



Solar Paint

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Abstract- Solar paint is an emerging photovoltaic (PV) technology that enables buildings, vehicles, and other surfaces to generate electricity through a thin, paintable coating. Unlike conventional rigid solar panels, solar paint leverages perovskite materials, quantum dots (QDs), and semiconductor nanoparticles dispersed in a liquid medium to convert sunlight into electrical energy. This research report provides an end-to-end examination of solar paint — covering its material composition, photovoltaic working mechanism, types, efficiency metrics, environmental challenges, commercialisation barriers, comparative economics, and future development pathways. The study draws on primary laboratory data, secondary academic literature, and market analyses to present a holistic assessment of the technology's current status and potential. Current solar paint technologies demonstrate power conversion efficiencies (PCE) of 3–8%, significantly lower than commercial silicon panels (18–22%). Nevertheless, the technology offers compelling advantages: low material cost, scalable application methods (spray, roll, brush), aesthetic flexibility, and strong suitability for building-integrated photovoltaics (BIPV). The project's analysis reveals a 20–35% performance drop under prolonged UV exposure, underscoring durability as the most critical bottleneck. Recommendations include graphene-based encapsulation layers, hybrid perovskite–polymer formulations, and investment in roll-to-roll (R2R) manufacturing. Solar paint holds significant long-term promise as a supplemental — and eventually primary — distributed energy source in the global transition to sustainable energy.

Keywords- Solar paint, photovoltaic, perovskite, quantum dots, BIPV, PCE, renewable energy, nanotechnology.

I. Introduction

Background

The global energy crisis and escalating greenhouse-gas emissions demand urgent diversification of renewable energy sources. Traditional solar panels — predominantly crystalline silicon — have achieved significant cost reductions over the past two decades; however, they remain constrained by high installation costs, rigid form factors, and the requirement for south-facing, unobstructed surface areas.

Solar paint represents a paradigm shift: rather than discrete panels, photovoltaic functionality is embedded in a liquid coating that can be applied to virtually any surface — roofs, walls, vehicles, furniture, and infrastructure — using conventional painting or printing equipment. This dramatically expands the addressable surface area for energy generation, particularly in dense urban environments.

Technology Overview

Solar paint combines discoveries from nanotechnology, semiconductor physics, and materials science. The photovoltaic effect — the conversion of photons into electron-



hole pairs — is achieved using light-absorbing nanoparticles (perovskites, quantum dots, or organic dyes) suspended in a film-forming binder. When applied to a substrate coated with a transparent conductive oxide (TCO) electrode, the paint layers act as a complete thin-film solar cell.

Scope of This Report

This report evaluates:

- **The scientific basis** and material composition of solar paint.
- Working mechanisms and types of solar paint.
- Quantitative performance data from laboratory tests.
- Economic and commercial viability compared with silicon panels.
- Key research gaps and proposed solutions.
- A roadmap for future development and commercialisation.

Significance

With global electricity demand projected to double by 2050 (IEA, 2023), distributed and low-cost photovoltaic solutions are essential. Solar paint — if scaled — could convert the billions of square metres of existing built- environment surfaces into power-generating assets without structural modification, contributing meaningfully to net-zero targets.

III. Review Of Literature

Early Paint-Based Photovoltaics: DSSCs

Research into paintable photovoltaics began with dye-sensitised solar cells (DSSCs) pioneered by Grätzel (1991). In a DSSC, a porous TiO_2 layer adsorbs light-sensitive dye molecules; absorbed photons excite electrons that are injected into TiO_2 and conducted to an external circuit. Grätzel's work demonstrated that low-cost organic or inorganic dyes could replace expensive silicon, achieving efficiencies around 7–11% in laboratory conditions. DSSCs remain commercially relevant for indoor, low-light applications.

Quantum Dot Solar Paint

Kim et al. (2015) demonstrated that semiconductor nanoparticles (CdS, PbS, ZnO) with diameters of 2–10 nm exhibit quantum confinement effects — their bandgap is size-tunable, enabling absorption across a broad solar spectrum. Dispersed in liquid binders, QD inks could be deposited by spray or slot-die coating, enabling roll-to-roll fabrication. Efficiencies of 3–6% were reported; the key advantage was stability under ambient conditions compared with perovskites.

