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Techno-economic analysis of an optimal integration of PV and BIPV systems in a residential network

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Abstract

The escalating global demand for sustainable energy solutions has prompted an increasing focus on solar photovoltaic (PV) systems. This research paper comprehensively investigates the modelling, and techno-economic analysis of an optimal combination of sets of PV and a BIPV system based on floor areas of residential buildings. The study employs advanced simulation techniques to develop a precise mathematical and optimization model and considers the levelized cost of electricity (LCOE) during the installation of PV and BIPV systems while addressing the challenge of variations in generated energy. The research contends that a comprehensive evaluation of LCOE is instrumental in determining the

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economic viability of optimal combinations for different sets of PV and BIPV installations based on floor area of the building while considering sustainable approaches to fulfilling energy needs.

The outcomes of this research contribute significantly to the burgeoning field of renewable energy by providing a robust framework for the assessment and optimization of a combined PV BIPV system leading to decision-making towards adoption of sustainable energy solutions.

Subject Classification: *47N10.*

Keywords: *Photovoltaic (PV), Building-integrated photovoltaics (BIPV), Levelized cost of electricity (LCOE).*

1. Introduction

Over the last few decades, India's energy consumption has grown significantly and consistently, reflecting the country's fast economic expansion, urbanization, rising living standards and increasing population. India's overall energy consumption has increased significantly, with an average yearly growth rate higher than the global average. The government has taken several initiatives, reforms and amendments in policy in order to meet this ever-increasing demand. According to the reports of Central Electricity Authority (CEA) India's energy generation increased by more than 100% between 2009-10 and 2022-23 [1].

Solar energy is critical to satisfying India's rising energy demands since it provides a renewable and plentiful power source. As per the 2023 Reports of CEA, 16.1% of the generation was by means of solar energy. In recent years, the development of the third and fourth generations PV materials that include transparent solar cells and flexible substrates, have enabled seamless integration into building components. These innovations not only absorb solar energy but also preserve the visual appeal of architectural aspects, promoting greater adoption in both residential and commercial projects [2]. The utilization of Building-Integrated Photovoltaics (BIPV) technology entails the direct integration of solar panels into structural components of a building, including roofing, windows, and facades. Each type offers unique benefits and challenges, influencing its suitability for different architectural contexts. Understanding the various types and practical applications of BIPV systems is foundational to harnessing their full potential in the construction industry [3].

Several literatures [4], [5] have extensively investigated factors influencing the performance of BIPV systems. Factors such as solar irradiance, shading effects, temperature variations, and module orientation are scrutinized to understand their nuanced effects on BIPV system performance. Integrating BIPV into distribution power networks has the potential to improve efficiency, diminish dependency on conventional sources, and contribute to the sustainable development of the built environment [6].

Grid compatibility, energy management, and power quality are all issues that arise during the integration of BIPV systems into distribution power networks. When BIPV and rooftop PV systems are optimally integrated, the issue of fluctuating energy production is mitigated. By obtaining a steady energy production profile, the end user's grid dependence is reduced, and the PV installation is optimized [7]

The literatures on Cost-benefit analyses encompass installation expenses, maintenance costs, and the economic value derived from energy generation. Studies also examine the Net present value(NPV), (Levelized cost of energy) LCOE and the financial feasibility of PV projects [8].

The problem lies in the gaps and challenges in the integrating the optimal number of PV and BIPV system for a given surface area. Existing research may lack comprehensive insights into the economic viability of PV and BIPV integration, hindering optimal performance and impeding widespread implementation. Addressing these gaps is crucial to advancing BIPV systems, and unlocking their full potential in sustainable construction.

The paper is organized as follows. In section 2, we develop and examine a mathematical representation of a typical BIPV system including the load estimation and developed project economics optimization model for an optimal combination of a PV and a BIPV system. Section 3 undertakes two test cases i.e. Off-grid and On-grid system each having two situations surplus or a deficit in energy generated by the installed system. Section 4 provide economic analysis (LCOE) of the optimal model for different floor areas by using optimization techniques. In section 5, we conclude with a discussion of prospective research.

