Transparent Solar Panels: Sustainable Integration into Modern Architecture

Krish Bindal

The Shri Ram School, Moulsari, Gurgaon, Haryana, India

Abstract: ***One technology under development is transparent solar panels (TSPs), which combine the production of renewable energy with the transparency of a building. This study explores the ways in which they can redesign the built environment in India by putting photovoltaic technology in direct installations in faade, windows and glass buildings. The study follows the history of TSPs since the first luminescent concentrators to advanced perovskite and organic photovoltaics and compares their appropriateness in Delhi, Mumbai and near-equatorial regions in India. Comparative Suitability Analysis (CSA) framework was used to determine factors like climate, energy yield, payback period, and maintenance requirements. The results show that, although the high solar irradiance in Delhi favors high output, dust and thermal stress issues decrease efficiency. The corrosion resistant paint is necessary, whereas the Mumbai coastline environment provides one with year-long sunlight. The tropical applications in Sri Lanka are also indicated in the paper as the case analogues applicable in India. Despite current limitations in cost and transparency efficiency trade-offs, transparent photovoltaics have great potential on Building-Integrated Photovoltaics (BIPV) and smart urban infrastructure. The mass deployment can be enabled with policy facilitation, pilot demonstrations and material innovation, as part of the net-zero and smart city goals of India.***

Keywords: Transparent Solar Panels; Building-Integrated Photovoltaics; Sustainable Architecture; India; Comparative Suitability Analysis

1. Introduction

The fast urbanization and the growing demand of energy in India has brought about the current pressure of the need to have more sustainable solutions that can give a balance between the development and environmental conservation. The towns like Delhi, Mumbai other urban areas are increasingly experiencing pressure due to the growing electricity demand, reliance on fossil fuel and consequent increase in greenhouse gases. The conventional solar panels have been effective in production of renewable energy; however, they need to be installed in a rooftop or an open space; an area that is usually unavailable in congested urban areas. This has resulted in increased desire to investigate new technologies that can produce clean energy without requiring more land and without compromising the architectural values of buildings. In this respect, Transparent Solar Panels (TSPs) can become a revolutionary development. These panels will enable the light of visible nature to pass through them, and they utilize the invisible UV (ultraviolet) and IR (infrared) part of sunlight to produce electricity. They can be easily incorporated into glass and window facades and skylights, their functionality as both sources of energy and building materials makes them the perfect blend of the two. This combination of functionality and aesthetics provides the architects and urban planners with the chance to transform the whole building envelope in the power-generating surface, and this is the idea of the net-zero and green buildings. Their potential notwithstanding, studies and extensive use of transparent photovoltaic systems based on the use of facades are limited in India. Majority of the existing literature emphasizes on traditional rooftop photovoltaic performance, and there is lack of research on the energy, economic and maintenance properties of TSPs in different climatic conditions. This is especially the case with tropical areas where temperature, humidity and particulate pollution play very crucial roles in photovoltaic efficiency and maintenance. This study aims at evaluating the viability and relative appropriateness of transparent solar panels under various climatic conditions in the Indian urban environments. Through studying hot and polluted environment in Delhi, humid and coastal in Mumbai, and tropical areas always sunny but moist near the equator, this paper will attempt to formulate the framework through which the evaluation of performance, cost-effectiveness, and long-term sustainability can be assessed. With this comparative analysis, the paper aims at presenting factual and informative results that can guide architects, policymakers, and energy planners to encourage transparent solar technologies into an effective and scalable solution to the urban energy future of India.