Perovskite Solar Paint

Perovskite materials (general formula ABX_3 , where A = organic/inorganic cation, B = metal, X = halide) revolutionised thin-film photovoltaics after 2012. Park et al. (2021) reported perovskite-based paint PCEs exceeding 8% in controlled conditions, leveraging perovskite's high absorption coefficient ($\sim 10^5 \text{ cm}^{-1}$), long carrier diffusion lengths, and tunable bandgap (1.2–2.3 eV). The principal drawback is moisture and oxygen sensitivity: unencapsulated perovskite degrades within hours under humid ambient conditions.



Hydrogen-Splitting Solar Paint

A breakthrough from RMIT University (Daeneke et al., 2017) introduced a solar paint capable of splitting atmospheric water vapour into hydrogen and oxygen using solar energy. The paint comprises synthetic molybdenum-sulphide (acting as a catalyst) and titanium oxide (as the light absorber). This concept extends solar paint beyond electricity generation to green-hydrogen fuel production — a potentially transformative application for the hydrogen economy.

Hybrid Organic–Inorganic Formulations

Recent literature (2022–2024) highlights hybrid formulations that combine the high efficiency of inorganic perovskites with the mechanical flexibility and UV stability of polymer matrices. These hybrids improve adhesion to curved surfaces, extend service life, and reduce sensitivity to moisture, albeit with a modest PCE penalty of 1–2 percentage points compared with pure inorganic films.

Market & Commercial Research

Market analyses (Grand View Research, 2023; MarketsandMarkets, 2024) project the global solar paint market to reach USD 50–70 billion by 2035, driven by BIPV adoption and green-construction mandates. Key players include Saule Technologies (Poland), Solaronics (Sweden), and Oxford PV (UK), with pilot installations on commercial buildings underway in Europe and East Asia.

3.7 Summary of Literature

Collectively, the literature confirms that solar paint is scientifically validated and commercially pursued, but is pre-commercial as of 2025. The primary consensus identifies three pillars for progress: (a) efficiency enhancement above 15% PCE, (b) environmental encapsulation to extend lifespan beyond 10 years, and (c) roll-to-roll manufacturing cost reduction below USD 10/m².

IV. Research Gap

A systematic review of existing literature reveals five critical gaps that this project addresses:

#	Gap	Current State	Proposed Direction
1	Low PCE	3–8%; well below silicon (18–22%)	Tandem perovskite–QD layers; light-trapping nanostructures
2	Poor Durability	20–35% PCE loss after 500 h UV; lifespan < 2 years	Graphene encapsulation; hydrophobic polymer matrices
3	Scalability	No proven R2R process at industrial scale	Slot-die & gravure printing optimisation
4	Storage Integration	Limited coupling with batteries or supercapacitors	Monolithic paint–storage architectures



5	Cost-Performance	Reapplication every 1-2 years inflates LCC	Durable encapsulants to extend lifespan to 10+ years
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V. Objectives

Primary Objectives

1. Evaluate the technical feasibility of solar paint as a renewable-energy solution under Indian climatic conditions.
2. Analyse material composition, photovoltaic mechanisms, and efficiency determinants of current solar paint formulations.
3. Quantify the performance degradation of solar paint under UV irradiation, humidity, and temperature cycling.

Secondary Objectives

- Identify key environmental, durability, and manufacturing challenges limiting commercial deployment.
- Compare solar paint with traditional crystalline silicon panels across efficiency, cost, aesthetic flexibility, and application versatility.
- Propose practical material improvements, encapsulation strategies, and manufacturing pathways.
- Map a commercialisation roadmap for solar paint in the Indian building sector by 2030.

VI. Methodology

A mixed-methods research design was adopted, combining qualitative literature analysis with quantitative laboratory experimentation.

Research Design

This study followed a five-phase iterative approach:

1. Material Review – systematic literature search (Google Scholar, ScienceDirect, ResearchGate).
2. Formulation – laboratory preparation of sample solar paint batches.
3. Application – deposition on multiple substrate types.
4. Testing – performance and durability measurements.
5. Analysis & Comparison – benchmarking against silicon panel standards.

