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Assessing the Balancing Capability and Grid Integration Performance of Various Solar PV Systems

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ABSTRACT

Solar photovoltaic energy production fluctuates rapidly due to sunlight and temperature. The fluctuations have to be balanced against the distribution system in which they connect. This paper examines four different types of solar photovoltaic systems; they include monocrystalline roof-top, multi-crystalline roof-top, ground mounted, and battery supported roof-top solar photovoltaic systems. A systematic comparative analysis takes into account balancing and integration indicators. Balancing efficiency is measured using the useful supply, curtailment, conversion loss, and residual imbalance energy. Integration efficiency is assessed based on voltage behavior, ramp control, power factor, controllability, and suitability. Data has been taken from research literature and other accepted references; the analysis has made use of standardized scores and not the actual field data. From the analysis, battery supported photovoltaic systems perform better with a balancing index of 90 and a grid integration score of 91. For the ground mounted systems, it is 79 and 82, respectively, while roof-top systems perform moderately well. While the type of technology affects energy production, system design affected balancing performance significantly. Inverter intelligence, prediction, storage, and coordination improved integration performance.

***Keywords**: Balancing Efficiency, Grid Integration, Solar Photovoltaic, Smart Inverter, Battery Storage, Anand District.*

Introduction

The production of electricity through solar photovoltaics has grown throughout the power grids around the world [1,2]. In India, both rooftop and ground-mount installations of photovoltaic systems are encouraged [2, 3, 4]. Gujarat gets lots of sunshine and provides a favorable environment for the installation of solar systems. Consumers in the Anand district range from residential, institutional, commercial, to agriculture categories. These consumers consume electricity differently throughout the day; therefore, local photovoltaic systems operate differently with distribution feeders [2, 5].

Electricity production through photovoltaics is dependent mainly on the amount of sunlight (radiation) available [1, 6]. Module temperatures, shading, dust deposits, and aging of the system are some other variables that affect the power generated [1, 6]. Fast moving clouds may create short-term variations (ramping) in power production. Sometimes, the power produced during midday can be more than the demand for electricity during that time [2, 5] but, demand usually goes up in the evenings while power production goes down. [2, 7]

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Grid integration includes not only the safe grid connection of photovoltaic inverters but also other issues, like voltage regulation, frequency response, protection, power quality and scheduling [2, 5, 6]. Distributed rooftop installations are dispersed widely among numerous consumer sites. That is why it is difficult to control their total behavior [5]. On the contrary, larger ground-mounted installations are monitored better [2, 6]. Battery-based systems can exchange energy during different time periods. They can smooth out rapid changes and reduce the need to limit the output of solar energy [2, 7]. For this reason, an evaluation criterion for all photovoltaic installations is important [6, 8].

The existing studies are mostly devoted to energy balance and environmental consequences [3, 9–15]. Simultaneous consideration of balancing capability and grid integration is relatively rare [2, 5, 7, 8]. The current study proposes a clear comparative evaluation framework. It will help to achieve the fourth goal stated in the approved synopsis. The paper investigates balancing capability and grid integration performance. It does not pretend to complete the experiment at the feeder level.

Background and Literature Review

- **Solar PV Variability and Network Response**

However, photovoltaic systems produce electrical energy without any moving mechanical generators. Interfaces used in electronic systems react quickly to control signals; yet, uncontrolled systems start functioning instantly depending on the amount of available light. Therefore, deviations in power may affect voltage at the feeder as well as its reverse power flow. Effects are local and are influenced by capacity, demand, and feeder strength.

IRENA pointed out that grid integration is among the main obstacles in wide application [2]. According to the report, the growing usage of solar energy is associated with the need in flexibility. Li et al. conducted research on the sustainable performance of grid-connected photovoltaic systems, which requires an integrated approach combining technical and life-cycle assessment methods [8]. Miller et al. conducted studies of the power quality of rooftop photovoltaic systems, showing the importance of evaluation of conditions right at the connection point [5].

