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Use of solar panels in civil engineering structures and railways: An Indian perspective

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Abstract
The integration of solar photovoltaic (PV) systems into civil engineering structures and railway infrastructure is increasingly relevant to India's sustainable development goals. With strong policy support from the Ministry of New and Renewable Energy (MNRE) and Indian Railways' Renewable Energy Mission, solar PV is becoming integral to reducing carbon emissions. This paper follows the standard academic format: introduction, literature review, methodology, results, and conclusion. Case studies from Delhi Metro, Indian Railways, and Gujarat canal-top solar projects are highlighted, with references to Bureau of Indian Standards (BIS) codes and Indian regulatory standards. A sample economic analysis is provided using the Levelized Cost of Energy (LCOE) model. The study concludes with recommendations for future research and policy alignment.

Keywords: Solar PV, Civil Engineering Structures, Indian Railways, BIPV, BIS Standards

1. Introduction
Global energy consumption has risen exponentially in the past few decades, creating urgent challenges associated with fossil fuel dependence and climate change. Renewable energy has become central to addressing these challenges, and among various renewable sources, solar energy stands out for its scalability, modularity, and declining costs (International Energy Agency [IEA], 2023). India, as one of the world's fastest-growing economies, faces a dual challenge: ensuring energy security while meeting commitments to reduce greenhouse gas emissions.

The Ministry of New and Renewable Energy (MNRE) launched the National Solar Mission in 2010 with the ambitious target of 100 GW solar capacity by 2022, later scaled up under the broader renewable energy goals of 450 GW by 2030 (MNRE, 2019). The falling cost of solar PV—from more than ₹10/kWh a decade ago to ₹2.5–3.5/kWh today—has made it a viable mainstream energy option (Central Electricity Regulatory Commission [CERC], 2023). A particularly significant area of application is the integration of solar PV into civil engineering structures and railway infrastructure. Civil structures such as rooftops, façades, bridges, and canal systems represent large underutilized surfaces that can generate electricity if covered with PV modules. Similarly, Indian Railways, which accounts for nearly 2% of national electricity consumption, has set an ambitious goal to become a "net-zero carbon emitter" by 2030 (Indian Railways, 2020). This requires embedding renewable energy solutions into its operations and infrastructure. Civil engineers play a pivotal role in this transition. Their expertise in structural design, material performance, and construction practices enables the safe integration of solar modules into buildings, transportation assets, and public utilities. Moreover, their collaboration with electrical and policy experts ensures compliance with standards such as Bureau of Indian Standards (BIS) codes, International Electro technical Commission (IEC) standards, and railway-specific safety norms.

This paper investigates the integration of solar PV in civil engineering structures and Indian Railways. It reviews existing literature, outlines methodology, presents results from case studies and modelling, and provides recommendations for the Indian context.

1.1 Research Objectives
1. Summarize PV integration typologies across civil structures and railway assets.
2. Provide design and analysis methods for structural, electrical, fire, and operations interfaces.

3. Present performance modelling and LCCA tools suitable for early stage feasibility and detailed design.
4. Identify risks, standards, and research gaps for reliable, safe, and economical deployment.

1.2 Scope and Method

A synthesis of peer reviewed literature, codes/standards, utility practices, and owner/operator case applications are consolidated into a decision support framework. Equations and tables are provided for quick application in feasibility studies.

2. Background and Literature Review

2.1 Global Experiences in PV Integration

Globally, solar PV has evolved from stand-alone ground-mounted projects to integrated systems in urban and transport infrastructure. Europe has pioneered building-integrated photovoltaic (BIPV), where PV replaces conventional construction materials in façades, roofs, and skylights. Countries such as Germany and Switzerland have experimented with PV in highway noise barriers, while Japan has advanced floating solar on reservoirs. The United States has explored solar canopies over highways and parking lots.

These international experiences demonstrate that civil infrastructure can double as energy-generating assets, offering co-benefits such as shading, water conservation, and noise reduction. However, challenges remain in ensuring structural safety under wind and seismic loads, fire safety of PV modules, and economic competitiveness compared with traditional power plants (Moser, 2020) [12].

2.2 PV Deployment in India

India has made significant progress in solar adoption, with cumulative installed capacity reaching more than 70 GW by 2023 (MNRE, 2023). While most installations are utility-scale ground-mounted projects, the potential of civil and transport infrastructure is increasingly recognized.

- **Delhi Metro Rail Corporation (DMRC):** Over 30 MW of rooftop PV has been installed across stations, depots, and parking areas, supplying up to 15% of daytime operational demand (Delhi Metro Rail Corporation [DMRC], 2022).
- **Indian Railways:** Solar rooftops at stations and workshops, combined with solar-powered signalling huts and crossing gates, already generate over 100 MW, with plans for 500 MW by 2030 (Indian Railways, 2020).
- **Canal-Top Solar Projects:** Gujarat pioneered canal-top PV in 2012, reducing water evaporation and land use. By 2021, over 100 MW had been installed across states, highlighting the dual benefits of infrastructure-integrated solar (Patel & Sharma, 2021) [13].

