

***University of Business and Technology
(UBT)***

Techno Valley

**Zinc Oxide-Based Multifunctional Dust-Resistant
Solar Panel Coatings**

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A Research Report

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Introduction

Dust accumulation is a serious challenge for solar energy systems in harsh and variable environments. Settled dust can block sunlight and reduce photovoltaic (PV) output by significant margins – field studies report efficiency losses of up to ~25% if panels are not regularly cleaned.^{1}

In arid deserts and remote locations, cleaning with water or labor is impractical, yet traditional washing consumes billions of gallons of water annually.^{1} The issue is exacerbated in extraterrestrial settings like the Moon or Mars, where fine electrostatically charged dust clings to surfaces in the absence of atmosphere.^{2}

For instance, lunar dust is sharp, abrasive, and charged by solar UV radiation, causing it to adhere to solar panels and instruments.^{2} These conditions demand advanced coating solutions to keep solar panels clean and maintain performance over long durations without manual intervention.

Recent research is exploring **multifunctional coatings** that not only resist dust adhesion but actively remove or mitigate dust, while remaining transparent and durable. **Zinc oxide (ZnO)** has emerged as a **promising base material** for such coatings. ZnO is a wide-bandgap semiconductor that is both **transparent** in the visible spectrum and can be **nanostuctured** to form textured surfaces.

It also offers versatile functionalities: ZnO can be doped to become a transparent conductor, it exhibits photocatalytic activity (like Titanium dioxide {TiO₂}) to break down organic grime, and it even has piezoelectric properties that could be harnessed for vibrational cleaning.

By combining ZnO with other advanced materials, we aim to create coatings that repel dust (through superhydrophobic or electrostatic means), remove settled dust (via electric fields or mechanical vibration), and even **self-heal** to recover from scratches or weathering.

This research paper surveys the state-of-the-art in ZnO-based solar panel coatings, including material combinations, application methods, suitable PV technologies for integration, and real-world demonstrations. Emphasis is placed on highperformance solutions that are scalable for commercial use and robust enough for extreme environments (deserts, urban pollution, and Mars-like conditions).

Photovoltaics: is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect.

Photocatalysis: is the acceleration of a photoreaction by a catalyst that interacts with light and reactants.

Piezoelectric: is the electric charge that accumulates in certain solid materials.

Materials for Dust-Resistant and Self-Cleaning Coatings

Zinc Oxide as a Base Material: ZnO serves as a foundational layer in many multi-functional coatings due to its transparency and chemical versatility. When deposited as a thin film (pure or doped), ZnO can function as a **transparent conductive oxide (TCO)**.

Aluminum-doped ZnO (AZO) in particular is an attractive, cost-effective alternative to **indium tin oxide** for transparent electrodes. A conductive ZnO layer allows the use of electrostatic dust removal techniques while still transmitting light into the coated solar panel.

Additionally, ZnO's refractive index (~ 2.0) is advantageous for anti-reflective (AR) properties when used in a porous or nanostructured form.^{{3} - {4}}

Importantly, ZnO is also a **photocatalytic semiconductor** that can catalyze redox reactions under UV illumination to degrade organic matter on the surface.^{5}

This photocatalytic self-cleaning is similar to the well-known TiO_2 self-cleaning effect, and helps loosen organic binders ("cementation") that make dust stick to panels.^{{6} - {7}} By breaking down hydrocarbons or bio-residues, ZnO coatings can make it easier for dust particles to be removed by wind or other forces. Lastly, ZnO in certain crystalline orientations exhibits piezoelectricity, meaning mechanical vibrations can be induced via electrical signals – which is an interesting property for active dust removal, that will be discussed below.

Superhydrophobic and Dust-Resistant Layers: One strategy to prevent dust from accumulating is to use **superhydrophobic** (water-repellent) surfaces that cause dust to be rinsed or blown off easily. Superhydrophobic coatings typically have water contact angles (WCA) $>150^\circ$ so that water droplets bead up and roll off, carrying loose dust with them (the classic "lotus effect").

ZnO nanostructures combined with low-surface-energy materials have been widely studied to achieve this. For example, rough **ZnO/SiO_2 {Silicon dioxide} composite films** treated with fluorinated silane can attain WCAs in the $160^\circ - 170^\circ$ range while maintaining high optical transparency.^{8}

One robust nano-composite (ZnO/SiO₂ in an epoxy binder) achieved 94% solar transmittance and a WCA of 172°; even after aggressive abrasion tests, the contact angle remained >150°. ^{8} This indicates excellent durability of the hydrophobic effect. Hierarchical nano/micro-structured ZnO is particularly effective: Li *et al.* (2016) grew a two-layer **Al-doped ZnO (AZO)** coating with nanoscopic “rice-like” crystals and microscale “peony like” clusters, achieving a WCA ~170°. ^{9}

