Original Paper

Demystifying the economic and energy potential of Building-Integrated Photovoltaics in achieving India's intended Nationally Determined Contribution

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Keywords: renewable energy, Building-Integrated Photovoltaics (BIPV), energy transition, decentralization, Levelized Cost of Energy (LCOE).

Abstract. *The focus of this paper is on a techno-economic analysis concerning Building-Integrated Photovoltaics (BIPV) in the Indian context. Globalization and swift urbanisation have led to increased energy demand across buildings. India's contributions to environmental improvement are the most ambitious in current global development. The nationally determined contributions (NDCs) look at the country's policies and programmes promoting clean energy, enhancing energy efficiency, and developing resilient urban centres. It also captures citizens' and private sector contributions to* *combating climate change and abating pollution. Buildings account for 35–45% of global energy consumption, and their use is increasing at an 8% annual rate. To overcome the environmental problems caused by fossil fuels, there is a need to use renewable energy sources optimally to meet the energy requirements of buildings in smart cities. Building-Integrated Photovoltaics (BIPV) is suitable for India's highly populated cities because solar rooftops alone can't meet building energy needs. BIPV adaptation in congested structures requires economic analysis and discussion of NDC to determine optimal use. In this paper, the BIPV module is considered a source of clean energy for the building's facade (vertical portion), and a techno-economic analysis of BIPV modules has been performed and compared with the optimally placed rooftop PV module to explore the potential of BIPV in achieving India's NDCs.*

1. Introduction

Rapid urbanization and infrastructural development across the globe has resulted in escalated energy consumption and carbonizing environment in emerging countries like India. Buildings are responsible for 35–45% of global energy consumption and increasing at an annual pace of 8% (Shankar et al., 2022; Shankar & Bukya, 2022). To overcome the environmental problems caused by fossil fuels, there exists a need to use renewable energy sources to meet the energy requirements of buildings in smart cities (BEE (2021), Mungai et al., 2022)). As a result, both the preservation and protection of our resources for future generations and environmental values are not jeopardized. Semi-transparent PV kinds are getting prominence for deployment in building walls, roofs, and windows due to their versatile properties, such as supplementing structural materials, offering great insulation, enabling daylight, and generating power (Gholami, & Rostvik, 2020; Banerjee, 2022). In this viewpoint, Building-integrated photovoltaics (BIPV) can be deployed where the building facade or rooftop of the building is made with Photovoltaic panels. It is an emerging technology that serves buildings' space constraints in urban environments.

NDC(s) stand for 'Nationally Determined Contributions, ' indicating each country's commitment to reducing greenhouse gas emissions. Every five years, countries are expected to review and improve their NDCs and propose more ambitious greenhouse gas reduction actions. India has said that at least 40% of its installed capacity for power generation will be derived from non-fossil fuel-based energy sources and is trying to achieve a projected capacity of 525 GW by 2030, as shown in Figure 1. The principal activity is to execute the energy transition from fossil fuel to renewable energy. Figure 2 manifests that the current status is 106 GW, and by 2022, the target output capacity will be 175 GW.

Between April 2000 and March 2021, India's renewable energy sector attracted 10.02 billion dollars in foreign direct investment. According to the analytics firm British Business Energy, India ranks third in the world in terms of renewable energy investments and intentions in 2020 (Shankar et al., 2021a).

Also, the PM of India has announced some key points at COP 26 summit held in Glasgow. Some of them are:

- To attain a non-fossil energy capacity of 500 GW by 2030, shown in Figure 1.
- To provide 40 percent energy requirements through renewable sources.
- Reduce approximately 1 billion carbon emissions by 2030.
- Reduce carbon intensity.
- India aims to achieve the target of Net-Zero by around 2070.