2. Literature Review

The idea of transparent solar panels (TSPs) was based on the desire to increase the possibilities of the renewable power industry beyond the conventional rooftop or ground-based systems. It was thought that the way to do this was to develop materials that produced energy that could be smoothly incorporated into the daily buildings, including windows, façades, and electronic displays without affecting perfection or the natural light. This was an innovation that sought to use the sunlight in the crowded city settings where there is a lack of open space to make buildings themselves clean energy producers. Transparent photovoltaic, also known as PV technology, is therefore a synergising of material science, optics and the field of architecture, in congruence with the current design and sustainability objectives. The development of transparent PV technology can be followed to the beginning of solar research. The traditional photovoltaic cell in the 1950s-1970s was basically an opaque silicon-based, bulky cell that lasted to absorb the entire spectrum of the sun. Another breakthrough to take place in the 1970s was the creation of the luminescent solar concentrators (LSCs), whereby the sunlight was redirected to the edges of the panel, covered with conventional PV cells. This law of focusing and directing light formed the basis of subsequent clear apparatus. Genuine transparency was made possible by the invention of Transparent Luminescent Solar Concentrators (TLSCs) which allowed panels to absorb ultraviolet (UV) and infrared (IR) wavelengths, invisible to the human eye, and allows passage of visible light. One of the most important achievements was made in 2014 when scientist at Michigan State University had created the first complete transparent solar concentrator which could transform any glass surface into a medium of energy collection. The technology was based on organic compounds which captured UV and IR radiation and were re-emitted to the panel edges where photovoltaic strips were used to convert it into electricity. In the 2000s and 2010s, transparent PVs were developed based on silicon, then on thin-film types of materials, such as perovskites, organic semiconductors, and quantum dots. These innovations greatly enhanced efficiency and light absorption and made them to be as transparent as 80 percent with power conversion efficiencies between 7 and 15 percent. There are now two primary varieties of transparent panel. The semi-transparent panels can strike a balance between visible light transmission and moderate power production (7-10% efficiency), which can be used in the facades and in glazing building architecture. Fully transparent displays using organic and perovskite materials have efficiencies of approximately 12% and are used in smart windows, car glass, and electronic displays. The growing commercialization has been further pushed by the demand of building-integrated photovoltaics (BIPVs) where companies like Ubiquitous Energy, Physee, and Heliatek have made strides at demonstrating real-world applications in both architectural and consumer settings. Even with these developments, optimisation in the trade-off of transparency and efficiency, lowering of high costs of production, and durability at harsh environments like dust, humidity, and thermal stress are still the issues. Modern studies are aimed at the improvement of material stability, the development of cost-effective production methods, and the combination of transparent PVs and smart building systems and energy storage technologies. Nevertheless, in the Indian case, there is a large gap in research. Although transparent PVs are under investigation worldwide in terms of integration into buildings, there are very few systematic studies that evaluate the performance, maintenance, and economic viability of transparent PVs under the various climatic conditions in India. Filling this gap is the key to the potential of transparent solar panels as a feasible approach to sustainable urban energy production.

3. Scientific Principles and Mechanism

Transparent solar panels (TSPs) are based on the fact that non-visible elements of sunlight, such as ultraviolet (UV) and infrared (IR) will be absorbed but not visible light. The special spectral separation will allow the panels to be transparent like the traditional glass, and therefore can be used in windows, facades, and other surfaces of the building. TSPs can be used because they convert the invisible parts of the solar spectrum to electricity, thus, combining functionality and aesthetics into a new category of photovoltaic material that can be used in crowded urban areas.

The most fundamental part of this technology is luminescent solar concentrators (LSCs) and their state-of-the-art equivalents, transparent luminescent solar concentrators (TLSCs). These systems have special designed organic molecules or quantum dots that are integrated on trans-parent materials like glass or polymer sheets. As sunlight is reflected off the surface the materials in the substrate absorb UV and IR photons, raising the electrons energy levels. The absorbed energy is then re-emitted in longer wavelengths by these materials, which are then directed by the panel via waveguides; optically clear layers that direct the light to the edges of the panel by total internal reflection.

Around the edge of the panel, there are thin strips of photovoltaic (PV) cell, usually silicon, perovskite or organic semiconductors, which absorb this re-emitted light and transform it into electrical energy. The electric contacts fitted to the structure subsequently conduct the circuit generated to the external circuit which creates a continuous link between the electric current or storage system of the building. It is an indirect capture process that enables the light to pass through internally without blocking the visible transparency of the glass surface.

Various optical and structural characteristics are used to support the conversion of energy that occurs in transparent panels. The surface on the outside is treated with an anti-reflective on to reduce glare and make the most of sunlight entry, but a reflective back layer (behind the active medium) reflects away the stray IR and UV light, and it is reread into the system. These improvements make the most out of the total photon use in the panel and minimize energy wastage.

When united these various elements enable the transparent solar panels to retain high degrees of optical clearness (up to 80 percent apparent transmittance) and still attain respectable converting efficiencies of power (between 7 and 15 percent) based on the type of material and the structure of the layers. TSPs are a innovation in the domain of building-integrated photovoltaics being a hybrid optical-electronic design that merges the generation of renewable energy and the beauty of the architecture.

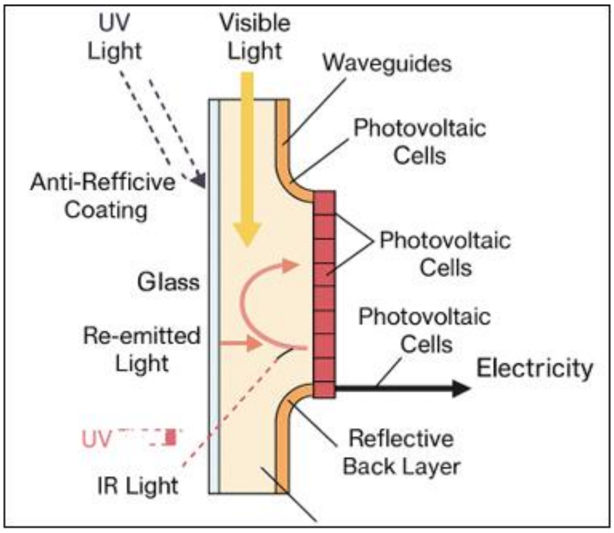

Figure 1: Mechanism of Transparent Solar Panel

4. Methodology

This paper poses the performance and suitability of Transparent Solar Panels (TSPs) in three different climatic regions in India namely, Delhi, Mumbai and tropical regions close to the equator through a Comparative Suitability Analysis (CSA) framework. The CSA system allows organizing the comparison of environmental, technical, and economic parameters that concern the long-term viability of the transparent integration of photovoltaic (PV) systems in building facades.

