

Enhancement of Optical Efficiency of CSP Mirrors for Reducing O&M Cost via Near-Continuous Operation of Self-Cleaning Electrodynamic Screens (EDS)

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I. EXECUTIVE SUMMARY

Over the past decade, techno-economical advancements in solar energy systems, particularly the improvement in the conversion efficiency of PV modules made with mono-crystalline silicon solar cells from 12% to 20%, as well as the cost reduction in manufacturing by a factor of about 10%, have made it possible to achieve a levelized cost of electricity (LCOE) in PV plants that is comparable to, or less than, the cost of deriving electricity from fossil fuels. Operating PV plants in mid-latitude sun-belt regions, where the solar irradiance level is highest, provides a high annual energy-yield (kWh/kWp) due to two factors: (1) the availability of predictable high solar irradiance throughout the year with the fewest interruptions in solar flux from clouds and rain, and (2) the increased conversion efficiency of crystalline solar cells, as recombination loss has decreased with increased intensity of the sunlight that illuminates the silicon solar cells. Semi-arid and desert regions, however, are plagued by high atmospheric dust concentrations and frequent sand storms. The deposition of a layer of dust on the optical surfaces of solar collectors such as PV modules and concentrating mirrors reduces the

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transmission efficiency of sunlight that actually reaches the solar cells or receivers, resulting in high energy-yield soiling loss.

There are two major cost components to operating a solar plant: (1) installation costs, and (2) operation-and-maintenance (O&M) costs. There is no fuel cost; hence operating a solar plant in a semi-arid or desert region provides high returns on investment if soiling losses are mitigated via efficient cleaning methods and optimized cleaning frequency. If solar collectors are not cleaned, the accumulation of dust layers on solar collectors may cause the operation of such plants in arid regions to become economically unviable.

Washing solar collectors with water and detergent, as is most commonly done now, is an efficient method for cleaning. The conventional approach in utility-scale solar plants is to use a large truck with a water tank and pump system for spraying deionized water on the surface of the solar collectors. Robotic cleaning with brushes, used for many solar plants, requires lesser water for cleaning. The water consumed using semi-automated cleaning of PV modules in utility-scale solar plants is approximately 2 liters/m² per cleaning cycle. The total optical surface area of the solar collectors in 1 TW-scale solar installation will be more than 3×10^9 m²; hence an enormous amount of water be needed for cleaning. There simply is not enough fresh water in the sun-belt areas of the world for predicted cleaning needs.

In solar power plants, the estimated cost of cleaning solar collectors includes expenses related to the equipment used, labor, cost of transportation of water, the energy required for cleaning, plus ancillary costs whereas the cost of water is not considered. The water used is obtained from sources located close to plant sites, unmindful of the environmental and societal impact as the power plants are oftentimes located in regions that face severe drought. This practice is very similar to the cost calculations in deriving the levelized cost of electricity (LCOE) in conventional power plants based on burning fossil fuel such as coal and gas, while disregarding the cost of climate change and health effects. Unless a water-free or low-water cleaning method is established, the expansion of solar plants may lose public support in areas suffering long intervals of drought.

The goal of this research project has been the development and application of the Electrodynamic Screen (EDS) as a means for a water-free, scalable cleaning process applicable to solar-power installations, including rooftop applications. We describe here the development of an EDS film-based cleaning process as an emerging method for use on PV modules, parabolic troughs, and heliostats. This report aims to show the feasibility of integrating or retrofitting EDS films onto the optical surfaces of solar collectors (both PV and CSP) while maintaining high transmission or reflection efficiency.

The cleaning action provided by the EDS film is an active method to remove dust deposits by electrodynamic force. Current lab-scale prototype EDS films, retrofitted onto solar panels and

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mirrors, have shown to be capable of maintaining optical transmission or specular-reflection efficiencies higher than 90% of initial values under clean conditions. The optical surfaces of solar collectors laminated with EDS films can remove more than 90% of deposited dust when the EDS is activated for less than two minutes. As an electrodynamic dust removal process, the EDS film-based method is designed primarily for the removal of dust in solar installations located in semi-arid and desert areas, where the atmosphere is often dry and dusty and rainfall is infrequent.

While EDS film application minimizes water consumption and facilitates cleaning as frequently as needed, it has limitations in removing contaminants such as soot, organic pollutants deposited as fine films on the surface, and bird droppings. The dust removal efficiency of the EDS is maximum at relative humidity RH is 40 to 50% and decreases at when $RH > 65\%$. Many solar plant sites undergo diurnal and seasonal cycles of high ambient, early afternoon temperatures and an RH that reaches the dew point early in the morning. These variations in atmospheric conditions do not limit the operation of the EDS film.

This report presents a brief review of the progress and the potential of EDS film technology for mitigating the impact of dust on solar collectors via water-free cleaning, as well as current technical challenges regarding efficiency and durability. Our experimental data on the performance of EDS films show that: (1) the dust-removal efficiency (DRE) can reach levels higher than 90%, (2) the specular reflectivity (SR) of EDS film-laminated second-surface mirrors reach levels in excess of 90%, (3) the specular reflectivity restoration (SRR) can exceed 90%, (4) the output-power restoration (OPR) of PV modules can exceed 95%, and (5) the optical transmission efficiency (TE) of the EDS films can be greater than 90%.

Working with Sandia National Laboratories (NM), Corning Research and Development Corporation (NY), Eastman Kodak (NY), Tomark-Worthen Industries (NH), and EDS Chile SPA (Chile), we have produced EDS film-laminated PV modules and demonstrated their self-cleaning functions without requiring water. We have demonstrated that the operational range of EDS films will cover the expected ambient temperature of solar fields at RH cycling varying from 20 to 95% as long as the EDS films are activated in the RH range 20 to 50%. (Typical solar-field climates in deserts and semi-arid lands often reach near dew point in coastal areas.) Our experiments on the application of hydrophobic-fluorinated nanoparticle coatings on EDS film surfaces show that the EDS operational range can be extended to higher RH levels that approach the dew point.

At Eastman Kodak, as one of our industrial partners, we were able to establish a process for manufacturing EDS films using flexographic printing of the electrodes onto transparent polymer films. This process utilizes an existing manufacturing line at Eastman Kodak that allows fabrication of medium-scale EDS films (26 cm $\times$ 30 cm). The manufacturing process

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has the capacity to produce EDS films at high production speeds. The medium-scale EDS films that have been printed at Kodak were evaluated in the lab at Boston University.

The EDS films produced at Kodak were laminated at Tomark-Worthen using an industrial scale vacuum laminator to produce EDS film stacks, which can be affixed onto the optical surfaces of PV modules or concentrating mirrors. The EDS film stack consists of the EDS films that have Willow[®] Glass (WG) which has a thickness of 100 μm as the front surface. The WG sheets obtained from Corning Research and Development Corporation are customized in size and shape to cover the active area of the EDS films. The back surface of the EDS film stack is integrated onto the optical surface of the solar panel or mirror using optically clear adhesive (OCA) films or silicone adhesives. The OCA films (thickness 25 μm) are produced by 3M. The EDS film stacks have the architecture: WG/OCA/EDS Film/OCA/ over PV module or solar mirror.

The power-supply units needed for activating the electrodes of the EDS film were designed and produced at Boston University. These power supply units provide three-phase, 1.2 kV voltage pulses at a very low current (micro-ampere) level and at a low frequency (≈ 5 Hz). The voltage pulses are applied to the electrodes in a sequence such that the train of pulses resembles a unidirectional traveling wave of electrical field on the surface of the EDS film. The dust particles on the surface become charged electrostatically and are levitated by the Coulomb force. The lateral sweeping action of the traveling electric field created by the three-phase voltages pulses then sweeps the dust off the surface. The energy consumed by the EDS electrodes is less than 0.2 Wh/m²/cleaning cycle, enabling energy-efficient restoration of output power (OPR) of PV module or specular reflectivity restoration (SRR) for solar mirrors.

The EDS system consists of (1) an EDS film stack laminated onto the solar collectors, (2) connection of the EDS film to its power supply unit and (3) Interconnection of the power supply to PV modules or solar mirrors. Design, construction and assessment of field-testing units that have EDS stack laminated PV modules for evaluating the performance of the EDS films in solar fields is being carried out at BU.

Our progress under this project, aimed at the advancement of EDS film technology, has reached DOE Technology Readiness Level (TRL) 6. Based on the extensive laboratory evaluations and limited field trials, as well as contacts with potential users, we believe that the technology has reached its commercial stage. We are conducting a cost analysis using the National Renewable Energy Laboratory (NREL) System Advisory Model (SAM) and are preparing for field trials of EDS films in different solar fields in the US, Chile, India and in the Middle East. A brief description of EDS film performance, construction and testing of the field-test unit, autonomous operation of the field-test unit for evaluating EDS performance in increasing energy yield, associated revenue savings, and water conservation is presented

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II. Project Goals and Objectives

GOALS:

The project is aimed at advancement of EDS film technology to a commercial stage by: (1) Developing processes for manufacturing to produce lab-scale (12.5 cm × 12.5 cm) and medium-scale (30 cm × 30 cm) prototype transparent EDS films, (2) Establishing lamination process to produce EDS film stack with Corning Willow[®] Glass at the top and affixing the EDS film stack onto the optical surface of solar panels or solar mirrors, (3) Integration of EDS systems with power supply units, (4) Laboratory and field evaluations of the films

Following the establishment of the EDS film production, we will conduct long-term field evaluation studies to a) demonstrate advantages of EDS operation for water-free cleaning of solar collectors which would increase annual energy yield and decrease operational cost, b) assess durability of the EDS films, and c) confirm water conservation while using the EDS technology thereby supporting sustainable TW-scale growth of solar industries.

SPECIFIC OBJECTIVES:

Phase 1. Specific objectives: (1) Establish the feasibility of using Electrodynamic Screen (EDS) films for water-free cleaning of solar collectors in solar fields so as to improve the optical efficiency of solar mirrors and solar panels; (2) Demonstrate the durability of EDS films; (3) Investigate the economic viability of using EDS films in large-scale solar plants, (4) Conduct modeling studies and their validation via experimental data, and (5) Conduct laboratory evaluation to demonstrate EDS films meet the following requirements:

Required EDS film performance: (a) Dust removal efficiency (DRE) > 90%, (b) Transmission efficiency (TE) of the EDS film > 90%, (c) Specular reflectivity restoration (SRR) > 90% of the solar mirrors and (d) Output power restoration efficiency (OPR) of the PV modules > 90% and (d) Durability of the EDS films in solar fields.

Phase 2. Specific Objectives: (1) Develop a manufacturing process for producing lab-scale (12.5 cm × 12.5 cm) and medium-scale (30 cm × 30 cm) EDS films; (2) Develop a process for laminating EDS films onto the optical surfaces of the solar collectors; (3) Evaluate the performance of EDS films to show that the films can meet the required goals; (4) Produce medium-scale (30 cm × 30 cm) prototype transparent EDS films; (5) Evaluate medium-scale

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solar collectors laminated with the EDS films with respect to their self-cleaning capability, enhanced optical efficiency, and gain in energy yield leading to a lower O&M cost with substantially reduced water usage, and (6) Conduct collaborative research leading to manufacturing of the product by US -based industries.

Phase 3. Specific Objectives: (1) Produce EDS films in lab- and medium-scales employing a roll-to-roll manufacturing process for producing the EDS films, lamination of EDS films onto solar collectors, and integration of the EDS system (including the EDS power-supply unit); (2) Demonstrate that medium-scale prototype EDS films laminated onto solar collectors meet performance goals of the project, (3) Conduct field testing at the Sandia National Laboratories (SNL) Solar Thermal Test Field as well as in solar fields at the Atacama Desert, (4) Resolve technical problems to establish the durability of medium-scale prototype EDS systems, (5) Design and construct an autonomous field-test setup for the EDS systems in different solar fields, (6) Establish methods for analyzing soiling losses, economic benefits of using EDS systems for increasing power output and performance ratio (PR), water conservation and reducing O&M costs based on the field data taken from the Field-Test setup.

Advance EDS film technology to TRL 6.

Advancement of EDS film technology to a commercial stage: (1) Develop a Technology-to-Market (T2M) plan based on the manufacturing and integration of EDS systems by the U.S.-based industries (2) Establish a method for retrofitting EDS film onto the optical surfaces of solar collectors. (3) Perform a long-term field evaluation study at the Sandia National Labs, (5) Perform field-trials at different solar fields and quantify the experimental data based on the field trials for analyzing increased energy-yield, decrease in O&M costs, water conservation, and lowering of LCOE, thus advancing EDS technology to TRL 6.

Electrodynamic Screen (EDS) Film

Principles of operation:

Dust Removal Process: The Electrodynamic Screen (EDS) film [1-3] consists of a series of parallel transparent conducting electrodes embedded between two transparent dielectric layers, as shown in Fig. 1, which can then be retrofitted or integrated onto the optical surfaces of solar collectors, such as PV modules and concentrating solar power (CSP) mirrors. The film at the top with the sun-facing front side is made of transparent ultrathin flexible film, Corning Willow[®] Glass (WG), for example, which can serve as a superstrate for depositing transparent (or reflective) conducting electrodes. The top dielectric layer is adhered to the electrodes by using a transparent pressure- sensitive optically clear adhesive (OCA) film.

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The backside of the OCA film has a release liner which when removed enables retrofitting the EDS film onto the front cover-glass plates of the solar panels or on the concentrating solar mirrors. Reflective conductive electrodes can be used for solar mirrors, while transparent conductive electrodes are currently used both for solar panels and mirrors.

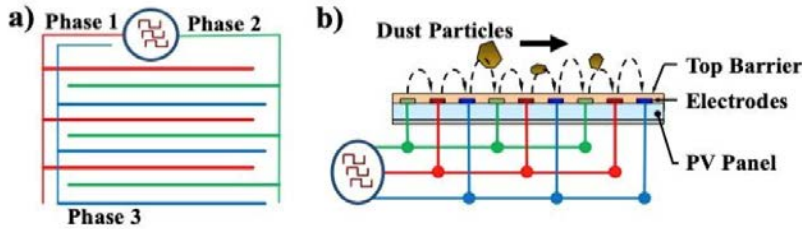


Fig.1 Schematic of an Electrodynamic Screen (EDS) film laminated on a PV panel and motion of dust particles by the traveling electric field (right) and three-phase connections to electrodes for activating the EDS film (left)

The embedded electrodes in an EDS are activated by three-phase voltage pulses (1.2 to 1.5 kV) at a very low current (micro-amp) level and at a low frequency (≈ 5 Hz), creating a laterally traveling electric field on the EDS film surface (Fig. 2).

120° Phased Square Waves (0 - 1.5 kV,
5 Hz, 50% duty cycle)

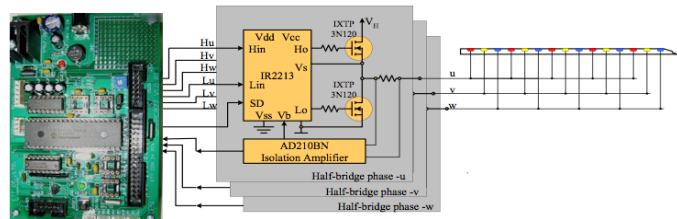
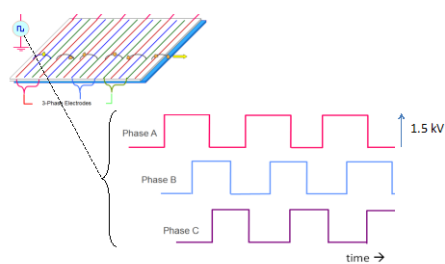


Fig. 2. Schematic diagram showing three-phase pulse voltage (1.2 to 1.5 kV) used for activating electrodes of an EDS film (left) and the pulsed high voltage (1.2 kV) power supply connected to the EDS film for activating electrodes (right)

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The traveling electric field caused by the applied pulsed voltage waveform charges and sweeps the dust particles from the module surface (Fig. 1) without requiring any water, moving parts, or consumable material. When the surface of the PV module is tilted, the gravitational force aids the removal of the dust particles levitated by the activated EDS film. Lab scale EDS films are produced at BU and evaluated for self-cleaning properties of dust samples collected from different deserts and semi-arid locations of the world. The lab evaluations are performed by first laminating EDS films onto the optical surface of solar mirrors and solar panels and evaluating their performance in an environmental chamber under temperature and RH ranges simulated according to the solar fields [4].

Figure 3 shows a transparent EDS film held over a medium-scale PV module (left) and a mirror laminated with an EDS film (right). Except for the electrodes, the light transmission efficiency of the glass film and the OCA films is higher than 98% when corrected for the reflection losses. The indices of refraction of the flexible glass and the OCA film match to that of the glass cover plates of the PV modules or second surface glass mirrors. The pressure-sensitive OCA films used for lamination of the EDS film meet solar field operation requirements with respect to temperature and RH cycling under solar UV radiation exposure.

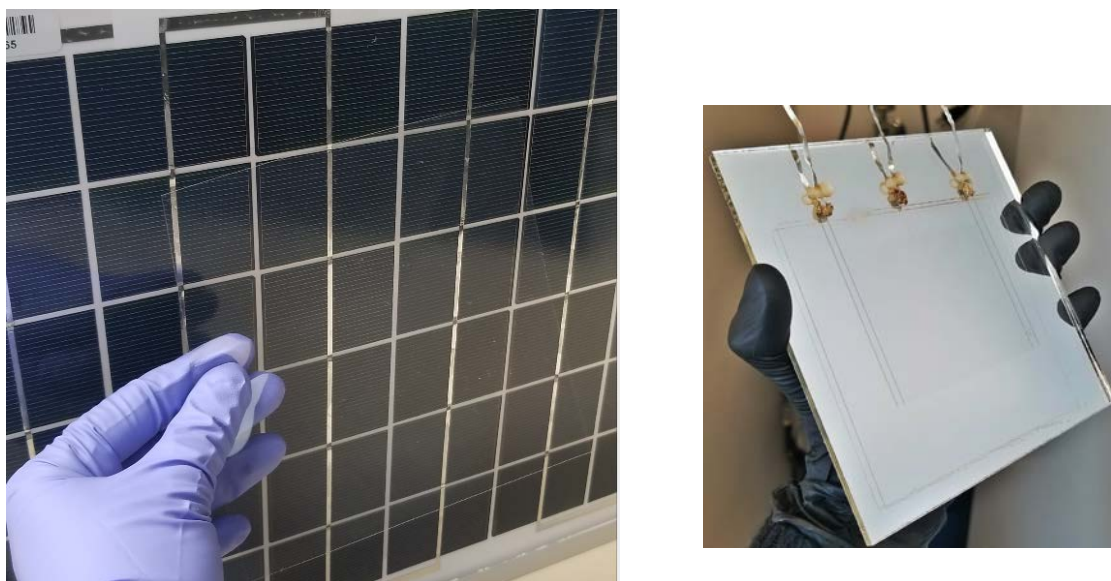


Fig. 3. A photo of a transparent EDS film held over a medium-scale PV module (left) and a mirror laminated with an EDS film (right)

Figure 4 provides an enlarged view of the EDS film, while Fig. 5 shows a field-evaluation site in a desert environment (Atacama Desert, Chile).

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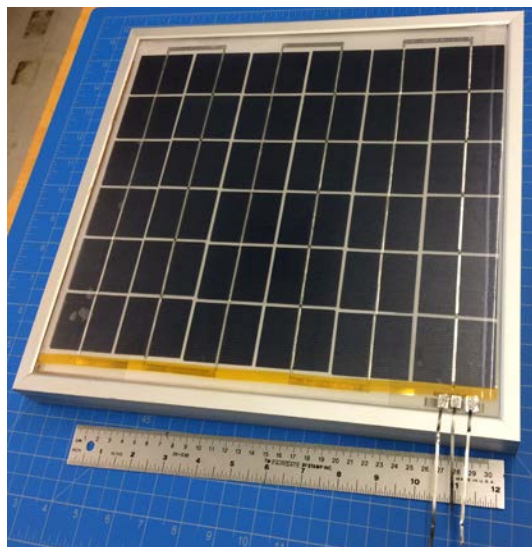


Fig 4: EDS film integrated with a solar panel



Fig 5: Lab-scale EDS film test setup in Chile

The dust particles on the surface become charged electrostatically, primarily by a combination of (a) tribocharging process in the presence of an electric field and (b) charge injections from the electrode edges to the EDS film surface [5]. Efficient electrostatic charging of the particles plays a critical role in EDS-based dust removal. Laboratory experiments were carried out by depositing commercially available standard JSC-1A test dust and dust samples collected from Negev and Dubai Desert areas to examine electrostatic charging characteristics under EDS operation. In all cases, the measured charge-to-mass ratio (Q/M) of the dust particles exiting the EDS surface after the electrode activation showed similar results. The dust particles removed by the EDS action and as measured by using a Faraday cup, show that the particles possess a predominant positive polarity, regardless of the source of the dust particles and is shown in Fig. 6.

Thus for removal of the dust layer without any water, each PV module or CSP mirror would be laminated by one or more transparent self-cleaning EDS films to cover the front surface of the solar collector and a compact power supply unit attached at the back of the solar collector for the activation of the EDS electrodes. Cleaning operation requires less than two minutes and can be activated from a control room without any interruption of the plant operation.

All dust samples were first baked in an oven at 200 °C for 2 h to remove organic materials. The samples were then sieved to remove dust particles with diameter larger than 98 μm . The dust samples tested were in the size of 1–98 μm in diameter. In air, saturation charge limit for an

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isolated particle is given by $26.4 \mu\text{C}/\text{m}^2$, which is independent of the dielectric constant of the particles. The measured values of Q/M of the dust samples were nearly identical, and were close to their saturation charge limit with positive polarity.