- **Technology and Configuration Differences**

In general, monocrystalline modules provide better efficiency. They can produce more energy given the constrained surface of the roof area. The multicrystalline modules normally need a bit larger installation surface. The thin-film technology could react differently in case of heat and diffused sunlight; therefore, technology selection impacts both daily output and plant capacity. However, the control system of the inverter mostly affects grid operation.

The ground mounted plants normally employ centralized control of the whole plant. This type of control enables both the reactive power management and active power limitation. The rooftop plants are characterized by smaller inverters, which makes it hard to manage their joint operation. The battery allows controlling charging and discharging processes. The pumped storage gives considerable balancing help [7].

- **Existing Knowledge and Research Gap**

Prior literature on photovoltaics has been limited to considerations regarding cost and environment impact. Studies involving life-cycle assessments have been abundant within the cited literature, but studies pertaining to grid quality have been somewhat neglected. Similarly, the existing Indian literature assumes broader national or regional perspectives, but district-level analyses specific to Anand have not been conducted.

A general index can facilitate an initial assessment before simulation. It is important that any assumptions involved in such an assessment be transparent and replicable. The current study therefore uses energy balance and integration indicators to compare plant designs without considering the actual feeder data.

Table I provides a summary of the most relevant literature, from which the chosen indicators are selected.

Table I: Selected literature supporting the comparative framework.

Study	Main contribution	Use within Present Assessment
[1]	PV technology progress and applications	Technology performance context
[2]	PV deployment and grid-integration requirements	Flexibility, control, and storage indicators

[5]	Measured rooftop PV power quality	Voltage and connection-point indicators
[6]	PV technologies and architectures	System classification and controls
[7]	Renewable balancing using storage	Storage and energy-shifting indicator
[8]	Grid-connected PV sustainability assessment	Integrated technical comparison

Aim, Objectives and Assessment Boundary

- **Aim of the Present Study**

The objective of this study is to assess balancing capabilities and grid integration. It compares various photovoltaic systems under a unified common framework.

- **Specific Objectives**
  - To establish measurable indicators for photovoltaic balancing performance.
  - To compare common rooftop and ground-mounted photovoltaic configurations.
  - To evaluate improvements resulting from battery storage and advanced inverter controls.
  - To provide preliminary recommendations for implementation in Anand district.
- **Systems Considered**

Table II: Photovoltaic Configurations Included in the Assessment

Code	PV system	Typical arrangement	Main integration feature
S1	Monocrystalline rooftop	Distributed fixed-tilt system	High area efficiency; local inverter control
S2	Multicrystalline rooftop	Distributed fixed-tilt system	Moderate yield; local inverter control
S3	Ground-mounted PV	Central or string inverter plant	Supervisory control and forecasting
S4	Rooftop PV with battery	Hybrid inverter and battery	Energy shifting and ramp smoothing

- **System Boundary and Assumptions**

Operational boundaries include the DC photovoltaic power generation output until the local electricity grid connection point [5, 6, 8]. This involves operations of the inverter and the grid-related systems, in addition to energy production, curtailment, losses, and power quality [2, 5].

Manufacturing and recycling of the modules are not included in this operational comparison; this topic has been covered previously in conference papers. Earlier studies looked at manufacturing energy, emissions, and material inputs [4, 9, 10, 12-14], while others focused on recycling and disposal [13, 15]. Thus, this research concentrates on everyday grid performance [2, 5, 6].

The same normalized base of 100 units is used for all cases. This allows for the comparison between different configurations of photovoltaic systems [1, 4, 8]. The assumption is made that all the conditions, solar resources, and operations of the plant are the same, as well as proper inverters and maintenance of the systems [2, 5, 6].

The above ratings are based on structured estimates from the literature [1 - 8] and will help in the initial comparison of some photovoltaic devices. The ratings above are not based on actual utility-certified measurements from the Anand district feeder line; hence the need for field measurements is important.