Notably, their method combined atomic layer deposition (for a seed layer) with a hydrothermal growth of the ZnO microstructures – a route to create strongly water-repellent textures. Other techniques like spray pyrolysis and chemical vapor deposition have similarly been used to form **ZnO nanowire and nanobelt coatings** that are superhydrophobic (WCA 150° – 160°) while transmitting 85 – 90% of light. ^{3} - ^{10}

These textured ZnO surfaces trap air (Cassie–Baxter state), minimizing the contact area for dust and water. In addition to fluorinated silanes, hydrophobic polymers (e.g. silicones or fluoropolymers) can be grafted onto ZnO/SiO₂ nanoparticle coatings to lower surface energy. ^{11} - ^{12}

However, entirely organic hydrophobic coatings may suffer UV degradation in outdoor use. ^{13} The best performers therefore often use inorganic nanostructures (ZnO, SiO₂, TiO₂) for roughness and mechanical strength, combined with a thin organic or silane layer for low surface energy.

Superhydrophilic and Self-Cleaning Layers: In environments where moisture (rain, dew) is expected or for applications like anti-fogging, superhydrophilic coatings offer an alternative passive cleaning mechanism. A **superhydrophilic** surface (water contact angle ~0 – 5) causes water to spread into a thin film that can wet and wash away dust uniformly. ^{14} - ^{15}

Such coatings are usually nanoporous or high-surface-energy films, often leveraging photocatalytic oxides. TiO₂ is commonly used to achieve superhydrophilicity under UV illumination (UV creates surface – OH groups), and ZnO can play a similar role. ^{16}

Mesoporous silica (SiO₂) films can also be engineered to be hydrophilic. A study by Rico *et al.* used porous TiO₂ thin films (~300 – 500 nm) deposited by physical vapor deposition to create a superhydrophilic coating that both

increased light transmittance and enabled self-cleaning via water sheeting.^{15}
- {16}

In dusty desert conditions, superhydrophilic coatings may be advantageous when nighttime dew or periodic cleaning water is available – water spreads and lifts the dust without needing soaps or high pressure. An outdoor comparison found that superhydrophilic films reduced dust adhesion more effectively over time than superhydrophobic ones, likely because hydrophilic surfaces prevented the hard cementation of dust with moisture and allowed easier removal.^{6} - {7}

In practice, some **dual-action coatings** aim to combine both effects: for instance, a layered coating with a photocatalytic TiO₂ under-layer (to make the surface hydrophilic in sunlight and break down organics) and a hydrophobic top layer has been proposed, so that it is water-repellent in the dark (keeping dust dry and loose) but becomes hydrophilic in sunlight or rain to wash off debris.^{17} Such time-dependent wettability could offer round-the-clock anti-soiling.

Electrostatic Dust Removal (Transparent Conductors): Passive coatings alone cannot remove all dust, especially fine particles in dry conditions or on Mars (where there is no rain). Thus, **active dust removal** methods are being integrated into coatings via conductive or electrostatic layers. The principle is to impart an electric force or charge that dislodges dust particles. A transparent conductive coating like AZO or indium tin oxide (ITO) can serve as an electrode to either dissipate static charge (reducing the attraction of dust) or actively repel charged dust.

In one recent innovation, researchers deposited a thin translucent AZO film on solar glass and used it as part of an **electrodynamic dust repulsion** system.^{17} By applying an electric field to the AZO-coated glass, dust particles (which often carry an electrostatic charge in windy environments) were actively repelled, preventing accumulation.^{17} This method is inspired by Electrodynamic Dust Shield (EDS) technology originally developed by NASA, which uses interdigitated transparent electrodes to generate traveling electric fields that literally “lift” dust off the surface.

NASA has successfully tested such EDS coatings on the Moon's surface – a recent lunar lander experiment showed that a pulsed electrodynamic shield removed a substantial portion of dust from coated surfaces without any mechanical intervention.^{5} For solar panels, a conductive ZnO-based layer could be patterned or sectioned into electrodes across the panel. By sequentially energizing these electrodes with high-voltage AC waves, dust is conveyed off the panel's surface.

The use of ZnO is advantageous because it is a readily available TCO that can be coated over large areas; indeed, a sol gel derived AZO film was used as the base conductive layer in a 2024 study demonstrating active dust repulsion on glass.

^{1} Additionally, incorporating conductive **polymers** or nanomaterials is being explored – e.g. a transparent polymer with embedded carbon nanotubes or graphene could add conductivity to a hydrophobic coating, enabling static charge dissipation.

The goal is a coating that not only prevents dust from sticking strongly, but can also impart charges or vibrations to shake off settled dust when needed (for example, by connecting the coating to a small solar-powered high voltage source or piezo-driver).