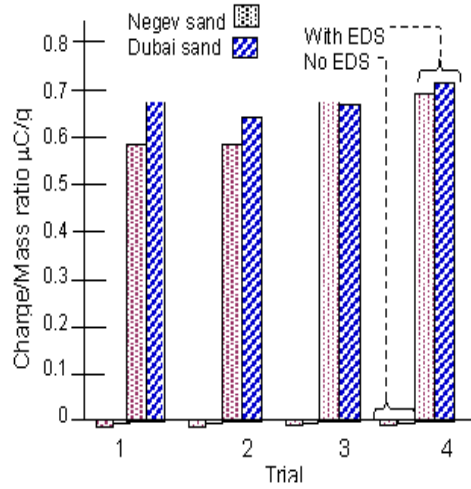


Fig. 6: Net average charge-to-mass ratio (Q/M) of the dust particle exited from an EDS film with urethane top dielectric layer with EDS electrodes activated by three-phase voltage pulses (1.5 kV).

The Coulomb repulsion force applied to a particle with a charge q is $q\mathbf{E}$, where $\mathbf{E}$ is the electric field experienced by the particle on the surface of the EDS film when the electrodes are activated. For an efficient cleaning, the Coulomb force F_C must exceed the sum of all forces of adhesion between the particles and the EDS film surface F_{adh} , including van der Waals F_{vdw} , capillary force F_{cap} , gravitational force F_g , and electrostatic image force F_i .

The capillary force of attraction is neglected in the analysis, since the EDS operation is performed under dry conditions at a low RH ($< 50\%$). For any charged particle on the surface at a low RH, the major force of adhesion is the electrostatic image force, which is proportional to q^2/t^2 , where q is the charge of the particles and t is the thickness of the ultrathin glass film at the top of the EDS film. The force of removal is the Coulomb force of repulsion $q\mathbf{E}$; thus, an electric field intensity E must be high enough to repel the particle. The field $\mathbf{E}$ has two components: one perpendicular to the EDS film surface and the other is parallel to the surface. Three-phase activation of the electrodes, as discussed before, creates a traveling electric field with both vertical and horizontal components, which helps removing the dust layer in a sweeping motion.

A. Research, Development and Evaluation of Lab-scale EDS film

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EDS Film design, printing and operation:

Major components of the EDS film are (1) transparent conducting electrodes applicable to both PV modules and CSP mirrors or reflecting conductive electrodes for CSP mirrors, (2) transparent dielectric substrates for printing the film, (3) transparent dielectric film at the top of the EDS film facing the sun, and (4) optically clear adhesive (OCA).

The critical aspects in the EDS film design are the electrode material and the process for printing the electrode. There is a trade off between achieving both high conductivity and high transmission efficiency of the electrodes. The electrode material must meet the requirement for optical and electrical properties for EDS films and be environmentally durable and electrically stable for pulse-voltage applications. It must be suitable for large-scale printing via flexography or screen-printing. Similarly the top surface of the EDS film must meet several requirements related to optical transparency, resistance to UV induced degradation and abrasion against dust impaction, and ability to sustain a high electric field at the surface and have a low dielectric loss.

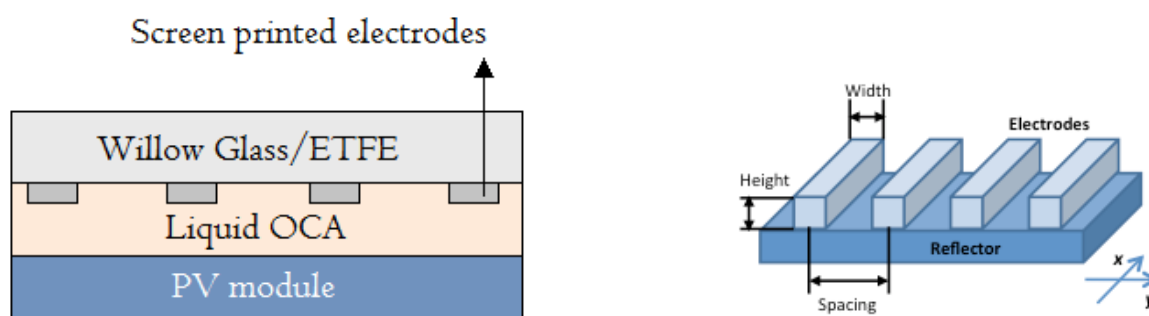


Fig 7: Layout and the geometry of the electrodes in an electrodynamic screen (EDS) film and their position with respect to PV module or solar mirrors.

The choice of materials used for the electrodes and the substrates depends upon (1) availability of the materials to meet scalability requirements of EDS film production, (2) compatibility of the materials to undergo lamination of the EDS films onto solar collectors, (3) environmental durability of the materials for EDS film function in solar fields under different climates.

EDS Electrode Printing: The printing method to be used for producing EDS films must meet the requirements of scalability in large volume production using additive methods for materials.

Additive printing methods such as screen-printing, flexographic printing and Gravure Offset Printing are based on adding ink on the substrate as needed for the electrodes. Transparent

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conductive inks that can be used for printing EDS electrodes are expensive, hence the additive printing method proves most practical

We have successfully used screen-printing and flexographic printing of electrodes for producing EDS films and laminated them ~~film~~ on lab and medium-scale solar panels. For PV module applications, the surface properties, particularly asperities, do not adversely affect output power restoration (OPR) since forward scattered light entering the solar cells are absorbed producing electron-hole pairs effectively.

In EDS electrode printing for the applications to CSP mirrors, photolithographic patterning (subtractive method) is a better choice since the surface properties of the deposited film, by sputtering for an example, can be controlled to minimize surface asperities enhancing specular reflection efficiency.

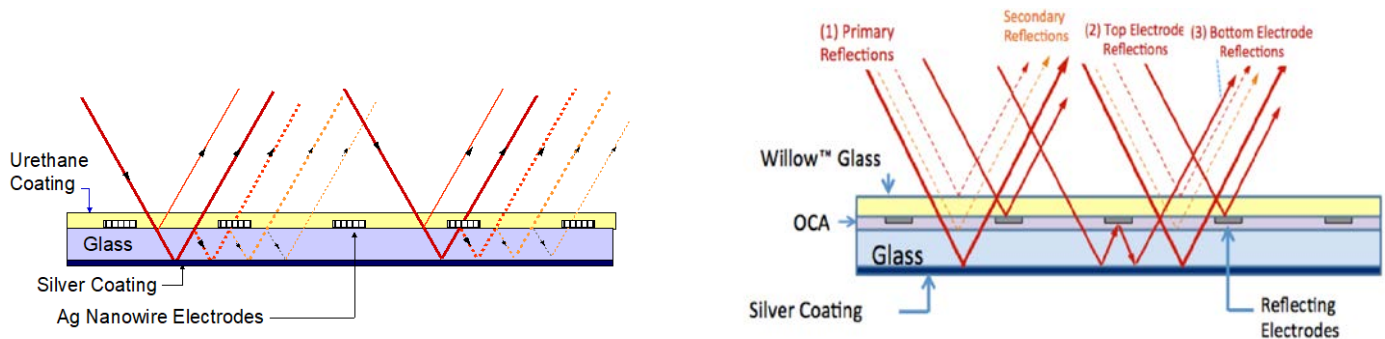


Fig. 8: Schematic of EDS film using transparent conducting AgNW electrodes (left) and conductive reflecting electrodes (right) for solar mirrors showing ray tracing for reflected beam. Figure number and reference?

EDS film architecture: The architecture of the EDS film includes Corning Willow® Glass (thickness 100 μm) as the front surface of the EDS film. The electrodes can be printed at the backside of the Willow® Glass as shown in figure 8. The physical and chemical properties of the EDS film play a major role in the self-cleaning action. Besides glass film, polymer materials such as Ethylene Tetrafluoroethylene (ETFE), Fluorinated Ethylene Propylene (FEP) films can also be used depending upon their transparency, dielectric properties, environmental durability and chemical and abrasion resistance. Similarly, there are choices for using optically clear adhesives (OCA) available for encapsulating the electrodes of the EDS with solar collectors. Examples are 3M 8146-1 OCA film and Quantum Silicone Qsil 216 products.

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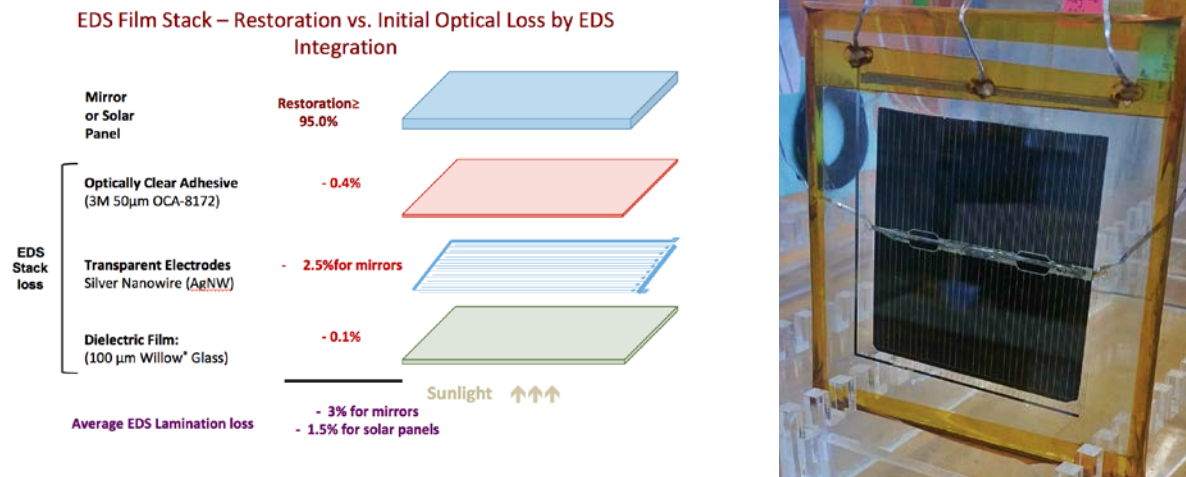
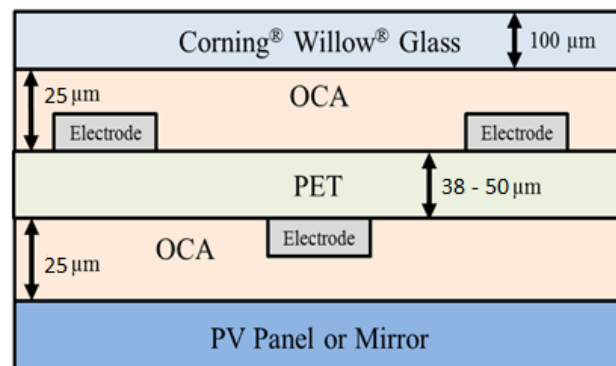
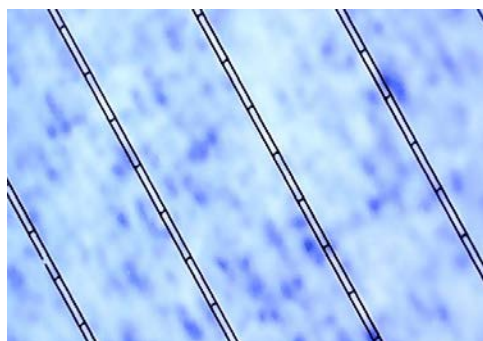


Fig. 9: EDS film stack (left), showing AgNW electrodes printed on Willow Glass laminated with OCA to a solar panel or a solar mirror with estimated transmission efficiency loss and a solar panel affixed with an EDS film stack (right).

EDS film electrode printing by flexography: One of our industrial partners of the project, Eastman Kodak developed a manufacturing process for producing the EDS film by printing ladder-structured, passivated Cu micro-wire electrodes on PET substrates using one of their existing roll-to-roll printing facilities. The electrodes are printed on both sides of the PET film for convenient inter-connections of the electrodes without requiring any crossover electrical connections. OCA films, either 3M 8146-1 OCA film or Quantum Silicone QSil 216 silicone encapsulant were used for lamination onto the solar collectors. Since many PV modules have textured surface of the top cover glass, liquid OCA like QSil silicone works best for laminating the module surface without trapping air bubbles.

Lab-scale EDS films produced at Kodak were laminated on solar panels and mirrors at the BU lab and were evaluated successfully by measuring output power restoration (OPR) and specular reflectivity restoration (SRR). Design and construction of the medium-scale field-test unit are based on the evaluation of the EDS films in lab-scale prototypes. The thickness of the EDS film stack is approximately 200 μm and it is transparent and flexible.



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Fig 10: EDS film printed on PET film with ladder structured electrodes (left) and schematic of the EDS film stack laminated on a PV module or solar mirror (right) for evaluating the performance of the EDS film for output power restoration (OPR) for solar panels or specular reflectivity restoration (SRR) for solar mirrors respectively.

EDS Electrode Geometry: Both physical properties and the geometry of the electrodes, as printed on the EDS film and as shown in Fig. 10 (right), with respect to their width (w), thickness or height (h), and the inter-electrode separation (s), play an important role in the performance of the EDS film. In general, there is a trade off between the dust removal efficiency (DRE) and the transmission efficiency of the EDS film for solar panel application or for the specular reflection (SR) efficiency for solar mirrors. Decreasing the inter-electrode separation ' s ' can increase the intensity of the electric field E , and the electric field intensity enhances dust removal efficiency (DRE). As ' s ' decreases, it reduces light transmission efficiency (TE) for solar panel application or the specular reflection (SR) efficiency for solar mirrors.

The width (w) and the height (h) of the electrodes are chosen based on the required sheet resistance of the electrodes for applying the electric field across the total area of the EDS film. Figure 8 shows electrode geometry of screen-printed transparent conducting electrodes and reflecting conductive electrodes with ray tracing. Table 1 shows model calculation of the specular reflection efficiency of an EDS film as functions of the geometrical and optical properties of the electrodes. The model calculations show that if the electrodes are reflecting on both front and backsides and if for a given width, if the separation is increased, we would get highest specular reflectivity.

Table 1. Fred optical model calculation of the specular reflection (SR) efficiency of an EDS film printed with silver electrodes as functions of the geometrical and optical properties of the electrodes.

Reflectance Loss from FRED Optical Modeling	Width = 42.5 μ m; Thickness = 3.5 μ m Electrode spacing (μ m)			Thickness = 3.5 μ m; Spacing = 500 μ m Electrode Width (μ m)			
	400	500	600	50	60	70	80
Reflecting Ag (according to Fresnel reflections)	0.982	0.985	0.986	0.981	0.980	0.979	0.978
Absorbing Ag w/ reflecting top surface (Fresnel)	0.881	0.905	0.920	0.885	0.881		
100% absorbing Ag	0.782	0.827	0.854	0.792			

Based on our theoretical modeling and experimental investigations on the optical and dust removal properties of the EDS films, we found that EDS electrode geometry with width $w = 80 \mu\text{m}$, inter-electrode separation distance $s = 700 \mu\text{m}$ and electrode height $h \approx 2 \mu\text{m}$ (depending

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upon their electrical conductivity) is an optimum choice. Since the electric field intensity calculated at the midpoint on the EDS film surface, when activated, varies with the magnitude of applied voltage pulses, thickness of the film at the top needs to be $\leq 200 \mu\text{m}$.

EDS Electrode Printing Methods

1. Screen-printing

Production of EDS films in lab-scale was carried out by screen-printing of electrodes with the following materials: (1) silver nanoparticles (Henkel) similar to silver paste in formulation used for metallization of solar cells, (2) silver nanowire (AgNW) inks obtained from Henkel and Novarials, and (3) Carbon nanotubes, obtained from Chasm. For CSP mirror application, we added silver flakes to the ink or silver-plated the electrodes to improve reflectivity. In addition, we synthesized screen printable ‘hybrid’ ink composed of silver nanowire (AgNW) and zinc oxide (ZnO) in our lab to serve as transparent conductive electrodes (TCE) with improved environmental durability of the EDS film [6,7]. ZnO is produced in the lab by combining 3 parts tetrahydrofuran (THF) and one part diethylzinc (DEZ) which is then mixed with the silver nanowire ink procured from Novarials to form the hybrid screen-printable ink.

2. Photolithographic patterning of electrodes

EDS films produced by photolithographic patterning of electrodes were evaluated using transparent silver nanowire (AgNW) ink coated as an uniform thin layer on transparent PET film (obtained from Cambrios) and aluminum doped zinc oxide (AZO) sputtered coated on glass substrates (MSE Suppliers). These films are highly transparent ($TE > 90\%$) with thickness less than $1\mu\text{m}$ and low sheet resistance ($R_s < 200 \Omega/\square$). Since AgNW is not environmentally durable, a topcoat, available commercially for improving UV radiation resistance, was applied after patterning of the electrodes.

3. Flexographic printing of electrodes

A manufacturing process for producing EDS film, involving the application of ladder-structured Cu micro-wire electrodes printed on polyethylene terephthalate (PET) film via flexographic printing process using an existing roll-to-roll printing facility at Eastman Kodak. The micro-wire electrodes could be printed in a roll-to-roll process on terephthalate PET films via a combination of flexographic printing and electro-less copper plating with passivation.

Metrics For Evaluating EDS Films

Metrics used for determining the efficacy of dust removal action by the EDS film activation:

A. Dust Removal Efficiency (DRE)

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Dust removal efficiency (DRE) = (Surface mass density of dust layer after the EDS film activation) / (Surface mass density of dust layer before the EDS film activation)

DRE is a function of the particle size distribution of the dust layer, relative humidity (RH), resident time of the dust layer going through RH and temperature cycling, and the surface properties of the EDS film and the particles.

B. Solar Mirrors

Specular Reflection Efficiency

SR or SRE = (Specular reflection of the EDS film laminated mirror) / (Specular reflection of the before EDS film lamination)

The measurement of the specular reflection before EDS film lamination is measured under clean conditions.

Specular Reflection Restoration

SRR = (Specular reflection efficiency restored by the EDS film activation for removing the deposited dust layer) / (Specular reflection of the EDS film laminated mirror with deposited dust layer before EDS operation)

C. PV Modules

Transmission Efficiency (TE)

TE = (Short circuit current I_{sc} of the solar panel with EDS film lamination) / (Short circuit current I_{sc} of the solar panel under clean condition and without the EDS lamination)

Measurements in both cases are performed under illumination at irradiance level > 500 Watts/m²

Dust Removal Efficiency (DRE)

DRE = (Initial surface mass density – surface mass density remaining after dust removal after EDS activation) / (Initial surface mass density)

Note: Surface mass density is typically measured in grams per unit area (g/m²).

Optical Power Restoration (OPR)

OPR = (Short circuit current I_{sc} of the solar panel with EDS film lamination and after EDS activation for removing the deposited dust layer) / (Short circuit current I_{sc} of the solar panel with EDS film lamination before EDS activation)

Additional metrics for evaluating EDS applications are given in the appendix.

Number of EDS films produced in the lab-scale by screen-printing and by photolithography.

Total number of Samples produced > 200

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Screen-printed samples > 150

Photo-lithographically produced samples > 50

Electrode geometry: $w = 80 \mu\text{m}$; inter-electrode separation $s = 700 \mu\text{m}$; front dielectric film used was Corning Willow[®] Glass (thickness $100 \mu\text{m}$).

Tilt angle = 30°

Test dust used were primarily dust samples collected from ground of Solar Thermal Test Facility, Sandia National Lab, Albuquerque, NM. Particle size range used after sieving was 1 to $98 \mu\text{m}$ (referred as SNL dust)

EXPERIMENTAL SETUP:

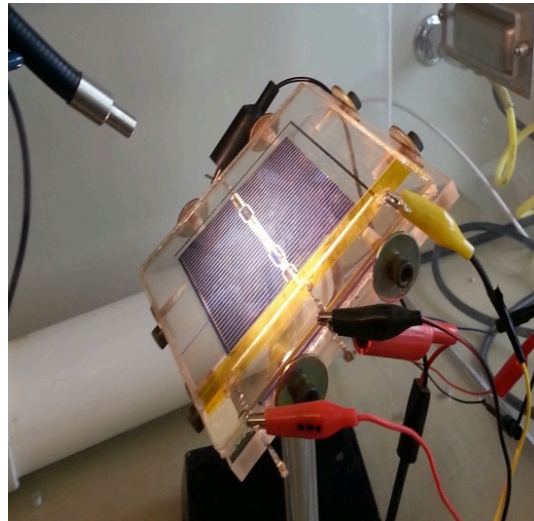
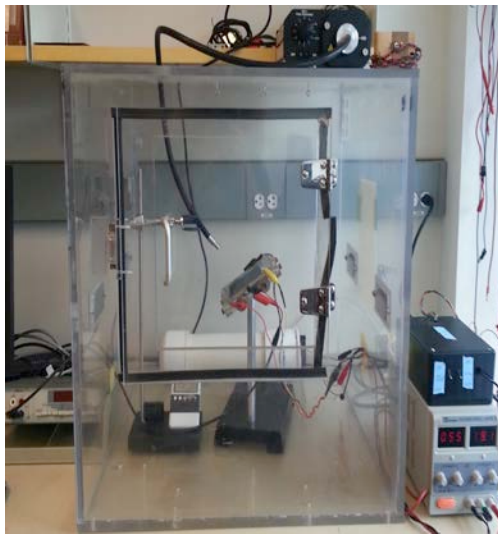
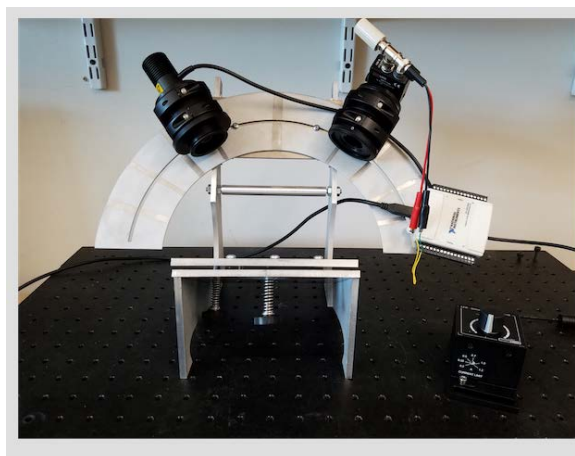


Fig11: Experimental setup for measuring optical Transmission Efficiency (TE), Dust Removal Efficiency (DRE), and Output Power Restoration (OPR).