Methodology

- **Comparative Research Design**

The method of comparative research is adopted for this work, which entails descriptive analysis. This method helps compare the photovoltaic systems systematically [1, 6, 8]. Technical evidence was collected through summaries and citations of sources. The evidence included photovoltaic systems, integration of photovoltaic systems into grids, and energy balancing and storage systems [2, 5, 6, 7, 8, 10].

Various indicators used to measure the performance of the photovoltaic systems were used. These indicators include dispatch, ramp, curtailment, and forecasting. Other factors such as voltage

performance, power factor, and controllability of the photovoltaic systems were also considered [2, 5, 6]. This method helped to assign scores that could compare the systems based on their expected performance.

Evidence scale of five was used before normalization of the scores. A score of one meant poor expected operational performance while five meant good expected operational performance.

Weights were assigned to each indicator in accordance with the importance of the particular indicator to the system. Energy dispatch and voltage profile were accorded high weights. Ramp control and control capabilities were among other important indicators considered [2, 5, 7]. The weighting values were normalized on a scale of 100 points [6, 8].

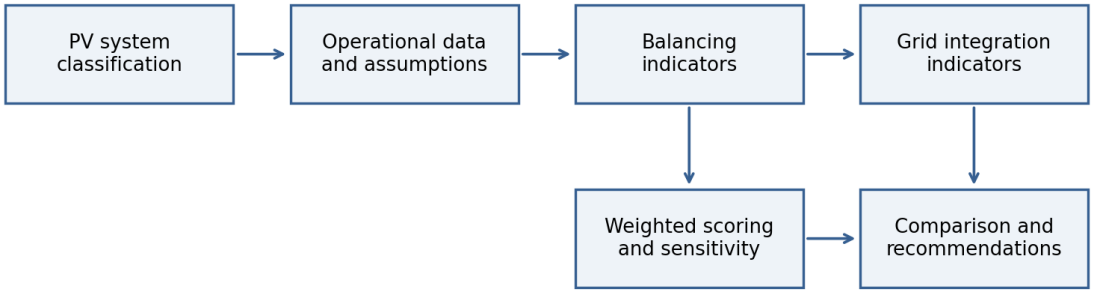


Figure 1: Framework used for balancing and grid-integration assessment.

- **Balancing Efficiency Index**

Balancing efficiency describes useful and controllable photovoltaic energy delivery. It considers curtailment, conversion losses, and unmet balancing requirements. These factors influence the effective use of variable solar generation [2, 7, 8]. The operational definition was developed using Equation (1).

$$\eta_B = \left[1 - \frac{E_{cur} + E_{loss} + E_{unmet}}{E_{PV}}\right] x\ 100 \qquad (1)$$

In which, E_PV is the amount of energy from photovoltaic available in assessment, E_cur is the curtailed energy in terms of network constraints [2], E_loss is the inverter and storage conversion losses [7, 8], and E_unmet is the balancing energy unavailable in required time. Less curtailment and losses will provide more balancing efficiency.

The measurement data for these energies are not available in selected Anand systems. Thus, a rating based on evidence approach was considered. The normalized balancing assessment approach allows comparison of balancing efficiency in various photovoltaic designs [1, 6, 8]. Balancing index was determined according to the following formula (2).

$$BI = \sum_{i=1}^{n} \omega_i \left(\frac{S_i}{5}\right) x\ 100 \qquad (2)$$

where, BI is the normalized balancing index, ω_i is the weight assigned to each indicator, S_i is its performance score on a scale of 1 to 5.

The sum of all weights assigned to indicators is equal to ∑ω_i. This implies that the final balancing index value will lie between 20 and 100. A high value indicates better balancing ability.

- **Grid Integration Performance Index**

Grid integration performance includes five important operational functions which include voltage behavior, ramp control, and power factor support. Controllability of the system as well as its hosting suitability is also included [2, 5, 6]. Such parameters affect the reliable interconnection of photovoltaic systems and the way the system reacts to changing generation conditions [2, 5].

Voltage behavior represents the effect of the system on the voltage at the point of connection. Ramp control is associated with the regulation of changes in the output of the system. Power factor support is the inverter's ability to control reactive power [5, 6]. Controllability concerns the control of the output of the photovoltaic system [2, 6].