4.1 Metrics of Evaluation

Four main metrics are examined as they all are used to assess the appropriateness of TSP implementation:

- Energy Yield (Y) - the energy amount produced by the facade each year per square meter of facade surface (kWh/m 2 per year). It relies on the local solar irradiance, panel efficiency, temperature effects and performance ratio.
- Payback Period (P) - the duration taken to overpay the initial cost of installation using the savings in energy, in years.
- Maintenance Effort (M) - the maintenance load due to dust levels, humidity or corrosion expressed as an annual maintenance frequency index.
- Environmental Exposure (E) - climatic stressors (high temperature, salinity, rainfall or air pollution) that affect the rate of degradation and the general lifespan of the panel.

4.2 Scoring and Weighting Approach

The evaluation of each city is done by means of a normalized scoring model in which all the metrics are scaled between 0 (least suitable), and 1 (most suitable). In order to combine all considerations into one composite measure, weighted contributions are taken to indicate their relative weight:

$$\text{CSA Score} = (0.40 \times Y) + (0.30 \times (1 - P)) + (0.15 \times (1 - M)) + (0.15 \times (1 - E))$$

An increase in CSA scores means that there are more positive situations concerning transparent solar panel applications. The weights give priorities to energy yield and payback period as a determining factor of economic and technical feasibility.

4.3 Data Assumptions and Regional Parameters

The model is based on the regional climate and solar data, which are sourced in National Renewable Energy Laboratory (NREL) and India Meteorological Department (IMD). Assumed parameters include:

- Average vertical solar irradiance: 1,600 kWh/m²·yr (Delhi), 1,400 kWh/m²·yr (Mumbai), 1,800 kWh/m²·yr (tropical regions).
- Average panel efficiency: 10% (semi-transparent TSPs).
- Performance ratio: 0.75, adjusted for urban shading and pollution.
- Electricity tariff: ₹7–9 per kWh for urban commercial use.
- CAPEX: ₹12,000–₹15,000 per m² of TSP façade.

4.4 Tools and Analytical Methods

The CSA model merges data with Microsoft Excel and simulation of PVWatts to estimate the energy yield when the tilt and orientation are varied. Comparative visualisation of findings (e.g. CSA bar charts and payback tables) will help in revealing region-specific benefits and difficulties. This approach offers a clear, quantitative basis on the apposition of the appropriateness of transparent solar panels in the varied climatic settings of India underpinning evidence-driven recommendations on the extensive implementation of building-integrated photovoltaic (BIPV) in the future.

5. Case Study: Use of Transparent Solar Panels in Sri Lanka

5.1 Application and Integration

The urbanization and green building focus of Sri Lanka has put transparent solar panels (TSPs) in the prospective of building industry. These panels have been largely used on high rise fronts, company offices and government buildings where functionality and aesthetic appeal are essential. Considering that there is not a lot of rooftop area in Colombo and other urban centers, the means of vertical energy production using TSPs mounted on the front would be an economical solution. Their transparent structure enables them to get daylight and do not rely on artificial lighting thus preserving the aesthetic uniformity of the modern architectural designs.

5.2 Operational Benefits

The clear-cut solar panels have provided several benefits of operation in the applications in Sri Lanka. First, they have been used in achieving the renewable energy goals in the country, as they are energy efficient, which follows the vision of Sri Lanka to have renewable electricity generation reaching 100 per cent by 2050. The tropical latitude also guarantees the country of steady sunshine to maximize the output of the panels all year round. It has also provided more flexibility in building designs through the aesthetic combination of TSPs into glass facades which appear as a smooth and futuristic look as opposed to the opaque photovoltaic modules.

5.3 Effectiveness and Performance Feedback

Early project field data and user feedback has shown that though TSPs have lower conversion efficiencies (approximately 712%) than traditional silicon panels, they have an extraordinary lifespan with an estimated service life of up to 25 years. Occupants of buildings and facility managers were found to have even increased their comfort levels by continuing to reduce the levels of glare and thermal gain as well as realized quantifiable reductions in greenhouse gas emissions. This evidence demonstrates that transparent PV systems do not have a large output but can play a crucial role in energy diversification and sustainability of the city, when implemented on a big scale.

5.4 Challenges Encountered

Though promising, there are several limitations to their extensive implementation. A significant problem that can be indicated is maintenance, high humidity and dust in the air require frequent cleaning, especially in the high-rise buildings, which are not easily reached. Also, high installation cost, which is determined using specialized material and skilled labour, is a financial hindrance in a developing economy. These financial and business challenges highlight

Paper ID: SR251127180006 DOI: https://dx.doi.org/10.21275/SR251127180006

the need to intervene in the technology through policy and technology to support its momentum.