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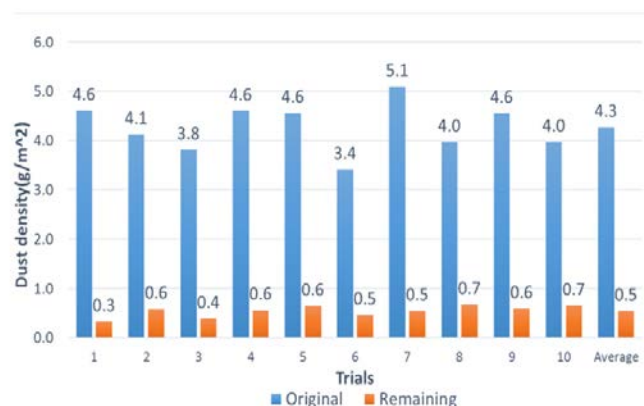
Fig 12: A photograph of a non-contact specular reflectometer constructed in the lab for measuring SR and SRR for EDS laminated mirrors

Lab-Scale EDS Film Evaluation

Figure 12 shows an experimental setup for non-contact measurements of Specular Reflectivity (SR) and Specular Reflectivity Restoration (SRR) of solar mirrors with EDS film lamination. Laboratory-scale (12.5 cm X 12.5 cm) EDS films were produced successfully by printing electrodes using (a) screen-printing, (b) photolithography at Boston University lab and (c) flexographic printing at Eastman Kodak. These films were evaluated for their optical transmission efficiency (TE) and for their self-cleaning properties using dust samples collected from different deserts and semi-arid regions of the world. We carried out lab evaluation by laminating EDS films onto the optical surfaces of solar mirrors and solar panels, then tested their performance inside an environmental chamber simulating ambient temperature and humidity (RH) conditions of solar fields.

We report here the results of our evaluation of EDS films with screen-printed and photolithographically patterned electrodes of different materials. The manufacturing process for EDS films including the lamination process and their experimental evaluations are described later in this report. Details of the experimental studies are not presented here. Measurements were performed using an environmental chamber and at temperature ranging from 20° C to 80° C and RH cycling from 20% to 85%. Only a few experiments were performed to examine the effect of wind at an average speed 1 m/s on the dust removal properties of EDS film. Typically, wind speed varies normally from 1 to 5 m/s.

EXPERIMENTAL DATA



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Fig 13: Measurement of initial surface density on the EDS film and corresponding surface mass density remaining on the film after EDS activation.

From the measured surface mass densities in each experiment, DRE was calculated by the ratio,

$DRE = (\text{Initial surface mass density } (m_o) - \text{surface mass density remaining after dust removal after EDS activation } m_f) / (\text{Initial surface mass density } m_o)$

$$DRE = (m_o - m_f) / m_o$$

Variation of measured values of DRE is often due to the experimental errors in gravimetric measurement of surface mass density.

DRE varies with the particle size distribution of dust sample used and the wavelength of light. For commercially available Arizona road dust AZ dust sample, the obscuration of light as a function surface mass density is shown in figure 14.

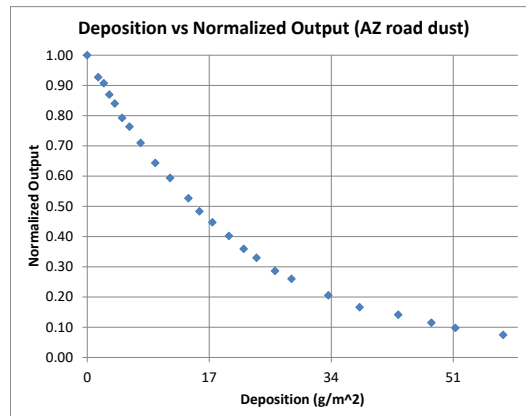
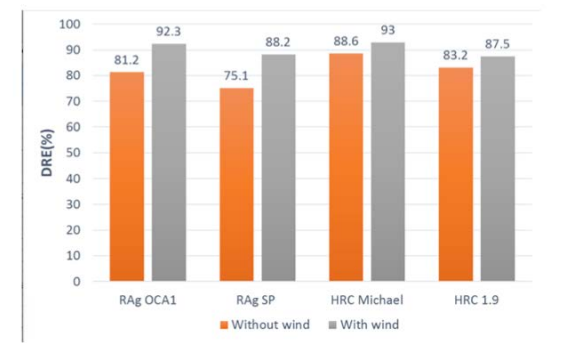


Fig 14: Attenuation of light ($\lambda = 650 \text{ nm}$) as a function of surface mass density of deposited dust layer on a glass plate.



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Fig. 15: Effect of wind at a velocity 1 m/s during the EDS film based dust removal process shows significance increase in DRE. The EDS films electrodes were screen-printed.

EDS films with AZO electrodes:

Table 2 shows the experimental data obtained for an EDS film with AZO electrodes patterned from sputter-coated film by photolithographic etching.

Table 2. Experimental data on SR, SRR and OPR on the performance of the AZO electrode based EDS film

Panel	SR %	SRR %	OPR %
AZO 2	96.6	92.2	97.7
AZO 3	98.5	93.2	97.1
AZO 4	98.4	94.5	98.3
AZO 5	98.8	89.3	96.7
AZO 6	99.5	93.6	96.1

The results shown in Table 2 shows AZO electrodes printed via a photolithographic process, which meets the requirements of the project for both PV modules and CSP mirrors with respect to SR, SRR, and OPR. However, the process is not easily scalable and may not be a economically viable.

EDS films with CNT electrodes:

Similar results were obtained by using screen-printed carbon nanotubes (CNT) electrodes. In this case, electrodes can be deposited in a scalable process and CNT electrodes would be less expensive compared to the AgNW electrodes. However, the durability of the electrodes was poor and needs further investigation.

Table 3. Experimental data on SR, SRR, OPR and TE obtained for EDS films with CNT electrodes printed by screen-printing process.

SR%	SRR%	OPR%	TE%
96.23	89.79	95.51	97.19
95.54	90.07	95.42	97.2

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96.05	90.11	95.83	97.47
96.26	89.92	95.56	97.22
95.87	89.84	96.03	97.34

The CNT electrodes showed a good potential in meeting the requirements of the EDS based dust removal process and restoration of SR and the output power of the CSP mirror and PV module respectively. Upon continuous testing, it was found that the electrodes were not stable and showed several discontinuities of the electrodes within a relatively short period. Further research on the stability of the electrodes and to improve adhesion of the screen-printed electrodes on the transparent substrates is needed.

EDS films with AgNW electrodes screen-printed and patterned by photolithography:

The most promising results were obtained by producing EDS films using AgNW electrodes by screen-printing and by patterning via photolithography. Our experiments showed AgNW electrodes have excellent electrical conductivity and optical transmission efficiency. The screen-printing process is scalable and the experimental data on the SR, SRR, and OPR values measurements obtained were very promising.

Table 4. Experimental data obtained from Silver Nanowire (AgNW) ink-based EDS Films produced via Screen-Printing

EDS Film Number	SR%	SRR%	OPR%
Nova 1.2	96.0	89.26	94.7
Nova 1.3	97.2	90.33	96.5
Nova 1.4	92.8	90.87	96.6
Nova 1.5	94.8	89.4	95.8
Nova 2.1	84.1	92.01	96.5
Nova 2.2	85.3	91.6	96.1

Table 5. Experimental data obtained from patterned electrodes produced via Photolithography using silver nanowire (AgNW) ink coated on PET film. A topcoat was used on the electrodes for improving UV resistance.

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EDS Film Number	SR%	SRR%	OPR%
AgNW 1.17	74.5	70.8	91.9
AgNW 1.19	77.5	76.38	93.9
AgNW 1.20	76.9	78.34	94.8
AgNW 1.27	85.0	86.1	95
AgNW 1.28	86.5	89.3	94.2
AgNW 1.29	86.5	88.3	95.9

The AgNW ink (Novaral) available for screen-printing is not environmentally durable. The PET film coated with a thin layer of AgNW commercially produced by Cambrios has stability outdoors when a topcoat is applied for improving resistance to degradation caused by UV radiation. However, its long-term durability has not been reported yet. Also, the PET film is subject to yellowing by solar radiation and photolithographic patterning of the electrodes is not scalable.

Development of Durable Hybrid Silver-nanowire Electrodes for improving transparency and durability of EDS film (lab-scale):

A screen printable ‘hybrid’ ink composed of silver nanowire (AgNW) and zinc oxide (ZnO) was developed in the lab to serve as transparent conductive electrodes (TCE) of the EDS film [6,7]. ZnO is produced in the lab by combining 3 parts tetrahydrofuran (THF) and one part diethylzinc (DEZ) which is then mixed with the silver nanowire ink procured from Novarials to form the hybrid screen printable ink. Accelerated weathering tests was conducted to establish environmental durability of the hybrid electrodes and to examine if sheet resistance (R_s) remains within the desired range of conductance needed for EDS operation.

The EDS films were produced in lab-scales with hybrid electrodes screen-printed on borosilicate glass substrates and laminated with Willow[®]Glass as the top surface dielectric layer using OCA 8146 as an adhesive. The EDS films were then subjected to accelerated UV radiation resistance tests, and RH and temperature cycling steps according to ASTM G154 standards [8]. The results showed that newly synthesized hybrid electrodes have the required environment durability needed to serve as EDS electrode material for outdoor applications. When we compared the performance of the EDS films with the hybrid (AgNW-ZnO) electrodes with the EDS films with AgNW electrodes, we found significant advantages of hybrid electrodes with respect to environmental durability and electrical stability.

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Our literature search and extensive experimental studies showed that we would be able to use the hybrid electrodes in meeting the needs of optical, mechanical and outdoor stability requirements for medium and large scale EDS film production. Commercially available LOCTITE 1010 E&C silver ink (Henkel) that uses silver nanoparticles with composition similar to that of silver paste also meet EDS film production requirements except for optical transparency. In the present studies, we refer to these electrodes as RAg – Reflective Silver electrodes since the ink is diffusively reflective. The hybrid electrodes based on silver nanowires and stabilized by ZnO has high optical diffusive transparency (forward scattering). Thus it would be possible to use RAg electrodes for EDS films for solar mirror applications and the hybrid electrodes for EDS films primarily for PV module applications.

Our studies showed that the silver nanowires exhibit electrical instability while being subjected to pulsed voltage operation and can become nonfunctional when a) exposed to temperatures above 80°C due to Joule heating b) exposed to high RH reaching the dew point (water immersion test) and c) UV exposure [8]. We also measured significant increase in the sheet resistance as local nanowire junctions fuse together [7]. In order to assess the protective function of the ZnO upon addition to the nanowires, we performed a) accelerated UV Exposure b) application of HV (1.2 kV) pulsed voltage c) annealing and d) complete water immersion. The hybrid samples showed substantially improved functionality upon completion of the test period whereas the plain AgNW showed rapid degradation. Results are shown in the Table 6.

Table 6: Results of Weathering Tests done on Plain AgNW and Hybrid Samples

Test Performed	Sample Tested	R_s Before Annealing	R_s After Annealing
Annealing	Plain AgNW	18.7 Ω . sq-1	1027 Ω . sq-1
	AgNW_ZnO Hybrid	1.4 Ω . sq-1	0.7 Ω . sq-1
Pulsed Voltage	Plain AgNW	18 Ω . sq-1	77.6 Ω . sq-1
	AgNW_ZnO Hybrid	1.2 Ω . sq-1	1.1 Ω . sq-1
UV Exposure	Plain AgNW	18.33 Ω . sq-1	1301.2 Ω . sq-1
	AgNW_ZnO Hybrid	1.1 Ω . sq-1	5.5 Ω . sq-1
Water Immersion	Plain AgNW	18.19 Ω . sq-1	72.76 Ω . sq-1
	AgNW_ZnO Hybrid	1.2 Ω . sq-1	1 Ω . sq-1

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We performed comparative analysis between hybrid AgNW-ZnO and silver microsphere RAg (Henkel LOCTITE 1010 E&C Ink) electrodes for their atmospheric durability and electrical stability for a long-term operation under pulsed HV operation. Both the electrodes worked well.

Optimization of the synthesis process for producing AgNW-ZnO hybrid ink will still require additional studies and analysis on the production of the EDS films and their applications outdoors.

Table 7 shows results of accelerated UV radiation exposure tests with hybrid AgNW-ZnO electrodes and the Table 8 shows the effect of RH cycling within a range of RH as specified by the ASTM standards.

Table 7. Results of OPR% with AgNW-ZnO Hybrid Ink Electrodes before and after the Accelerated ASTM G154 test performed using UVA-340 ultraviolet radiation

OPR% Before ASTM G154 test with UVA-340 Exposure	OPR% After ASTM G154 test with UVA-340 Exposure
95.28	89.36
96.02	90.04
95.8	88.65
95.74	88.2
96.13	87.36
Average OPR% =95.79	Average OPR% = 89.06

Table 8: Results of OPR% measurements with EDS films with AgNW-ZnO hybrid ink electrodes before and after the accelerated ASTM G154 Humidity Range Variation test performed using the environmental chamber.

OPR% Before ASTM G154 Humidity Range Variation test	OPR% After ASTM G154 Humidity Range Variation test
95.45	90.65

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95.22	91.21
96.31	91.7
95.22	91.8
95.08	90.05
Average OPR% = 95.46	Average OPR% = 91.08

Production Of Lab-Scale EDS Films By Flexographic Printing

EDS Film Production: A roll-to-roll production process for EDS films has been established using flexographic printing of the electrodes onto transparent polymer films. This process utilizes an existing manufacturing line at Eastman Kodak. Kodak fabricated double-sided EDS films which have advantages in both EDS film manufacturing process and integration into EDS systems via convenient electrical connection. Medium-scale EDS films (26 cm × 30 cm) produced by printing two-sided ladder-structured micro-wire electrodes onto transparent polyethylene terephthalate (PET) films at Kodak and have been successfully laminated and evaluated in the laboratory.

The Kodak manufacturing line has a size limitation of 33 cm × 55 cm, but commercially viable form factors could readily be manufactured in the current processing line to create larger films suitable for integration onto PV panels, CSP heliostats, or parabolic mirrors.

Summary of EDS film samples Produced

Total number of Samples produced > 400

Screen printed > 150 (both silver ink and silver nanowire and hybrid AgNW-ZnO inks)

Photolithography samples > 200

Kodak EDS Samples > 30 medium-scale

Kodak EDS Samples > 200 lab-scale

Notes: Only fully functional samples were counted.

Assembly of the EDS film stack with the power supply unit, Integration and

Interconnection:

Assembly of the EDS film-stack with EDS films received from Kodak was realized by affixing two 3M Optically-Conductive Adhesive (OCA) layers, one on the top surface of the EDS film laminated with Corning™ Willow® Glass serving as the front cover glass film, and the back side of the EDS film onto the optical surface of the medium-scale PV module. The EDS film

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stacks laminated into PV modules were then connected to EDS power supply units. The two-sided printing of the EDS electrodes eliminated entirely the need for a crossover connection previously required for three-phase connections to the power supply. This new feature eliminates a complexity of the assembly process.

The new design of two-sided printing was modeled at BU to examine if there is any significant decrease of the electrical field intensity at the top surface of the EDS films. Modeling studies showed that the decrease in the field intensity by moving one electrode phase to the backside of the PET film (38 to 50 μm) has minimal impact on EDS cleaning performance. The two-sided printing of the electrodes makes the assembly process more robust. Experimental evaluation of the two-sided electrode configuration validated the model calculations.

Industrial-scale Production of EDS Film Stack:

We established a process to produce EDS film-stacks by laminating EDS films obtained from Kodak and laminating the film using an industrial-scale vacuum laminator in collaboration with Tomark-Worthen Industries (Nashua, NH). One of the goals of the project is to have the manufacturing of the EDS film, including production of the EDS film stack, be performed in collaboration with US-based industries. Working with Tomark-Worthen has provided access to full-scale solar lamination equipment used in solar industries; therefore the lamination process developed can be utilized for full-scale EDS film-stack leveraging our partnership with Kodak, Corning and Tomark_Worthen Industries. We optimized the lamination process and identified the encapsulating materials including the optically clear adhesives (OCA) needed to produce EDS film-stacks. We optimized the process conditions for the adjustment of pressure on the films, the temperature and the curing time period for laminating Willow Glass, EDS film and release liner under vacuum. The optimization of these variables is critically important to minimizing air bubble entrapment, haze, and improved optical transmittance.

Lab-Evaluation of medium-scale EDS films:

EDS film stacks produced at Tomark-Worthen were evaluated for their performance at Boston University. The film stacks were laminated onto PV modules and solar mirrors. The results show that the EDS film-laminated PV modules meet the OPR and TE requirements, but not for the solar mirrors with respect to the targeted SR and SRR values. Increasing the inter-electrode spacing to meet the milestone requirement $\text{SR} > 90\%$ was possible it led to films having low SRR. The main problem is that the PET film we are using for the substrate on which the ladder-structured micro-wire EDS electrodes are printed has low transmission efficiency. Micro-wire electrodes meet the optical transmission performance but the 50 μm -thick PET films have absorption and scattering losses close to 10% for a single pass of sunlight. It is possible to use PET film with higher transmission efficiency at an added cost.

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Figure 16 shows the EDS film stack architecture as laminated on a solar panel (left) and the collaborating teamwork for producing EDS film and laminating EDS film stack onto solar panels either by integration or retrofitting (right)

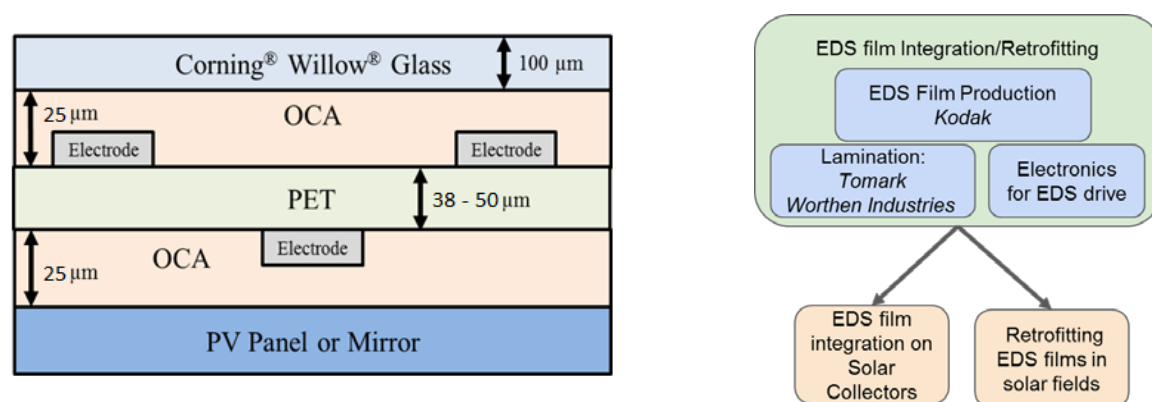


Fig 16: EDS film-stack (left) lamination architecture (Corning Willow® Glass/ Worthen eTPU OCA/Kodak EDS film on PET substrate / Worthen eTPU OCA/PV Panel. Collaborating teamwork is shown at the right for production, integration or the retrofitting the film stack on solar collectors.

Energy Consumption During EDS Film Operation: A new power-supply design was implemented to increase the magnitude of the pulsed voltage output while ensuring power supply safety and decreased power requirement. A method for three-phase interconnection between the EDS electrodes and the power supply output leads was established. Experimental studies showed that the energy required for EDS film operation was less than 0.2 Wh/m²/cleaning cycle.

Lab-evaluation of medium-scale PV modules laminated with EDS Film: OPR Results

Table 9: Selected OPR Results from the data collected from evaluating EDS film laminated medium-scale solar panels tested with dust samples collected from the solar thermal test field of the Sandia National Laboratories

EDS PV NUMBER	TOTAL POWER RESTORED OPR (%)	EDS PV NUMBER	TOTAL POWER RESTORED OPR (%)
2M.19	97.12	W 2.9	92.74

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1M.29	95.6	W 1.1	93.05
1M.26	95.65	W 1.2	93.28
2M.16	95.14	W 1.3	91.82
1M.25	90.97	W 1.4	93.45
W 1M.30	99.53	W 1.5	93.31
W 3M.4	99.35	W 2.1	92.62
W 1M.31	99.43	W 2.2	93.3
W 3M.14	99.81	W 2.3	91.85
AG 1010M 1.3	99.1	W 2.4	92.74
AG 1010M 1.2	99.11	W.I	93.88
W 1M.13	98.29	W.III	93.31
W 2M.12	98.24	W.V	92.9
W 2M.13	96.79	W.V*	91.97
W 1.6	92.51	W.VI	93.06
W 1.9	90.47	W.VII	92.54
W 2.9	91.85	W.VII*	93.25
W.VIII*	94.97	W.VIII	94.96

Test results with dust samples collected from Saudi Arabia: OPR

Dust sample collected from Saudi Arabia was used to study dust removal properties of the medium-scale EDS films. Dust samples were directly deposited on the EDS laminated panels, and so size distribution and composition of dust represent the most accurate test of the EDS function expected in Saudi Arabia. Dust from Saudi Arabia (SA) has a finer size distribution compared to that of desert dust collected from other deserts. EDS based dust removal has a trade off between the application of high electric field and having high transmission efficiency, resulting in a larger number of small particles that are harder for the EDS to remove. Also fine particle forms agglomerates easily and are difficult to disperse; hence it is more difficult for the EDS action to break up aggregates. Despite these factors, the OPR measured was above 90% for a majority of the tests conducted.

