Electrostatic dust removal using adsorbed moisture–assisted charge induction for sustainable operation of solar panels

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Dust accumulation on solar panels is a major challenge, as it blocks a large portion of sunlight. Solar panels are therefore cleaned regularly using large quantities of pure water. Consumption of water for cleaning, especially in deserts, poses a substantial sustainability challenge. Here, we present a waterless approach for dust removal from solar panels using electrostatic induction. We find that dust particles, despite primarily consisting of insulating silica, can be electrostatically repelled from electrodes due to charge induction assisted by adsorbed moisture. We experimentally determine dust particle charge by conducting Stokes experiments under an electrostatic field. By considering electrostatic, van der Waals, and gravitational forces, we define the threshold electric potential for particle removal. We also demonstrate dust removal over a broad range of relative humidity, making our approach widely applicable. Last, we develop a lab-scale prototype and demonstrate up to 95% recovery of lost power output using our approach.

INTRODUCTION

As a result of collective efforts to move toward clean energy, renewable energy systems have shown tremendous growth, reaching a capacity of 25% of global power output in 2018 (1). Photovoltaic (PV) systems have played a key role in this growth by increasing their global power production capacity from 9 GW in 2007 to 509 GW by the end of 2018 (2). It is projected that solar power will amount to 10% of global electricity generation by 2030 (3) in comparison to 2.2% in 2018 (4). Along with the increase in number of PV installations, there is also great focus on making cheaper and more efficient solar panel systems (5) including efforts for improving the power conversion efficiency of PV cells (6), use of antireflective coatings for minimizing reflective loss (7), keeping solar panels cool by active and passive methods (8), actively changing the angular positioning to track sun (9), nanotexturing the silicon for maximizing absorbance (10, 11), etc.

Despite all of the recent improvements in PV technology, dust accumulation on solar panel surfaces blocks a significant portion of incident sunlight and remains a major operational challenge for the industry (12–17). Many large-scale solar farms are located in geographical regions that have an abundance of land and sunlight, such as deserts. The list includes some of the biggest solar power projects in the world such as in Tengger Desert Solar Park (China), Bhadla Solar Park (India), Dubai Solar Park, and Desert Sunlight Solar Farm (United States), which are all located in deserts. Although the abundance of sunlight in these locations is favorable for solar power production, these regions also tend to have significant airborne mineral dust (18) that gradually accumulates on solar panel surfaces, reducing their efficiency. We performed an accelerated in-lab study that simulated harsh soiling conditions on a lab-scale solar panel and found that the power output decreases exponentially with dust coverage as shown in Fig. 1 (A and B). In harsh environments with dust accumulation rates close to 1 g/m² per day (17), it takes only about a month for dust accumulation of 3 mg/cm² to occur (19, 20). For example, as shown in Fig 1B, dust accumulation of 5 mg/cm² corresponds to almost 50% loss in power output. There can also be rapid loss of efficiency in regions where dust storms are frequent (17). It has been shown that an average power loss of 3 to 4% on a global scale amounts to an economic loss of 3.3 to 5.5 billion USD (12). Thus, solar panels are usually cleaned regularly (up to several times a month) depending on the severity of soiling conditions (12).

The most common method of cleaning is using pressurized water jets and sprays (19). Since water is scarce in desert regions, it has to be transported from elsewhere before being sprayed onto solar panels. Water-based cleaning contributes up to 10% of the operation and maintenance cost of solar farms based on cleaning frequency (12, 21). Studies report that both PV and concentrated solar power plants consume about 1 to 5 million gallons of water per 100 MW per year for cleaning (21, 22). At a global PV capacity above 500 GW (2), we estimate on the basis of reports (21, 22) that up to 10 billion gallons of water are being consumed every year worldwide for solar panel cleaning purposes, which can otherwise satisfy the annual water needs of up to 2 million people in developing and underdeveloped countries. As the solar install base grows, water consumption by solar farms is only expected to rapidly increase. To eliminate water consumption, some small-scale farms have implemented manual or robotic dry scrubbing (12, 23). However, dry scrubbing is less effective at removing dust and introduces irreversible surface scratching (24) that reduces the light transmittance over time. Currently, the lack of efficient approaches for maintaining dust-free solar panels remains a major challenge in the global effort to drive down the cost of solar energy (12). Therefore, there is a pressing need for alternate cleaning approaches that can eliminate the giant water footprint of the solar industry not only to reduce the operational costs but also to be truly sustainable.