5.5 Advantages and Recommendations

The experience of Sri Lanka highlights some of the most important advantages:
- Environmental impact: There will be a tangible decrease in carbon emissions and help meet the national sustainability targets.
- Space optimization: Adequate use of surfaces of buildings in high-density urban setting.
- Corporate social responsibility: Direct support to Sustainable Development Goals (SDG 7 and 11) through facilitation of clean energy and sustainable cities.

Nonetheless, cost cutting measures like tax breaks, waiving of import levies and pilot programs supported by the government should be adopted to hasten the process. Additionally, emerging technologies of self-cleaning surfaces or dust-resistant surfaces would help to reduce maintenance challenges in humid conditions.

5.6 Comparative Summar

Aspect	Advantages	Disadvantages
Energy Efficiency	Generates energy using UV/IR while maintaining transparency.	Lower conversion efficiency (7–12%) than conventional PVs.
Aesthetic Appeal	Enhances modern building designs with transparent façades.	Limited retrofit potential for older structures.
Application Flexibility	Integrates with windows and façades seamlessly.	Retrofitting complexity in non-glass architectures.
Space Optimization	Utilizes vertical space, minimizing land use.	Generates less energy per unit area than roof panels.
Environmental Benefits	Reduces carbon footprint and supports SDG goals.	Manufacturing still entails embodied energy.
Durability	Lifespan up to 25 years with maintenance.	Efficiency loss from dust and humidity exposure.
Cost	Long-term savings through energy production.	High initial capital and installation costs.
Maintenance	Routine cleaning ensures stable performance.	Difficult access for high-rise applications.
Technological Potential	Compatible with smart façades and net-zero buildings.	Efficiency and cost still under improvement.
Energy Security	Diversifies building-level energy generation.	Insufficient as a sole power source.

5.7 Lessons for India

The experience with Sri Lanka shows that even transparent solar panels will work in tropical climate, having humidity and high irradiance like those of the coastal and southern areas of India. To Indian metros, this model would be a good choice to optimize on the use of the facade in the generation of renewable energy and save on the urban space. A policy-based framework which comprises incentives, local production and performance-based subsidies would speed up deployment. Also, by incorporating the usage of transparent solar screens into the Indian Green Building Code (IGBC and GRIHA) it might be feasible to encourage the early adoption, to turn the city skylines into clean energy resources.

6. Comparative Analysis of Delhi and Mumbai

Transparent Solar Panels (TSPs) demonstrate different performance and functioning characteristics in regard to the climatic, environmental, and economic conditions. In this section the suitability of each of them in the deployment in Delhi and Mumbai two large cities in India with different sets of weather patterns and environmental stresses is evaluated and compared. It analyses its structure based on the Comparative Suitability Analysis (CSA) model taking into consideration the climatic conditions, the energy output, cost-effectiveness, and maintenance needs.

6.1 Climate Profiles of Each City

Delhi has a hot summer (25 C -45 C, March to June), humid monsoon (July to September) and cool winter (5 C -20 C, November to February) climate. The solar irradiance in the city is high during most of the year, and this has made it ideal in the production of solar energy. Nevertheless, continuous air pollution and dust may have a serious impact on the efficiency of panels and raise cleaning frequency. By comparison, Mumbai features a wet and dry tropical climate, with heat (25o C-35o C) and heavy rainfall during the summer (June-September) months, and cold weather (20o C-30o C) during the winter. Although the yearly solar power is great beyond the monsoon seasons, the humidity, saltiness, and the high rate of rainfall pose maintenance and corrosion issues to the photovoltaic sets and electric wiring.

6.2 Energy Yield Estimation (Quantitative Model)

The annual energy yield (Y) for vertical transparent solar façades was estimated using the simplified model:

$$Y = G_{\text{vert}} \times \eta_{\text{eff}} \times PR$$

Where:
- G_{vert}: Average vertical solar irradiance (kWh/m²·yr)
- η_{eff}: Effective panel efficiency (10% for semi-transparent TSPs)
- PR: Performance ratio (accounts for shading, pollution, and system losses)

Parameter	Delhi	Mumbai
Vertical irradiance G_{vert}(kWh/m²·yr)	1,600	1,400
Effective efficiency η_{eff}	10%	10%
Performance ratio (PR)	0.70 (pollution losses)	0.75 (humidity losses)
Estimated Yield (Y) (kWh/m²·yr)	112	105

Although Delhi shows slightly higher yield potential due to higher irradiance, its dust-laden atmosphere reduces system performance over time.

6.3 Payback Period and Cost Comparison

The simple payback period (P) is derived using:

$$P = \frac{\text{CAPEX}}{\text{Annual Savings}}$$

Assumptions:
- CAPEX: ₹13,000/m²
- Electricity tariff: ₹8/kWh
- Annual maintenance: ₹250/m²

City	Annual Generation (kWh/m²)	Annual Savings (₹/m²)	Net Savings (₹/m²)	Payback Period (Years)
Delhi	112	896	646	20.1
Mumbai	105	840	590	22.0

By comparison, Mumbai features a wet and dry tropical climate, with heat (25o C-35o C) and heavy rainfall during the summer (June-September) months, and cold weather (20o C-30o C) during the winter. Although the yearly solar power is great beyond the monsoon seasons, the humidity, saltiness, and the high rate of rainfall pose maintenance and corrosion issues to the photovoltaic sets and electric wiring.