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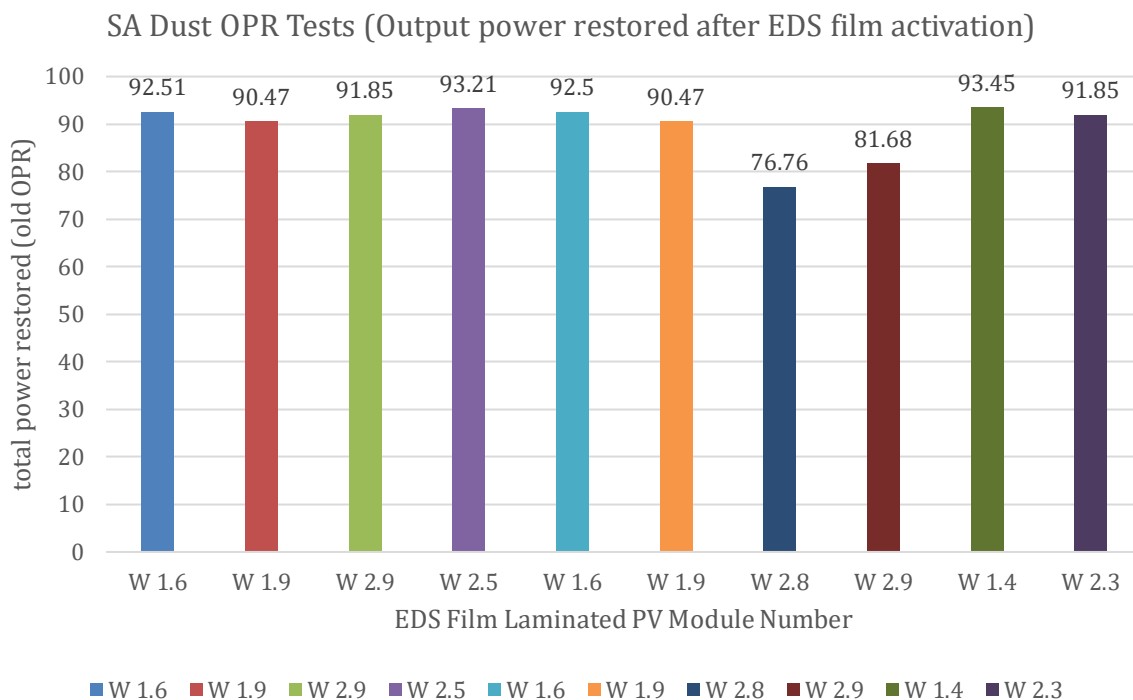


Fig 17: Selected OPR results of EDS film laminated PV modules tested using dust from Saudi Arabia (SA)

Continuous Activation Trials

In order to determine the electrical stability of the EDS electrodes, a lab scale EDS film was connected to a power supply that was programmed to activate the EDS film periodically for two minutes at an interval of every 13 minutes, resulting in 4 activations per hour. If we consider EDS film based cleaning twice a week in a solar plant, approximately 100 times a year, we can conduct an accelerated test of electrical stability of the EDS electrodes by operating the film at shortened intervals over several hundred operations. The delay used in this experiments was long enough to prevent heat dissipation into the EDS films after each activation.

Table 10– SRR, SR, and OPR data of an EDS film in periodic activations four times an hour for 100 activations. The film was tested for SRR, OPR and SR after 100 operations for a total of 800 operations.

ACTIVATIONS	SRR (%)	OPR (%)	SR (%)
100	81.87	91.68	86.29
200	81.76	92.3	82.14

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300	82.18	90.88	79.58
400	82.27	92.49	82.77
500	94.34	78.9	86.68
600	92.78	74.15	83.8
700	93.91	66.89	86.17
800	95.4	80.48	89.03

Effects of ambient RH on DRE

The primary forces used for removing the dust are the Coulomb repulsion force and gravitational force depending upon the tilt angle used in a solar field. The results presented here were taken at a tilt angle 30°. Since electrostatic forces are involved, EDS function depends upon the ambient RH and the resistivity of the glass surface.

Table 11: Experimental data on DRE of an EDS film as a function of relative humidity (RH) ranging from 40% to 85%

EDS Number	Relative Humidity (%)	Dust Mass Before (g)	Dust Mass After (g)	DRE (%)
N.A-4.1	40%	0.0348	0.0051	85.6%
N.A-4.1	50%	0.0353	0.0031	91.2%
N.A-4.1	60%	0.061	0.0107	82.4%
N.A-4.1	70%	0.046	0.0087	81%
N.A-4.1	80%	0.0374	0.0174	53.47%
N.A-4.1	85%	0.0473	0.0453	4.6%

The Table 11 shows the dust removal efficiency of the EDS film as a function of RH variation. In these experiments, we deposited the test dust collected from the solar field of the Sandia National Lab on the EDS film by using a sieve. The dust layer loaded film was then placed in an environmental chamber and exposed it to an environment at a desired RH level for several hours. The film was then activated to remove dust at tilt angle 30°.

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At humidity range of 40% to 60%, EDS films show good performance of repelling most dust out of the surface. Most importantly, while DRE of EDS decreases significantly when ambient RH is high ($> 75\%$) but EDS regains high DRE when ambient RH decreases back to 60% or below. This results show that RH cycling would not cause a decrease in dust removal function of the EDS film unless the dust particles are having a long residence time on the PV module surface (more than a few days) leading to strong bonding of the particles with the glass surface.

Environmental durability against UV radiation damage and operating above temperature 80° C:

EDS films with silver micro-particle electrodes designated in this report as RAg electrodes and with AgNW-ZnO hybrid electrodes were tested following ASTM.

The ASTM G154 test consists of exposing the screen-printed individual samples to 42 cycles of 8 hours of UVA-340 ultraviolet light at 60°C, followed by 4 hours of condensation (mimicking dew) at 50°C as shown in table 8.1. Overall, this test involves 21 days of exposure. The same cycle will be followed for humidity cycling and temperature cycling tests. Each test will have its own, separate sample that is dedicated to a testing cycle and will be evaluated before and after subjection to the testing period. The measurements that are to be considered as proof of concept for functionality are SRR and OPR as they evaluate an EDS film for the dust removal efficiency and thereby viability of the electrodes of the sample in contest. Measurements recorded before and after each test period from the subjected samples showed that the silver microsphere electrodes printed with LOCTITE 1010 E&C showed negligible or no change in their functionality as self-cleaning EDS films. The EDS films made with the hybrid ink (AgNWs and ZnO) showed minor degradation, which can be speculated to fabrication issues or manual error due to misalignment of the third phase bus bar rendition.

Table 12: Results of OPR% - Before and After the Accelerated ASTM G154 test performed using UVA-340 ultraviolet light for LOCTITE 1010 E&C Ink Electrodes

OPR% Before ASTM G154 test with UVA-340 Exposure	OPR% After ASTM G154 test with UVA-340 Exposure
94.14	93.69
94.2	95
94.33	92.54
93.87	94.29

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93.83	91.66
Average OPR% =94.07	Average OPR% =93.44

The test to evaluate the viability of the EDS film with the silver microsphere ink electrodes in an erratic temperature cycling was performed as follows: the test panel was set in the environmental chamber and let to rest at a humidity level of about relative humidity RH = 40% which is considered to be a standard normal humidity range in a desert condition. The temperature of the environmental chamber was set at about 70°C for 8 hours. The temperature was then reduced to about 40°C and the resting humidity was maintained at RH = 40 for 4 hours. The EDS film was activated for 2 minutes once in every 4 days with the standard amount of dust deposition and the standard procedure for measuring OPR% was followed. The OPR% results recorded before and after the test period are given in Table 13.

Table 13: Results of OPR% before and after the Accelerated ASTM G154 Temperature Cycling test performed using the environmental chamber for LOCTITE 1010 E&C Ink Electrodes

OPR% Before ASTM G154 Temperature Cycling test	OPR% After ASTM G154 Temperature Cycling test
71.5	62.8
71.47	73.706
72.12	65.95
71.19	68.17
72.5	72.86
Average OPR% = 71.76	Average OPR% = 68.8

The standard drop in the short circuit current is maintained at about 10% drop in order to assess the restoration performance for the OPR tests. The OPR tests conducted for assessing the temperature tolerance had an average drop of about 43%, which reflects in the OPR% restored both before and after subjecting the test EDS panel to the varying temperature cycles.

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Similar testing procedures were followed to assess the performance of the silver nanowire and zinc oxide (AgNWs-ZnO) hybrid electrodes for their environmental durability and rate of degradation. The results of the accelerated weathering tests are listed in Table 14.

Table 14: Results of OPR% Before and After the Accelerated ASTM G154 test performed using UVA-340 ultraviolet light for AgNWs_ZnO Hybrid Ink Electrodes

OPR% Before ASTM G154 test with UVA-340 Exposure	OPR% After ASTM G154 test with UVA-340 Exposure
95.28	89.36
96.02	90.04
95.8	88.65
95.74	88.2
96.13	87.36
Average OPR% =95.79	Average OPR% = 89.06

Under UV-A exposure, the sheet resistance (R_s) of electrodes increased gradually as when measured in steps of 30 minute increment and showed an abrupt stop or leveling after 2 hours of testing period. This could be due to the fusion action of the ZnO as explained in chapter 4. The decrease in OPR% after the UV exposure is hypothesized to be due to beading of the silver nanowires at the overlap or junction spots, which leads to dead electrodes and hence the percentage of dust removed is decreased overall.

Table 15: Results of OPR% Before and After the Accelerated ASTM G154 Temperature Cycling test performed using the environmental chamber for AgNWs-ZnO Hybrid Ink Electrode-

OPR% Before ASTM G154 Temperature Cycling test	OPR% After ASTM G154 Temperature Cycling test
93.45	91.18

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94.22	91.32
94.3	90.26
93.02	92.6
94.07	91.13
Average OPR% = 94.6	Average OPR% = 91.2

Hence, the accelerated testing experiments reconfirmed the viability and environmental durability of the silver microsphere electrodes and the hybrid silver nanowire-zinc oxide electrodes.

EDS Film Production And Lamination On Full-Scale PV Modules Or Heliostats

EDS film Production:

Production Method: Kodak has established methods of manufacturing EDS films in medium-scale (26 cm × 30 cm) on PET films with a double-sided architecture using Kodak's existing manufacturing line in Rochester NY. As manufactured, the electrical and optical performance of Kodak's copper micro-wires electrodes printed on PET films meet the objectives set out in the DOE Project. The full roll-to-roll process starts with generating world-class high-resolution flexographic plates. These plates are then used to print patented catalytic ink, which provides the pattern for the electroless plating and reduces reflections at the interface of the micro-wire with the substrate with a matte neutral color. A schematic diagram of their roll-to-roll manufacturing process is shown in Figure 18.

The Gen-1 architecture uses the capability of the flexographic process to print catalytic and other inks on both sides of the substrate. After printing, the substrate is conveyed through a touchless plating line where electroless copper is deposited on the printed catalyst pattern. The deposited copper is treated in-line with an environmental passivation and darkening agent, simultaneously protecting the micro-wires from corrosion and minimizing front-side reflection with a neutral color, all without contacting a roller to minimize the risk of conveyance related defect formation. The end of the manufacturing line is equipped with in-line inspection tools for both electrical and optical measurements, and protective liner is applied to the device substrate post-inspection.

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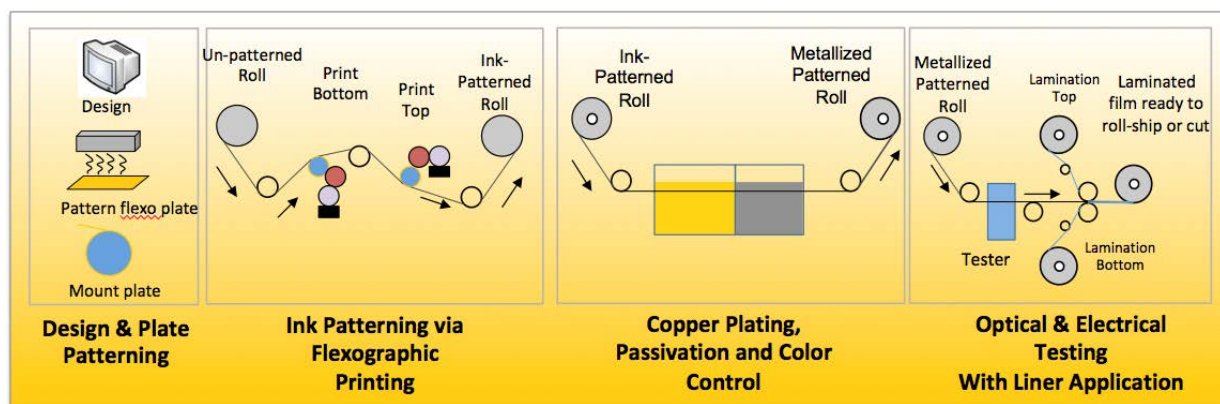


Fig 18: Kodak's roll-to-roll manufacturing line for producing EDS film by flexographic printing of Cu-microwire electrodes on PET film with a double-sided architecture.

EDS film size limitation: The existing Kodak manufacturing line has an EDS size limitation of 33 cm × 55 cm for active Gen-1 EDS films area. However, it is believed that this Gen-1 size represents a commercially viable form factor which is readily be manufactured and suitable for integration onto PV panels, and CSP heliostats or parabolic mirrors using a tiled approach.

Integration or retrofitting of EDS films onto full-scale PV modules and heliostats is shown in figure 19. For full-scale operation, our plan is to have four or more EDS film-sections placed as "tiles" that will cover the optical surface without gaps except at two edges where electrical connections are made to the electrodes. The most cost effective and efficient lamination method would be to integrate EDS film at the point of production of the solar collectors.

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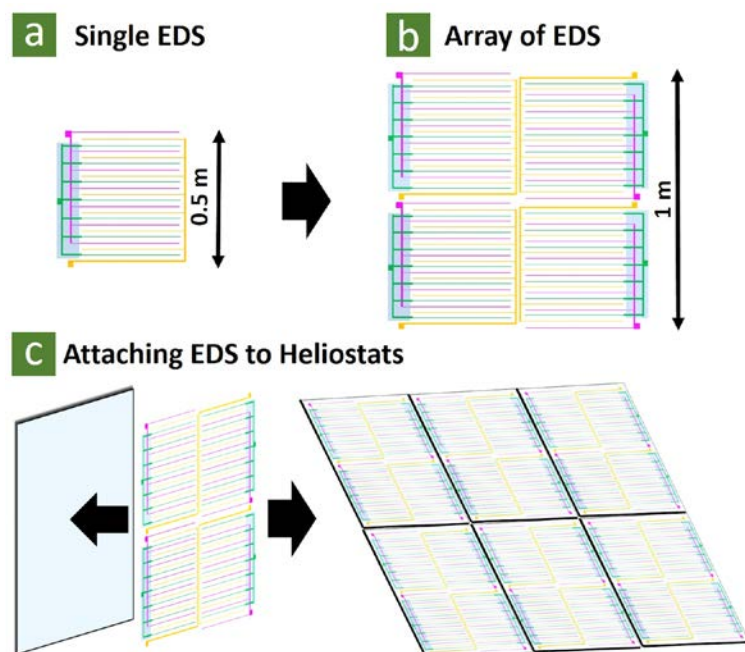


Fig 19: Full-scale lamination by tiling EDS film sections for convenient retrofitting

POWER SUPPLY AND INTERCONNECTIONS

Power Supply Units and Connections: The latest version of the three-phase pulse, low current (micro-amp level), pulsed high-voltage power supply has been tested at DC input voltages ranging from 6 to 14 V. Figure 20 shows a block diagram of a power supply unit deriving its power from a 12 V solar panel. We will continue to ensure power supply safety while further reducing power requirements and cost. We are pursuing a process for making interconnections for activating multiple EDS film-laminated PV modules or heliostats from one power supply unit via a multiplexing process as shown in Figures 21 and 22.

The electrodynamic screen (EDS) power supplies are three-phase high-voltage, low power pulse generators, which are used to activate the electrodes of the EDS films. The high voltage is generated by a simple voltage multiplier circuit consisting of high-voltage diodes and capacitors. Op-amp based oscillators generate the three-phase timing pulses. The output stage consists of three identical sections, one for each phase. Each section consists of a totem-pole MOSFET pair. The upper MOSFET of each totem-pole MOSFET pair is driven by a high-side gate driving voltage. Rather than using expensive high-side driving chips, we have designed a high-side driving circuit. The output stage combines the high-voltage from the voltage multiplier with the timing signals from the op-amp oscillators to produce three outputs of high-voltage pulses of zero to 1.2 kV magnitude, at a frequency of 5 Hz, duty cycle of 50% and 120° electrical degrees out of phase of each other.

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The power supplies generate three-phased, high voltage pulses of zero to 1.2 kV in magnitude at a frequency of 5 Hz and duty cycle of 50%. The electrode sets are thus energized at 120° electrical degrees out of phase of each other. The current drawn by the power supply with EDS connected is about around 80 mA, for a total power consumption of about 1 W.

For safety purposes, the power supplies are enclosed in an insulating box of polycarbonate or acrylic with all circuit boards housed within the box. Three well- insulated wires extend from the supply to connection points on the EDS film. The power supplies can be turned on by a simple switch or via a microcontroller and relay.

Figure 20 shows a block diagram of power supply. The power supply derives primary power from 12V, either from a wall adapter (for lab tests) or eight C-cell batteries (for outdoor/field tests). The lower current requirements of the power supply (< 100 mA) facilitate the use of simple batteries for field tests outdoors.

Alternately, rechargeable lead acid batteries can also be used with a standalone solar panel to charge the battery as shown in the Fig. 21.

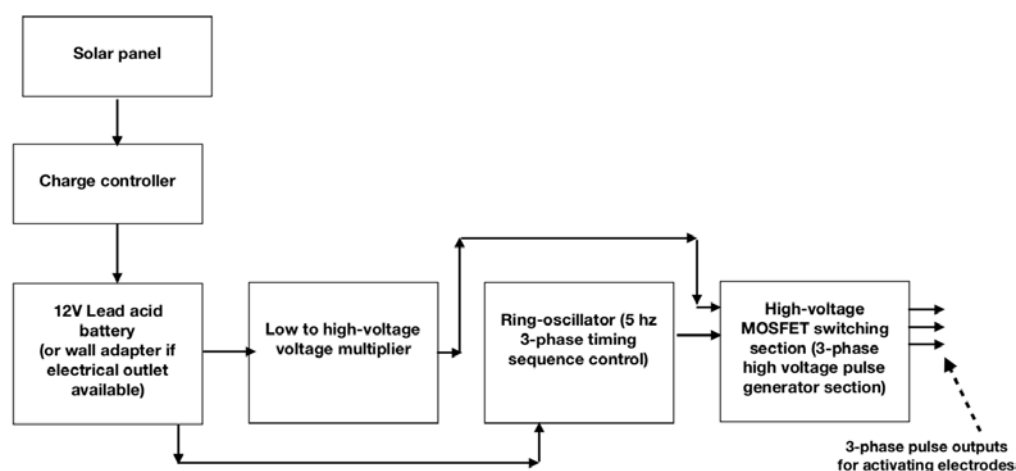


Fig 20: Block diagram of a three-phase pulsed voltage power supply used for activating EDS electrodes.

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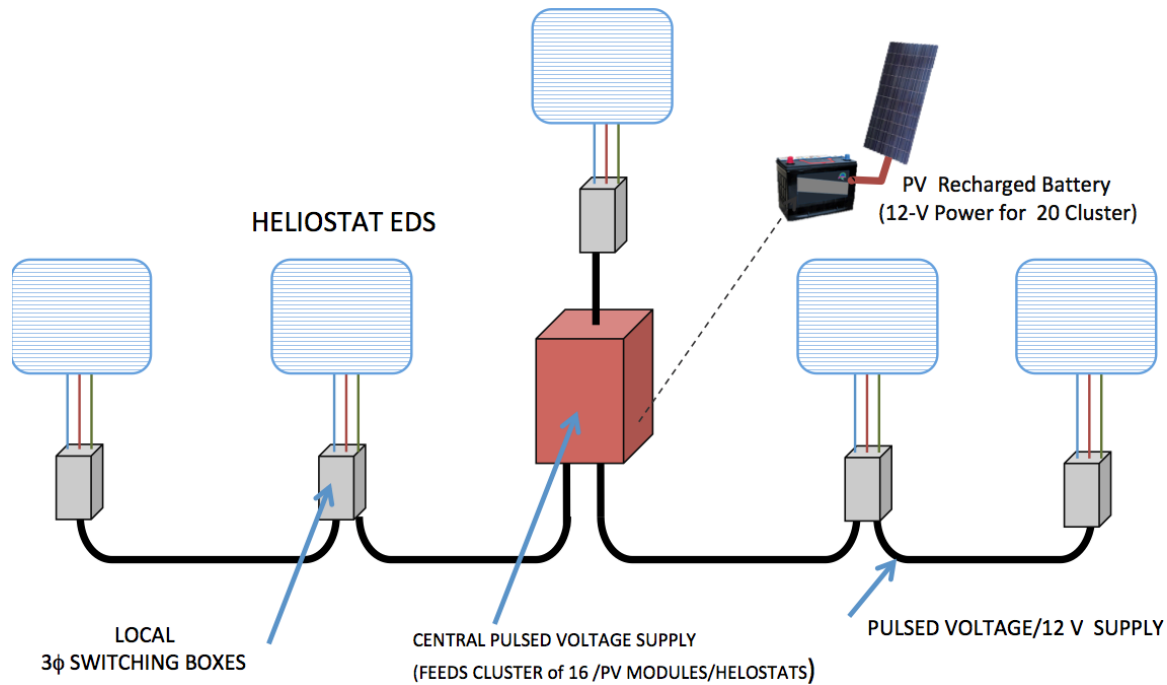


Fig 21: Power supply connections to concentrating solar mirrors (Heliostats).