One of the PV's major challenges is an area with solar panels deployed in broad open spaces to extract the maximum power. Transmission losses arise due to transmission lines used to deliver power to the load. PV panels can be employed to generate required energy at the load centre but often, buildings in urban areas have limited rooftop areas and other constraints described in Figure 3, which in turn limits the energy generated from using PV panels alone. The usage of BIPV mitigates these drawbacks. The proximity of energy-generating facilities to the location of energy consumption distinguishes the BIPV system. (Ghosh, 2020)) conducted an economic analysis of BIPV systems as the building envelope in European structures. BIPV is one of the most important characteristics of zero-energy buildings that also improves the built environment's aesthetic appeal. However, it now only accounts for around 1% of the worldwide photovoltaic industry. This necessitates a greater focus on this topic (Osseweijer et al., 2018)). BIPV modules can switch an energy-hungry building into an on-site sustainable energy generator, minimizing transportation losses and, resulting in the cost of power. The amount of energy produced by BIPV modules is largely measured by the amount of solar irradiation received from the sun. The energy generated by BIPV modules is affected by the facing of the BIPV module on the building site, and the local topographical variables (Shankar et al., 2021a; Chopda et al., 2021).

The primary findings of this paper are encapsulated as follows:

- BIPV module is proposed as an envelope material in the North, East, South, and West directions of the building facade.
- The solar irradiation falling at the surface of the BIPV module erected vertically at different azimuth angles (North, East, South, and West directions) are estimated using the solar transposition model (Shankar et al., 2021).
- The energy performance of the BIPV module mounted in each direction of the building facade is presented and compared with the optimally placed PV module.
- Economic analysis of BIPV mounted vertically at different azimuth angles (North, East, South, and West directions) is presented and compared with the optimally placed PV module.
- Analysis of the environmental sustainability of BIPV modules mounted vertically as an envelope of the building facade in each direction is presented.