Material Study

Three principal formulation families were reviewed and synthesised in laboratory quantities:

- Perovskite (MAPbI₃) dispersed in dimethylformamide solvent with spiro-OMeTAD hole-transport layer.
- CdS/PbS quantum dot ink in hexane, stabilised with oleic acid ligands.
- TiO₂ nanoparticle–DSSC hybrid paint using N719 ruthenium dye.



Paint Formulation

Nanoparticles were dispersed in polymer binders (polyurethane, acrylic) at concentrations of 5–15 wt% using ultrasonic bath agitation (40 kHz, 30 min). Viscosity was adjusted to 50–200 mPa·s for spray application compatibility.

Application Testing

Substrate	Application Method	Coat Thickness (µm)	Curing Condition
Galvanised steel sheet	Spray	150–200	100°C, 10 min
Cement board	Roller	200–250	Ambient, 24 h
PVC plastic sheet	Brush	100–150	UV lamp, 5 min
Glass (TCO-coated)	Spin-coat	80–120	100°C, 10 min

Performance Testing Protocol

The following parameters were measured for each substrate–formulation combination:

1. Open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}) using a solar simulator (AM1.5G, 100 mW cm⁻²).
2. Power conversion efficiency (PCE) calculated as $PCE = (J_{sc} \times V_{oc} \times FF) / P_{in} \times 100\%$.
3. UV endurance: 500-hour UV-B accelerated weathering (ASTM G154 Cycle 1).
4. Humidity stability: 85°C/85% RH damp-heat test (IEC 61215).
5. Temperature cycling: –40°C to +85°C, 50 cycles (IEC 61215).

Data Sources

Primary data were collected from laboratory experiments conducted at JAIN University's nanotechnology research facility. Secondary data were sourced from peer-reviewed journals (Nature Energy, Solar Energy Materials & Solar Cells, Advanced Energy Materials) and commercial reports (NREL, Fraunhofer ISE, IRENA).

VII. Data Collection & Analysis

7.1 Efficiency Performance Data

Table 7.1 summarises the measured PCE values for each formulation across substrates.

Formulation	Steel PCE (%)	ht PCE (%)	PVC PCE (%)	Glass PCE (%)
Perovskite (MAPbI ₃)	7.8	6.4	5.9	8.1
QD (CdS/PbS)	4.2	3.8	3.5	4.6
DSSC (TiO ₂ /N719)	5.1	4.7	4.3	5.8
Hybrid Perovskite–Polymer	6.3	5.8	5.2	6.9

Key observations: Perovskite on glass achieved the highest PCE (8.1%). Glass substrates consistently outperformed others due to their smooth surface promoting



uniform film morphology. PVC substrates showed the lowest performance, attributed to thermal deformation during curing affecting film integrity.

UV Degradation Analysis

Table 7.2 shows PCE retention after 500 hours of accelerated UV-B weathering.

Formulation	Initial PCE (%)	After 500 h (%)	Retention (%)
Perovskite (unencapsulated)	8.1	5.3	65.4%
QD (CdS/PbS)	4.6	3.9	84.8% ✓
DSSC (TiO ₂ /N719)	5.8	4.6	79.3%
Hybrid + graphene topcoat	6.9	6.5	94.2% ✓✓

The hybrid formulation with a graphene-oxide topcoat showed exceptional UV retention (94.2%), confirming graphene's role as a UV barrier and radical scavenger. Unencapsulated perovskite exhibited the steepest degradation (34.6% PCE loss), consistent with published literature on halide perovskite instability.

Comparative Economics

Parameter	Solar Paint	Silicon Panel	Verdict
Material cost (USD/m ²)	5–15	50–100	Paint ✓
Installation cost	Very Low (spray/brush)	High (frame, mounting)	Paint ✓
Parameter	Solar Paint	Silicon Panel	Verdict
PCE (%)	3–8	18–22	Silicon ✓
Lifespan (years)	1–3 (current)	25–30	Silicon ✓
Form factor flexibility	Any surface	Flat only	Paint ✓
Levelised energy cost (USD/kWh)	0.25–0.45	0.04–0.09	Silicon ✓
Aesthetic integration (BIPV)	Excellent	Limited	Paint ✓

While solar paint holds a decisive advantage in material and installation cost as well as form flexibility, silicon panels currently outperform in every energy-yield metric. Parity in levelised cost of energy (LCOE) will require solar paint PCE to exceed 12% and lifespan to surpass 10 years.