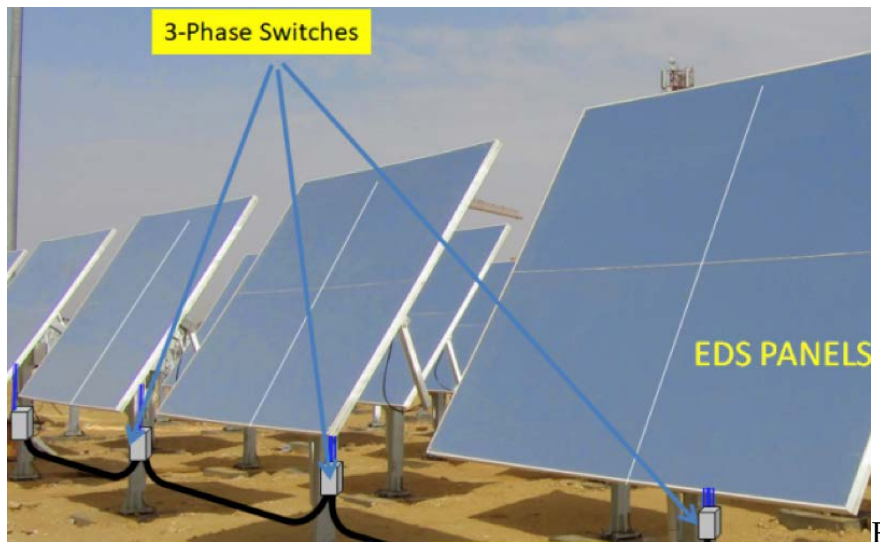


Fig 22: Power supply connections to PV Modules; the figure shows one power supply unit is used in activating 4 PV modules.

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Production of Lab-scale EDS films by flexographic printing

EDS Film Production: A roll-to-roll production process for EDS films has been established using flexographic printing of the electrodes onto transparent polymer films. This process utilizes an existing manufacturing line at Eastman Kodak. Kodak fabricated double-sided EDS films which have advantages in both EDS film manufacturing process and integration into EDS systems. Lab-scale EDS films (12.5 cm × 12.5 cm) produced at Kodak have been successfully evaluated. The EDS films were produced by printing two-sided ladder-structured micro-wire electrodes onto transparent polyethylene terephthalate (PET) films.

Power Supply Connections: The power supply for the EDS converts 12-VDC power into three-phase, 1.2 kV pulsed power supply at the proper frequency needed for most efficient particle transport. Figure 22 shows a concept for EDS films laminated on heliostats together with its power-supply unit. Given the low power requirements, each power supply will be able to operate multiple EDS films. Therefore, the optimal design will include just a single power supply per panel or CSP mirror. Alternatively, one power supply may be able to power a full size PV module or a heliostat with area more than 1 m². It may be more convenient and economical if each PV module or a heliostat has an EDS power supply unit. Several EDS power supply units can be connected to one PV panel and a charge controller for providing DC 12 V for providing power to several EDS power supply units in an array.

Performance of Lab-Scale EDS Films produced by flexographic printing at Kodak: The experimental data for SR, SRR, and OPR with lab-scale EDS film produced at Kodak and laminated at BU are given in Table 16. Effects of electrode geometry and lamination imperfections were analyzed from the results. When the inter electrode spacing was increased, SR also increased but SRR decreased, as expected. Entrapment of micro-air bubbles during the lamination process decreased EDS performance.

Table 16 Effects of EDS electrode geometry and lamination efficiency on the SR, SRR and OPR of solar collectors

Panel Name	SR (%)	SRR (%)	OPR (%)	Panel Name	SR (%)	SRR (%)	OPR (%)
L 1.1	97.19	92.21	97.02	L 3.1	94.84	80.1	94.2
L 1.2	93.91	89.66	95.93	L 3.2	94.11	78.6	95.44
L 1.3	97.37	92.05	95.46	L 4.1	94.6	81.92	92.68
L 2.1	90.8	85.94	96.36	L 4.2	94.86	80.99	88.24

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L 2.2	86.66	94.05	97.86	L 5.1	92.03	76.15	98.08
L 2.3	91.09	91.61	96.6	L 5.2	95.68	79.71	97.17
L 2.4	93.94	-	93.01	L 6.1	92.52	77.1	97.66
L 2.5	94.54	82.35	94.87	L 7.1	94.86	77.43	97.98
L 2.6	93.61	77.14	94.98	L 8.1	91.97	85.28	98.58

Currently, there are two types of EDS that we have been developing: an EDS with screen-printed electrodes produced on campus, and an EDS printed by Kodak on a PET film with electrodes on both sides.

Field evaluation of lab-scale EDS Films (Atacama Desert, Chile)

Table 17: The OPR values for four different trials and their average OPR values measured

Temperature variation: 55° F to 110° F; Humidity variation 10 to 35% RH

	EDS Sample 1	EDS Sample 2	EDS Sample 3	EDS Sample 4
Trial 1 OPR	98.8%	98.18%	98.77%	98.18%
Trial 2 OPR	95.77%	95.53%	94.41%	96.45%
Trial 3 OPR	91.66%	94.44%	93.75%	97.04%
Trial 4 OPR	95.24%	94.07%	92.44%	96.46%
Avg. OPR	95.37%	95.55%	94.84%	97.03%

Test results shown in the Table 17 represent OPR data taken in a solar field at the Atacama Desert.

Trial 1. February 7, 2017 to March 8, 2017 near the city of Cachiyuyo, Chile. Trial 2. April 6, 2017 to May 5, 2017 near the city of Diego de Almagro. Trial 3. May 6, 2017 to June 5, 2017 near the city of Diego de Almagro. Trial 4. Manual dusting of solar panel with dust collected from solar field during the month of June 201

Design and Construction of Test Units for Field Evaluation: The field-test unit we are constructing consists of four EDS-laminated PV modules, two control PV modules, one PV

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module having an EDS film to be used for recharging the battery, one self-cleaning pyranometer, a control module, and a rechargeable battery. Each panel having an EDS film will have an EDS power supply unit. The control module will be used for autonomous operation of the field-test unit using a single board computer Raspberry Pi, powered by the rechargeable battery, for monitoring (a) ambient temperature and RH, (b) solar irradiance, (c) irradiance-corrected I_{sc} , V_{oc} , and power output of the EDS-laminated- and control panels, (d) OPR, DRE, SR and SRR.

The USB-stored information obtained from the solar field will be analyzed and used to determine (a) soiling ratio, (b) soiling rate, (c) average soiling loss during the period of measurement and annual soiling loss in percentage, (d) performance ratio (PR) of the plant, (e) water conservation, and (f) gain in the energy yield with EDS film application and the associated increase of revenue.

Field-Trials

For optimizing operation of the EDS film application in lowering of LCOE, and for water conservation, we have been working with Sandia National Labs (U.S.) EDS Chile SpA (Santiago); and at the Indian Institute of Technology (Mumbai). Our objective is to install field-test units in solar PV plants in their facilities and work with them for a detailed comparative cost analysis of EDS-based and water-based solar collector cleaning. In each field test, we will first implement optimized operation of the EDS film before performing comparative-cost analysis.

Resources for Field Tests: (1) SNL has extended the time period for completion of the field test at their facility based on the BU-SNL sub-award. We are seeking DOE approval for carrying out the field test in the solar thermal test field of Sandia National Labs, since we could not complete the test during the Phase 3 project period. (2) We received a US-India partnership 2020 award for carrying out collaborative research on low-water solar collector cleaning for the application of EDS films with an anti-soiling hydrophobic nanoparticle coating for reducing adhesion of dust particles in hot and humid climates. The collaboration will be with the Indian Institute of Technology- Bombay (IITB), Mumbai. IITB has a rooftop solar test facility for studying different technologies for mitigating soiling losses.

F. Solar Energy Growth Potential:

EDS Film Technology: Progress Towards Commercialization: Over the past 20 years, there have been multifaceted technical advancements and a steady price reduction of the PV modules and the Balance of System (BOS) that includes installation. Similar progress has been made via advancements in energy storage, the grid integration, and manufacturing advancements.

A recent article published in SCIENCE (May 31, 2019), jointly authored by 45 well-established scientists, engineers and economists from different parts of the world, emphasized that solar

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energy has the potential to meet global energy needs throughout the year. The article pointed out that Photovoltaic (PV) plant capacity exceeded 500 GW at the end of 2018. Current PV growth worldwide shows that planned installations would bring an additional growth of 500 GW by 2022 to 2023, reaching Terawatt (TW) scale photovoltaic plant capacity [9].

Solar energy received by the land areas in semi-arid lands and deserts (nearly 30% of the landmass of earth, mostly at mid-latitudes) and wind energy available at higher latitudes of the globe could generate 3 to 10 TW of electricity by 2030 and 70 TW by 2050. For this rapid growth solar energy industry to be sustainable, energy conversion technologies must avoid any major negative environmental impact.

The sunniest areas of the world such as deserts and semi-arid lands have a high direct normal irradiance. For harvesting the highest solar irradiance throughout the year, large-scale solar plants are installed mostly in these semi-arid and desert regions. These areas also have high concentrations of atmospheric dust, frequent dust storms, dust hazes, and extreme water scarcity. PV plants in these locations suffer power output losses 5 to 40% due to the natural deposition of dust on the module surface [10,11].

Scarcity of Water and Sustainability: Use of fresh water for cleaning the PV modules of utility-scale solar plants can result in a major negative impact in many areas of the world suffering from shortage of fresh water. As an example of how much water is now required for cleaning, one can consider the Ivanpah facility in the Mojave Desert. Ivanpah must truck in about 6.8 million gallons of water per year cleaning purposes [12]. PV plants in Rajasthan, India will suffer a 60% to 80% loss/year if PV modules are not cleaned frequently, yet India is now facing its biggest water crisis to date [13, 14]. If solar power is to grow to the terawatt level capacity as predicted, there is not enough fresh water available in semi- arid and desert areas of the world to clean the solar collectors.

To prevent key barriers in long-term growth of solar PV and CSP plants, mitigation of soiling losses requires an economically viable, water-free or low-water technology for cleaning solar collectors. The cleaning must be done at an optimal frequency, depending upon the rate of dust deposition, in order to maintain high optical efficiency and to conserve water. To date, there is no well-established soiling mitigation technology that meets the operation requirements for utility-scale solar plants as well as sustainability requirements [15].

Presently Used Cleaning methods: At the present time, several methods are used for cleaning PV modules (Fig. 23). The most common methods include: (1) manual cleaning with water using brushes followed by wiping; (2) removing dust by brush and vacuum cleaners; (3) application of anti-soiling coating (ASC) — either hydrophilic or hydrophobic for increasing wetting properties of the surface or for reducing adhesion of dust to the surface respectively, followed by cleaning with water at a low consumption rate; (4) manual or robotic spraying of

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water from a high pressure jet operated using trucks; (5) deluge cleaning with water using large trucks; and (6) robotic cleaning with microfiber cloth brushes and vacuum cleaners.

Current Cleaning Techniques



Fig. 23. Photographs showing different currently used methods from hand wiping with water to robot-based vacuum cleaners.

One of the promising low-water based cleaning processes is to apply a transparent superhydrophobic (SH) coating with nanostructured surface on the optical collectors for reducing adhesion of dust particles to improve cleaning efficiency with low water use. This is a passive method for modifying the surface for making solar collectors easily cleanable. Current SH coating process suffers from three technical challenges: (1) water is still needed for cleaning, (2) outdoor lifetime of the SH film is very limited to few months unless it is frequently cleaned (3) application of coating in large-scale is yet to be established.

Problems With Current Low Water Cleaning Methods: Anti-soiling coating (ASC) with added anti-reflective property is a low-cost, low water cleaning method. It is a passive method used for either increasing wettability of the surface or for reducing adhesion between dust particles and solar module surfaces. Both processes require water for cleaning. Because of its low abrasion resistance and relatively low adhesion of the coating to the module surface, the coating is not durable, particularly during heavy rains and when the surface is cleaned with a pressurized jet or with brush cleaning of the PV modules with water and detergent.

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Loss of Revenue: There are two major components of costs in operating PV plants: (1) installation costs and (2) operation and maintenance (O&M) costs. Hence operating PV plants in semi-arid and desert regions can provide a high return on investment if the soiling losses are mitigated using efficient cleaning methods. At the present time, soiling represents a substantial operating loss. Estimated annual global revenue losses due to soiling of solar collectors are predicted to approach \$6 billion per year by 2023 [15].

The number above is a projected loss by 2023 reported by a group of authors in Germany where as the current annual revenue loss estimated by NREL is approximately \$1 billion.

Features of EDS Films:

1. Allows frequent water-free cleaning with low energy requirement; automated operation does not interfere with the plant operation; cleaning is performed in under 2 minutes.
2. Provides active dust removal forces as and when needed.
3. Dust removal in the particle diameter range 2 to 100 μm has been established with dust samples obtained from different deserts.
4. The output power restoration (OPR) of the EDS film after dust deposition with surface mass density ranging from 1 to $\geq 30 \text{ g/m}^2$ on the surface is above 95%.
5. Light transmission efficiency is greater than 90%.
6. Performs PV module cleaning with a low energy consumption of $0.2 \text{ Wh/m}^2/\text{cleaning cycle}$. If the cleaning is performed twice weekly, the total energy requirement will be approximately 0.006% of the energy produced by the PV module.
7. Cleaning is performed without any manual labor, mechanically moving parts, or consumed materials.

Industrial-Scale Manufacturing and Lamination of EDS Films

Production methods and facilities to be used commercializing EDS films at Eastman Kodak have been established.

Materials/Components and Supplies for EDS Films: The necessary supply chain has been established.

One obvious difference between the two EDS stacks is that the screen-printed stack is thinner, because the electrodes, which must be encased in a dielectric to ensure proper EDS function, are printed on one side. However, there are some added complications from the EDS being on only one side. In order to make the third phase connection, a dielectric strip (usually Mylar tape) with holes that lines up with the third phase electrodes is added and then a conductive strip is added on top of the dielectric strip to electrically connect all of the third phase electrodes together. This adds a lot of complexity to the assembly of the EDS and reduces its

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reliability. This tradeoff between ease of assembly and EDS film thickness is an important factor in deciding how we will make the EDS film in the future.

When assembling EDS films, we have to take several factors into consideration. For an EDS film to be considered viable, it must have a high optical transparency, high electric field on the surface during operation, and a surface which is reasonably resistant to moisture, UV, and abrasion. Optical transparency is improved by reducing the number of layers in the stack and using materials with high optical transmission efficiency. In low quality laminations, air bubbles can be trapped in between layers, reducing the optical transparency of the stack. In order to maintain a high electric field all layers within the stack need high dielectric strength so that there is a high resistivity between the phases of the EDS. Furthermore, the strength of the electric field is inversely correlated with the distance between the electrodes and the top surface, so as the thickness of the laminate layer and top surface increase the electric field is reduced. Abrasive-resistant top surfaces will maintain better optical clarity and dust movement prolonging the life of the EDS. Using materials that will not yellow over time from extended exposure to UV radiation will increase the lifetime of the EDS film stack.

Durability of EDS Films: Based on the similarity of the manufacturing processes and materials used in PV modules production with c-Si solar cells and EDS films with PET films with ultrathin glass film (Willow® Glass) superstrate, we believe the durability of the EDS film will be similar that of the PV modules. There are a few unresolved issues: (1) The currently used PET film was chosen based on its low cost, whereas durable PET film (20+ years, under glass) with higher TE are available from DuPont, and (2) the lifetime of the currently used copper wire micro-wire electrodes has not yet been determined. The electronic components of the power supply units, like the inverters used along with PV modules, may have a shorter lifetime but the electronic unit can be replaced easily. Currently, the EDS film stack is not hermetically sealed against moisture ingress. We need to use a frame to provide a robust edge seal for encapsulation similar to what is done with PV modules. An aluminum frame is used extensively in constructing PV modules to provide convenient handling and to prevent moisture ingress to the solar cells.

In order to provide hermetically sealed EDS stack integration of PV modules, we are working with SBM Solar Inc. (North Carolina) to combine an EDS film stack with the PV module during the manufacturing process. A schematic view of this process is shown in Fig. 25, which shows an EDS film integrated with a PV module. A thin transparent dielectric film or Corning® Willow® Glass is currently used as a substrate for the EDS film stack laminated onto a solar mirror or a PV Module.

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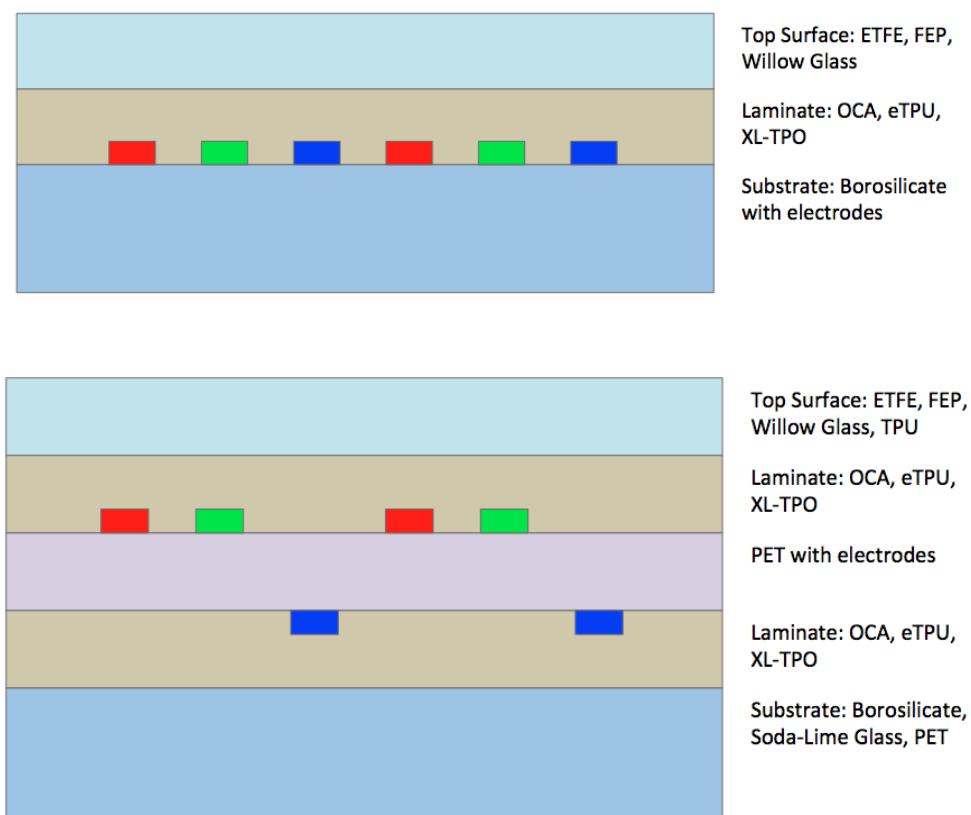


Fig. 24. EDS film lamination process with BU Lab-made (top) and Kodak produced EDS stacks.

For lab-scale EDS film lamination, we used a 3M Product, a pressure sensitive adhesive called 8211, for OCA film to laminate with Willow Glass and the solar collector. However, 3M films used as OCA cannot eliminate air bubbles entrapped in surface asperities of the top glass cover of PV Modules and air trapped between the layers. We are now working with Tomark-Worthen Industries using their industrial lamination facilities used for solar panel lamination. Two products, similar to EVA used for lamination, are used: thin film cross-linkable thermoplastic polyolefin (“XL-TPO”) and thin film thermoplastic polyurethane (“eTPU”) – both products of Worthen Industries, an adhesive manufacturer based in New Hampshire. Under heat and vacuum, the OCA films melt and fill in the interstitial spaces hermetically sealing the layers of the EDS stack.

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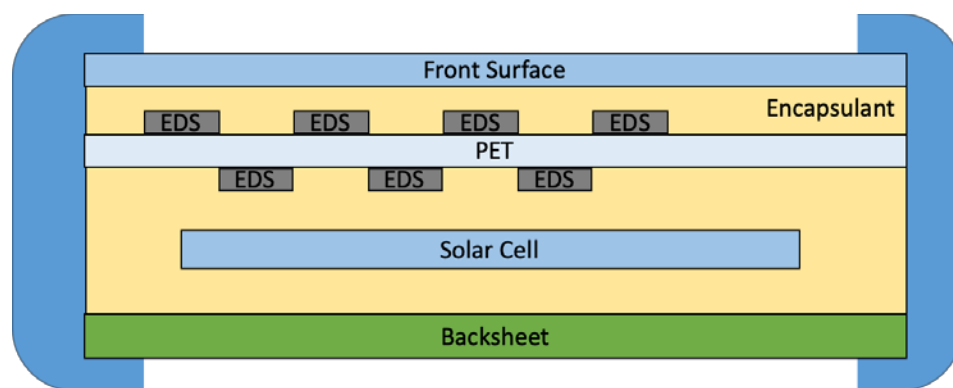


Figure 25: Integration of the EDS film stack on solar panel and encapsulation by aluminum frame

The Enclosure for power supply units: The enclosure is made of acrylic, with three slide-rails along both the long edges of the box. The three sections of the power supply, which will slide into place along these rails, are wired together and (for current lab-testing) powered by a 12-V wall adapter. For outdoor applications, we will use a bank of eight C-cell batteries to produce the needed 12 volts.