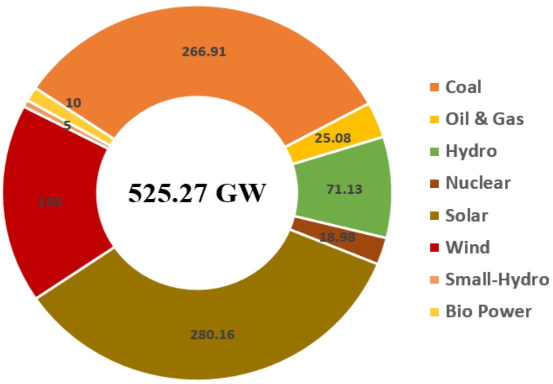

Figure 1. Projected capacity of total energy generated by 2030

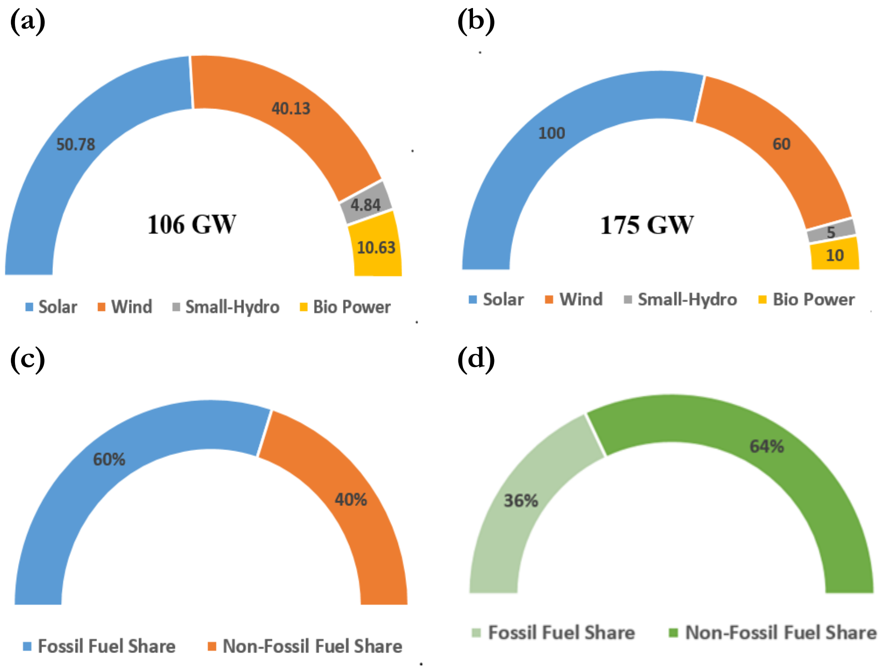

Figure 2. India's NDC tracking. (a) Currently installed capacity of renewable energy; (b) Target by 2022; (c) NDC target by 2030; (d) Projected capacity by 2030.

(a) Helipad (b) Roof garden (c) HVAC system

Figure 3. Challenges of rooftop PV

2. Methods

Building-integrated photovoltaics are a viable method for incorporating renewable energies into the built environment. This integrates solar PV panels into building roofs, windows, facades, and shading systems. BIPV maximises renewable energy generation, making a building more sustainable and environmentally beneficial. After optimising the design, the next step to be considered is technical evaluation. Here the assessment of BIPV layouts integrated within the building architecture from a technical standpoint is necessary. This includes the performance of the PV and BIPV system and Energy cost calculations.

The rooftop PV is considered to be optimally placed, whereas the BIPV modules are mounted vertically across the building facade in all directions of the building. The yearly solar irradiation at the geographical location of New Delhi, India, was acquired from the European Commission's Photovoltaic Geographical Information System (PVGIS), and the output power was produced from optimally placed rooftop PV and BIPV modules mounted in each direction (North, East, South, and West) is calculated by Equ.1 and Equ.2 respectively (Pvgis, 2021), A. Shankar et al. 2021b).

The power performance of PV and BIPV modules is formulated as follows:

$$P_{PV,t} = \eta_{PV}\, A_{PV}\, \frac{H_{PV,t}}{H_{stc}} \left[1 + \alpha_p (T_c - T_{stc})\right] \eta_{dr_{PV}} \tag{1}$$

$$P_{BIPV_N,t} = \eta_{BIPV}\, A_{BIPV}\, \frac{H_{BIPV_N,t}}{H_{stc}} \left[1 + \alpha_p (T_c - T_{stc})\right] \eta_{dr_{BIPV}} \tag{2a}$$

$$P_{BIPV_E,t} = \eta_{BIPV}\, A_{BIPV}\, \frac{H_{BIPV_E,t}}{H_{stc}} \left[1 + \alpha_p (T_c - T_{stc})\right] \eta_{dr_{BIPV}} \tag{2b}$$

$$P_{BIPV_S,t} = \eta_{BIPV}\, A_{BIPV}\, \frac{H_{BIPV_S,t}}{H_{stc}} \left[1 + \alpha_p (T_c - T_{stc})\right] \eta_{dr_{BIPV}} \tag{2c}$$

$$P_{BIPV_W,t} = \eta_{BIPV}\, A_{BIPV}\, \frac{H_{BIPV_W,t}}{H_{stc}} \left[1 + \alpha_p (T_c - T_{stc})\right] \eta_{dr_{BIPV}} \tag{2d}$$

Where:

η_{BIPV}, η_{BIPV} : Efficiency of the PV and BIPV module, %

A_{PV}, A_{BIPV} : Intrinsic area of the PV and BIPV module, m²

$H_{PV,t}$: Solar irradiation falling at the surface of optimally placed rooftop PV, kW/m²

$H_{BIPV_N,t}$ $H_{BIPV_E,t}$ $H_{BIPV_S,t}$ $H_{BIPV_W,t}$: Solar irradiation falling at the surface of BIPV module mounted vertically at north, east, south, and west facade of the building, kW/m²

H_{stc} : Solar irradiation under standard test conditions (STC)