2. Mathematical modeling of BIPV systems

2.1 *System description*

A 1 kW rooftop system installed at 25.618201^0 north and 85.183081^0 east. The system has mono-crystalline panels and a dedicated micro-inverter with an aggregated data logger. Parameters of the BIPV system is considered same as that of the normal PV mentioned below.

DC characteristics of PV panel:

$$P_{\max} = 375W, I_{SC} = 9.90A,\ V_{SC} = 44.5V$$

AC characteristics:

$$P_o = 290W, I_o = 1.26A,\ V_o = 185 - 275V$$

2.2 Mathematical Modelling of PV system

Researchers are actively engaged in simulating and estimating the performance of photovoltaic (PV) cells, modules, panels, and arrays using various computational software during the development, fabrication, and evaluation stages. The primary focus lies in the investigation of two widely employed models for PV cells, namely the single-diode and double-diode PV cells.

The electrical mathematical equation of PV cells is given by (1)

$$I = I_{ph} - Is\left[e^{\frac{q(V+Ic)}{nKT}-1}\right] - \frac{V + R_s I}{R_{sh}} \tag{1}$$

A photovoltaic system is an assortment of solar modules consisting of a variety of power-generating solar cells. A further generation of electricity is achieved by connecting numerous modules in an array. A PV array as shown in the Figure 1 consist of MXN PV modules that can be constructed by aligning N identical PV strings in parallel, where each string comprises M identical modules.

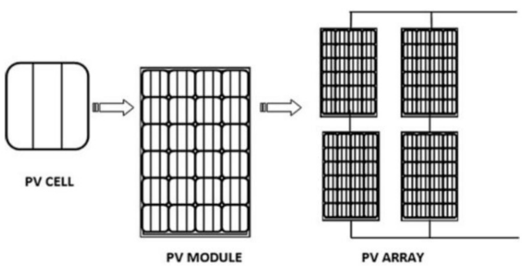

Figure 1

PV Array arrangement

The comprehensive multidimensional array model equation is depicted in Equation (2)

$$I = N_p\left[I_{ph} - Is\left[e^{\frac{q\left[\left(\frac{V}{N_s}\right)+\left(\frac{I}{N_p}\right)R_s\right]}{KT}}-1\right] - \frac{\frac{V}{N_s} + R_s\frac{I}{N_p}}{R_{sh}}\right] \tag{2}$$

where, V and I are PV Cell termainal Voltage [V] and Curret [A]

T is PV Cell temperature [K] and K is Boltzmann's constant

I_{ph} and I_s are Photo generated and Saturation current respectively

R_s and R_{sh} are Cell Series and Shunt resistance respectively

N_s and N_{sh} are Number of series and parallel cells

An equivalent circuit diagram for the mentioned system may be expressed in the Figure 2 as follows.

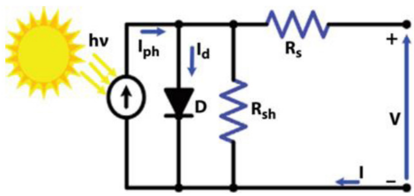

Figure 2

Electrical equivalent circuit PV circuit

2.3 *Load Estimation*

Load estimation for photovoltaic (PV) and building-integrated photovoltaic (BIPV) systems in buildings is necessary to evaluate available roof or installation space in order to calculate the system's potential capacity. Applying cost analysis methodologies prior to the installation of a photovoltaic (PV) system, organizations or individuals can ensure that the investment in solar energy is in line with their financial objectives and offers a sustainable and economical energy solution. Optimal No. of PV and BIPV for 10 different cases based on available area is shown in Table 1.