For field applications, the EDS power supply unit will be powered by a PV module coupled to a charge controller and a rechargeable battery for a long-term operation. The power supply draws approximately 100 mA, which represents but a fraction of the power generated by a single solar panel in the field. Moreover, the EDS need not be energized continuously, but only for several minutes when needed to clear dust. Thus its effect on overall plant efficiency, whether PV or CSP, should be minimal.

Cost of the EDS power-supply units: Digikey is the vendor for all the parts used. The cost of the power supply is calculated in a per-part basis, assuming quantities of 1000 units. The present design can be produced for about \$25-\$30, including the cost of the parts and the printed circuit boards. Adding to that the cost of the power supply enclosure, the total cost of the new power supplies would be around \$120 each. The power supplies are built to activate an EDS area of 10 m². Thus the cost per m² comes to around \$12.

EDS Field Evaluations

Continuous Activation Trials

In order to determine the lifetime durability of the EDS, a lab scale sample was connected to a power supply that activated the EDS for two minutes, ever 13 minutes, resulting in 4 activations an hour. OPR, SR and SRR were measured after every 100 activations (Fig. 26 a).

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The delay was to prevent heat dissipation into the EDS, which would not occur under normal activations.

Table 18 – SRR, SR, and OPR of an EDS every 100 activations, up to 800 activations.

ACTIVATIONS	SRR (%)	OPR (%)	SR (%)
100	81.87	91.68	86.29
200	81.76	92.3	82.14
300	82.18	90.88	79.58
400	82.27	92.49	82.77
500	94.34	78.9	86.68
600	92.78	74.15	83.8
700	93.91	66.89	86.17
800	95.4	80.48	89.03

Average SRR, Average OPR and Average SR

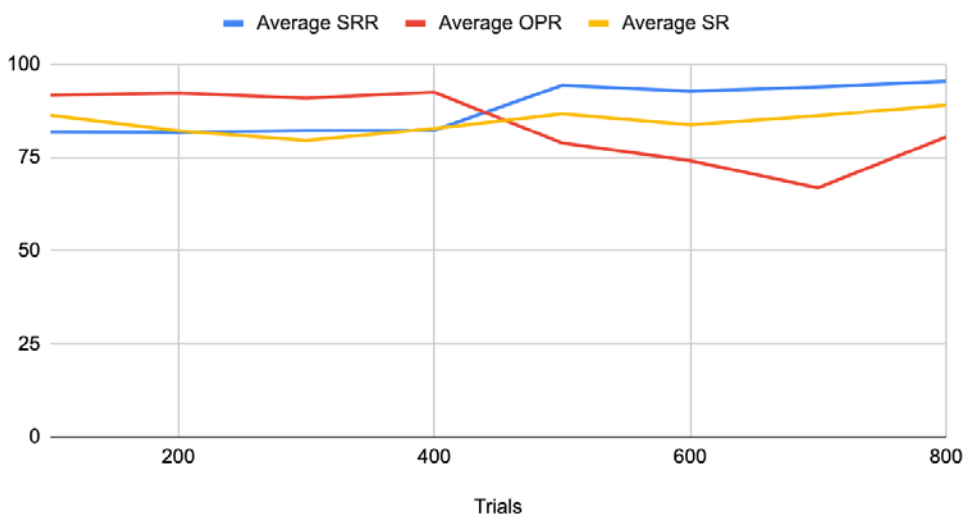


Figure 26a – OPR, SRR, and SR of a sample after 800, two-minute activations, called trials. Values were measured every 100 trials

Dust Removal Efficiency as a function of the frequency of pulsed voltage activation

We conducted a test to determine how frequency of pulsed activation alters for an efficient dust removal. The test consisted of operation at low frequencies of 2, 4, 6, 8 & 10 Hz and measurement of DRE vs. frequency. The test used was collected from the Sandia Lab with

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particle diameter varying from 1 to 88 micrometers. SRR was collected to complement the DDA and provide a comparison to the efficiency of the EDS. The data indicated that different particle sizes respond better for certain frequencies (Figure 26b). The lower frequencies allow for a high percent change for larger particle diameters, 15 to 20 micrometers. For the SNL test dust, the best frequency is 6 Hz that provide DRE > 90% for particle diameters of 4 to 6.

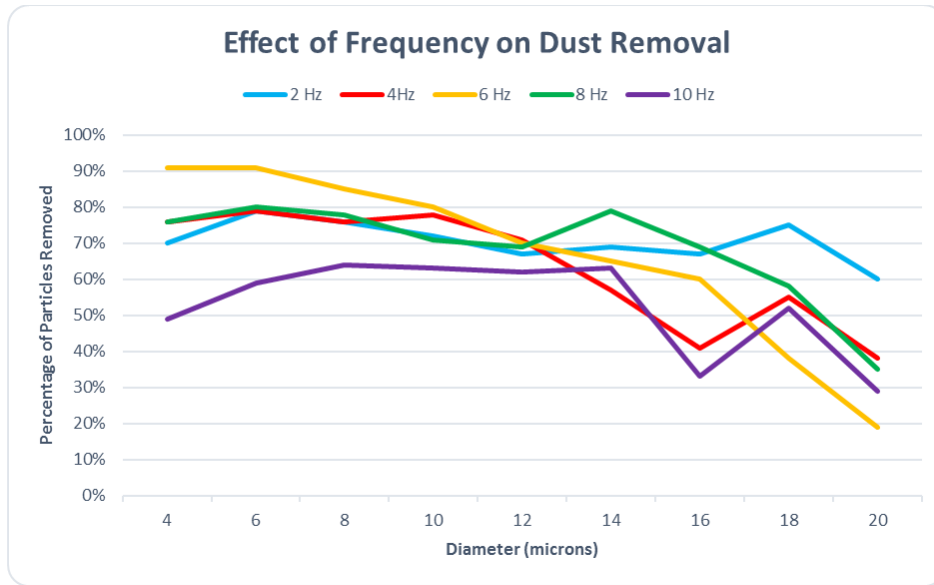


Figure 26 b: The calculated percent change of dust particle displacement with different AC frequencies

According to the data, the highest true restoration is with an AC frequency of 6 Hz, with a value of 65%. With the majority of particles having a diameter of 4-10 micrometers, the ideal frequency is 6 Hz to allow for the highest percentage of particle removal.

OPR Results

Dust samples collected from Saudi Arabia

Dust collected from solar panels of a PV plant in Saudi Arabia was used to study dust removal properties of the medium-scale EDS films. Dust samples were directly deposited on the EDS laminated panels, and so size and composition represent the most accurate test of the EDS function. Dust from Saudi Arabia (SA) is also finer than typical desert dust, resulting in a larger number of particles that are harder for the EDS to remove, and results in more clumps when deposited, which are also more difficult for the EDS to break up. Despite these factors, the OPR measured was still above 90% for a majority of the samples.

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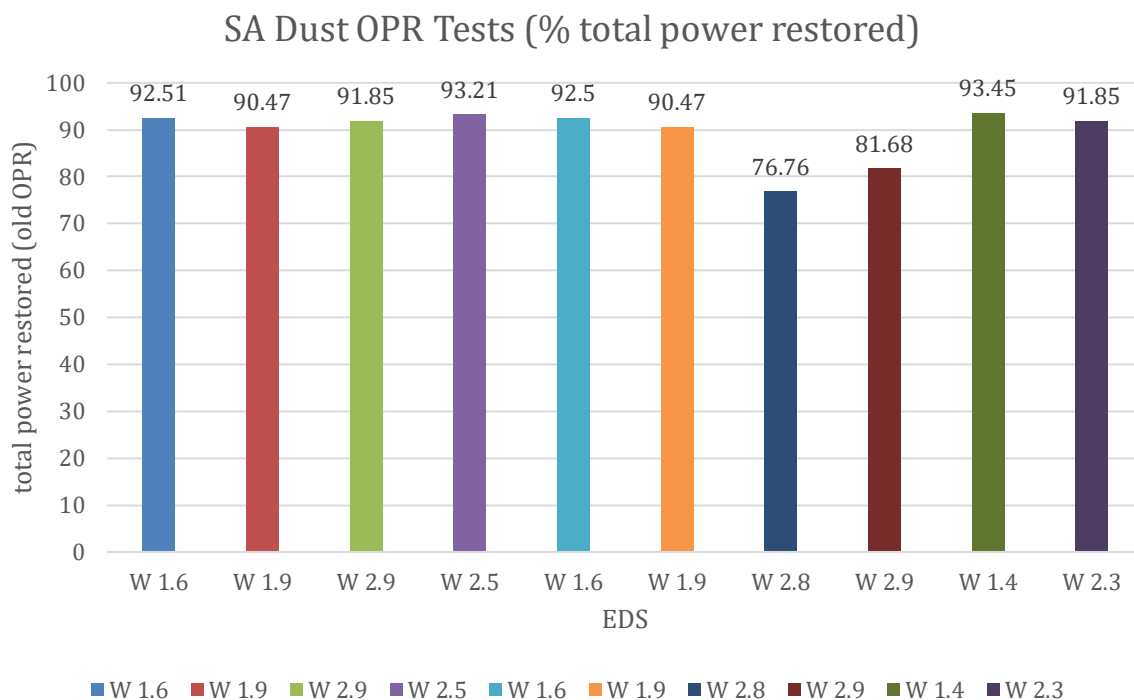


Figure 27 – Selected OPR results of EDS tested using dust from Saudi Arabia (SA)

Selected List of OPR Results

Table 19 – Selected List of medium scale EDS OPR results.

EDS NAME	TOTAL POWER RESTORED (%)	EDS NAME	TOTAL POWER RESTORED (%)
2M.19	97.12	W 2.9	92.74
1M.29	95.6	W 1.1	93.05
1M.26	95.65	W 1.2	93.28
2M.16	95.14	W 1.3	91.82
1M.25	90.97	W 1.4	93.45
W 1M.30	99.53	W 1.5	93.31
W 3M.4	99.35	W 2.1	92.62
W 1M.31	99.43	W 2.2	93.3
W 3M.14	99.81	W 2.3	91.85
AG 1010M 1.3	99.1	W 2.4	92.74
AG 1010M 1.2	99.11	W.1	93.88

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W 1M.13	98.29	W.III	93.31
W 2M.12	98.24	W.V	92.9
W 2M.13	96.79	W.V*	91.97
W 1.6	92.51	W.VI	93.06
W 1.9	90.47	W.VII	92.54
W 2.9	91.85	W.VII*	93.25
W.VIII*	94.97	W.VIII	94.96

Effects of ambient RH on DRE

The primary forces used for removing the dust are the Coulomb repulsion force and gravitational force depending upon the tilt angle used in a solar field. The results presented here were taken at a tilt angle 30°. Since electrostatic forces are involved, EDS function depends upon the ambient RH and the resistivity of the glass surface.

Table 20: DRE of EDS under humidity range from 40% to 85%

EDS Number	Relative Humidity (%)	Dust Mass Before (g)	Dust Mass After (g)	DRE (%)
N.A-4.1	40%	0.0348	0.0051	85.6%
N.A-4.1	50%	0.0353	0.0031	91.2%
N.A-4.1	60%	0.061	0.0107	82.4%
N.A-4.1	70%	0.046	0.0087	81%
N.A-4.1	80%	0.0374	0.0174	53.47%
N.A-4.1	85%	0.0473	0.0453	4.6%

At humidity range of 40% to 60%, EDS films show good performance of repelling most dust out of the surface. Most importantly, while DRE of EDS decreases significantly when ambient RH is high (> 75%) but EDS regains high DRE when ambient RH decreases back to 60% or below. This results show that RH cycling would not cause a decrease in dust removal function of the EDS film unless the dust particles are having a long residence time on the PV module surface (more than a few days) leading to strong bonding of the particles with the glass surface.

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Field Testing

Sandia National Laboratory Field Testing Results

New samples have been shipped to SNL for field-testing. These include three lab-scale Kodak EDS films and two BU-produced silver nanowire EDS films. The samples were installed onto the previous field-testing unit at SNL. To date, however, the test has been inconclusive. The previous testing setup relied on manual activation, requiring personnel at SNL to walk to the setup and turn on the EDS for two minutes, and then switch it off. Due to the nature of making each SR measurement, requiring the application of a device over the surface of the mirror, the SR of each mirror must then be conducted manually. As a result of the intensive time for testing, results were collected every two to five days. The combination of several rain events made the dust adhere to sections of the EDS and control-mirror surfaces.

Future field testing setups are being designed to have automatic activation and to perform short-circuit measurements automatically. However, there is currently no way to automate SR measurements. To make up for this deficiency, future designs will rely more on control mirrors and will compare to mirrors attached with EDS in order to determine the effect that the EDS has over time.

Chile Field Testing Results

EDS Chile completed field evaluation of the first batch of EDS film-laminated solar panels at three solar fields of Atacama Desert for a period of four months. These tests showed successful operation of the EDS films in dust removal without any degradation. The output power restoration remained high during the entire period of outdoor exposure in solar fields. The field-evaluations data are shown in the following table. We are sending another batch of EDS films to Chile SpA for field-testing in the Atacama Desert.

Table 21 - The OPR values for four different trials and their average, where in each trial four different EDS films experienced manual dust deposition.

Temperature variation: 55° F to 110° F; Humidity variation 10 to 35% RH

	EDS Sample 1	EDS Sample 2	EDS Sample 3	EDS Sample 4
Trial 1 OPR	98.8%	98.2%	98.8%	98.2%
Trial 2 OPR	95.8%	95.5%	94.4%	96.5%
Trial 3 OPR	91.7%	94.4%	93.8%	97.0%
Trial 4 OPR	95.2%	94.1%	92.4%	96.5%
Avg. OPR	95.4%	95.5%	94.8%	97.0%

Trial 1. February 7, 2017 to March 8, 2017 near the city of Cachiyuyo, Chile. Trial 2. April 6, 2017 to May 5, 2017 near the city of Diego de Almagro. Trial 3. May 6, 2017 to June 5, 2017

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near the city of Diego de Almagro. Trial 4. Manual dusting of solar panel with dust collected from solar field during the month of June 2017.

An additional trial was conducted in March 2018 in Santiago, Chile, which would represent ten months since the initial deployment. Manual dust was utilized in order to expedite data collection. Unfortunately, an error occurred in the testing, and initial clean values were not reported. Therefore, OPR values could not be calculated. The results below are presented to show the percentage increase in power after EDS activation. Given the missing clean data, the main purpose of the data below is to show that the EDS films are still functional.

Table 22–The percent of power increase in the field test setup currently deployed in Chile after manual dust deposition.

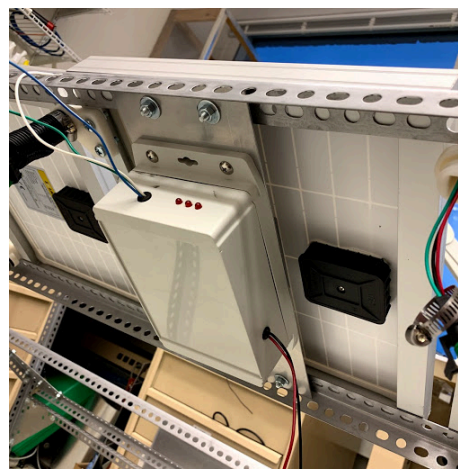
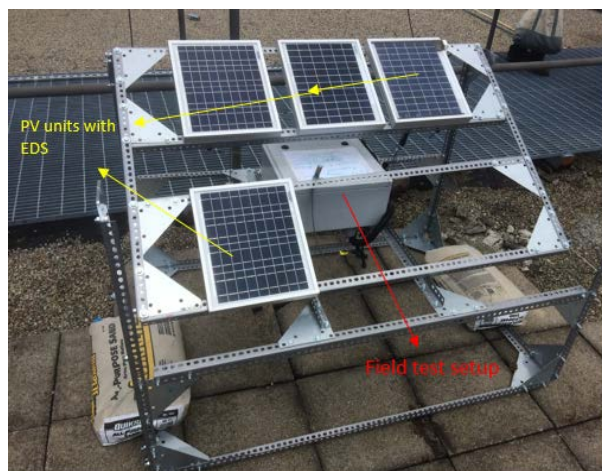
	EDS Sample 1	EDS Sample 2	EDS Sample 3	EDS Sample 4
Trial 1	7%	7%	6%	7%
Trial 2	16%	16%	13%	11%
Trial 3	16%	14%	10%	7%
Trial 4	17%	17%	17%	18%
Trial 5	16%	13%	7%	5%
Trial 6	15%	7%	5%	5%
Average	15%	12%	10%	9%

Field-Test Setup: Design and Construction:

The field-test unit (Fig. 28) is designed for evaluation of the EDS films in solar fields. The operation of the field-test unit is automated with a control system that is powered by a rechargeable battery. The system is designed to be semi-portable and consists of:

- Four EDS laminated PV modules
- Two Control PV Modules (without EDS lamination)
- One PV module with EDS film to be used for recharging the battery
- One EDS film on a glass enclosure used for housing a solar cell pyranometer for its self-cleaning operation.

Each solar panel with EDS lamination has a power supply unit mounted in the rear. The control box houses a single-board computer (Raspberry Pi) and rechargeable battery.



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Fig. 28 – Field-test unit under assembly. Only four solar panels and the control box are shown in the left. For EDS film activation, a control box (shown left) can be used for operating the EDS films with the power supply mounted at the back of each panel (right).

When deployed in a solar field, the field-test unit will provide relevant information on soiling losses and the performance of the EDS films via automated monitoring of the following parameters: (a) Irradiance- corrected I_{sc} , V_{oc} , and FF for both EDS film laminated PV modules and control modules, (b) time of measurement, ambient temperature, and relative humidity (RH), (c) soiling losses (e.g., soiling ratio), soiling rate and average soiling loss measured as a percentage, (d) output power restoration (OPR), (e) performance ratio (PR), and (f) global irradiance at the plane of array (POA) (which is dependent on the latitude of the PV site). Over a field-test period of three to six months, it will be possible to analyze field data for evaluating overall cost and performance.

Use of an electronic data-collection system and the recording of data on a USB flash drive will provide autonomous monitoring of each of the above listed parameters. The control system is shown schematically in Fig. 29.

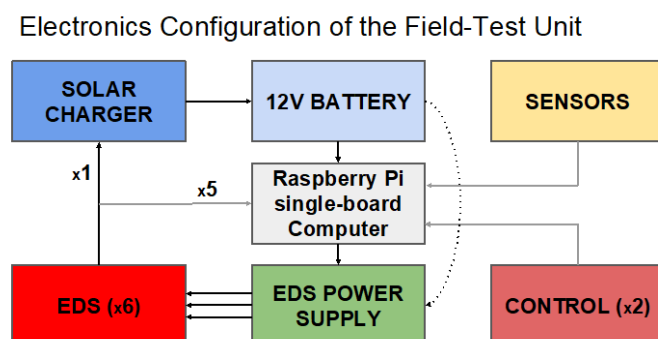


Fig. 29. Control system for autonomous operation of the field test unit.

Once field data has been monitored and collected over the desired period of time, the information will be used to determine the following parameters: (a) Efficiency of EDS films in restoring output power of dust-laden PV modules, (b) Effectiveness of the EDS film in removing deposited dust, (c) Ability to clean solar collectors without interrupting plant operation, (d) Reduction of the O&M cost, (e) Annual energy-yield gain by cleaning solar collectors more frequently in comparison with normal water cleaning cycles and (g) Water conservation.

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Demonstrating the commercial viability of EDS films will depend on such field-test data as well as the total addressable market (TAM) for EDS films. A brief outline of the TAM is provided below.

Economic Analysis Cleaning -- Sustainability, Scalability and Durability

Robotic Vacuum Cleaning with Micro-fiber Cloth Wiper

Their cost analysis referred only the cost of weekly cleaning not on the total revenue loss of the plant due to soiling. They found that weekly cleaning was most the most efficient interval. Given the cost of water and its scarcity as a local resource, however, weekly cleaning could become cost prohibitive for large-scale solar plants unless an alternative method can be found.

Automatic robotic cleaning with microfiber brushes and vacuum cleaners is considered to be a scalable low-water cleaning method [16], but this method requires the customized design and installation of extensive rail systems for transporting the robots over the PV field. . Although water consumption is minimized with such a vacuum cleaning system, installation and maintenance of microfiber brushing and vacuuming to remove sand particles from the surface of utility-scale plants without abrasion of the collectors' surface has not yet been established. Brushing of sand particles introduces abrasion and wear of the vacuum cleaners, leading to ongoing maintenance requirements. Installation and operation of the robots and vacuum cleaners in large utility-scale solar plants with a million or more PV modules and water cleaning of the micro-fiber brush loaded with sand is labor intensive and expensive.

The authors [16] concluded that microfiber-based wiping with vacuum cleaners provides an effective method for producing an overall output gain of 6% if cleaning is performed on a weekly basis. After every brush/vacuum cleaning, a fine layer of dust remains on the surface of the PV modules, with layer thickness increasing as the frequency of cleaning is decreased. The authors estimated the cost of weekly cleaning would be \$54.45/m²/year if a robotic system with microfiber cloth wiper and vacuum cleaner is used.