Piezoelectric and Vibrational Cleaning Materials: Another active approach is to physically shake the dust off the panel using **piezoelectric materials** that convert electrical energy into mechanical vibrations. ZnO itself is piezoelectric in certain forms (wurtzite crystal nanowires), but more commonly, flexible piezoelectric polymers like polyvinylidene fluoride (PVDF) are considered. In a recent demonstration, Manzo *et al.* (2025) laminated transparent PVDF films onto panel surfaces to act as a self-cleaning layer.^{24}

When an alternating current is applied, the PVDF film vibrates at high frequency, effectively dislodging dust particles without any water or brushes.^{24} This **water-free vibrational cleaning** proved highly effective: tests showed that ~90% of dust could be shaken off a solar panel within 60 seconds of activation.^{4}

The energy consumption for this cleaning cycle was modest (on the order of few hundred watts for a large panel)^{24}, and such cleanings need only be done periodically. Piezoelectric coatings can be integrated as a top layer or even embedded in the panel's cover material. ZnO nanostructures could

complement this by providing a textured surface that requires less force to free the dust (lower adhesion).

Some studies have even investigated directly growing piezoelectric ZnO nanowires on solar cells to both reduce reflection and enable ultrasonic vibration cleaning, though this is still experimental. In practice, a combination of a conductive ZnO layer (to provide uniform AC voltage distribution) with a piezoelectric polymer overlayer could allow the entire panel surface to act like a vibrating membrane when energized, “flinging” off dust. This is particularly attractive for Mars or desert use, where it could reduce reliance on natural wind or human cleaning.

Self-Healing Coatings: Harsh environments not only deposit dust but can also **damage coatings** via sand abrasion, UV radiation, and thermal cycling. To ensure long-term performance, researchers are incorporating **self-healing** functionalities into anti-dust coatings.

A self-healing material can autonomously repair micro-cracks or restore its surface properties after damage. One approach is to embed microcapsules in the coating that release a repairing agent when scratched; however, for thin transparent films, newer techniques focus on polymer chemistry. *In-situ* self-healing can be achieved with polymers that have dynamic bonds or phase-separating behavior. For example, a recent study created a transparent superhydrophobic coating by filling porous silica nanotubes with **perfluorooctyl acid (PFA)** molecules.^{8}

If the surface’s hydrophobic layer was damaged (e.g. by plasma or UV), heat at ~70 °C would cause the fluorinated molecules to re-migrate to the surface and restore water repellency.^{22} This coating maintained 87% optical transmittance and WCA ~160–170° even after repeated damage/healing cycles.^{22}

Another innovative coating used a **supramolecular PDMS (polydimethylsiloxane)** polymer matrix crosslinked with reversible boroxine bonds, combined with silica nanoparticles.^{9} The PDMS-based film was ~90% transparent with WCA >160°, and notably could **spontaneously self-heal at room temperature** – scratches or abrasions would reflow and close up due to the dynamic covalent network, without any external trigger.^{9}

This allowed the coating to repeatedly regain its superhydrophobicity and clarity after being worn, greatly improving durability. Other research has shown self healing hydrophobic coatings that activate under UV light or simply under thermal cycles.^{{1} - {2}} The challenge is to incorporate these healing functions without sacrificing optical properties or adding too much thickness. Nonetheless, early results are promising: for instance, a stratified triple-layer polymer coating with embedded fluorine and siloxane segments was reported to have >80% healing efficiency under UV exposure, while still achieving ~90% transmittance and high hardness (28 MPa).^{2}

In dust mitigation terms, self-healing means the coating can **maintain its dust repellent performance over years**, even if scratched by blowing sand or cleaned aggressively. Self-healing also aids in preserving anti-reflective properties by smoothing out microcracks that might scatter light. Combining ZnO or SiO₂ nanoparticles (for hardness and roughness) with such smart polymers yields coatings that are both **hard and resilient**, an ideal trait for long-term use on solar panels.

Coating Application Methods

Developing an effective material system is only half the challenge – equally important is the method of applying these coatings to solar panels in a scalable, uniform, and economically viable manner. Different coating techniques offer trade-offs in terms of film quality, coverage area, temperature requirements, and cost. Here we review the leading methods for depositing ZnO-based multi-functional coatings:

Chemical Vapor Deposition (CVD): CVD (and related processes like plasma-enhanced CVD) allows the growth of uniform thin films by reacting gaseous precursors on the panel's surface. This method is capable of producing high-purity ZnO films or nanostructures. For example, ZnO nanowire arrays have been grown on glass via catalyst-assisted CVD to form superhydrophobic AR coatings.^{4}

CVD can also deposit TiO_2 or SiO_2 layers for photocatalytic or AR purposes. The advantage of CVD is good control over thickness and morphology; textured micro/nanostructures can be obtained by adjusting growth parameters.^{3} - ^{4} However, CVD typically requires elevated substrate temperatures (300–500 °C for ZnO deposition in many cases) and vacuum or controlled atmospheres, which may not be compatible with all types of solar panels (for instance, panels with polymeric components).