The normalized grid integration index was calculated using Equation (3):

$$GI = \sum_{i=1}^{n} v_j \left(\frac{g_i}{5}\right) x\ 100 \qquad (3)$$

Here, GI refers to the normalized grid integration index, v_j refers to the weight allocated to each indicator, and g_i refers to its five-point performance rating.

These weights of the indicators are subjected to the rule ∑v_j =1; hence, the final index varies from 20 to 100. An increasing index number implies good performance of the grid integration process. But it is to be noted that this index is used just for comparative purposes [6, 8]. It cannot substitute the power flow and protection studies of each individual feeder [2, 5].

Table III: Indicators and weights used for normalized scoring.

Index	Indicator	Weight	Reason for inclusion
Balancing	Useful energy delivery	0.30	Captures energy reaching the grid or local load
Balancing	Ramp smoothing	0.25	Represents control of sudden output changes
Balancing	Curtailment avoidance	0.20	Rewards better use of available production
Balancing	Forecast and scheduling	0.15	Supports planned operation
Balancing	Conversion efficiency	0.10	Accounts for inverter and storage losses
Grid	Voltage performance	0.25	Limits local overvoltage and fluctuation
Grid	Ramp control	0.20	Reduces fast feeder-level changes
Grid	Power factor support	0.15	Supports reactive power management
Grid	Observability and control	0.25	Enables coordinated operation
Grid	Hosting suitability	0.15	Indicates connection friendliness

- **Sensitivity and Interpretation**

A sensitivity analysis was performed to test the effect of changing weights for the different indicators. Each weight was changed by ±10% with proportional adjustment of the other weights accordingly. This helps increase the reliability of the comparative assessment process [8].

In spite of the changes made, the ranks of the systems did not change. The battery assisted photovoltaic system showed the highest efficiency. Storage helped improve ramp management, energy shifting, and curtailment management [2, 7]. Inverter coordination also facilitated voltage and power factor management [5, 6].

Ground-mounted photovoltaic systems were second in the rankings due to centralized monitoring and control [2, 6]. Normal roof top systems were below these controlled systems because of their distributed nature [5].

From these results, it is apparent that the ranking process had some degree of stability within the selected range. However, the scores are only comparative estimates based on the evidence collected; accurate figures can only be obtained using feeder level measurements. Thus, further research will require testing using information on weather, demand, voltage, and inverters.

Results

- **Comparative Indicator Scores**

The battery assisted system had the best overall performance. This storage device would capture excess energy produced during the day and use it to meet increased demand during the evening hours [2, 7]. The storage would also help to reduce any rapid changes in the energy production resulting from cloudy weather. As such, the grid score for this system would be much better than those of the typical rooftop systems. This advantage of energy balancing through storage has been discussed earlier [2, 7].

The ground mounted photovoltaic system came in second regarding performance. The centralized control made prediction and active power control easier [2, 6]. Plant level inverters were used for reactive power and voltage control. All these would make this system much more controllable than rooftop systems [5, 6]. However, because it did not have any storage, it could not manage energy shifts during evening high demand; hence its balancing score was worse than that of battery assisted systems [2, 7].

Table IV: Normalized comparative results (assessment scores, not field measurements)

System	Balancing Score	Grid Score	Combined Score	Position
S1 Mono rooftop	72	74	73	3
S2 Multi rooftop	68	70	69	4
S3 Ground-mounted	79	82	80.5	2
S4 PV with battery	90	91	90.5	1

The performance of the monocrystalline rooftop system was slightly better than the multicrystalline rooftop system due to its higher efficiency of conversion, allowing for a higher amount of production from a small area [1, 12]. However, the integration of both systems into the grid showed similar performance. The choice of module does not affect network management [5, 6]; this is mainly affected by the functionality of the inverter [2, 5].