This discussion on the estimated cost of cleaning does not address comparative revenue losses based on the cleaning processes and frequency adapted. A comprehensive revenue loss analysis must include both cost of cleaning and the reduced soiling losses

EDS Film Based Cleaning

Estimated Operational Cost: If the levelized cost of electricity production (LCOE) is \$0.06 /kWh (current DOE target), then the operating cost for the EDS film (based on an energy requirement of 0.2 Wh/m²/cleaning cycle) will be approximately \$0.13 /m²/year if the PV modules are cleaned twice per week. This estimate does not include the capital cost of installation, which is yet to be determined.

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Estimated Installation Cost of EDS System: The capital cost of an EDS-based cleaning system will depend on the cost of the EDS film itself, the cost of lamination, and the cost of the activating power supply. In addition, the cost of integrating or retrofitting EDS films must be considered. The cost of the EDS film, installation, maintenance, monitoring and control system will be available once we have a startup company or a solar-panel manufacturing company taking the lead toward commercializing the EDS film. The EDS system commercializing company (An original equipment manufacturing firm together with plant operators) would be able to utilize the current resources for EDS film production using a roll-to-roll film manufacturing process together with an EDS-based lamination, encapsulation and integration facilities.

Estimation of the Upfront Cost of EDS-Film Installation: A comparison between the basic construction and assembly of a conventional c-Si PV module versus that of an EDS film stack, as shown in Fig. 30 provides a few common features of a screen-printing of electrodes, encapsulation with EVA films, and the use of a glass cover plate, used in the lamination of EDS films with a crystalline silicon solar cell PV module. In the PV module, the most expensive components are the silicon cells themselves. The overall cost of a PV module is thus dominated by the cost of the silicon solar cells. A good quality PV module with conversion efficiency close to (or higher than) 18% costs approximately \$250/m² (based on current selling price) when the modules are produced at high volume.

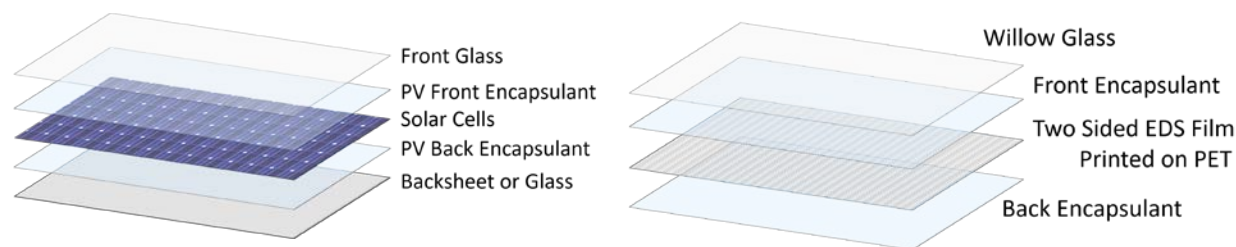


Fig. 30: PV Module assembly (left) showing crystalline solar cells, typically with 36 or 72 series-connected solar cells laminated with optically clear adhesive (EVA) encapsulant sheets, front and back, with back plate (Tedlar) and the front glass plate (low iron) before encapsulation in an aluminum frame. In the EDS film-stack assembly (right) electrodes are printed on a polymer film, encapsulated by optically clear adhesive films between a front glass film (Willow Glass) and a bottom solar collector (PV module or solar mirror).

Solar cells are constructed using wafers of single crystals of purified silicon, textured and coated with antireflective coating, and screen-printed silver-paste electrodes using laser grooved tracks. In comparison, EDS films are printed on PET film via flexographic roll-to-roll printing or screen printing.

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It is reasonable to assume that EDS films, produced in large volume, can be integrated onto a PV module or solar mirror at the solar-collector's manufacturing facility at a cost not exceeding one-fifth of the cost of manufacturing PV modules. Based on this assumption, we arrive at an estimated cost \$85/m². This estimated cost figure represents the printing of electrodes on PET film, lamination via OCA materials such as silicone, polyurethane or EVA, and with a thin Willow Glass cover plate. By comparing the costs of c-Si-PV modules and EDS-film assemblies, it appears that the manufacturing processes for encapsulations are very similar with respect to lamination, except for the solar cell. We thus assume that EDS film cost will not exceed more than 30% of the PV module price when manufactured in high volume. An EDS-film integrated solar collector, mirror or solar panel must be activated by a power supply, adding an additional cost of about \$15/unit.

Based on the assumptions outlined above, a PV module integrated with an EDS film and power supply is expected to cost about \$100/m² with a lifetime of 25+ years, assuming that the solar PV module is integrated with EDS film. Since the EDS operational cost is only about \$0.13 /m²/year (for EDS-based PV cleaning twice per week), the EDS film application should be commercially viable based on the energy-yield gain and conservation of water. Our projection of \$65/ m² is an initial estimate based on multiple assumptions. An OEM investing in EDS ought to test and validate these assumptions in order to establish the commercial viability of this technology.

Estimated Total Addressable Market

As of the end of 2018, the global capacity of photovoltaic power was 518 GW, with an expected growth of 99 GW in 2017 and 109 GW in 2018 [18]. A 1-GW PV plant needs approximately 5 M m² of PV panels. India currently has 20 GW of PV capacity and plans to have a solar plant-capacity of 40 GW 2040. Similarly, Saudi Arabia plans to have 600-GW solar-plant capacity by 2040. Such a capacity would require approximately 3 billion square meters for the panels alone, an area roughly size of Rhode Island. According to the International Energy Agency, the expected growth is estimated to be 100 GW of new plant capacity by 2040 in sun-belt areas where water shortage is critical.

If we consider a total addressable market based on 100 GW of PV and CSP plants with average conversion efficiencies of 18 to 20 %, then the total area required for the solar collectors will be approximately 500×10^6 m². If we assume that EDS film would be applied to 10 GW of additional plant capacity every year, the estimated total addressable market would be 50 million square meters of PV. These assumptions do not include CSP applications.

EDS Technology to Marketing Plan

Except for the field evaluation and detailed cost-analysis based upon field data, most of the steps towards commercialized production of EDS film technology have been completed. These

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steps include (a) proof of concept, (b) extensive laboratory-scale development and evaluation of EDS film for removal of dust collected from different deserts in the world, (c) simulated field conditions performed within an environmental chamber, (d) some field testing at the Atacama Desert (Chile), (e) establishment of high-volume roll-to-roll production and lamination processes in an industrial environment.

Patents: The two patents [19, 20] one on the direct printing of electrodes on the PV modules and the other on the application of the EDS film for integration and lamination are listed in the references. In our joint effort with Saudi Aramco, there are opportunities to file for patents as we develop new processes for full-scale application of EDS films.

Comparative Analysis of Estimated EDS film Cost and Robotic Cleaning with Vacuum Cleaners Cost: Al-Housani, Bicer and Koc [16] recently reported a comparative analysis of different low-water PV-module cleaning processes with respect to their advantages and disadvantages and the relative cost of cleaning. Their cost analysis referred only the cost of weekly cleaning not on the total revenue loss of the plant due to soiling. They found that weekly cleaning was most the most efficient interval. Given the cost of water and its scarcity as a local resource, however, weekly cleaning could become cost prohibitive for large-scale solar plants unless an alternative method can be found.

Thus, if a solar power plant were to have PV modules having a total surface area of 0.5×10^6 m², the annual cost of cleaning operations would be \$25M, and the total cost would be approximately \$500 M over the 20 year lifetime of the robotic cleaning system.

A PV module integrated with EDS film and power supply is expected to cost about \$100/m² based on the comparison between PV module and EDS film production. If the lifetime is 20 years for the integrated unit, and if the operational cost is only \$0.13 /m²/year (if the PV modules are cleaned twice per week), the EDS film application will be commercially viable based on the energy-yield gain and conservation of water. It appears that the cost of the EDS operation would be lower than the robotic operation of the micro-fiber cloth brush with vacuum cleaners.

The discussions presented here address the estimated cost of cleaning based on the cleaning processes and frequency adapted. The revenue loss calculation will include cost of cleaning and the reduced soiling losses achieved by the selected cleaning process.

Model Based Cost Analysis of EDS Film Application: Cost Analysis of the Application of EDS Film Laminated EDS PV Modules

Methods of conducting economic analysis for establishing the cost effectiveness of EDS system for the PV plant in the specific location will be conducted via modeling and quantifying

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the lowering of Levelized cost of Electricity (LCOE), and conservation of water as functions of output capacity of the solar field (name-plate rating). The metrics for this analysis are: (a) LCOE with and without EDS film application, (b) the Internal Rate of Return (IRR) on EDS investment, and (c) the breakeven cost per kWh for installing EDS systems. The analysis requires field data on the effective soiling rate for both EDS – and water-based cleaning and the amount and the cost of water needed for cleaning annually. During the field trials, we will have access to the soiling rates along with the cost for water usage for conventional PV plants from the partnering solar company.

Our approach for cost analysis leverages a publicly available data and system analysis tools such as (1) Greenius Model [21] (developed in Germany) and the (2) System Advisory Model (SAM) developed the U.S. National Renewable Energy Lab. One advantage of using the Greenius model is that some publications provide data on the water-based cleaning strategies for a reference plant site in Spain. We will use this as a reference case.

We would be able to compute the reduction in LCOE and conservation of water as functions of output capacity of the solar field, depending upon location, soiling rates, and cost of water-based cleaning.

Cost Analysis Models

Methods of conducting economic analysis for establishing the cost effectiveness of EDS system for the PV plant in the specific location will be conducted via modeling and quantifying the lowering of Levelized cost of Electricity (LCOE), and conservation of water as functions of output capacity of the solar field (name-plate rating). The metrics for this analysis are: (a) LCOE with and without EDS film application, (b) the Internal Rate of Return (IRR) on EDS investment, and (c) the breakeven cost per kWh for installing EDS systems. The analysis requires field data on the effective soiling rate for both EDS – and water-based cleaning and the amount and the cost of water needed for cleaning annually. During the field-trials, we will have access to the soiling rates along with the cost for water usage for conventional PV plants from the partnering solar company.

Model Based Cost Analysis of EDS Film Applications

(1) Greenius Model: We have conducted an economic analysis for establishing the cost effectiveness of an EDS system intended for PV usage. The metrics of interest in this analysis are: LCOE while using EDS, the Internal Rate of Return (IRR) on EDS investment, and the breakeven cost per kWh for installing EDS films. We have tried to access the cost for water usage for conventional PV plants-- e.g., by reaching out to a partner firm (Fortum Inc). However, these costs are not readily available as yet. Hence, we have used a publicly available system analysis tool (Greenius, 2018). The advantage of using the Greenius model over SAM (Gilman et al. 2018) analysis is that some publications (e.g., Wolferstetter et al. 2018, for CSP)

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provide data on cleaning strategies (such as time of cleaning and irradiance correction) using the Greenius tool. We have used a top-down approach within the Greenius system model to predict LCOE and to determine the comparative cost of operating a reference PV power plant.

Model Setup:

Currently, the sensitivity analysis was conducted for a reference PV Plant in Spain with a levelized energy output of 6.54×10^5 MWh/Annum. The base case (i.e., for a plant without EDS) fixed cost is \$1157/kWp, and the base-case O&M cost is \$11/kWp. The base case LCOE for this plant is \$0.23/kWh. Allied internal rate of return on investment for this plant is 0.41%. These base cases are established based on a PV module's performance of 250W/module, and can be compared with its clean counterpart, which produces 260W/module, 270W/module, 280W/module, 290W/module, and 300W/module. For the LCOE and IRR sensitivity analysis, only the best performance case is presented in this study (300W per module).

Table 23 shows Levelized Cost of Electricity (LCOE) sensitivity for the reference plant with soiled panels by assuming that each soiled panel produces 250W while its clean counterpart produces 300W. Arguably, installation of EDS will increase the investment level (i.e., fixed cost) and reduce the O&M costs. The table shows that percentage change in LCOE (with respect to base case) decreases with reduction in O&M cost and increases with rise in investment. That is, LCOE can be ascertained based on the observed field EDS performance (i.e., increase in wattage from 250W to 300W per panel) and corresponding reduction in O&M cost along with investment needed to install an EDS system.

Table 24 shows the Internal Rate of Return (IRR) sensitivity in the reference plant when each soiled panel produces 250W and its clean counterpart that produce 300W. This table documents that percentage change in IRR (with respect to base case) increases with reduction in O&M cost and reduces with rise in investment. That is, IRR can be ascertained based on the observed field EDS performance (increase in wattage from 250 W to 300 W per panel) and the corresponding reduction in O&M cost along with investment needed to install an EDS system.

Similar tables can be plotted if the solar panel produces 260W, 270W, 280W, 290W, and 300W. The BE cost indicates a maximum cost (\$/kWp) that the power plant can invest on the EDS for the project to breakeven. This table documents that BE costs increases with reduction in O&M cost and with improved PV module performance. This is an anticipated response because improved PV module performance indicates to more energy production, which translates to revenue surplus. Hence, the power plant would have more capital to invest in the EDS for the project to break-even. Similarly, when there is reduction in O&M, the cost savings translate to a higher BE cost. Therefore, the BE cost is an indicator of how much the power plant can spend to install the EDS. It does not have any implications to the manufacturing and production of the EDS film.

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Table 23. LCOE sensitivity for the reference plant with soiled panels by assuming that each soiled panel produces 250 W while its clean counterpart produces 300 W.

		LCOE Decreases as O&M Decreases					
							
% Change in LCOE (for Output of 250W/ Module)							
		O&M Cost					LCOE Increases as
		Base	95%	90%	85%	80%	Investment Increases
Investment Level	Base	-0.5%	-0.6%	-0.8%	-0.9%	-1.1%	
	101%	-0.2%	-0.3%	-0.5%	-0.6%	-0.8%	
	102%	0.1%	0.0%	-0.2%	-0.3%	-0.5%	
	103%	0.4%	0.3%	0.1%	0.0%	-0.1%	
	104%	0.7%	0.6%	0.4%	0.3%	0.1%	
	105%	1.1%	0.9%	0.8%	0.6%	0.5%	
	110%	2.6%	2.5%	2.4%	2.2%	2.1%	
	115%	4.2%	4.1%	3.9%	3.8%	3.6%	
	120%	5.8%	5.6%	5.5%	5.3%	5.2%	
Normalized wrt Base LOCE is 0.2044 Euro/kWhe					for Output of 250 W/ Module		

Table 24: IRR Sensitivity (300W Output)

		IRR Increases as O&M Decreases					
							
		% Change In IRR (for Output of 250 W/Module)					
		O&M Cost					IRR Decreases as
		Base	95%	90%	85%	80%	Investment Increases
Investment Level	Base	24%	34%	41%	51%	61%	
	101%	12%	20%	29%	39%	46%	
	102%	-2%	7%	15%	24%	34%	
	103%	-17%	-7%	2%	10%	20%	
	104%	-29%	-20%	-12%	-2%	5%	
	105%	-44%	-34%	-27%	-17%	-7%	
	110%	-110%	-100%	-93%	-83%	-76%	
	115%	-173%	-163%	-156%	-146%	-139%	
	120%	-234%	-227%	-217%	-210%	-200%	
Normalized wrt Base IRR 0.41%		for Output of 250W/Module					

Table 24 shows IRR (internal rate of return) sensitivity for the reference plant when each soiled panel produced 250 W and its clean counterpart that produced 300 W. This table documents that percentage change in IRR (with respect to base value) increases with reduction in O&M cost and reduces with rise in investment. That is, IRR can be ascertained based on the observed

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field EDS performance (increase in wattage from 250 W to 300 W per panel) and the corresponding reduction in O&M cost along with investment needed to install an EDS system.

(2) SAM Model based economic analysis: Like the Greenius Model, the SAM model is based on the measurements of average annual or seasonal soiling loss for the specific plant site to determine enhancement of performance ratio (PR) using EDS film-based cleaning method compared to the water-based cleaning. The economic gain and the conservation of water will be the determining factors for EDS application. The performance ratio and soiling losses are used in the Python library for the System Advisory Model (PySAM) as the NREL's performance and financial modeling tool for energy systems, and the irradiance information available in Typical Meteorological Year (TMY) datasets that provide annual weather and solar resource data based on historical values. The TMY datasets are organized based on latitude and longitude and are found in NREL's National Solar Radiation Database (NSRDB). The details of the method for calculations are given later in this report.

The analysis requires field data on the soiling index (SI) and the soiling loss rate (SLR) [24-25] measured by using two identical solar panels, one is cleaned with water every day to measure I_{sc} (clean) and the other is left un-cleaned as dust layer accumulate on the surface. The un-cleaned panel is used to measure I_{sc} (soiled). Both the readings of I_{sc} are irradiance corrected (normalized with respect to standard one sun irradiance 1 kW/m^2). An EDS film laminated PV module can be used to collect I_{sc} (clean) automatically without using an water-based cleaning.

$$SI = \frac{I_{sc(avg.soiled)}}{I_{sc(avg.cleaned)}} \quad (1)$$

The soiling loss rate (SLR) per day is given by the average soiling loss per day expressed as

$$SLR = \frac{\Delta(SI)}{\Delta t} = \frac{SI(t + \Delta t) - SI(t)}{\Delta t} \quad (2)$$

where, Δt is the time period, usually one day. The slope of the SI (SLR) plot is a negative quantity, measured by using two identical solar panels, one being cleaned with water every day to measure I_{sc} (clean) and the other is left un-cleaned as dust layer accumulate on the surface, measured by I_{sc} (soiled) as shown in Equation 1. Both the measured values of I_{sc} are irradiance corrected (normalized with respect to standard one sun irradiance, 1 kW/m^2).

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As dust layer deposits on a PV module, it reduces the output power, lowering the optical efficiency ρ of the front glass plate of the module due to soiling losses (attenuation caused by absorption and scattering). The optical efficiency is defined as the ratio of the solar irradiance illuminating the solar cells inside the PV module to the solar irradiance incident on the front glass plate of the module with the deposited dust layer. Thus ρ is a measure of irradiance captures efficiency of the solar cells underneath the glass plate.

$$\text{Optical Efficiency } (\rho) = \frac{G_{cell}}{G_{module}} \quad (3)$$

The optical efficiency $\rho = 1$ when the optical surface is clean it decreases as soiling increases; $\rho = 0$ when the dust layer is thick enough to obscure the sunlight completely for reaching the solar cells. The relationship between the value of ρ as a function of the thickness of the dust layer is exponential for a given particle size distribution of the dust.

Since the daily soiling rate varies widely depending upon the concentration of the atmospheric particulate pollutants and the climatic condition, the average soiling index is measured by the slope of the soiling index curve plotted for a period of 15 consecutive days for a solar panel without any cleaning [25].

If the PV modules are cleaned with water at an interval of every n days i.e. the soiled panels remain un-cleaned for n days, and since the soiling losses are cumulative; if the soiling loss rate is constant, then the soiling loss on the n^{th} day after the last cleaning will be $n \times \text{SLR}$. Thus the optical efficiency (ρ) at any time on the n^{th} day will be

$$\rho = 1 - n|\text{SLR}| \quad (4)$$

The average value of (ρ) representing the irradiance capture efficiency of the solar cells within the PV modules subjected to soiling, will be the average value ρ during the period of n days. The application of the EDS film is aimed to increase the average value of (ρ).

The Performance Ratio (PR) of a solar PV plant is defined by the ratio of actual DC or AC power output to the nameplate DC or AC output rating of the plant. The PR of a PV plant accounts for system losses, including losses in operation, losses in the wiring, inverters and in

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grid connections. PR varies with temperature, shading, soiling, weather conditions, and many other factors. The PR in a well-designed plant varies in the range 0.65 to 0.80. In analyzing the effects of soiling on the Performance Ratio, we will consider all other loss factors are remaining constant and only soiling losses are variables.

Losses in PR due to soiling loss can be measured by comparing the ratio of power or energy outputs of a PV module under soiled and clean surface conditions. Thus, if we use two identical PV modules installed in a plant site in the same orientation as arrays of the PV modules of the plant, and one of the two modules is cleaned every day and the other is left un-cleaned, we can express PR, for the panels as

$$PR = \frac{\sum_i P_{DC}}{\sum_i P_{NP} \times \left(\frac{G_y(\beta, \gamma)}{G_{STC}} \right)} \quad (5)$$

Here, P_{DC} is the measured DC power, G_{STC} is the Standard Test Conditions (STC) solar irradiance (1000W/m^2), $G_y(\beta, \gamma)$ is the annual plane-of-array (POA) irradiance, and P_{NP} is the “Name Plate” rated power output assuming an ideal operating system of the plant. The tilt angle (β) varies depending upon the location and the azimuth angle (γ) is usually zero degree considering the solar PV modules are facing north (in the Northern Hemisphere).

The optical efficiency varies from 0 to 1 where $\rho = 1$, means that the PV module is under clean condition. The soiling effects on the PR can be expressed as

$$PR = \frac{\rho \times P_{DC}}{P_{NP} \times \left(\frac{G_y(\beta, \gamma)}{G_{STC}} \right)} \quad (6)$$

The optical efficiency ρ is the average value of soiling index (SI). The soiling index is given by the ratio of solar irradiance reaching the solar cells to the solar irradiance incident on the PV module.

Financial Viability Analysis

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By comparing the changes in the effective average soiling loss rates or irradiance capture efficiency of the solar panels, we can assess the economic advantages of using the EDS-film based cleaning in a solar power plant. The economic advantage can be calculated by comparing the cost savings for an EDS film laminated panels versus the control panels without EDS.

$$P_{eds} = \rho(EDS) \times \eta_{elec} \times E_{available} \times \$(PPA) \times 365 \text{ days} \times 25 \text{ years}$$

$$P_{ctrl} = \rho(water) \times \eta_{elec} \times E_{available} \times \$(PPA) \times 365 \text{ days} \times 25 \text{ years}$$

$$P_{eds} = \text{Profitability per unit area of the solar panel with EDS film} \left[\frac{\$}{m^2} \right]$$

$$P_{ctrl} = \text{Profitability per unit area of the solar panels without EDS film} \left[\frac{\$}{m^2} \right]$$

$$\eta_{elec} = \text{solar to electricity efficiency, set to 18\% [\%]}$$

$$E_{available} = \text{available solar energy based on TMY analysis} \left[\frac{kWh}{m^2 \text{ year}} \right]$$

$$\$(PPA) = \text{Purchase Power Agreement of electricity} \left[\frac{\$}{kWh} \right]$$

ρ = Optical efficiency based on the soiling loss per day.