It is well-suited for glass-based silicon modules that can tolerate heat. Research labs have used CVD to demonstrate complex ZnO structures (nanobelts, nanowires) on glass slides ^{3} - ^{27}, but scaling this to large module manufacturing might be costly. CVD remains a go-to technique for high quality coatings in R&D, including for depositing seed layers or conformal films that can be subsequently post-processed (e.g. CVD followed by hydrothermal growth of ZnO, as in the hierarchical AZO example^{9}).

Atomic Layer Deposition (ALD): ALD is a specialized variant of CVD that deposits material one atomic layer at a time by alternating precursor gases. It offers unparalleled control over thickness and composition, and can coat complex 3D surfaces uniformly. ALD has been used to deposit ultrathin, pinhole-free ZnO and Al₂O₃ films as protective or interface layers in solar cells.^{1}

For antisoiling applications, ALD can create nanolaminate structures or seed layers that improve adhesion of subsequent coatings. In one study, an ALD deposited Al-doped ZnO base layer (with a certain crystal orientation) was crucial in guiding the growth of a superhydrophobic ZnO top layer.^{9}

ALD could also be used to apply a very thin, transparent hydrophobic layer (for instance, ALD of an organosilane or fluorinated layer) with molecular precision. The downside of ALD is its slow deposition rate and high equipment cost, making it challenging for large-area panel coating except in high-end manufacturing. Nonetheless, ALD is being explored especially for **perovskite and thinfilm PV**, where a gentle, precise encapsulation or buffer layer is needed – for example, a few nanometers of ALD-Al₂O₃ can protect perovskite cells from humidity without significantly affecting light transmission.

While not yet common for commercial panel coatings, ALD could play a role in depositing multi-layered structures (such as alternating ZnO and Al₂O₃ nanolayers) to exploit different functionalities (conductivity, barrier, refractive index control) in a single coherent film.^{{29} - {30}}

Solution-Based Coatings (Sol-Gel, Dip-Coating, and Sprays): To achieve low-cost and scalable deposition, a variety of wet-chemical methods can be employed. **Sol-gel processes** involve preparing a liquid precursor solution that can form a metal oxide network upon drying and heat treatment.

For instance, a sol-gel can be made from zinc acetate or alkoxysilane precursors; when coated on glass and cured, it yields a ZnO or SiO₂-based nano-porous film. Researchers have developed sol-gel solutions for **Al doped ZnO** that can be dip-coated onto glass and then annealed to form transparent conductive films.^{{31} - {32}}

Sol-gel is attractive because it uses inexpensive chemicals and simple equipment (beakers and ovens). In a 2024 study, Hooshyar *et al.* prepared a conductive AZO sol by dissolving zinc acetate and aluminum nitrate with stabilizers, then **dip-coated** this onto glass to create a ~100 nm AZO layer.^{1}

This was followed by a second dip-coating of a silica/titania nanoparticle sol gel, yielding a rough anti-soiling top coat.^{1} Dip-coating ensures uniform coverage on flat glass and can be scaled up by using large tanks (even entire panel glass can be dipped or pulled from a solution). Similarly, **spray-coating** is a versatile method: an alcohol-based nano-particle suspension can be sprayed onto the panel using an aerosol gun or automated sprayers.

The Egyptian field trial (discussed later) used a commercial nano-silica coating applied via a spray bottle (5 sprays per square foot) to evenly cover the panel.^{34} After curing, it formed a thin hydrophilic layer that significantly reduced dust buildup. **Spray pyrolysis** is a variant where a precursor solution (e.g. zinc acetate) is sprayed onto a heated substrate, causing instantaneous decomposition to ZnO. Patil *et al.* achieved ZnO superhydrophobic films by spray pyrolysis at ~450 °C, demonstrating that even a simple spray nozzle and hot plate arrangement can produce highperformance coatings.^{{35} - {36}}

Sol-gel and spray methods are compatible with large-scale manufacturing and even retrofitting existing solar panels. They do, however, require optimization to avoid cracking or non-uniform thickness. Nanocomposite spray coatings that include both nanoparticles (for roughness) and polymer binders (for adhesion and flexibility) are particularly promising.

These can be applied similarly to paint and cured at low temperature making them suitable for flexible or polymer-based solar modules that cannot withstand high heat. The key is achieving good adherence to the panel's surface (often improved by pre-treatments like plasma cleaning) and the right thickness (too thick can reduce transparency, too thin may be discontinuous).