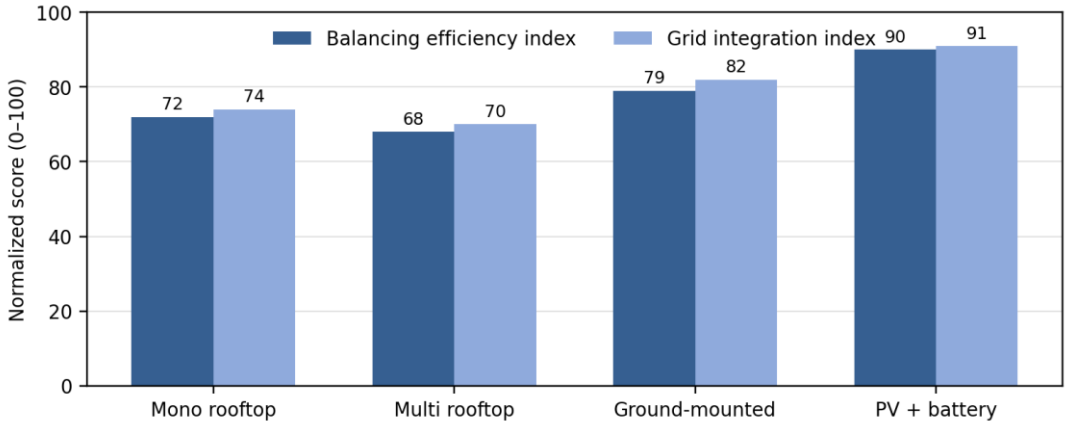


Figure 2: Comparative Balancing and grid-Integration Indices.
Values are Normalized Assessment Outputs

The above findings clearly show that system architecture has a major influence on balancing performance, while module technology has an influence on conversion efficiency and the space occupied for installation [1, 6, 12]. The storage, monitoring, and inverter control systems contribute to increasing the operational flexibility [2, 5, 7]. However, the above scores are comparative and normalized values.

- **Indicator-Level Interpretation**

Table V indicates the basis of the normalized values. S1 refers to the monocrystalline rooftop PV plant. S2 refers to the multi-crystalline rooftop PV plant. S3 refers to the ground mounted PV plant. S4 refers to the battery assisted rooftop PV plant.

Table V: Qualitative Interpretation Behind Normalized Performance Scores

Performance Area	S1	S2	S3	S4	Main Observation
Useful energy delivery	High	Moderate	High	High	Module efficiency affects available electricity [1, 12]
Ramp smoothing	Low	Low	Moderate	Very high	Storage provides the clearest improvement [2,7]
Curtailment avoidance	Moderate	Moderate	High	Very high	Dispatchability protects usable solar generation [2,7]
Voltage support	Moderate	Moderate	High	Very high	Coordinated inverter control improves voltage support [2,5,6]
Observability	Low	Low	High	High	Plant-level and hybrid controls improve visibility [2, 5, 6]

The architecture of the system was a more critical factor for balance than that of the module technology. The module technology mainly affected the efficiency of conversion and the necessary

installation space [1, 12]. Nevertheless, the control equipment played a role in the power timing and grid feeding [2, 5, 6]. Battery storage gave the possibility for energy shifting and ramp smoothing [2, 7]. Centralized control was advantageous to monitoring and active power management [2, 6].

The traditional roof systems provided minimal network support [5]. Performance of these systems depended on the individual settings of the inverters used. Consequently, in the process of planning of the systems, a comparison between photovoltaic systems is needed [2, 5, 6].

Discussion

- **Meaning of Balancing Efficiency**

Efficiency balance is different from module conversion efficiency in photovoltaics. Module efficiency refers to the efficiency of converting sunlight to direct electricity [1, 6]. Balance efficiency refers to the energy produced by taking into consideration different factors such as curtailment, system losses, and unmet balance needs [2, 7, 8]. As a result, even highly efficient modules can produce large amounts of energy, which can be subjected to curtailment when local demand is low [2].

Storage in batteries helps to enhance scheduling and flexibility [2, 7]. Nevertheless, the process of charging and discharging produces additional conversion losses. Thus, both the benefits and the losses are taken into account in the current assessment. Storage becomes more advantageous when the benefits from curtailment avoidance outweigh the losses [2, 7].