6.4 Maintenance Burden & Operational Suitability

There are high maintenance requirements in both cities though they are not of the same nature:
- Delhi: Transparency and performance are minimized by dust and smog as well as suspended particulate matter. During dry months, there is the need of cleaning once a week. Surface fouling can be reduced by implementation of anti-smog and hydrophobic coating.
- Mumbai: The coastal condition brings with it the risks of moisture intrusion and corrosion. When there is no rainy season, cleaning is less, yet in the case of long-term durability, salt-resistant finishes and covered edges of the panels are necessary.

6.5 CSA Results and Comparative Assessment

On a scale of 0 to 1, normalized scores of each of the factors were determined on the basis of the metrics in the CSA framework (Section 4).

Metric	Weight	Delhi	Mumbai
Energy Yield (Y)	0.40	0.85	0.80
Payback Period (P)	0.30	0.70	0.65
Maintenance Effort (M)	0.15	0.55	0.65
Environmental Exposure (E)	0.15	0.60	0.70
Composite CSA Score	1.00	0.72	0.71

The similarity between the two cities is that their overall suitability is similar with Delhi slightly better than Mumbai because of greater solar irradiance and less annual humidity. Nevertheless, Mumbai has more architectural potential due to the high concentration of skyscrapers, which provides the possibility of large areas of facades to produce energy.

6.6 Summary Chart: Comparative Performance

Factor	Delhi	Mumbai
Climate	Hot summers, mild winters, moderate monsoons	Warm, humid, with heavy monsoons
Average Vertical Irradiance (kWh/m²·yr)	1,600	1,400
Average Efficiency	10%	10%
Performance Ratio	0.70	0.75
Energy Yield (kWh/m²·yr)	112	105
Payback Period (Years)	20.1	22.0
Maintenance Level	High (dust, smog)	Moderate to High (humidity, corrosion)
Recommended Materials	Anti-smog coating, thermal management	Corrosion-resistant, hydrophobic surfaces

Transparent Solar Panels are technically possible in both Delhi and Mumbai though they need material and maintenance modifications specific to the regions. Delhi has a marginally higher energy output and cost break-even rate, whereas Mumbai has more options of integrating its facade. Dust-repellent and corrosive technology-based optimized designs can improve the long-term sustainability in the two cities in support of the Indian dream of sustainable urban energy systems.

7. Suitability of Transparent Solar Panels in Near-Equatorial Indian Regions

The almost equatorial region of South India in Kerala, Tamil Nadu, coastal Karnataka, Andhra Pradesh and the Lakshadweep islands and Puducherry region provide a good case study of the facade integrated transparent solar panels (TSPs). These places are high with year-round insolation with long daylight schedules, hence glazing regions on offices, malls, transit centers and high-rise residential buildings can add significant on-site production without interfering with views and daylight. This same climate provides a high level of sunlight with a high degree of humidity, periods of heat waves and heavy downpour rains, all of which has a direct effect on the energy production, soil erosion and the longevity of materials.

During monsoons, Kerala and coastal Karnataka receive high precipitations and sustained moisture; TSP fronts would work fine during dry season, yet heavy sealing and management of moisture are required to prevent occurrence of fogging, delamination, and contact corrosion. Tamil Nadu (e.g., Chennai, Coimbatore) is more consistent in sunshine and less violent in monsoons, which is better in annual productivity and frequency of cleaning, well favored to window and skylight retrofit in across the business districts. The coast of Andhra Pradesh (e.g. Visakhapatnam) is the location with high solar availability but introduces salted air to the risk profile that requires anti-corrosion design. Lakshadweep is a mix of clean sun and constant exposure to the sea whereas Puducherry is a mix of coastal humidity and long sunny days-both are necessitating marine protection.

The main issues along the belt are: (i) rain-induced and aerosole soiling which reduces the performance and transmittance of the facade, (ii) corrosion of busbars, frames, and connectors by the sea, (iii) thermal stress of the organic or perovskite absorbers in hot common periods, and (iv) the inability to cleaning tall facades during a monsoon.

TSPs are scaled to be used through targeted optimization strategies:

- Surface engineering: hydrophobic/oleophobic nanocoatings to lose water and dust; anti-fog surfaces to use in wet mornings; UV-resistant AR to retain visible transmittance.
- Design-based durability: stainless/ anodized frames, edge cells are not corrosive, sealed perimeters with low-WVTR encapsulants, desiccant spacers, IP-rated junctions, and marine-grade fasteners in seaside areas.
- Thermal and electrical control: ventilated cavity at facade, spectrally selective interlayers to reduce heat absorption, and low current densities to lower temperature increase.
- Operations integration: seasonal cleaning (pre-/post-monsoon), predictive maintenance with the help of the systems of access to the facade, building energy management ties, which in turn give priority to the loads during the day (lights, fans in the air conditioning) to optimize on-site consumption.