α_p : Temperature coefficient of power, %/^{0}C

T_c : Historical data of temperature, ^{0}C

T_{stc} : Temperature of the PV module under STC, ^{0}C

$\eta_{dr_{PV}}$ $\eta_{dr_{BIPV}}$: De-rating factor of PV and BIPV module, %

The cost of the 100 m^2 BIPV module and the cost of the power converter are included in the proposed PV-BIPV system's economic analysis. Equ.3 is used to compute the present worth (PW) of each factor's cost, which encompasses investment, operation, and maintenance. The total of all the components of PW is the life cycle cost (LCC). Annualized LCC (ALCC) from Equ.5 utilizing the cost of cumulative present worth PW yields the levelled cost of energy (LCOE).

Energy cost calculations are as below:

$$PW = \left(\frac{1+r_f}{1+r_i}\right)\left(1-\left(\frac{1+r_f}{1+r_i}\right)^n\right) \tag{3}$$

$$R = C_0\left(\frac{1+r_f}{1+r_i}\right)^n,\ M = C_0\,PW \tag{4}$$

$$ALCC = \frac{K+R+M}{PW},\ LCOE = \frac{ALCC}{E_T} \tag{5}$$

Where:

r_i , r_f : Rate of interest and inflation, %

C_0, n : Present worth (PW), INR and life of the project, Yr

K : Initial investment on project, INR

R, M: PW of replacement and O& M cost, INR

ALCC: Annualized life cycle cost, INR

LCOE: Levelized cost of energy, INR/kWh

E_T: Annual energy generation

3. Results and Discussion

The results of the analysis of this study were as follows: (i) Power generated by optimally placed PV module; (ii) Output power from 100 m^2 of BIPV module mounted as an envelope of the building façade; (iii) Energy profile for PV and BIPV modules; (iv) GHG reduction, Comparison of PV; (v) BIPV modules on LCOE.

The output power provided by the BIPV module positioned vertically in all four directions (various azimuth angles for the North, East, West, and South facades) is computed and displayed in Figure 5. Similarly, the intrinsic area of an ideally located PV module is considered, and the PV module's output power is depicted in Figure 4. Because of their ideal positioning, rooftop PV modules generate more electricity than BIPV modules. Furthermore, as shown in Figure 6, the BIPV module put on the North façade produces less electricity than the BIPV modules mounted on the building's other sides.

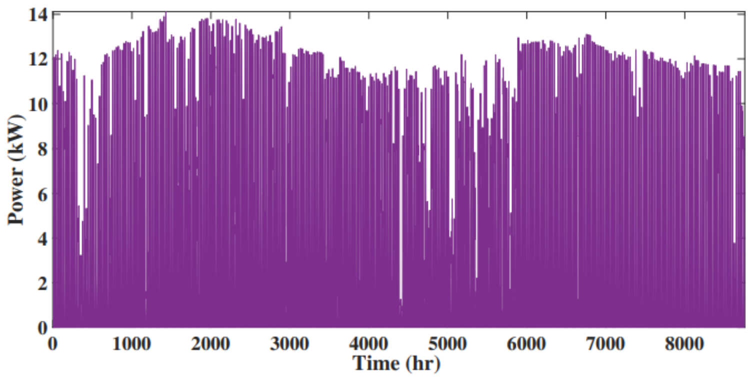

Figure 4. Power generated by optimally placed PV module

Energy profiles for PV and BIPV modules have been plotted for all months of the year ranging from January to December. It has been noticed that the PV module generates a relatively higher amount of energy compared with the BIPV module. Energy generated by BIPV modules facing North, East, West, and South directions have been simulated and it's evident out of all directions energy generated by the BIPV module facing North direction is least and energy generated by BIPV module facing South is maximum.

