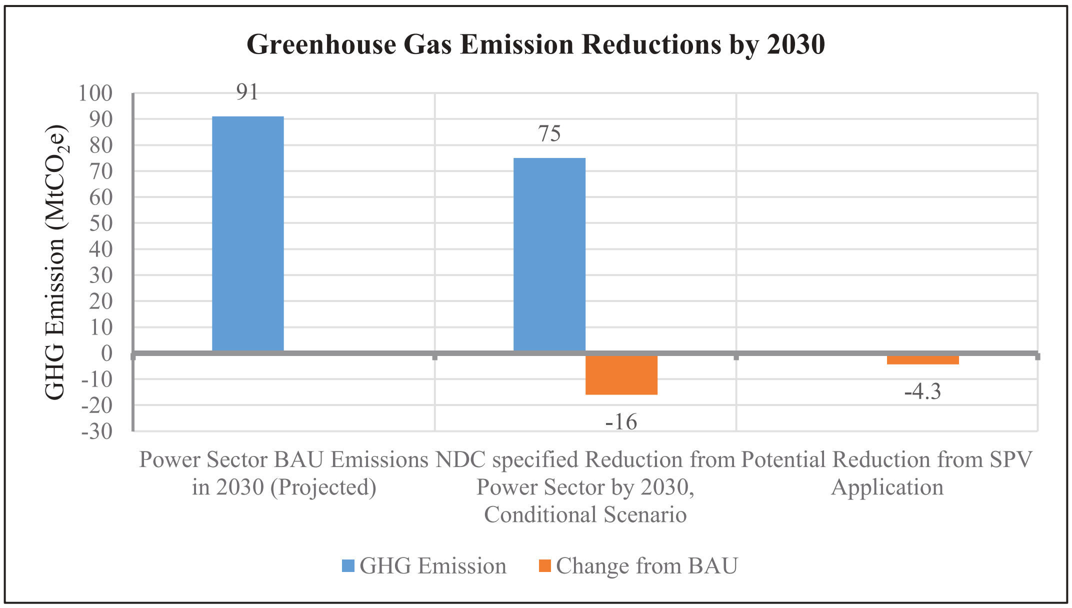

Figure 5: NDC Specified GHG Emission Reductions and Potential GHG Emission Reduction by SPVs

COST AND ENVIRONMENTAL CONSIDERATIONS

For a proposed 1 MW grid-connected solar PV system, it has been found in a study that the per-unit electricity generation cost varies from 13.25 to 17.78 BDT. For grid-connected fuel-oil-based power generation, the per-unit electricity generation cost is 15-18 BDT; therefore, the solar PV system is competitive (Mondal & Islam, 2011). People have a misconception about the price of renewable energy; many are unaware that an incredible transition has occurred where renewable energy has become cost-competitive with fossil-fuelled energy (Usher, 2019). Furthermore, there is a satisfactory trend of cost reduction of PV technology with time (Morsalin, 2013). Therefore, considering the LCOE (levelized energy cost) of solar PVs, the wide-scale adoption of solar PVs would be a competitive option compared to other renewable technologies.

SPV technology produces zero emissions and zero consumption of fossil fuels during its operation. However, during its life cycle, it emits GHGs and absorbs energy during stages like manufacturing, assembly, transportation, and recycling. Therefore, when evaluating the environmental impacts of SPV systems, these must be considered, which is done in the life cycle assessment (LCA). The indicators that are most used to do so are energy payback time (EPBT) and GHG emission rate. The EPBT of different PV systems ranges from 0.75 to 3.5 years. This is considerably good compared to the average lifespan of 25 years. The GHG emission rate of other SPV systems ranges from 10.5-50g CO_2eq/kWh, which is excellent compared to that of fossil fuel-based electricity, which is about 700gCO_2eq/kWh (Peng, Lu, & Yang, 2013).

CONCLUSIONS

With economic growth and population increase, the electricity demand in Dhaka will only keep increasing. Therefore, the city will benefit from being supplemented by SPV-based electricity. Furthermore, Dhaka is one of the world's most polluted cities, and fossil-fuel power generation contributes to the problem; hence, power generation from renewable sources can offer mitigation. The slum population of Dhaka does not have access to sufficient or reliable electricity, and SPVs may be a solution (Karim, Lipu, & Mahmud, 2017). From this study, it has been found that substantial electricity can be generated through SPV application, and consequently, a significant amount of greenhouse gas emissions can be reduced. The NDC target year is 2030, and the GHG emission reduction from BAU (business as usual) levels must be achieved by 2030. This study shows the potential of SPVs for the year 2023. With the rapid urban growth of Dhaka, the roof area in 2030 would be significantly greater; consequently, the potential SPV-based electricity generation and potential greenhouse gas emission reduction would be considerably higher. Even considering the cost and environmental aspects, SPVs are a cost-competitive, sustainable, and environment-friendly option. Therefore, SPVs should be widely adopted in Dhaka. The government should take appropriate steps toward this goal, academicians and stakeholders should conduct further research, and awareness must be raised among potential consumers.

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