Based on these interventions, Indies cities located almost at the edges of the equatorial region are able to transform the vast glass facades into predictable energy sources, aligning the building openness with the predictable, climate-sensitive sunlight supply.

8. Policy and Regulatory Framework

The currently existing building energy codes and green ratings in India already leave space to incorporate the PV into the facade. The Energy Conservation Building Code (ECBC 2017) has minimum performance requirements on large commercial buildings and on-site renewables are an accepted compliance pathway; numerous states duplicate ECBC on a local basis. GRIHA and IGBC systems Green rating systems give credits on on-site renewable energy that may be achieved through BIPV/facade PV if it is structurally and electrically feasible. The Green Energy Open Access Rules, 2022, at the grid edge reduced open-access requirements and defined banking/charges, enhancing corporate access to renewables; increasingly states do so, but is regulated at the state level. In the projects where distribution is connected, net-metering is still state-specific; new amendments in Rajasthan that have expanded virtual/group net metering are an example of an extended toolkit beyond rooftops, good news about facade PV. The programme communications, and market direction of MNRE is periodically alluding to BIPV options as well as rooftop schemes, which supports the policy visibility despite capital subsidies mainly focusing on residential rooftops. There are also emerging municipal incentives, such as property-tax rebates on certified green buildings, which have the side effect of implicitly favouring the adoption of BIPV when used to obtain green ratings.

Proposed policy levers for TSP/BIPV façades.

- Recognition and standards of eligible assets. Request a BIS/MNRE technical note on transparent/BIPV facades (fire-safety, wind load, electrical protection, glare) to simplify the approvals; refer to recent work on BIPV standardisation (TERI-GIZ) to establish test protocols and warranties.
- Capital support. Pilot central/state capex incentives or expedited depreciation namely of PV on facades in publicly owned buildings, transport hubs and hospitals; enable BIPV to receive green-building-linked property-tax rebates and credit-lines.
- Tariff mechanisms. Request states to legalize virtual/group net metering of common-areas loads in high-rise buildings and to release transparent banking/settlement of BIPV behind-the-meter through the Open Access framework.
- Procurement & visibility. Request tender specifications on transparent PV facades in government buildings; provide daylighting and glare requirements such that facades are competing on energy as well as appearance. Such clarity has already been advised in (BIPV policy manuals).

Environmentally friendly building and smart grid. At the grid end, the National Smart grid mission and associated reform is refocusing less on capacity addition, more on absorption and flexibility (smart meters, storage, peak-supply tender). The TSP/BIPV facades must be registered as controlled DER to demand response and building-to-grid programs and allow varying export limits and time-of-day self-consumption.

At the building level, document TSP trails on IGBC/GRIHA conformity (credits to daylighting synergy, glare control, and PV on the facade), such that developers gain the rating points and municipal incentives at the same time.

9. Applications and Implementation Strategies in India

Multi-sectoral Transparent solar panels (TSPs) are a potential multi-sectoral opportunity to the growth of renewable energy in India. Implementation based on a policy-connected pilot plan must be adopted to reach a quicker deployment, which will be in line with the nationwide renewable energy goals and the vision of Smart Grids 2030 as well as national BIPV guidelines.

9.1 Commercial Buildings: Early Adoption Mandates

Application Areas: Shopping malls (such as Phoenix Market City), company towers (such as Bandra Kurla Complex) and airports (such as Delhi and Bengaluru).

Implementation Strategy:

- Mandate the inclusion of BIPV facades of new commercial complexes with a floor area of more than 20,000 m 2 under building approval bylaws of metro cities.
- Offer tax break and quicker depreciation to those developers that use facades with transparent panels attached through the facade.
- Airports, SEZ campuses can be location sites, being demonstrations of hybrid daylighting-energy facades, which support the Ministry of Civil Aviation sustainability directives.
- Policy Link: Under inclusion criteria in the Energy Conservation Building Code (ECBC) and embedded in IGBC/GRIHA certification schemes, through renewable-energy credits.

9.2 Residential High-Rises and Smart Windows: Incentivized Retrofits

Application Areas: High-rise apartments, housing societies, and smart homes in Mumbai, Chennai, and Hyderabad.

Implementation Strategy:
- Introduce capital subsidies (1520) of facade retrofittings with semi-transparent panels to substitute traditional glass used on the balconies and the windows.
- Promote smart-window with home automation system integration, which allows daylight, and energy production.
- The state housing boards can test TSP facade within common housing programs to illustrate the affordability of low carbon.
- Policy Proposal: PM Surya Ghar Yojana incentives should be extended to BIPV windows and TSPs to be added to Smart City missions as a component of net-zero housing.