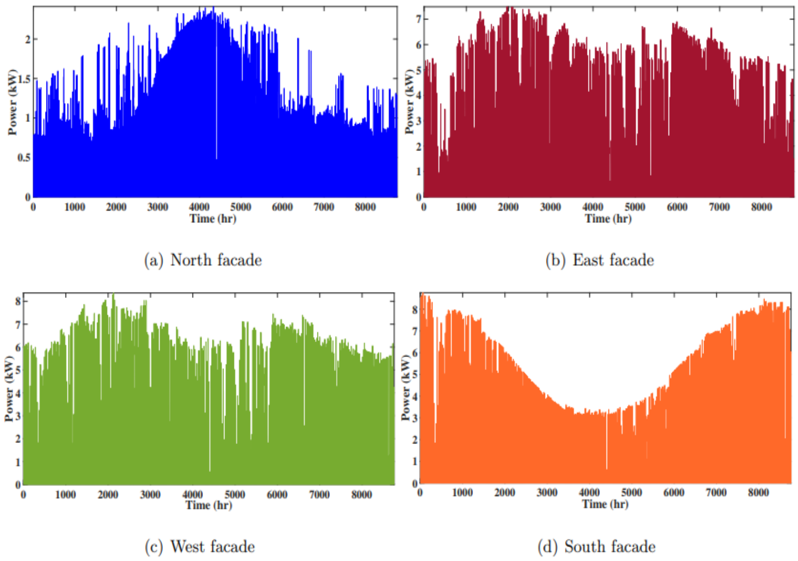

Figure 5. Output power from 100 m² of BIPV module mounted as an envelope of the building façade.

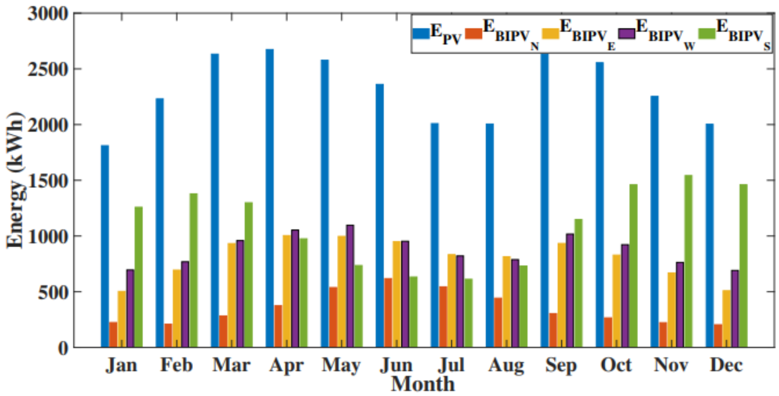

Figure 6. Energy profile for PV and BIPV modules

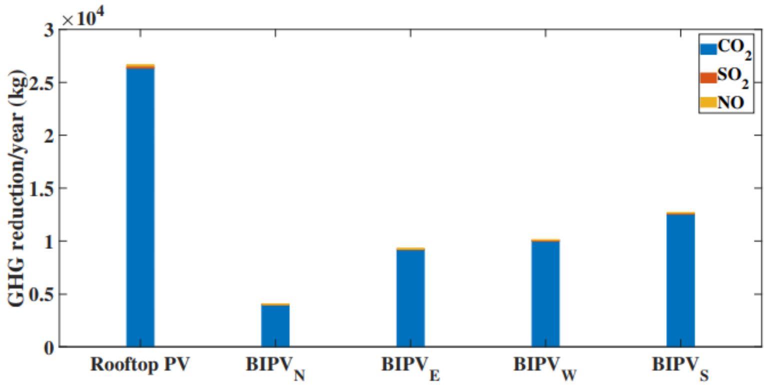

Figure 7. GHG reduction

In India, CO_2 emissions per unit of energy are projected to be 0.91 to 0.95 kg/kWh, SO_2 emissions are 6.94 to 7.20 g/kWh, and NO emissions are 4.22 to 4.38 g/kWh (Mittal et al., 2012). The environmental sustainability study of the PV and BIPV modules presented in Figure 7 shows that the BIPV module, as an envelope of the building facade, serves to eliminate a significant quantity of GHG from the environment without taking up any functional space.