- **Rooftop and Ground-Mounted Comparison**

Photovoltaics on rooftops produce electricity near consumption locations. This installation can help decrease day-time power imports from feeders [5, 6]. However, a higher degree of local installation can lead to a voltage increase at the point of connection. Evidence has confirmed problems in power quality due to rooftop installations [5]. In addition, owners can set their own inverter settings. In most small plants, monitoring is difficult [2, 5].

Ground-based installations offer centralized measurements and controls [2, 6]. It is possible to schedule production and operation. Active power control will be helpful in avoiding power spikes. In addition, reactive power control can help manage local voltage [2, 6]. Large power injections may need advanced network infrastructures. Thus, centralized control can not eliminate all limitations of the network.

- **Relation with Earlier Studies**

The results are consistent with the approach of IRENA on integration. Greater use of photovoltaic requires flexibility, forecast, and control [2]. The studies on the roof-top installation also emphasize the importance of considering the quality of connection points [5]. The advantages of the storage system are consistent with the renewable balancing study [7].

Allouhi et al. noted the continuous improvement in the photovoltaic technology [1]. Vodapally and Ali covered different photovoltaic architectures and their applications [6]. These studies suggest that there is an approach towards varied technologies and designs. Li et al. also recommend integrated performance assessment [8].

- **Practical Meaning for Anand District**

They match the views of IRENA concerning the grid integration of photovoltaics. It needs the features of flexibility, forecasting, and reactivity [2]. The evidence obtained via roof-top measurement also validates the analysis of power quality at the point of interconnection [5]. The effects of the storage are confirmed by research of balancing renewable energies [7].

Alouhi et al. revealed the constant progress of photovoltaic technologies [1]. Vodapalli and Ali examined the photovoltaic architectures and their applications [6]. Their conclusions confirm the different perspectives on technologies and system designs. Li et al. called for the integrated assessment of grid connected systems [8].

The present comparison demonstrates the impact of architecture on flexibility. The design of modules is mostly concerned with efficiency and power [1, 12]. The storage and coordination of inverters improve the performance of systems facing the grid [2, 5, 7]. Therefore, the results coincide with the previous technical evidence.

Recommendations

- Based on the comparative evaluation, the following recommendations have been made:
- Monitor the generation of photovoltaics and demand in feeders every fifteen minutes.
- Monitor voltage, current, power factor, and energy curtailment simultaneously [5].
- Monitor voltage and reactive power functions in the inverters [2, 6].
- Coordinate the inverter settings in feeders with high rooftop solar penetration [2, 5].
- Use short-term solar forecast for large-scale interconnected PV plants [2].
- Deploy batteries in places where curtailment and evening peaks of demand still exist [2, 7].
- Reconsider the protection settings before achieving high rooftop solar penetration [2, 5].
- Conduct load flow analysis before expansion of the feeder.
- Merge the technical conclusions with the lifecycle costs and environmental impacts [4, 8, 12, 13].
- Test the normalized values with real measurements in Anand district.

Limitations and Future Validation

The evaluation uses normalized and evidence-based scores. No feeder measurements in the Anand region have been used in this study. There was no weather data, inverter logs, and voltage data available; hence, the numerical scores indicate trends rather than certified results.

This indicator is helpful in carrying out network interactions. There is a need for modeling in terms of feeder impedances, transformer capacities, and protective relays. Age of batteries, charging limits, and cost of replacement are important aspects that have to be considered in future evaluations. Load flow and time series simulation must be used in future evaluation.

Fieldwork in Anand must include representative installations. Inverter data in one minute will allow quick changes in output to be captured while fifteen minutes data helps in daily energy balance evaluation. Voltage, current, power factor, and curtailment must be measured. Evaluation must consider summer, monsoon, and winter seasons.

