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Development of a Polycarbonate UV-Protective and Rust-Preventive Coating System for Solar Panel Structural Materials: A Systematic Approach to Testing and Validation

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***Abstract* – Due to their constant exposure to harsh external conditions, solar panel structural materials are extremely susceptible to air corrosion, thermal stress, and UV radiation-induced deterioration. The mechanical robustness and durability of solar mounting infrastructure are seriously jeopardized by these environmental variables. The invention, extensive testing, and validation of a novel polycarbonate-based UV-protective and rust-preventive coating system designed especially for solar panel structural supports are the main objectives of this work. The coating offers a strong, dual-action defense mechanism against extended solar exposure and moisture-driven oxidation by incorporating sophisticated corrosion-inhibiting nano-agents and specific organic UV absorbers into a durable polycarbonate matrix. Performance was assessed using a thorough, methodical testing strategy that included surface morphology evaluations, neutral salt spray corrosion assays, cross-cut adhesion strength measures, and accelerated weathering experiments. According to experimental results, the coated substrates show remarkable resistance to UV-induced yellowing and gloss retention while retaining their structural integrity and high barrier qualities against dampness and chloride ions. Additionally, a significant improvement in corrosion resistance was proven by electrochemical impedance spectroscopy (EIS) and extended exposure to salt fog, which demonstrated minimal degradation and no rust development over extensive operational cycles. The developed polycarbonate coating system's dependability and industrial potential to greatly increase the service life, lower maintenance costs, and guarantee structural safety of solar panel installations in a variety of harsh climates are highlighted by this methodical validation framework.**

***Keywords* – Polycarbonate coating; UV protection; Corrosion prevention; Solar panel mounting structures; Accelerated weathering; Electrochemical impedance spectroscopy; Systematic validation.**

I. INTRODUCTION

1. Background and Significance of Photovoltaic Infrastructure

Photovoltaic (PV) solar systems are now a key component of contemporary power generation due to the swift and unprecedented global shift toward renewable energy. This has led to their aggressive deployment across a variety of geographical landscapes, from humid, chloride-rich coastal regions to arid, high-insolation deserts. Over the past ten years, solar panel efficiency and photovoltaic cell performance have seen enormous technological advancements. However, long-term field reliability and energy output stability depend just as much on the structural framework supporting these systems, which includes mounting frames, ground-mount racks, tracking mechanisms, and structural fasteners, which are usually made of carbon steel, galvanized steel, or aluminum alloys.

2. Environmental Degradation Mechanisms and Structural Risks

Over the course of their anticipated 25 to 30-year operational lifespans, these structural supports are repeatedly exposed to harsh, uncontrolled outside environments despite their crucial load-bearing function. A multifaceted degradation landscape is produced by prolonged, unprotected exposure to intense solar ultraviolet (UV) radiation, atmospheric oxygen, ambient moisture, diurnal thermal cycling, and aggressive airborne pollutants (such as sulfur dioxide in industrial zones or chloride ions in marine-adjacent installations). Severe surface phenomena such as photochemical polymer degradation, photo-oxidation, matrix embrittlement, coating chalking, and destructive electrochemical corrosion, often known as rust, are caused by this environmental aggression. The mechanical integrity, load distribution, and structural rigidity of structural supports are seriously jeopardized as they deteriorate.

3. Conventional Protective Coatings' Drawbacks

Protecting solar infrastructure from early failure requires the development and use of sophisticated, extremely durable protective surface treatments. Standard alkyd paints, simple epoxy primers, and common zinc galvanization are examples of traditional anti-corrosive coatings that often fail in contemporary utility-scale deployments. They frequently suffer from early micro-cracking, interlayer delamination, UV-induced yellowing, and deterioration when subjected to cyclic heat stress and moisture penetration, making it difficult for them to concurrently offer strong, long-term UV shielding and active corrosion inhibition. Unmodified polycarbonate matrices are still intrinsically vulnerable to UV-induced photo-Fries rearrangement, chain scission, and consequent loss of mechanical performance when exposed to extended natural weathering, despite the fact that polycarbonate-based systems have long been acknowledged in materials science for their remarkable impact resistance, high dimensional stability, weatherability, and favorable optical and mechanical clarity.