Electrostatic solar panel cleaning has been proposed as an exciting alternative that can potentially eliminate the consumption of water and contact scrubbing damage due to the absence of mechanical components that rub against the panel. Electrodynamic screens (EDS) are the most popular electrostatic dust removal systems.
Some approaches for implementing EDS involve fabricating arrays of interdigitated transparent indium tin oxide (ITO) microelectrodes that are embedded in a dielectric film or installing insulated copper mesh electrodes on top of solar panel surfaces (25–28). Upon activating the electrodes, the electric field propels the dust particles via weak, short-range dielectrophoresis and/or weak, passive triboelectric charging. While the EDS systems are promising and have been successfully implemented in extremely dry environments such as solar panels on Mars rovers (29, 30), there are several challenges for implementation in solar panels on Earth. A key challenge is moisture intrusion over time into the dielectric film that insulates the electrodes due to its finite porosity. Moisture accumulation could eventually lead to electrical shorting of the electrodes and failure of the system (31, 32). Furthermore, embedded interdigitated micro-electrode arrays in EDS are expensive for commercial implementation due to the costs associated with microfabrication (12). In the case of interdigitated copper electrodes, there are also limitations arising from significant shadowing of the surface.

Here, we propose a novel electrostatic approach to “actively charge” dust particles and impart strong Coulombic force for dust repulsion. Our approach overcomes the prior limitations that occur due to reliance on relatively weak, short-range dielectrophoretic/triboelectric force and eliminates the issue of electrical shorting. Our work was motivated by the experiment shown in Fig. 2A, where we observed that dust particles resting on the bottom electrode in a parallel plate setup are repelled from the surface on application of sufficient voltage (movie S1). This occurs because of induction that causes charge accumulation on the dust, as shown in the schematic of Fig. 2B. When we performed similar experiments by replacing dust particles with conductive iron or insulating Teflon particles, we observed that dust particles qualitatively behaved like iron rather than Teflon. Both dust and iron particle liftoff (fig. S1) are removed from the electrode surface when the applied voltage exceeds certain threshold value as shown in Fig. 2C.

Although “dust” is a term that encompasses a wide variety of particulate matter, typical desert dust particles that foul solar panels are mineral particulate matter (13, 17, 18, 33). There can be variation in mineral/chemical composition of the particles depending on the geographical location (18). However, mineral dust particles commonly consist of a significant fraction (~30 to 75%) of silica (34, 35), which is known to adsorb moisture (36). Although pure silica is a good insulting material, adsorbed moisture reduces its apparent electrical resistivity (37), and it becomes charged upon contact with an electrode (38). We use Arizona test dust (Intermediate and miscellaneous test dust fractions from Powder Technology Inc.) also known as crystalline silica dust whose chemical composition emulates that of typical desert mineral dust particles in our experiments (see Materials and Methods) (39).

We make use of the conductor-like behavior of dust particles to repel them from solar panel surfaces. First, we estimated the charge on dust particles and then defined the condition for particle removal in terms of applied voltage. We then varied the relative humidity to study the effect of variation in moisture adsorption on electrostatic dust removal. Last, we designed an electrostatic dust removal system for a lab-scale solar panel by transforming the top surface of the panel into a transparent electrode.

**RESULTS**

**Estimation of charge on dust particles**

To design an electrostatic cleaning system where voltage is the primary control parameter, we systematically study the electrostatic dust removal process. As shown in the free body diagram of a dust particle (Fig. 3A), the electrostatic force \( F_E \) acting to remove the particle from the surface is opposed by the forces of adhesion \( F_A \) and gravity \( F_G \) that tend to keep the particle on the surface. As shown in Fig. 2C, the presence of a critical threshold voltage shows that the particle lifts off from the surface when charge induction results in a strong enough electrostatic repulsive force to overcome adhesion and gravity.