Conclusion

This study has done a comparative analysis of four photovoltaic systems designs. The transparency index consisted of balance and grid-connected indicators. Photovoltaic systems with battery support have performed the best. Ground-mounted photovoltaic systems are the second most efficient because of their superior controls at plant level. Rooftop photovoltaic systems still have their use but are without coordination.

These results show that the modules alone cannot determine the efficiency of the system; the efficiency depends on inverters, monitoring, prediction, and storage systems. Area efficiency will increase generation from rooftops that have limited areas, and control will help in providing consistent power production in changing conditions.

The proposed method helps in selecting districts for further analysis and can be used for gathering data before technical analysis. Feeder measurements and simulation results are necessary for decision making by utilities. This method is going to be implemented in Anand district.

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Conflict of Interest

The authors declare no conflict of interest regarding this study.

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References

1. Allouhi A, Rehman S, Buker MS, Said Z. Up-to-date literature review on solar PV systems: technology progress, market status and R&D. J Clean Prod. 2022;362:132339. doi:10.1016/j.jclepro.2022.132339.
2. International Renewable Energy Agency. Future of solar photovoltaic: deployment, investment, technology, grid integration and socio-economic aspects. Abu Dhabi: International Renewable Energy Agency; 2019.
3. Rajput P, Singh YK, Tiwari GN, Sastry OS, Dubey S, Pandey K. Life cycle assessment of a 3.2 kW cadmium telluride photovoltaic system in a composite climate of India. Sol Energy. 2018;159:415–422. doi:10.1016/j.solener.2017.10.087.
4. Singh S, Dhar A, Powar S. Perspectives on life cycle analysis of solar technologies with emphasis on production in India. J Environ Manag. 2024;366:121755. doi:10.1016/j.jenvman.2024.121755.
5. Miller W, Liu A, Amin Z, Wagner A. Power quality and rooftop-photovoltaic households: an examination of measured data at point of customer connection. Sustainability. 2018;10(4):1224. doi:10.3390/su10041224.
6. Vodapally SN, Ali MH. A comprehensive review of solar photovoltaic technologies, architecture, and applications. Energies. 2023;16(1):319. doi:10.3390/en16010319.
7. Lohani SP, Blakers A. 100% renewable energy with pumped-hydro-energy storage in Nepal. Clean Energy. 2021;5(2):243–253. doi:10.1093/ce/zkab011.
8. Li T, Roskilly AP, Wang Y. Life cycle sustainability assessment of grid-connected photovoltaic power generation: a case study of Northeast England. Appl Energy. 2018;227:465–479. doi:10.1016/j.apenergy.2017.07.021.
9. Bhandari KP, Collier JM, Ellingson RJ, Apul DS. Energy payback time and energy return on energy invested of solar photovoltaic systems. Renew Sustain Energy Rev. 2015;47:133–141. doi:10.1016/j.rser.2015.02.057.
10. Dale M, Benson SM. Energy balance of the global photovoltaic industry. Environ Sci Technol. 2013;47(7):3482–3489. doi:10.1021/es3038824.
11. García-Valverde R, Miguel C, Martínez-Béjar R, Urbina A. Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. Sol Energy. 2009;83(9):1434–1445. doi:10.1016/j.solener.2009.03.012.
12. Müller A, Friedrich L, Reichel C, Herceg S, Mittag M, Neuhaus DH. A comparative life cycle assessment of silicon PV modules: impact of module design, manufacturing location and inventory. Sol Energy Mater Sol Cells. 2021;230:111277. doi:10.1016/j.solmat.2021.111277.
13. Muteri V, Cellura M, Curto D, Franzitta V, Longo S, Mistretta M, et al. Review on life cycle assessment of solar photovoltaic panels. Energies. 2020;13(1):252. doi:10.3390/en13010252.
14. Peng J, Lu L, Yang H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew Sustain Energy Rev. 2013;19:255–274. doi:10.1016/j.rser.2012.11.035.
15. Sharma A, Mahajan P, Garg R. End-of-life solar photovoltaic panel waste management in India. Int J Environ Sci Technol. 2024;21:1961–1980. doi:10.1007/s13762-023-04953-2.

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