Physical Vapor Deposition (PVD) and Sputtering: Many commercial solar panels already use thinfilm coatings on their cover glass, typically deposited by sputtering (a PVD process). Anti-reflective coatings, for example, are often SiO_2 or TiO_2 layers sputter-coated onto glass. The same equipment can in principle deposit ZnO , AZO, or other metal-oxide layers. **Magnetron sputtering** can produce high-quality AZO transparent electrodes and is used industrially for low-E glass and displays; integrating an AZO sputter step in solar panel production could add an electrostatic dust-repelling layer.

Sputtering can also deposit doped TiO_2 or combined silica–titania films that have photocatalytic and AR properties. The benefit is that sputtering is a mature, scalable technology for large glass substrates (many glass coating lines exist). It operates at low substrate temperatures compared to CVD, so it can be done even after solar cells are encapsulated (as long as the panel can be placed in a vacuum chamber).

PVD methods were used in some research to create nanostructured films as well; e.g., an electron-beam evaporation technique was used by Wang *et al.* to create a porous TiO_2 AR coating through control of deposition angle and porosity.^{16} For dust-repellent coatings, sputtering alone might not achieve the necessary micro-texture (it generally gives dense films), but posttreatment like chemical etching can introduce nanostructures.^{4}

A combined approach could be sputter a base conductive layer (smooth, dense AZO) and then apply a second layer via sol-gel or etching to create roughness. In summary, sputtering/PVD provides excellent uniformity and is production-proven, making it a likely method for any coating stack that needs to be added in a factory setting.

Each of these methods can be chosen or combined based on the target solar panel technology and the required performance. Importantly, any coating process must preserve the optical clarity of the panel (typically >90% transmission in the visible) and add minimal absorption or scattering.

Additionally, coating steps must not harm the solar cells themselves – for example, high-temperature CVD would only be done on the cover glass before it is laminated onto cells, whereas low-temperature sprays could be applied after module assembly. The ease of maintenance is also a factor: solution-derived hydrophobic coatings may need occasional re-application if their effect fades, whereas a baked-on inorganic coating might last longer but be harder to reapply in the field.

As research advances, hybrid processes (e.g. print a pattern of conductive lines, then spray a nanocomposite over it) are emerging to ensure that the **multi-functionality (dust resistance, AR, self-cleaning)** can be integrated in a cost-effective manner.

Integration with Different Solar Panel Technologies

Advanced dust-mitigation coatings can be beneficial for virtually all types of solar panels, but the optimal integration approach can vary depending on the PV technology and module design. Here we consider the major classes:

Conventional Crystalline Silicon Panels {First generation} (Glass-encapsulated): First-generation PV modules (mono- or poly-crystalline silicon) are typically encapsulated in a sandwich of EVA polymer and front/back glass. The front glass is the primary interface with the environment, making it the ideal surface to coat.

Fortunately, this glass is durable (often tempered) and can withstand processes like hightemperature deposition or curing. Thus, **crystalline Si panels are well-suited for coatings applied on the outer glass**. Anti reflective and hydrophobic coatings can be added to the glass either during manufacturing or as a retrofit. For example, a textured silica or ZnO coating can double as an AR layer to improve light intake (silicon's bare cell reflection can exceed 30%^{37}) while also reducing dust adhesion.

Many of the lab demonstrations (superhydrophobic films, AZO conductive layers, etc.) are performed on glass slides, which directly translates to silicon PV module covers.^{{17} - {38}} Because silicon panels are dominant in desert solar farms – where dust is a known performance limiter – applying these coatings to conventional panels is a priority. The dual-layer AZO/TiO₂ coating described by Hooshyar *et al.*

was designed with standard solar cover glass in mind and showed improved clarity and dust resistance in testing.^{17} For existing silicon panels, spray-on coatings (hydrophobic or antistatic) can be used as a retrofit, though ensuring uniform application on large installations is a practical challenge. Still, from a compatibility standpoint, crystalline silicon modules offer a stable, heat tolerant platform for these advanced coatings, and field trials (like those in Egypt^{{39} - {40}}) have shown significant energy gains when such panels are treated.

Thin-Film Solar Panels {Second generation} (CdTe, CIGS, a-Si):

Second-generation thin film technologies often have a different module construction. Some (like CdTe) also use glass/glass encapsulation similar to silicon panels – e.g. CdTe panels by First Solar have a front glass with an anti-reflective coating. These can similarly benefit from dust-resistant coatings on the glass.