II. LITERATURE REVIEW

1. Environmental Degradation of Photovoltaic Supporting Structures

The long-term weatherability of the structural frame materials, which are mostly made of carbon steel, galvanized steel, and structural aluminum alloys, is crucial to the longevity of photovoltaic (PV) power plants. Numerous field investigations show that the combined impacts of solar ultraviolet (UV) irradiation, temperature fluctuations, and hostile atmospheric electrolytes cause these metallic substrates to degrade more quickly when used in hard outdoor environments. When protective barriers are breached, ambient moisture and airborne chloride ions (Cl-) facilitate rapid electrochemical oxidation, while solar UV radiation (especially in the 290 nm to 400 nm spectrum) initiates severe photochemical reactions at organic coating interfaces. As a result, one of the main goals of research on renewable energy infrastructure is to stop localized pitting corrosion and rust formation.

2. Advancements in Polycarbonate and Polymer-Matrix Composite Coatings

Its remarkable impact strength, dimensional stability, high glass-transition temperature, and advantageous optical and mechanical clarity, polycarbonate (PC) has become a popular choice for coating matrices. Under extended UV exposure, unmodified polycarbonate is naturally vulnerable to photo-Fries rearrangement and polymer chain scission, which can lead to optical yellowing and mechanical failure. Recent research shows that adding specific ultraviolet absorbers (UVAs) and hindered amine light stabilizers (HALS) to polycarbonate resins efficiently inhibits photodegradation while maintaining film integrity.

Table 1: Comparison of Conventional Protective Coatings vs. Advanced Polycarbonate Systems

Coating Category	Primary Binder / Material	UV Resistance Performance	Corrosion Inhibition Mechanism	Typical Lifespan in Aggressive Climates
Conventional Systems	Alkyd paints, standard epoxies	Poor (susceptible to chalking and yellowing)	Passive barrier (prone to early micro-cracking)	3 - 7 years
Zinc Galvanization	Hot-dip zinc coatings	Moderate	Sacrificial anodic protection	10 - 15 years (dependent on local humidity)
Advanced Polycarbonate Systems	Polycarbonate-modified resin with UVAs and HALS	Excellent (high resistance to photo-oxidation)	Dual-action (UV shielding plus active nano-inhibitors)	> 25 years (aligned with solar plant lifespans)

III. METHODOLOGY AND EXPERIMENTAL FRAMEWORK

The polycarbonate-based coating system is developed and validated by an organized, multi-step process that combines material composition, accurate application, and stringent analytical testing. Because of its remarkable impact resistance and dimensional stability, high-performance bisphenol-A polycarbonate (BPA-PC) resin is used as the fundamental film-forming polymer binder. Hindered amine light stabilizers (HALS) and specific organic ultraviolet absorbers (UVAs) of the benzotriazole class are mixed directly into the resin matrix to prevent photo-oxidation. Moreover, functionalized silica nanoparticles and active zinc-aluminum molybdates are added to give active electrochemical passivation against rust. Before applying a coating, structural coupons made of structural carbon steel and galvanized steel that measure 150 mm x 75 mm x 3 mm must be mechanically abraded, solvent-degreased, and chemically cleaned.

To guarantee that the stabilizers and nano-inhibitors are evenly distributed throughout the polycarbonate solution, the coating formulation is made using high-shear mechanical dispersion. The liquid system is sprayed to the prepared metal substrates using automated spray-coating equipment in order to maintain a controlled, uniform dry film thickness (DFT) of 75 + 5 um. In order to ensure full solvent evaporation and cross-linking of the polymer matrix, the coated panels go through a multi-stage thermal curing procedure in a convection oven, rising from ambient temperature to 120oC during a 60-minute period.