9.3 Transportation and Public Infrastructure: Government Demonstrators

Application Areas: Metro stations (e.g., Delhi Metro, Namma Metro), railway stations (e.g., Chhatrapati Shivaji Terminus), airports, and electric vehicle (EV) charging hubs.

Implementation Strategy:
- Introduce pilot projects within the framework of which the Ministry of Railways and Urban Affairs introduces the use of transparent solar facades in terminals and station atriums.
- Promote EV infrastructure, where clear PV roofs may operate lighting and signage.
- Take advantage of Public-Private Partnerships (PPP) to fund the demonstrators at transport nodes with guaranteed feed-in tariffs.
- Policy Connection: Inclusion, as part of Green Railway and Smart Metro programs, connection of TSPs to renewable procurement requirements, and a National Smart Grid Mission of grid-synchronized publicly-owned assets.

9.4 Educational, Healthcare, and Institutional Demonstrators: Incentivized Models

Application Areas: IIT campuses, hospitals, and research institutions.

Implementation Strategy:
- Grant innovation grants funded by MNRE to educational institutes that use TSP facades.
- Hospitals: by installing panels on the facade and skylights, hospitals can limit cooling and lighting load, which would enhance resilience to power outages.
- Policy Connection: Conformity with National Institutional Ranking Framework (NIRF) sustainability indicators and carbon neutrality in the public sector.

9.5 Implementation Roadmap

Category	Pilot Type	Policy Mechanism	Example Project
Commercial Buildings	Mandated early adoption	ECBC, Green Building Codes	BKC Towers, Delhi Airport
Residential High-Rises	Incentivized retrofit	PM Surya Ghar Yojana, Smart Cities Mission	Mumbai Housing Board Smart Homes
Transportation Hubs	Government demonstrator	Smart Grid, Green Railways Policy	Delhi Metro PV Atrium
Institutions	Funded R&D pilots	MNRE Innovation Grants	IIT Madras Campus Façade PV

The adoption approach taken by India in relation to transparent solar panels should be a combination of the regulatory requirement (large commercial and public buildings), financial incentive (retrofit of residential buildings), and demonstrator projects (transport and institutional campuses). Integrating TSP deployment with ECBC compliance, Smart Grid integration and renewable portfolio requirements of MNRE can facilitate scalability and coherence of policy that will promote transparent PV facades as a visible icon of sustainable urban transition in India.

10. Conclusion and Future Work

The comparative and regional studies show that transparent solar panels (TSPs) are also a possible and aesthetically acceptable direction in which India can make the energy change, particularly in cities and tropical environments. The Comparative Suitability Analysis (CSA) allowed the recognition of Delhi and Mumbai as opposite yet complementary locations to deploy. The solar irradiation in Delhi and the architectural diversity are very promising background to the use of photovoltaics in facades, as the high solar irradiation is combined with the widespread architectural diversity, although the dust load and thermal deterioration can be regarded as the limitations in the use of photovoltaics. On the other hand, the steady sun rays at Mumbai, combined with a high level of humidity and saline influence, cause the need to use corrosion-resistant materials and hydrophobic layers to ensure long-term use. In near equatorial areas like Tamil Nadu, Kerala, and Andhra Pradesh, solar radiation is abundant and hence the efficiency of energy is guaranteed and hence the transparent panels are very productive in combination with the appropriate maintenance plans.

The paper has pinpointed some of the main obstacles to large-scale adoption. The first impediment is the cost of production and installation as there has been little local production of highly advanced perovskite and organic photovoltaic (OPV) materials. Complexity of maintenance, especially in a polluted or coastal area, also makes it less efficient and short-lived without frequent cleaning or anti-fouling technology. An enduring trade-off between transparency and efficiency consequently constrains optimization since increased transparency in most cases decreases the energy conversion rates. These challenges will need to be overcome in a coordinated effort that includes research, policy changes and pilot-scale experiments.

In order to expedite practical application and market preparedness, the following directions of the future work are suggested:

On-Site Demonstration Projects: Introduce pilot façades to metro infrastructures, airports, and institutional campuses to test performance and user feedback during the entire year with varying Indian weather conditions.

- Material Research and Scale-Up Domestically: Focus on perovskite stability, organic semiconductor, and nanostructured coating research and development to improve durability and affordability.
- Smart Monitoring and Digital Twin Models: Create digital twins of systems built into the facade to track energy output, degradation, and cost-payback in real-time, on a basis of AI-facilitated predictive maintenance.
- Façade Integration Design Frameworks: To design standard architectural principles of integrating TSPs into curtain walls, skylights and windows without affecting structural safety or aesthetics.
- Policy and Incentive Alignment: Implement focused subsidies, net-metering of BIPV systems, and as part of green building codes, so that transparent solar panels are not bypassed in renewable compliance programs.

To sum up, transparent solar panels have the potential to change the urban skyline of India - to convert glass surfaces into passive architectural tools into active and power-producing ones. Through technological creativity, enabling policy tools, and multidisciplinary cooperation, India would be in the lead of a sustainable, net-zero building over the next decade.