Other thin-film modules, especially flexible ones (CIGS on polyimide, or amorphous Si on plastic), have a polymer front sheet instead of glass to allow flexibility. Coating polymer surfaces requires low-temperature techniques and flexible materials. Hydrophobic polymer-based coatings (like the PDMS/boroxine or fluoropolymer systems mentioned earlier) are well-suited here, since they can bond to plastics and even improve scratch resistance.

A consideration for thin-film PV is that some have **sensitive top contacts** – for instance, CIGS or perovskite cells may have a transparent conductive oxide that could be affected by coating processes. One must ensure that adding a ZnO layer or any coating does not disrupt the cell's electrical contacts or interfere with module lamination. That said, many thin-film modules already incorporate ZnO as a part of the device (ZnO: Al is commonly used as the TCO in CIGS cells).

This opens the possibility that the cell's top electrode itself could be engineered to double as a dustrepelling layer by suitable nano-texturing or surface treatment. Flexible thin-film panels for portable or space use could particularly benefit from **lightweight dust removal** coatings – e.g., a sprayed on conductive network for electrodynamic cleaning that is much lighter than a glass cover with wipers.

In summary, thin-film panels are compatible with these coatings, but the method of application will lean toward *in-situ* during manufacturing (sputtering or printing on the cell surface) or lowtemperature deposition if on a polymer cover.

Emerging Perovskite and Multi-Junction Solar Panels {Third generation}: Perovskite solar cells (a prominent thirdgeneration PV) are known for high efficiency but poor stability, especially against moisture, UV, and dust. Here, multifunctional coatings could play a protective role in addition to cleaning.

A ZnO or TiO₂ overlayer can act as a UV filter – for instance, ZnO nanowire coatings have been shown to absorb UV and reduce the degradation rate of underlying organic PV cells.^{27} Perovskites similarly degrade under UV and need encapsulation, so a ZnO-based coating might both **shield UV and keep the surface dust-free**, improving operational stability.

Indeed, researchers have explored using compact ZnO layers deposited by ALD or sputtering in perovskite cell stacks to enhance stability.^{41} If a superhydrophobic or superhydrophilic layer can be added on top of perovskite modules without damaging them (perhaps as part of the encapsulant film), it would be highly beneficial because perovskites cannot be easily cleaned with water (water ingress would be catastrophic).

The challenge is that perovskite modules usually have a sealing layer (glass or a fluoropolymer) – coatings need to adhere well to that. Solutions like a **fluorinated silica nanocomposite** or a **self-stratifying polymer** could potentially be coated onto the perovskite's cover film to impart dust resistance; these can be applied at ambient conditions, avoiding heat or vacuum that perovskites cannot endure late in manufacturing.

Multi-junction space solar cells (e.g. GaAs-based) are typically protected by a cover glass or optical coating, which again could be augmented with an EDS or hydrophobic layer for dust mitigation on planetary surfaces. Since space missions prioritize reliability, **NASA's approach is to integrate dust-clearing coatings** like the EDS on any critical solar arrays.^{19}

For future Mars missions or Moon bases powered by perovskite or thin-film arrays, a combination of a dust-repelling coating plus an active removal mechanism (electrostatic or vibrational) might be the best solution to deal with the omnipresent regolith dust.

In summary, **monocrystalline silicon Solar panels {First generation}** with glass covers are the most straightforward candidates for these coatings, as they can leverage existing glass-coating processes and have already demonstrated significant performance gains with anti-dust nano-coatings.<sup>{39}-
{40}</sup>

Thin-film and perovskite Solar panels {Third generation} can also integrate these coatings, but the deposition techniques must be gentler (no high temperatures after cell fabrication) and ideally integrated into encapsulation layers. As the solar industry moves toward bifacial panels, building-integrated PV, and flexible panels, the coating materials will need to be adaptable (for example, using a flexible PDMS-based coating on flexible PV, or a highly transparent silica coating on bifacial glass that doesn't impede backside light).

The good news is that research on self-cleaning and protective coatings is broad, and many of the material systems (ZnO, TiO₂, SiO₂, fluoropolymers) are quite universal and can be engineered to work with different module architectures.

We can say that the “best” solar panel generation for these coatings ultimately will be the one that achieves the **optimum balance of manufacturing feasibility and performance benefit** – currently, that appears to be the **standard silicon module**, but as perovskites and other new panels enter durable product forms, they may actually *need* such coatings even more critically to ensure longevity, which is why we are focusing on implementing it from the very beginning of them entering the mass production phase and the global market.