Environmental Impact Assessment

A preliminary lifecycle analysis (LCA) indicates that solar paint requires approximately 0.8–1.2 GJ/m² of embodied energy during manufacture — roughly 40% of equivalent silicon panel production. Carbon payback period is estimated at 0.5–1 year at Indian solar irradiance levels (5–6 kWh/m²/day), compared with 1–3 years for silicon panels. However, lead content in MAPbI₃ perovskites raises end-of-life toxicity concerns,



necessitating take-back schemes and encouraging the shift to lead-free alternatives (tin, bismuth-based perovskites).

VIII. Findings & Suggestions

Key Findings

- Solar paint is scientifically validated but remains pre-commercial: no product has surpassed 500-hour outdoor stability at the panel level.
- Perovskite formulations yield the highest PCE (up to 8.1% in this study) but suffer from rapid degradation without encapsulation.
- QD-based paints offer superior stability (84.8% PCE retention) and are lead-free, making them preferable for regulatory environments.
- Graphene-oxide topcoats improve UV retention to 94.2% — the most effective single intervention identified.
- Glass substrates provide 15–25% higher PCE than cement or PVC, relevant for window-integrated BIPV applications.
- Current LCOE (USD 0.25–0.45/kWh) is 3–5× higher than grid parity; achieving cost-competitiveness requires lifespan extension and PCE improvement.
- Solar paint is best positioned as a supplemental energy source integrated into new green buildings and smart cities, not a standalone grid-scale solution.

Suggestions for Improvement

Material Innovations

- Adopt lead-free perovskites (FASnI_3 , $\text{Cs}_2\text{AgBiBr}_6$) to eliminate toxicity concerns.
- Develop graded quantum dot structures to harvest a broader solar spectrum.
- Incorporate upconversion nanoparticles to utilise infrared photons.

Encapsulation & Durability

- Apply graphene-oxide barrier layers (50–100 nm) over the active paint to block moisture and UV.
- Use atomic layer deposition (ALD) of Al_2O_3 for pinhole-free encapsulation.
- Develop self-healing polymer matrices that repair micro-cracks during operation.

Manufacturing Scale-Up

- Invest in R2R slot-die coating: demonstrated at 1 m width for OPV, transferable to solar paint.
- Standardise ink viscosity specifications and substrate surface-energy requirements for industrial reproducibility.
- Establish quality-control metrics (PCE uniformity $\pm 0.5\%$ across panel) for commercial acceptance.

System Integration

- Co-design solar paint with thin-film solid-state batteries for monolithic energy-harvesting-and-storage façades.
- Develop smart-surface controllers that maximum power point track (MPPT) multiple paint zones independently.



Policy & Market Enablement

- Advocate BIPV-specific feed-in tariffs in India's solar policy framework.
- Establish IS/IEC certification standards for solar paint longevity and electrical safety.
- Promote pilot projects in JAIN University's campus buildings to generate real-world performance data.

IX. Discussion

Interpretation of Results

The experimental data confirm the theoretical trade-off between efficiency and stability that permeates the solar-paint literature. Perovskite materials, with their direct bandgap and high absorption coefficient, are the natural candidates for high-efficiency solar paint. However, their intrinsic ionic nature makes them susceptible to ion migration under illumination and electric field, leading to reversible efficiency losses (hysteresis) and irreversible degradation under moisture.

Quantum dots, by contrast, benefit from the quantum confinement effect: their bandgap can be tuned by particle size alone, without changing chemical composition. This allows a single ink formulation — by varying particle size — to target different regions of the solar spectrum. The trade-off is lower inherent PCE due to inter-dot carrier-transport barriers. Future multi-layer architectures stacking QD layers of increasing bandgap may partially overcome this.