To calculate the cost savings, we use the soiling loss rate values derived from the Field-Test unit. The solar to electricity efficiency, η_{elec} , is assumed as 18%. The available solar energy $E_{available}$ is $5.83 \frac{kWh}{year \cdot m^2}$ was derived using PySAM and TMY analysis (NREL SAM Model).

The levelized cost of electricity, LCOE, is assumed as \$0.06/kWh.

For every 1kWp solar installation, approximately 9.29 m² of solar panels are needed with an average efficiency of 18%

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CONCLUSIONS

This report presents a review of the progress made in advancing EDS film technology for mitigating the impact of dust on solar collectors via water-free cleaning, as well as identifying current technical challenges in advancing the technology for industrial production, field trials and marketing. Our experimental data on the performance of EDS films show that: (1) the dust-removal efficiency (DRE) can reach levels higher than 90%, (2) the specular reflectivity (SR) of EDS film-laminated second-surface mirrors reach levels in excess of 90%, (3) the specular reflectivity restoration (SRR) can exceed 90%, (4) the output-power restoration (OPR) of PV modules can exceed 95%, and (5) the optical transmission efficiency (TE) of the EDS films can be greater than 90%. These achievements depend upon the design and fabrication of the EDS films.

Working with Eastman Kodak, we were able to establish a process for manufacturing EDS films using flexographic printing of the electrodes onto transparent polymer films. This process utilizes an existing manufacturing line at Eastman Kodak that allows fabrication of medium-scale EDS films (26 cm $\times$ 30 cm).

We developed partnership with Sandia National Laboratories (NM), Corning Research and Development Corporation (NY), Eastman Kodak (NY), Tomark-Worthen Industries (NH), and EDS Chile SPA (Chile), and produced EDS film-laminated PV modules and demonstrated their self-cleaning functions without requiring water. We have demonstrated that the operational range of EDS films will cover the expected ambient temperature of solar fields at RH cycling varying from 20 to 95% as long as the EDS films are activated in the RH range 20 to 50%.

The EDS films produced at Kodak were laminated at Tomark-Worthen using an industrial scale vacuum laminator to produce EDS film stacks, which can be affixed onto the optical surfaces of PV modules or concentrating mirrors. The EDS film stack consists of the EDS films that have Willow[®] Glass (WG) which has a thickness of 100 μ m as the front surface protecting the electrodes from environmental degradations. The WG sheets obtained from Corning Research and Development Corporation are customized in size and shape to cover the active area of the EDS films. The back surface of the EDS film stack is integrated onto the optical surface of the solar panel or mirror using optically clear adhesive (OCA) films or silicone adhesives.

The power-supply units needed for activating the electrodes of the EDS film provide three-phase, 1.2 kV voltage pulses at a very low current (micro-ampere) level and at a low frequency ($\approx$ 5 Hz). The voltage pulses are applied to the electrodes in a sequence such that the train of pulses resembles a unidirectional traveling wave of electrical field on the surface of the EDS film. The dust particles on the surface become charged electrostatically and are levitated by the Coulomb force.

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The lateral sweeping action of the traveling electric field created by the three-phase voltages pulses sweeps the dust off the surface. The energy consumed by the EDS electrodes is less than 0.2 Wh/m²/cleaning cycle, enabling energy-efficient restoration of output power (OPR) of PV module or specular reflectivity restoration (SRR) for solar mirrors.

Based on the extensive laboratory evaluations and limited field trials, as well as contacts with potential users, we believe that the technology has reached its commercial stage. We have conducted a cost analysis using the National Renewable Energy Laboratory (NREL) System Advisory Model (SAM) and are working on the field trials of EDS films in different solar fields in the US, Chile, India and in the Middle East. A brief description of EDS film performance, construction of the field-test unit, its autonomous operation a solar field is provided. The field-test unit can be used for evaluating the advantages of the EDS film applications in mitigating soiling losses and its performance in increasing energy yield, associated revenue savings, and water conservation is presented

Advantages of EDS film lamination for self-cleaning function of solar collectors include:

1. Water-free cleaning of the dust layer deposited on PV modules and heliostats; removes dust by the application of an electrodynamic field [SEP]
2. Occasional water based cleaning may be needed to remove contaminants like soot, birds' droppings and deposition of photochemical pollutants; overall water consumption for cleaning for solar plants will be reduced by more than 80% [SEP]
3. Maintaining high optical efficiency throughout the year and increased annual energy-yield [SEP]
4. Increased reliability of plant operation
5. Increased optical efficiency may provide a potential benefit in [SEP] having the same energy-yield with a fewer number of PV modules/heliostats [SEP]
6. Energy requirement for cleaning is very small; under 0.2 [SEP] Wh/m²/cleaning cycle [SEP]
7. Cleaning of solar collectors without interrupting plant operation via remote wireless operation of EDS films as needed
8. Reduction of the O&M cost.

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Appendix A

Metrics used for determining the efficacy of dust removal action by the EDS film activation:

A. Dust Removal Efficiency (DRE)

Dust removal efficiency (DRE) = (Surface mass density of dust layer after the EDS film activation) / (Surface mass density of dust layer before the EDS film activation)

DRE is a function of the particle size distribution of the dust layer, relative humidity (RH), resident time of the dust layer going through RH and temperature cycling, and the surface properties of the EDS film and the particles.

B. Solar Mirrors

Specular Reflection Efficiency

SR or SRE = (Specular reflection of the EDS film laminated mirror) / (Specular reflection of the before EDS film lamination)

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The measurement of the specular reflection before EDS film lamination is measured under clean conditions.

Specular Reflection Restoration

SRR = (Specular reflection efficiency restored by the EDS film activation for removing the deposited dust layer) / (Specular reflection of the EDS film laminated mirror with deposited dust layer before EDS operation)

C. PV Modules

Transmission Efficiency (TE) and Optical Power Restoration (OPR)

TE = (Short circuit current I_{sc} of the solar panel with EDS film lamination) / (Short circuit current I_{sc} of the solar panel under clean condition and without the EDS lamination)

Measurements in both cases are performed under illumination at irradiance level > 500 Watts/m²

OPR = (Short circuit current I_{sc} of the solar panel with EDS film lamination and after EDS activation for removing the deposited dust layer) / (Short circuit current I_{sc} of the solar panel with EDS film lamination before EDS activation)

Soiling Metrics

Daily soiling index = $\rho(\text{si}) (i)$ [or $\rho(\text{s-ratio}) (i)$] = $I_{sc}(\text{avg. soiled})(i) / I_{sc}(\text{avg. cleaned}) (i)$

The soiling rate for a given period of time Δt is expressed as $\Delta \rho(\text{si}) / \Delta t = [\rho(t + \Delta t) - \rho(t)] / \Delta t$

Δt needs to be 15 days or longer without any natural (rainfall) or artificial cleaning.

For solar mirrors, the soiling loss affects optical efficiency of the mirrors and is measured by the ratio of the specular reflection losses;

$$\rho(\text{SR}) = \text{Specular Reflectivity (soiled)} / \text{Specular reflectivity (clean)}.$$

The average soiling loss over the period of measurements is determined by the product:

$$\text{Average soiling loss (\%)} = \text{soiling rate} \times \text{measurement period in days}$$

Performance ratio (PR)

$$\text{PR} = (\text{Electrical Yield}) \times (\text{Ref. Irradiance}) / (\text{POA irradiance}) \times (\text{Nameplate Rating})$$

The electrical yield, E_{DC} is calculated from I_{sc} (irradiance corrected) X V_{oc} X FF as discussed above. Using the soiling ratio, we can write

$$\text{PR} = [\rho \times E_{DC} \times 1000 \text{ W/m}^2] / G (\text{POA}) \times \text{Nameplate rating (10 W)}$$

PR varies with temperature, shading, soiling, weather conditions, and many other factors. Reference irradiance is 1000 W/m²; POA refers to the Plane of Array, β is the tilt angle and γ is

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the Azimuth angle of the module and the nameplate rating is the power output under ideal operating condition without any loss.

$$PR = (E_{AC} \times G^*) / (G_y(\beta, \gamma) \times P_M^*)$$

Where E_{AC} is the annual AC energy yield, G^* is the STC irradiance, $G_y(\beta, \gamma)$ is the annual array irradiance, and P_M^* is the rated power output assuming an ideal system. PR generally varies from 0.65 to 0.85. (Ref. Boyd)

Writing PR as:

$$PR = (\sum_i P_{DC} \times G^*) / (\sum_i P_{STC} \times G_{POA})$$

$$P_{DC}(i) = \rho(i) \cdot \eta \text{ (conversion efficiency)} \cdot (G_y(\beta, \gamma))$$

$\rho(i)$ will depend upon the cleaning method and the frequency of cleaning.

Appendix B – List of Publications supported by the DOE Grant

1. Environmental durability of the Electrodynamic Screen (EDS) film as a self - cleaning technology for photovoltaic modules and concentrated solar mirrors to Mitigate energy yield loss caused by soiling. Annie Rabi Bernard, Xuyao Duan, Celia Wilkins, Ryan Eriksen and Malay Mazumder. 47th PVSC IEEE June 14-19, 2020, Calgary, Alberta, Canada
2. Development of Transparent Hybrid Electrode Based Electrodynamic Screen Film for Self-Cleaning CSP Mirrors with High Specular Reflectivity and Environmental Durability - Annie Rabi Bernard, Ryan Eriksen and Malay Mazumder, Proceedings of the ASME ES 14th International Conference on Energy Sustainability -For a Sustainable Planet, Denver, CO, June 7 – 11, 2020
3. Lamination of Prototype Transparent Electrodynamic Screen Films for Their Industrial Production and Application to Self-Cleaning Photovoltaic Modules and Concentrated Solar Power Mirrors Dylan Jones, Merlin Hoffman, Annie Rabi Bernard, Shannon Chang, Celia Wilkins, Ryan Eriksen, Carolyn Ellinger, Sean Garner, Andreas Rothacker, Chris Thellen, Malay Mazumder *MRS Annual Meeting Spring 2020/ MRS Energy and Sustainability, Phoenix, Arizona, April 13-17, 2020*
4. Water Free Cleaning Solution: Environmental Durability of Electrodynamic Screen (EDS) Films in Water-Free Cleaning of Solar Collectors - Annie Rabi Bernard, Ryan Eriksen, Malay Mazumder, 46th IEEE PVSC Conference, Chicago IL. USA, June 16-21. 2019
5. Electrical and Optical Modeling of Electrode Configuration for Optimal Dust Removal in Electrodynamic Screens (EDS) - Joshua Bone, Ryan Eriksen, Carolyn Ellinger, Kevin O'Connor, Doug Garman, Annie Bernard, Malay Mazumder, Mark Horenstein, 46th IEEE PVSC Conference, Chicago IL. USA, June 16-21. 2019

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6. PV Modules and System Reliability Industrial Production and Field Evaluation of Transparent Electrodynamic Screen (EDS) Film for Water-free Cleaning of Solar Collectors - Malay K Mazumder, Carolyn R Ellinger, Kevin M O'Conner, Ryan S Eriksen, Annie A. R. Bernard, Mark N Horenstein, Julius E Yellowhair, Nitin R Joglekar, Sean M Garner, Joshua T Bone, Cristian Morales, Acuna O Hugo 46th IEEE PVSC Conference, Chicago IL. USA, June 16-21. 2019
7. Water and Cost Reduction from the Application of EDS to Facilitate Water Free Cleaning in Concentrated Solar Power R Eriksen, A Turkoglu, A Bernard, N Joglekar, M Horenstein, M Mazumder *MRS Advances* 3 (25), 1405-1410
8. Large-Scale Printing of Micro-Wire Electrodes for Roll-to-Roll Manufacturing of Transparent Electrodynamic Screen (EDS) Films for Self-Cleaning Solar Collectors, Malay K. Mazumder, Caroline Ellinger, Kevin O'Connor, Sean Garner, Julius Yellowhair, Ryan Eriksen, Annie Rabi Bernard, Cristian Morales, Mark Horenstein *2018 MRS Fall Meeting, November 25 - 30, 2018 Boston, MA*
9. Development of Hybrid Structures of Silver Nanowire Electrodes for the Electrodynamic Screen (EDS) Films to Mitigate Energy Yield Loss Incurred by Solar Collectors due to Soiling, Annie A.R. Bernard, Ryan S. Eriksen, Malay.K.Mazumder *2018 MRS Fall Meeting, November 25 - 30, 2018 Boston, MA*
10. How does sand get unipolar charge in an Electrodynamic Screen (EDS) Film?, Annie A.R. Bernard, Ryan S. Eriksen, Mark.N.Horenstein, Malay.K.Mazumder *2018 Electrostatics Joint Conference June 18-20, 2018 Boston*
11. Optimization of Optical Performance and Dust Removal Efficiency of Electrodynamic Screen (EDS) Films for Improving Energy-Yield of Solar Collectors, Annie A.R. Bernard, Ricci la Centra, Eric Argentieri, Ryan S. Eriksen, Sean Garner, Mark.N.Horenstein, Malay.K.Mazumder *World Conference on Photovoltaic Energy Conversion (WCPEC-7) June 10-15, 2018 Waikoloa, Hawaii*
12. Dust Settles, We Don't: The Electrodynamic Screen - a Self-Cleaning Technology for Concentrated Solar Power Mirrors and Photovoltaic Panels Annie A.R. Bernard, Cristian Morales, Ryan S. Eriksen, Sean Garner, Mark.N.Horenstein, Malay.K.Mazumder MRE-2017-0080, *MRS Annual Meeting Fall 2017/ MRS Energy and Sustainability, Boston, MA, November 27th, 2017*
13. Application of EDS to Facilitate Water Free Cleaning in Concentrated Solar Power, Ryan Eriksen, Aykut Turkoglu, Annie Bernard, Cristian Morales, Nitin Joglekar, Mark Horenstein, Malay Mazumder. *MRSF17-2799048, MRS Annual Meeting Fall 2017/ MRS Advances, Boston, MA, November 27th, 2017*
14. Mitigation of Dust Impact on Solar Collectors by Water-Free Cleaning With Transparent Electrodynamic Films: Progress and Challenges Malay K. Mazumder, Mark N. Horenstein, Nitin R. Joglekar, Arash Sayyah, Jeremy W.Stark, Annie A. R. Bernard, Sean M. Garner, Julius E. Yellowhair, Hung Yi Lin, Ryan S.Eriksen, Alecia C. Griffin, Yujie Gao, Ricci La Centra, and Alexis H. Lloyd, *Article · Jul 2017 · IEEE Journal of Photovoltaics*
15. Design, Development, and Evaluation of Electrodynamic Screens for Self-Cleaning Solar Panels and Concentrating Mirrors, Annie Bernard, Cristian Morales, Ryan S. Eriksen, Alecia C. Griffin , Yujie Gao ,Ramakrishnan Lakshmanan, Ricci La Centra, Arash Sayyah,

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- Julius E. Yellowhair, Sean M. Garner, Mark N. Horenstein, Malay K. Mazumder *44th PVSC_IEEE conference 2017*
16. Field-Evaluation of Electrodynamic Screens for Maintaining High Optical Efficiency Operation of Solar Collectors Cristian Morales, Annie Bernard, Ryan Eriksen , Julius Yellowhair, Sean Garner ,Ricci La Centra , Alecia Griffin , Alexis Lloyd; Yujie Gao, Ramakrishnan Lakshmanan ,Mark Horenstein, and Malay Mazumder, *44th PVSC_IEEE conference 2017*
 17. Development of self-cleaning reflective electrodynamic screen and its applications to CSP mirrors for solar thermal energy generation, Annie Bernard, Ryan Eriksen ,Mark Horenstein, and Malay Mazumder, *MRS Fall 2017*
 18. An experimental study on the characterization of electric charge in electrostatic dust removal A Sayyah, DR Crowell, A Raychowdhury, MN Horenstein, MK Mazumder *Journal of Electrostatics 87, 173-179 2017*
 19. Mitigation of dust impacts on solar collectors by water-free cleaning with transparent electrodynamic films: Progress and challenges Malay K. Mazumder, Mark N. Horenstein, Nitin R. Joglekar, Arash Sayyah, Jeremy W.Stark, Annie A. R. Bernard, Sean M. Garner, Julius E. Yellowhair, Hung Yi Lin, Ryan S.Eriksen, Alecia C. Griffin, Yujie Gao, Ricci La Centra, and Alexis H. Lloyd, *IEEE 43rd Photovoltaic Specialists Conference 2016*
 20. Performance analysis of electrodynamic screens based on residual particle size distribution A Sayyah, RS Eriksen, MN Horenstein, MK Mazumder *IEEE Journal of Photovoltaics 7 (1), 221-229 2016*
 21. Electrostatic force distribution on an electrodynamic screen A Sayyah, MN Horenstein, MK Mazumder, G Ahmadi *Journal of Electrostatics 81, 24-36*
 22. Development of Transparent Electrodynamic Screens on Ultrathin Flexible Glass Film Substrates for Retrofitting Solar Panels and Mirrors for Self-Cleaning Function M. K. Mazumder, J. W. Stark, C. Heiling, M. Liu, A. Bernard, M. N. Horenstein, S.Garner, and H. Y. Lin, *MRS Fall 2015*
 23. Electrostatic Charging of Particles in Electrodynamic Screens David R. Crowell, Annie A.R Bernard, Carlos H.P. Coutinho, Michael P. Condakes, Mu Liu, Arash Sayyah, and Mark N. Horenstein *Particulate Science and Technology 2015*
 24. A comprehensive analysis of the electric field distribution in an electrodynamic screen A Sayyah, MN Horenstein, MK Mazumder *Journal of Electrostatics 76, 115-126 2015*
 25. Performance restoration of dusty photovoltaic modules using electrodynamic screen A Sayyah, MN Horenstein, MK Mazumder 2015 *IEEE 42nd Photovoltaic Specialist Conference (PVSC), 1-3*
 26. Environmental degradation of the optical surface of PV modules and solar mirrors by soiling and high RH and mitigation methods for minimizing energy yield losses Malay K Mazumder, Mark N Horenstein, Calvin Heiling, Jeremy W Stark, Arash Sayyah, Julius Yellowhair, Atri Raychowdhury *IEEE 42nd Photovoltaic Specialist Conference (PVSC), 1-6 2015*
 27. Energy yield loss caused by dust deposition on photovoltaic panels A Sayyah, MN Horenstein, MK Mazumder *Solar Energy 107, 576-604 2014*

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28. Electrodynamic removal of dust from solar mirrors and its applications in concentrated solar power (CSP) plants Malay Mazumder, Mark Horenstein, Jeremy Stark, John N Hudelson, Arash Sayyah, Calvin Heiling, Julius Yellowhair 2014 IEEE Industry Application Society Annual Meeting, 1-7
29. Optimization of electrodynamic screens for efficient removal of dust particles Arash Sayyah, Jeremy W Stark, John N Hudelson, Mark N Horenstein, Malay K Mazumder ASME 2014 8th International Conference on Energy Sustainability collocated with the ASME 2014 12th International Conference on Fuel Cell Science, Engineering and Technology
30. Self-cleaning solar mirrors using electrodynamic dust shield: Prospects and progress Malay K Mazumder, Mark N Horenstein, Jeremy W Stark, John N Hudelson, Arash Sayyah, Nitin Joglekar, Julius Yellowhair, Adam Botts ASME 2014 8th International Conference on Energy Sustainability collocated with the ASME 2014 12th International Conference on Fuel Cell Science, Engineering and Technology
31. Mitigation of soiling losses in concentrating solar collectors A Sayyah, MN Horenstein, MK Mazumder Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, 0480-0485
32. Development of self-cleaning solar collectors for minimizing energy yield loss caused by dust deposition Malay Mazumder, Mark Horenstein, Jeremy Stark, Daniel Erickson, Arash Sayyah, Steven Jung, Fang Hao ASME 2013 7th International Conference on Energy Sustainability collocated with the ASME 2013 Heat Transfer Summer Conference and the ASME 2013 11th International Conference on Fuel Cell Science, Engineering and Technology

Appendix C – Degrees Received by the students working on the project

- Bachelor Degrees received by students supported by this project: 11
- MS Degrees received by students supported by this project: 20
- PhD Degrees received by students supported by this project: 4

Appendix D – List of Students supported by the Project

Graduate: Fang Hao, Mu Liu, Paul Chiampa, Eric Argentieri, Preetom Borah, Yujie Gao, Alexis H. Lloyd, Michael Kondakes, Arash Sayyah, Jeremy W. Stark, Calvin Heiling, Carlos H.P. Coutinho, Afzal Sopariwala, John N Hudelson, Daniel Erickson, Steven Jung, Aykut Turkoglu, Shannon Chang, Brian Anthony Cha, Danielle Lobo, Annie Rabi Bernard, Aditya Wikara, Dylan Jones, and Xuyao Duan

Undergraduate: Atri Raychowdhury, Bill Chaiyasarikul, Benjamin Gross, Celia Wilkins, Brian Mahabir, Zachary Wollman, Samuel Evans, Angela Hernandez, Yumin Lisa Wei, William Krska, and Benjamin Livney,

High School: Stephen Lee, Joe Zou, and Daniel Back