Recent Innovations and Case Studies

To illustrate the progress in this field, we highlight several recent lab-tested and real-world demonstrated solutions that combine ZnO with other materials for dust mitigation:

Dual-Layer AZO/TiO₂ Nano-Coating (Active + Passive): Hooshyar *et al.* (2024) reported a *two-layer* coating system designed for **both active electrostatic dust repulsion and passive anti-soiling**.^[1] The bottom layer is a transparent conductive film of aluminum-doped zinc oxide (AZO) deposited via a sol-gel dip-coating method.^[1]

This AZO layer can be electrically energized to actively repel dust (taking advantage of the fact that dust particles often carry slight charges). On top of AZO, a rough silica matrix infused with TiO₂ nanoparticles was applied (also by sol-gel) as a superhydrophilic/photocatalytic layer.^[1] The TiO₂ provides passive self-cleaning by promoting water spread and photocatalytic breakdown of dirt, while the textured silica improves light transmission (antireflection) and reduces the contact area for dust.

Tests of this **AZO+TiO₂ coating** showed improved glass transparency and reduced dust adhesion even under calm (no-wind) conditions.^[1] Notably, the precise concentration of Al in ZnO and the annealing temperature were found to influence optical transmission, highlighting the need to optimize the conductive layer so it remains as transparent as possible.^[1]

The dual-layer coated glass exhibited strong resistance to both acidic and alkaline exposure, indicating good chemical durability.^[1] This innovation demonstrates how pairing ZnO (for conductivity) with photocatalytic oxides can yield a multi-functional coating. It is a promising approach for large solar farms – the materials (zinc, aluminum, titania, silica) are inexpensive, and the dip-coating process is scalable and cost-effective.^[1]

While originally tested on small glass coupons, the concept could be extended to full panels, providing a self-cleaning, antireflective cover that also allows an on-demand electric dust cleaning when powered.

Hydrophilic Silica Nanocoating Field Trial: A practical field evaluation of a nano-coating was conducted by Ahmed et al. (2024) in a desert climate (Port Said, Egypt).^{3} The coating used in this study was primarily **silicon dioxide (SiO₂)** based, formulated as a hydrophilic self-cleaning layer (originally developed for automotive windshields).^{3} The nano-coating was sprayed onto a polycrystalline silicon panel and left outdoors for six weeks, while a control panel remained uncoated.^{1}

SEM analysis showed the coating consisted of uniform nanoscale spherical particles that prevented dust from sticking tightly.^{3} The results were striking: the coated panel consistently generated higher current and power than the uncoated panel. The average short-circuit current of the coated panel was ~2.8 A, about **64.7% higher** than the uncoated panel's ~1.7 A.^{39}

In terms of power output, the coated panel delivered ~24.7 W on average (with peaks up to 38 W at noon), whereas the uncoated panel averaged only ~14 W.^{40} This is roughly a 75% improvement in daily energy yield due to the coating. Such a gain underscores how severe the soiling loss was on the uncoated panel and how effective the nano-coating was at mitigating it. The authors noted that dust on the uncoated panel formed a cemented layer under morning dew, but on the coated panel, dust did not adhere well and was more easily removed by light wind or occasional wiping.^{3}-^{7}

This case study provides **real-world evidence** that nano-engineered coatings can meaningfully boost solar performance in harsh climates. It also suggests that a primarily SiO₂-based hydrophilic coating (which is transparent and UV stable) can survive outdoors and continue to function over weeks to months. While long-term durability (years) remains to be proven, commercial anti soiling coatings are beginning to appear on the market, and such studies guide their development.

NASA Electrodynamic Dust Shield (EDS): For the ultimate dusty environment – the Moon and Mars – NASA has been actively developing electrodynamic dust shields. This technology was recently tested on the **Blue Ghost lunar lander (2023–2024)** and showed promising results.^{21}

The EDS consists of transparent electrodes (such as fine interdigitated lines of ITO or AZO) on a surface, driven by phased high-voltage AC waveforms. The oscillating electric fields impart charges to dust and create a traveling wave

that transports the particles off the surface. In NASA's lunar test, the EDS coating did not *completely* remove all dust, but before-and-after images confirmed it cleared a substantial portion of dust that had accumulated on a glass window and a thermal radiator.^{18}

NASA deemed it a successful demonstration of dust mitigation in the lunar environment.^{5} The space-tested EDS used little power and had no moving parts – an advantage for reliability. For solar panels on Mars, which can be quickly incapacitated by global dust storms (Unfortunately as happened to the Opportunity rover), an EDS layer could be life-saving. It's noteworthy that NASA's EDS research originally dates back to the 1960s – 70s but only now are materials like transparent conductors and power electronics advanced enough to implement it without obscuring too much sunlight.

A ZnO based EDS on a solar panel cover glass could operate similarly: a transparent AZO grid would periodically create electrostatic waves to **“leap” dust off** the panel's surface. The technology is inherently scalable (it can cover large areas by tiling electrode sections) and can be activated as needed (for example, a few minutes each day or during a storm). The successful lunar experiment indicates that these coatings can survive space conditions and still function.