2.3 Challenges in Indian Conditions

Despite rapid growth, several challenges persist in India:

- **Dust Deposition:** Research shows efficiency losses of up to 15–20% in dusty regions without regular cleaning (Kumar & Goyal, 2020) [5].
- **Thermal Effects:** High ambient temperatures reduce PV efficiency, making module selection and ventilation crucial.
- **O&M Barriers:** Accessing solar arrays on railway canopies, bridges, and façades can be difficult and costly.
- **Safety Concerns:** Glare for train operators, electromagnetic compatibility with signalling systems, and risks of fire are issues requiring strict standards compliance (RDSO, 2022).

2.3 Research Gap

Existing literature in India focuses primarily on utility-scale solar parks. Few studies address the engineering challenges of integrating PV into civil and railway infrastructure with location-specific constraints. This study fills that gap by synthesizing policy, engineering standards, and case study insights into a structured evaluation.

3. Methodology

This research adopts a mixed-method approach combining policy review, engineering analysis, case study evaluation, and economic modelling.

3.1 Policy and Standards Review

Documents reviewed include

- MNRE National Solar Mission policy documents (2019, 2023).
- Indian Railways Renewable Energy Mission Roadmap (2020).
- BIS codes such as IS 875 (wind loads), IS 1893 (seismic), IS 14286 (modules), IS 17092 (inverters), and NBC (2016).
- IEC standards: IEC 61215 (design qualification), IEC 61730 (safety).
- Railway-specific standards from RDSO regarding clearance and safety.

3.2 Case Study Method

Case studies were selected to illustrate different applications:

- Delhi Metro rooftop PV (urban transport).
- Indian Railways station and depot solar (rail sector).
- Gujarat canal-top solar (dual-use infrastructure).

3.3 Economic Analysis

The financial viability was evaluated using the Levelized Cost of Energy (LCOE), calculated as: LCOE=∑t=0nIt+Ot(1+r)t∑t=1nEt(1+r)tLCOE = \frac{\sum_{t=0}^n \frac{I_t + O_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}LCOE=∑t=1n(1+r)tEt∑t=0n(1+r)tIt+Ot

Where ItI_tIt is investment, OtO_tOt is operations & maintenance, EtE_tEt is energy generated, rrr is discount rate, and nnn is project life. Benchmarks from CERC (2023) were used to model scenarios with investment of ₹4 crore/MW, O&M at ₹6 lakh/MW annually, and output of 1.5 million kWh per MW per year.

3.4 Decision Matrix

A qualitative scoring framework was developed to compare options such as rooftop PV, BIPV façades, railway canopies, trackside solar, and canal-top arrays. Parameters included energy yield, capital cost, safety, ease of O&M, and policy alignment.

4. Results

4.1 Technical Feasibility

- **Rooftop PV (BAPV):** Suitable for railway stations and depots; requires BIS-compliant wind load design and NBC fire safety provisions.
- **BIPV Façades:** Still at a nascent stage in India but offer architectural value for high-rise civil structures.
- **Railway Canopy PV:** Can supply up to 40% of daytime power at stations; requires glare analysis and RDSO clearance.
- **Canal-Top PV:** Dual benefits of land saving and water conservation; technical feasibility proven in Gujarat.

4.2 Economic Viability

The LCOE model showed

- Rooftop PV: ₹2.8–3.2/kWh.
- Canal-Top PV: ₹3.2–3.6/kWh (slightly higher due to structural cost).
- Railway canopies: ₹3.0–3.4/kWh.

These costs remain below grid tariffs for commercial/industrial consumers (~₹6–7/kWh), confirming economic attractiveness.

4.3 Case Study Findings

- Delhi Metro: Rooftop PV reduced grid dependency, avoided ~45,000 tons of CO_2 annually, and achieved payback within 6 years (DMRC, 2022).
- Indian Railways: Over 100 MW already installed; target of 500 MW by 2030 aligns with net-zero pledge (Indian Railways, 2020).
- Gujarat Canal-Top: Demonstrated water savings of ~9 million litres annually per MW alongside clean energy (Patel & Sharma, 2021) [13].

4.4 Decision Matrix Outcomes

- Rooftop PV scored highest for feasibility and cost.
- Canal-top PV scored high for environmental co-benefits.
- Railway canopy PV scored well on policy alignment but lower on O&M ease due to accessibility challenges.

5. Conclusion

This study demonstrates that integrating solar PV into civil engineering structures and Indian Railways is both feasible and economically viable. Key enablers include supportive MNRE policies, declining costs of PV technology, and institutional commitment by Indian Railways to net-zero emissions. However, India's unique challenges—dust deposition, high ambient temperatures, and complex railway safety requirements—must be addressed through robust engineering design and adaptive O&M practices.

6. Recommendations

1. **Policy Alignment:** Continued support through MNRE subsidies, railway tenders, and Renewable Energy Certificates.
2. **Engineering Innovation:** Development of dust-repellent coatings, high-temperature resistant modules, and lightweight mounting systems.
3. **Digital O&M:** IoT-enabled monitoring and predictive maintenance for railway PV systems.
4. **Future Research:** Detailed studies on glare impacts for railway operators, long-term reliability under Indian climate conditions, and integration with storage systems for grid stability.

By treating civil structures and railway assets not just as service infrastructure but as energy-generating systems, India can accelerate its transition to a low-carbon future.

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