The gravitational force can be determined by knowing the density (assuming silica) and approximate size of the dust particle...
**Fig. 2. Repulsion of dust by electrostatic charge induction.** (A) Dust particles spread on the bottom metallic electrode are observed to repel on application of voltage (~12 kV) between the plates separated by ~1.5 cm. Particles have an average density of 2.6 g/cm$^3$ and consists of up to 77% silica. (B) The electrostatic repulsion results from charging by induction, where charge of same polarity as that of the contacting electrode accumulates on the dust particle. (C) The behavior of dust particles is similar to that of conductive iron particles where particle liftoff happens when the applied voltage reaches a threshold value that enables particles to overcome the force that adhere them on to the surface.

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**Fig. 3. Charge estimation experiments.** (A) Schematic of the forces acting on a dust particle with forces of adhesion ($F_A$) and gravitation ($F_G$) acting against the electrostatic force ($F_E$). Here, to determine $F_E$ charge $Q$ needs to be estimated. (B) Schematic of the experimental setup with parallel plates immersed in silicone oil bath for estimating particle charge. (C) Snapshot from high-speed imaging of dust particles (~327 μm) bouncing between electrodes spaced at 1.5 cm. (D) Estimated charge ($Q$) for different sized dust particles plotted against applied electric field strength $E$. $Q$ scales linearly with $E$ for dust particles similar to what we expect for conducting particles. (E) $Q$ scales proportional to the square of particle size ($-R^2$) indicating the conductor-like behavior. (F) On the basis of $Q_{th} = 4πR^2\varepsilon_0\varepsilon_rE$, we define a nondimensional charge $Q^* = Q/Q_{th}$ that scales as $Q^* \sim 1$ (here, $\varepsilon_r \sim 3$ for oil). We see that, while Teflon shows no sign of charging ($Q^* \sim 0$), $Q^* \sim 1$ for both dust and metallic particles shows that dust particles are exhibiting conductor-like behavior. Error bar corresponds to SD over three experiments and five different particles per experiment.
the actual charge is well approximated by the expression for

\[ Q \approx \frac{4}{3} \pi R^3 \rho \]

Similarly, at the moderate relative humidity range where we performed our experiments (45 to 55%, unless specified), the force of adhesion of microparticles with surface roughness is primarily governed by van der Waals force (40–42). van der Waals force for microparticles is very well charac-
terized and can be estimated by using Hamaker’s model (43) after incorporating a correction factor for surface roughness (44, 45). Last, electrostatic force is given by the product of particle charge and applied electric field \((F_E = QE)\). In our parallel plate electrode configuration, the electric field strength is easily determined. However, since the electrical conductivity of dust particles is not well charac-
terized, the particle charge \((Q)\) remains unknown. Thus, to be able to predict the electrostatic force and thereby the dust removal voltage, particle charge needs to be estimated.

To estimate the charge \(Q\) for dust particles, we performed particle repulsion experiments by immersing the electrodes in a silicone oil bath (38) (see Materials and Methods and the Supplementary Materials) as shown in Fig. 3B. As potential difference was applied between the plates, particles acquired charge and bounced back and forth between the plates. Figure 3C shows the snapshot of high-speed images taken from one of these experiments. Viscosity of the oil (500 cSt) was chosen to be high enough to minimize the effect of inertia, and thus particles attained terminal velocity of motion between the plates quickly compared to the total travel time of particles between the plates (see the Supplementary Materials and movies S3 and S4). We balance the electrostatic force with Stokes drag force, gravitational force, and buoyancy force as \(QE + mg + 6\eta RU + F_B = 0\). We measure the terminal velocity of particles from high-speed images and estimate the charge on particles that lift off from the surface as shown in Eq. 1

\[ Q = \frac{6\eta RU + (\rho - \rho_{oil})\frac{4}{3} \pi R^3 g}{E} \quad (1) \]

Figure 3D plots the charge against the applied electric field strength for dust particles of different sizes. The charge is found to be linearly proportional to the applied electric field strength, as in conducting materials. Similarly, Fig. 3E plots the estimated charge against the particle radius. The accumulated charge is quadratically proportional to the radius \((Q \sim R^2)\). This confirms that charge accumulation occurs on the particle surface rather than in the bulk vol-
ume of the particle, similar to conducting materials (46).