Table 1

Optimal No. of PV and BIPV for 10 different floor areas

Test Cases	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Rooftop Area (sqf)	250	500	750	1000	1250	1500	1750	2000	2250	2500
BIPV Panels	2	10	13	19	23	28	30	38	42	48
Roof-Top Panels	1	6	9	13	15	19	20	26	28	32

3. Project Economics Optimization Model

Techno-economic assessments of power plants typically rely on the Levelized Cost of Electricity (LCOE), which signifies the expenditure required to generate one kilowatt-hour of electricity using a particular model of the power plant. The expenses generally comprise the starting capital investment, the expenses related to operation and maintenance (O&M), and the costs of fuel and consumables if relevant), while the total amount of energy produced can be adjusted considering the degradation rate of the power plant and its components. A simplified LCOE equation given in given equation (3)

$$LCOE = \frac{\Sigma_{\forall Life} Cost_t}{\Sigma_{\forall Life} E_t} \qquad (3)$$

where, E_t = Energy served year

$Cost_t$ = Total annualized cost of energy per unit

3.1 *Objective Function*

The purpose of installing the roof-top and BIPV system is to reduce the cost of electricity. To visualize the exact savings and benefits of installing the system, we must evaluate the effective cost of energy over the life of the project.

Optimization is the process of finding the best solution to a problem by adjusting variables to meet specific criteria. The purpose of optimization in electrical engineering is to build and run electrical systems in the most efficient and cost-effective way feasible.

The objective here is to minimize the cost of a combined rooftop PV and BIPV system incurred in installation, operation, maintenance, replacement etc. throughout the lifespan of the system. The cost of energy can be measured by LCOE parameters mentioned in eq.(1). The objective function can be determined for optimization problem as in eq.(3)

$$\min \| LCOE \| \qquad (4)$$

Subject to different constraints

$$P_i^D = P_i^{pv} + P_i^{Grid} + P_i^{bipv} \qquad \forall_i \qquad (5)$$

$$0 \le P_i^{pv} \le P_{\max}^{pv} \qquad \forall_i \qquad (6)$$

$$0 \le P_i^{bipv} \le P_{max}^{bipv} \qquad \forall_i \quad (7)$$

$$P_i^{Grid} \ge 0 \qquad \forall_i \quad (8)$$

$$P_i^{pv} \le P_i^{Grid} \qquad \forall_i \quad (9)$$

$$P_i^{bipv} \le P_i^{Grid} \qquad \forall_i \quad (10)$$

When an ESS is included in the system, additional battery constraints are considered which are as follows:

$$\xi_{\min} \le \xi_i \le \xi_{\max} \qquad \forall_i \quad (11)$$

$$\Delta\xi_{dis} \le \xi_{i+1} - \xi_i \le \Delta\xi_{cha} \qquad \forall_i \quad (12)$$

$$\Delta\xi_i \times E_{ESS} = \eta_{cha/dis} \int_{\Delta t} P_{ESS}\, dt \qquad \forall_i \quad (13)$$

$$P_{max}^{ESS,dis} \le P_i^{ESS} \le P_{max}^{ESS,cha} \qquad \forall_i \quad (14)$$

where,

$$\text{Installation Cost} = \sum_{\forall pv} C_{PV} + \sum_{\forall converter} C_{Converter} + \sum_{\forall ess} C_{ESS} + C_{Grid} + \sum_{\forall bipv} C_{BIPV}$$

$$\text{Cost of Grid Import} = \sum_{\forall i} F_G\, P_i^{Grid}$$

$$\text{Maintenance Cost} = \sum_{\forall pv} M_{PV} + \sum_{\forall ess} M_{ESS} + \sum_{\forall bipv} M_{BIPV}$$

$$\text{Replacement Cost} = \sum_{\forall pv} R_{PV} + \sum_{\forall ess} R_{ESS} + \sum_{\forall bipv} R_{BIPV}$$

$$\text{Salvage Cost} = \sum_{\forall pv} S_{PV} + \sum_{\forall ess} S_{ESS} + \sum_{\forall bipv} S_{BIPV}$$

3.2 *Test Cases*

Two types of PV operational strategies, on-grid and off-grid/hybrid, are tested here is calculated under two different circumstances as shown in Figure 3, first without relacing façade and second after replacing the facade.