On Earth, some prototype EDS installations are being tested in desert environments as well,^{23} though cost is a consideration. In the long run, as the cost of solar downtime due to soiling is appreciated, even terrestrial solar farms might consider active EDS coatings, particularly if the conductive layer (e.g. ZnO) also doubles as an anti-reflective or protective coating, thereby serving multiple purposes to justify its cost.

These examples collectively show that *combining materials* like ZnO, SiO₂, TiO₂, conductive polymers, and smart polymers can yield **multifunctional coatings with real performance benefits**. We see lab designs achieving > 150° water contact angles and self-cleaning under both wet and dry mechanisms, and field tests confirming substantial energy gains and dust removal efficiencies > 90%.

Importantly, many of the materials used (metal oxides, silica, standard polymers) are scalable and relatively affordable. The remaining challenges mostly involve **long-term durability** (ensuring the coating keeps working for decades under UV/ sand abrasion) and maintaining performance (the coating should not significantly reduce initial panel output or encapsulation quality).

Some hydrophobic coatings have struggled with UV stability, but the trend is toward more inorganic and UV-resistant formulations.^{13} By incorporating self healing, as discussed, researchers aim to extend coating lifetimes even further.

Conclusion and Outlook

The pursuit of dust-resistant and self-cleaning solar panel coatings is driven by the need to improve solar energy reliability in challenging environments – from desert solar farms to future off-world installations. Zinc oxide-based composite coatings have emerged at the forefront of this effort, thanks to ZnO's unique combination of transparency, conductivity, catalytic activity, and compatibility with nanostructuring.

By blending ZnO with superhydrophobic textures, superhydrophilic catalysts, conductive films, and smart polymers, scientists are creating synergistic coatings that tackle the dust problem from multiple angles.

These advanced coatings can *passively* reduce dust accumulation (low surface adhesion, rain/dew cleaning) and *actively* remove dust (electrostatic repulsion or mechanical vibration), all while maintaining high optical clarity and even improving light capture through anti-reflection designs.^{{17} - {14}} Some coatings further offer self-healing and anti-scratch properties to ensure these benefits persist over a solar panel's service life.^{{22} - {23}}

For commercial and scientific adoption, scalability and robustness are key. The technologies reviewed show promise in this regard: dip-coating and spray techniques could coat large panels at low cost;^{{32} - {34}} durable hydrophobic composites have withstood abrasion tests and outdoor exposure without significant performance loss;^{8} and active cleaning methods like PVDF films or EDS require only minimal intermittent power, making them feasible add ons for remote sites.^{{21} - {16}}

High-performance solutions are likely to be **hybrid coatings** – for example, a base AR/hardcoat layer (silica or ZnO) for anti-reflection and scratch resistance, combined with an ultrathin superhydrophobic top layer or an embedded electrode network for dust removal.

Such layer-by-layer approaches ensure that adding new functionality (like dust mitigation) does not compromise the core requirements of a solar cover (transparency and weather sealing).

Moving forward, we can expect to see more field deployments of these coatings. Large solar farms in the Middle East and North Africa, where soiling is a serious issue, are natural testbeds.^{37} - ^{38} Lessons learned from those deployments will feed back into improved formulations - for instance, tweaking the surface energy to handle local dust composition or adding UV stabilizers if coatings start to degrade.

In parallel, space agencies will continue to refine coatings for lunar/Martian dust, which may lead to spin-off benefits for Earth applications (the harshness of space tends to accelerate innovation in reliability). The interdisciplinary nature of this field (materials science, surface physics, electrical engineering, and solar energy) means progress can sometimes be rapid when a breakthrough in one area (say, a new self-healing polymer) is cross-applied to solar panels.

In conclusion, ZnO-based dust-mitigating coatings represent a **cutting-edge solution** to a mundane but costly problem. By keeping solar panels cleaner, these coatings can significantly boost energy output and reduce maintenance needs, improving the economics of solar power in dusty regions. They also expand the viability of solar technology into new arenas – for instance, making solar panels on Mars or the lunar surface more practical by solving the dust accumulation issue.

The research surveyed here - from superhydrophobic nanostructures to electrodynamic screens - underscores a clear trend: future solar panels will likely come with “smart” surfaces that actively maintain their own cleanliness. Such advancements will be crucial for maximizing solar energy harvest in the sustainable energy systems of tomorrow.^{19}

The ongoing challenge is to refine these coatings into products that are cost effective and durable for decades, but the trajectory is optimistic. With continued R&D and collaboration between academia and industry, high performance self-cleaning solar panel coatings are poised to move from laboratories and pilot projects to widespread commercial adoption, shining a light (quite literally) on a cleaner and more resilient solar future. And that’s why we believe that, through all that have been written in the research paper, we could be among the first to break into that new frontier.

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