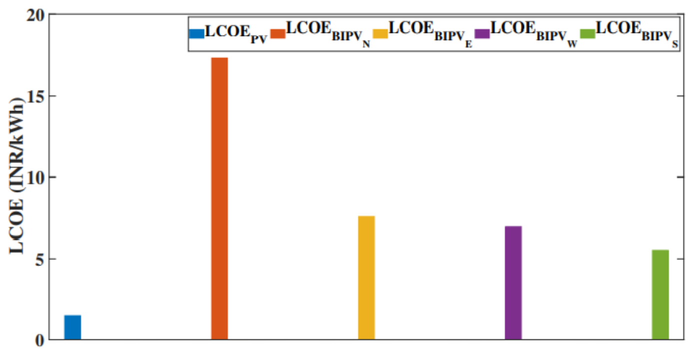

Figure 8. Comparison of PV and BIPV modules on LCOE

Figure 8 shows the LCOE of a 100 m² PV and BIPV module. The BIPV module positioned as an envelope of the building facade delivers energy at a lower rate than an appropriately placed PV module. Furthermore, the BIPV module positioned on the North facade produces the least yearly energy, resulting in energy supply at a higher rate. Similarly, because BIPV on the southern façade creates more energy than BIPV on the other sides of the building, it supplies energy at a reduced amount than other facades.

S.No	Parameters	Value
1	Capital cost of rooftop PV and BIPV module, INR/kW	45000, 135000
2	Capital cost of power converter, INR/kW	8400
3	Maintenance cost on PV and BIPV module, INR/Yr	2%
4	Inflation and real interest rate, p.a.	6.5%, 6 %
5	Lifespan of rooftop PV, BIPV and converter, Yr	25, 25, 10
6	Efficiency of PV and BIPV module, %	17.32%, 12.7%
7	αp, Hstc	-0.4%/ ^{0}C, 1 kW/m^2
8	Tstc	25^{0}C
9	$\eta_{dr_{PV}}$ $\eta_{dr_{BIPV}}$	80%, 85%

Table 1. Input parameters for power performance and economic analysis of PV and BIPV module (Shankar et al., 2022).

Table 1 shows a comparison of the performance of an appropriately positioned PV and a vertically installed BIPV module. PV modules with a 100 m^2 intrinsic area achieve a peak rating of 17.32 kW, whereas BIPV modules with a comparable intrinsic area achieve 12.7 kW. Table 1 further indicates that 100 m^2 of appropriately positioned PV modules produce more energy yearly than BIPV modules.

4. Conclusion

In urban environments, the available space for photovoltaic (PV) modules on rooftops are frequently insufficient to meet the total energy consumption of the buildings. The demand for the BIPV module on the building facade's vertical portion to generate on-site clean energy is the solution to mitigate the energy demand for the building. Discussed India's NDC and the techno-economic study of the BIPV module suggested a building envelope installed on the North, East, South, and West facades are presented in this research. A 100 m^2 BIPV module is used for the energy performance analysis compared to a similar area of the ideally positioned PV module. The BIPV on the building's south façade is the most energy-efficient, followed by the West, East, and North sides. Although a well-placed PV module delivers more energy than BIPV modules put on the building's façade, PV installation necessitates horizontal space, which is restricted in the urban setting. As a result, BIPV may be used as a secondary source of sustainable energy generation in metropolitan areas. At INR 5.52, 6.94, and 7.56 per kWh, the LCOE from the South, West, and East facades is shown to be cost-effective. BIPV can eliminate a significant amount of GHG emissions from the environment as a building facade envelope, according to an environmental sustainability analysis.

India's renewable energy capacity, excluding big hydro, has surpassed 100 GW, and the country is aiming for a 500 GW target by 2030. The infrastructure of high-rise buildings is rising in tandem with urbanization. As a result, BIPV modules can potentially be a major player in India's ambitious goal of 500 GW of renewable energy installation and carbon neutrality.

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Competing Interests

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