In accordance with worldwide industrial standards, a strict testing process is developed to thoroughly evaluate the protective efficiency of the coating. In compliance with ASTM G155, accelerated weathering testing is carried out in a xenon-arc weathering chamber, exposing panels to alternating cycles of UV radiation and moisture condensation to assess resistance to yellowing and gloss retention. Additionally, in order to monitor the spread of sub-film corrosion, neutral salt spray (NSS) experiments are carried out in accordance with ASTM B117 standards

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by subjecting scribed coated panels to a continuous 5% sodium chloride (NaCl) fog at 35oC for 1,000 hours. The cross-cut tape test (ASTM D3359) is used to quantify adhesion strength by evaluating interfacial adhesion stability to the metal substrate by scoring the coating in a lattice pattern. Lastly, coating pore resistance, capacitance, and long-term barrier degradation in saline environments are measured by electrochemical impedance spectroscopy (EIS) using a typical three-electrode electrochemical cell setup spanning a frequency range of 105 Hz to 10-2 Hz.

Table 2: Overview of Systematic Testing Parameters and Standards

Test Category	Standard Protocol	Primary Operating Conditions	Target Performance Metric
Accelerated Weathering	ASTM G155	Xenon-arc lamp, 0.35 $W/(m^2 . nm$ @340nm), cyclic moisture	Minimal gloss loss (< 10%), zero yellowing
Neutral Salt Spray (NSS)	ASTM B117	5% NaCl solution, 35°C continuous fog exposure	Zero rust creepage from scribe, no blistering
Adhesion Strength	ASTM D3359	Cross-cut lattice blade, 1 mm spacing, pressure-sensitive tape	Classification rating of Class 5B (0% detachment)
Electrochemical Impedance (EIS)	ASTM G106 / ISO 16773	3.5% NaCl electrolyte, open circuit potential	Low-frequency impedance $((\|Z\|_{0.01Hz}) < 10^9 \ \Omega . cm^2$

IV. RESULTS AND DISCUSSION

1. Enhanced Optical Performance and Weathering

Compliance with ASTM G155, xenon-arc exposure was used to assess the polycarbonate-based coating system's accelerated weathering performance. The combination of benzotriazole-class UV absorbers and hindered amine light stabilizers (HALS) effectively reduced the photo-Fries rearrangement and polymer chain scission commonly linked to virgin polycarbonate matrices over a prolonged exposure period equivalent to several years of intense solar radiation. Spectrophotometric measurements showed remarkable color stability, with gloss retention surpassing 92% of original values and little yellowing index (Δ YI) alterations. This suggests that high-energy ultraviolet photons were effectively absorbed and dispersed by the UV stabilization network without compromising the polymer film's structural integrity.

2. Salt Spray Performance and Corrosion Resistance

Neutral salt spray (NSS) testing in accordance with ASTM B117 standards was used to thoroughly evaluate the protective barrier's effectiveness against air oxidation and moisture penetration. Scribed panels showed exceptional corrosion resistance after being continuously exposed to a 5% sodium chloride fog at 35o C for 1,000 hours. The coated carbon steel and galvanized substrates showed no rust formation from the scribe line, in contrast to traditional alkyd or basic epoxy systems, which usually exhibit substantial sub-film rust creepage, blistering, and delamination within hundreds of hours. The synergistic effect of the dense polycarbonate barrier matrix in conjunction with functionalized silica nanoparticles and active zinc-aluminum-molybdates, which actively passivate possible micro-defects and impede ionic diffusion, is responsible for this outstanding performance.

3. Strength of Interfacial Adhesion

The cross-cut tape test (ASTM D3359) was used to measure the mechanical adhesion stability between the coating system and the metallic substrates. A categorization rating of Class 5B was obtained from experimental observations across several test coupons, indicating that none of the coating's lattice squares separated from the substrate. Strong interfacial bonding was guaranteed by the pre-treatment procedures as well as the superior wetting qualities and high cross-linking density attained during the heat curing cycle (120oC). In real-world solar farm settings, this strong adhesion strength stops moisture buildup at the metal-polymer interface, preventing mechanical peeling and under-film corrosion progression during cyclic thermal expansion.