3.0.1 Off-grid PV System

The energy generated by the DC source is converted into AC electricity through the utilization of an inverter and a charge controller having efficiency η_{inv} and η_{cc} respectively.

Hence, two scenarios may arise: one- an excess where the PV system generates an energy surplus compared to the demand P_D, another- a deficit where the PV system falls short in generating sufficient energy to meet the household demand. The energy generated from the pv whether in excess or deficit is represented by the following equation

$$P^+ = (\eta_{cc}\eta_{inv})P_m - P_D \tag{15}$$

where,

$P^+ > 0$ during an excess and $P^+ < 0$ during a deficit

In case, $P^+ = 0$ The battery exhibits a lack of charging or discharging capabilities, resulting in the consumption of all generated power instantly.

3.2.1 On-grid PV System

Similarly, for an on-grid system, there are two possible outcomes: an excess, and a deficiency.

During an excess situation, a portion of the power generated by the PV system is utilized to meet the demand $(P_{sat} = P_D)$, while any excess power is transmitted to the electrical grid $(P_{\exp} = P_{\text{inv}} - P_D)$.

whereas, in the event of a deficit, output power of the inverter is utilized to meet a portion of the demand $(P_{sat} = P_{inv})$, while the remaining power required to address this shortfall is obtained from the grid $(P_{grid} = P_D - P_{inv})$.

Lastly, all generated power is instantly consumed if $(P_{inv} = P_D)$.

4. Results and Discussion

In this paper the critical importance of a comprehensive approach to modelling, evaluating performance, and conducting techno-economic analysis for rooftop PV systems, building-integrated photovoltaic systems (BIPVS), and hybrid systems.

By incorporating advanced simulation techniques, the LCOE of the project for an optimal number of PV and BIPV for different floor area is calculated under two circumstances one, without relacing façade and other after replacing the façade. The first case considers the cost of not only the BIPV but also it includes the cost of the façade. Whereas in the second case the cost of the façade is excluded, thereby the LCOE for all the considered cases gets reduced by a significant value.

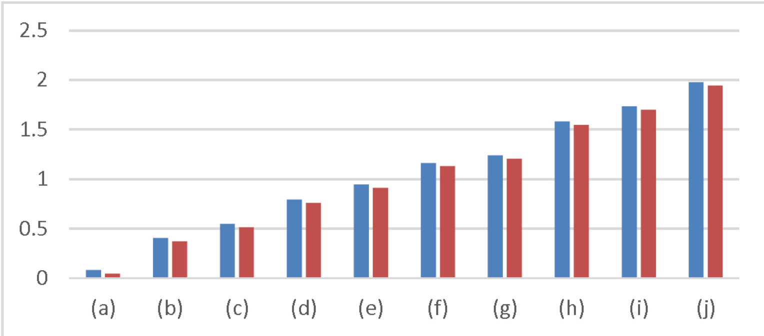

Figure 3

LCOE calculations without replacing facade and after replacing facade for 10 different floor area cases

This study provides a robust framework for assessing the economic viability of optimal combinations for different sets of PV and BIPV installations based on floor area of the building . The findings offer valuable insights for policy-makers, investors, and energy professionals, enabling informed decision-making in the pursuit of sustainable energy solutions. The emphasis on LCOE allows economies, even those facing energy deficits, to identify the most cost-effective and environmentally sound options for meeting their energy needs.

5. Future Scope

It is noteworthy that even after the lifespan of BIPV it will continue to serve as a façade. Thus, treating salvage value of the BIPV as façade cost can be included in future works along with the effect of load shedding on the LCOE calculation of the optimal combination of the PV and BIPV system.

Ultimately, the outcomes of this research contribute significantly to advancing renewable energy adoption, supporting the realization of a greener and more sustainable future on a global scale.

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