Comparison with Benchmarks

The National Renewable Energy Laboratory (NREL) best-research-cell efficiency chart (2024) records the highest reported PCE for perovskite solar cells at 26.7% (single-junction) and 33.9% (tandem with silicon). The 8.1% achieved in this study for a painted (not vacuum-deposited) film reflects the inherent crystallinity trade-off: solution-processed films have more defects than vacuum-deposited counterparts. Closing this gap requires hot-injection synthesis of perovskite nanocrystals and anti-solvent crystallisation techniques adapted for spray-coating.

Implications for India

India receives an average of 5.0–5.5 kWh/m²/day of solar radiation, making it ideal for BIPV deployment. With approximately 11 billion m² of rooftop and wall area in urban India (Ministry of New and Renewable Energy, 2023), even a 5% PCE solar paint at 10% deployment would generate ~30 GWh/day — equivalent to ~3% of India's daily electricity demand. At scale, this is a non-trivial contribution to the national 500 GW renewable target by 2030.

Limitations of This Study

This study has several limitations that future research should address:

- Laboratory solar simulator conditions (AM1.5G, 25°C) do not replicate the variable irradiance,
- temperature swings (–5°C to 45°C), and dust deposition of Indian field conditions.



- Sample sizes were small (10 cm × 10 cm coupons); larger-area deposition may introduce uniformity challenges.
- Economic analysis is based on 2024 material costs, which are expected to decline significantly with scale.
- LCA was preliminary and did not account for regional electricity-grid carbon intensity.

X. Conclusion

This research report has provided a comprehensive, end-to-end analysis of solar paint technology — from its nanoscale working principles to its macroeconomic implications for India's energy transition.

The principal conclusions are:

- Solar paint is a scientifically credible, potentially transformative photovoltaic technology that can be applied to surfaces inaccessible to conventional solar panels.
- Current PCE (3–8%) and lifespan (1–3 years) are the critical barriers to commercial deployment, not materials cost or application complexity.
- Graphene-oxide encapsulation is the most effective near-term intervention, improving UV stability retention from ~65% to ~94% with minimal PCE penalty.
- Hybrid perovskite–polymer formulations provide the optimal balance of efficiency and durability for near-term pilot applications.
- The technology is best deployed in Phase 1 as supplemental BIPV on new buildings, generating real-world performance data to justify Phase 2 mass-market rollout.
- Lead-free perovskite and quantum-dot formulations must be prioritised to meet environmental regulations and ensure long-term sustainability.

Solar paint will not replace silicon panels in the near term. It will, however, complement them — expanding photovoltaic coverage to surfaces that panels cannot reach. This complementarity is sufficient to make solar paint a strategically important technology in achieving net-zero built environments.

XI. Future Scope

Short-Term (2025–2027)

- Field pilot on JAIN University campus: instrument 100 m² of exterior wall with hybrid solar paint, monitor output vs. weather data.
- Collaborate with Indian paint manufacturers (Asian Paints, Berger) to develop commercial-grade formulations meeting BIS standards.
- Develop a techno-economic model for solar paint BIPV under Indian building energy codes (ECBC 2017).

Medium-Term (2027–2030)

- Achieve PCE > 12% through tandem QD–perovskite architecture on glass substrates.



- Commission an R2R pilot line (1 m wide, 10 m/min) to validate manufacturing economics.
- Integrate solar paint with thin-film lithium-ion batteries for off-grid building applications.

Long-Term (2030–2040)

- Target PCE > 20% using 2-junction tandem solar paint, approaching silicon panel equivalence.
- Deploy solar paint on electric vehicle (EV) bodies to extend range — estimated 5–10% range gain under Indian sunlight.
- Explore space applications: lightweight solar paint on satellite surfaces where rigidity is prohibitive.
- Develop transparent solar paint for window integration, enabling zero-energy buildings.

Research Agenda

Priority research topics identified for the next 5 years:

- Self-healing perovskite matrices that regenerate under mild heating.
- AI-driven formulation optimisation for PCE maximisation.
- In-situ characterisation of degradation mechanisms using synchrotron X-ray techniques.
- Circular-economy design for solar paint: recyclable solvents, recoverable nanoparticles.

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