4. Analysis of Electrochemical Impedance Spectroscopy (EIS)

In a 3.5% sodium chloride electrolyte solution, long-term barrier degradation and ionic transport characteristics were assessed using electrochemical impedance spectroscopy (EIS), a sensitive, quantitative metric. Within days, the low-frequency impedance magnitude of uncoated control samples rapidly decreased, suggesting direct electrolyte penetration to the metal substrate. On the other hand, throughout extended immersion cycles, the formed polycarbonate coating retained very high low-frequency impedance values (|Z|0.01Hz) reaching < 109 Ω . cm2. This persistent high impedance validates the coating system's remarkable capacitive behavior and pore-blocking effectiveness, confirming its appropriateness for long-term deployment in harsh weather conditions.

Table 3: Overview of Coating Performance Measures and Experimental Findings

Evaluation Parameter	Testing Method / Standard	Uncoated Control Substrate	Developed Polycarbonate Coating System	Performance Enhancement
Gloss Retention	ASTM G155 (Weathering)	< 40% retention after 500 hours	> 92% retention after extended exposure	Superior optical stability
Yellowing Index (ΔYI)	Spectrophotometer ASTM E313	Severe yellowing (Δ YI > 12)	Negligible change (Δ YI < 0.8)	Complete UV degradation suppression
Corrosion Creepage	ASTM B117 (1,000h NSS)	Extensive rust propagation (> 15 mm creep)	Zero rust creepage (0 mm from scribe)	Complete inhibition of sub-film rust
Adhesion Classification	ASTM D3359 (Cross-Cut)	Class 0B (> 65% detachment)	Class 5B (0% detachment)	Maximum interfacial bond strength
Low-Frequency Impedance	ASTM G106 (EIS Analysis)	$< 10^4 \ \Omega . cm^2$ (rapid failure)	$< 10^9 \ \Omega . cm^2$ (stable barrier)	Five-order magnitude improvement

V. CONCLUSION AND FUTURE RECOMMENDATIONS

1. Explanation of Results

An improved polycarbonate-based UV-protective and rust-preventive coating system designed especially for photovoltaic solar panel structural supports was successfully developed, optimized, and methodically evaluated in this work. By combining active zinc-aluminum-molybdate nano-inhibitors, hindered amine light stabilizers (HALS), and specialized organic ultraviolet absorbers (UVAs) into a high-performance bisphenol-The coating creates a strong, dual-action defensive system using a polycarbonate matrix.

The systematic testing framework demonstrated exceptional performance across all evaluated parameters:

- Weathering & Optical Stability: The coating successfully inhibits photo-Fries rearrangement and polymer chain scission, retaining over 92% gloss retention and minimal yellowing (Δ YI < 0.8), according to accelerated xenon-arc weathering (ASTM G155).

- Corrosion Resistance: After 1,000 hours of intense exposure to saline fog, neutral salt spray tests (ASTM B117) demonstrated zero creepage from the scribe line, confirming total suppression of sub-film rust propagation.
- Mechanical Adhesion: A Class 5B rating was obtained from cross-cut tape testing (ASTM D3359), confirming better interfacial adhesive strength under thermal expansion stress.

2. Benefits for Industry

The use of this cutting-edge polycarbonate coating technique offers a conclusive technical answer to the early deterioration of solar installation infrastructure in harsh outdoor environments. This technology reduces lifecycle maintenance costs, prevents structural sagging or collapse under heavy environmental loads, and improves the overall bankability and safety of large-scale renewable energy installations by greatly extending the service life of carbon steel and galvanized support frames beyond the typical 25- to 30-year operational lifecycle of solar plants.

3. Future Recommendations

Building on the results of this study, future research should concentrate on a number of important areas to further develop the technology. To confirm laboratory results against real-world microclimatic fluctuations and long-term weathering, coated structural coupons must first be deployed in a variety of geographical test beds, such as hyper-arid deserts and high-salinity coastal installations. Second, in order to automatically fix microcracks caused by severe mechanical stress or seismic activity, researchers should investigate the integration of microcapsule-based self-healing agents within the polycarbonate matrix. Lastly, assessing the carbon footprint, manufacturing viability, and commercial scalability of mass-producing the nano-modified polycarbonate coating system for global utility-scale solar infrastructure will require a thorough environmental and economic life cycle assessment (LCA).

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