References

Academic and Technical Sources

[1] Balaya, P., & Singh, R. (2022). *Transparent solar technologies for energy-harvesting windows: A comprehensive review. Renewable and Sustainable Energy Reviews, 161*(1), 112312. https://doi.org/10.1016/j.rser.2022.112312

[2] Cao, Y., Zheng, J., & Chen, J. (2021). *Perovskite-based transparent photovoltaics: Materials, design strategies, and applications. Progress in Photovoltaics: Research and Applications, 29*(12), 1042–1058. https://doi.org/10.1002/pip.3482

[3] Chen, X., Manders, J. R., Tsang, S. W., & So, F. (2012). *Role of interfacial layers in organic photovoltaic cells. Journal of Materials Chemistry, 22*(47), 24202–24212. https://doi.org/10.1039/C2JM34974G

[4] Lunt, R. R., & Bulović, V. (2014). *Transparent, near-infrared harvesting solar cells for building-integrated photovoltaics. Advanced Materials, 26*(47), 7958–7965. https://doi.org/10.1002/adma.201403448

[5] Jelle, B. P., & Breivik, C. (2012). *Building-integrated photovoltaics: A state-of-the-art review. Energy Procedia, 20*, 68–77. https://doi.org/10.1016/j.egypro.2012.03.009

[6] Ubiquitous Energy Inc. (2023). *Transparent Solar Technology Overview.* Retrieved from https://ubiquitous.energy

[7] Physee Group. (2022). *SmartWindow and PowerWindow Technologies.* Retrieved from https://www.physee.eu

[8] Heliatek GmbH. (2023). *Organic Photovoltaic Films for Architectural Integration.* Retrieved from https://www.heliatek.com

Indian Context and Policy Sources

[9] Ministry of New and Renewable Energy (MNRE), Government of India. (2023). *National Solar Mission Phase II – Guidelines for Grid-Connected Rooftop and Small Solar Power Plants.* Retrieved from https://mnre.gov.in

[10] Bureau of Energy Efficiency (BEE). (2017). *Energy Conservation Building Code (ECBC 2017).* Ministry of Power, Government of India. Retrieved from https://beeindia.gov.in

[11] Indian Green Building Council (IGBC). (2021). *IGBC Green Building Rating System: New Construction.* Confederation of Indian Industry. Retrieved from https://igbc.in

[12] Green Rating for Integrated Habitat Assessment (GRIHA). (2020). *National Rating System for Green Buildings in India.* The Energy and Resources Institute (TERI). Retrieved from https://grihaindia.org

[13] Central Electricity Authority (CEA). (2022). *National Smart Grid Mission – Annual Report 2022–23.* Ministry of Power, Government of India. Retrieved from https://nsma.gov.in

[14] NITI Aayog. (2021). *Harnessing Solar Energy for Sustainable Growth: BIPV and Building-Scale Integration Opportunities.* Retrieved from https://niti.gov.in

[15] TERI–GIZ India. (2020). *Developing Standards for Building-Integrated Photovoltaic (BIPV) Applications in India.* The Energy and Resources Institute, New Delhi.

[16] Ministry of Environment, Forest and Climate Change (MoEFCC). (2022). *India's Long-Term Low Emission Development Strategy.* Retrieved from https://moef.gov.in

[17] Indian Meteorological Department (IMD). (2023). *Climatological Data of Indian Metros.* Retrieved from https://mausam.imd.gov.in

[18] Central Public Works Department (CPWD). (2022). *Sustainable Building Design Guidelines for Government Projects.* Retrieved from https://cpwd.gov.in

Supporting Data and Comparative Studies

[19] Singh, D., & Chatterjee, A. (2021). *Performance evaluation of solar façades under Indian climatic conditions. Energy Reports, 7*, 224–233. https://doi.org/10.1016/j.egyr.2021.08.110

[20] Bhattacharya, S., & Ghosh, A. (2020). *Quantitative analysis of transparent photovoltaics for tropical climates. Solar Energy Materials and Solar Cells, 210*, 110449. https://doi.org/10.1016/j.solmat.2020.110449

[21] Kumar, N., & Basu, P. (2022). *Economic viability of transparent BIPV façades in Indian metros. Journal of Cleaner Production, 350*, 131562. https://doi.org/10.1016/j.jclepro.2022.131562

[22] Ramesh, K., & Pillai, M. N. (2019). *Building-integrated solar technologies: Opportunities for South India. International Journal of Sustainable Energy Development, 8*(4), 179–188.

[23] World Bank Group. (2023). *Scaling Up Solar in Emerging Economies: Market Trends and Policy Frameworks.* Retrieved from https://www.worldbank.org/solar

Web Resources and Datasets

[24] National Institute of Solar Energy (NISE). (2023). *Solar Radiation Resource Assessment (SRRA) Data Portal.* Retrieved from https://srra.nise.res.in

[25] International Energy Agency (IEA). (2022). *World Energy Outlook: Renewables and Solar Integration Trends.* Retrieved from https://www.iea.org