Last, to compare the magnitude of charge on dust particles with that of particles of known electrical conductivity \(\sigma\), we performed silicone oil bath experiments using Teflon \((\sigma \sim 10^{-24} \text{ S m}^{-1} \text{ good insulator})\) and steel \((\sigma \sim 10^{6} \text{ S m}^{-1} \text{ good conductor})\) spheres (fig. S2). While Teflon particles remained stationary at the bottom electrode indicating negligible charge induction, steel particles bounced between the electrodes similar to dust particles. We estimate the charge \(Q\) using force balance. We define a nondimensional charge \((Q^*)\) based on the experimentally estimated charge and the theoretical approx-
imation for charge on a perfect conductor \((Q_{th} \sim 4\pi R^2\epsilon_0\epsilon_r E)\) (46, 47) as \(Q^* = \frac{Q}{Q_{th}}\). In Fig. 3F, we plot \(Q^*\) for Teflon, dust, and steel particles. While charge on Teflon is \(-0\), charge on both steel and dust particle scales is \(-1\). Although the exact numerical value of the non-
dimensional charge is higher for steel particles, the scaling of charge indicates that dust particles act very much like a conductor and that the actual charge is well approximated by the expression for \(Q_{th}\).

The similarity in charging behavior between dust and steel particles is also explained by charge relaxation time \((\tau = \frac{Q}{Q_{th}})\). Charge relaxation time is the characteristic time scale for a particle to reach the saturation charge \(Q_{th}\) (46). For many metals, charge relaxation time ranges from \(10^{-15}\) to \(10^{-18}\) s \((\tau \ll 1\) s\), and hence the particle charging is instantaneous. For dust particles, the variability in chemical composition and the presence of absorbed moisture makes the exact definition of \(\tau\) challenging. However, we can define an effective conductivity \((\sigma_{eff})\) of the dust particle ensemble and thereby an effective charge relaxation time \((\tau_{eff})\). We arrive at an upper limit for \(\tau_{eff}\) by experimentally measuring a lower estimate for the effective conductivity (see the Supplementary Materials, \(\sigma_{eff} > 5 \times 10^{-8} \text{ S m}^{-1}\), fig. S3). We find that \(\tau_{eff} \ll 1\) s, which explains the nearly instantaneous charging behavior of dust and steel.

**Defining the dust removal voltage**

From the estimated charge and resulting expression for charge as a function of voltage, we write the full expression for force balance for a perfectly spherical particle considering electrostatic, gravitational, and van der Waals forces of adhesion. Here, for a given particle size, electrostatic force is limited by the maximum electric field strength that can be sustained in air \((3\) MV/m\)) without causing dielectric breakdown (46). We assume this upper limit for \(E\) and material properties of silica where Hamaker constant \(A \sim 6.3 \times 10^{-20} \text{ J}\) (in air), density \(\rho \sim 2650 \text{ kg m}^{-3}\), and particle surface atomic separation of \(d_o \sim 0.4\) nm (48, 49). We write an expression for the sum of the forces (Eq. 2) and plot it as a function of particle size to obtain the bell-like curve as shown in Fig. 4A. Because van der Waals force scales with particle size, electrostatic force scales with surface area, and gravitational force scales with particle volume, the resulting balance shows that, as particle size becomes larger, \(F_{net} < 0\) due to dominance of gravity. Similarly, as particle size becomes small (expanded inset of Fig. 4A) \(F_{net}\) again becomes \(<0\) due to the dominance of adhesion. However, at intermediate particle sizes, this analysis confirms that electrostatic force is sufficient for the experimentally observed removal of particles from charged surfaces.

\[ F_{net} = F_E - F_A - F_G = (4\pi \epsilon_0 \epsilon_r E^2)R^2 - \left( \frac{A}{6d_o} \right) R - \left( \frac{4}{3} \pi \rho g \right) R^3 \quad (2) \]

To experimentally determine the particle removal condition, we designed the setup shown in Fig. 4B, where dust particles rest on the bottom plate (made of silicon wafer) of the parallel plate setup placed on a weighing scale having 1 mg precision. The top plate is independently held in position such that its weight is not transmitted through the scale (see Materials and Methods). We applied voltage between the plates and measured the reading on the scale as a function of voltage. We define the fraction of dust removed \((M^* = M_{\text{max}} - M_{\text{min}})/M_{\text{max}}\) by nondimensionalizing the scale reading \((M)\) using initial \((M_{\text{max}})\) and final readings \((M_{\text{min}})\). By plotting \(M^*\) against the applied voltage, we obtain the curve shown in Fig. 4C. It can be seen that, for different particle sizes, there exists a unique threshold voltage at which most of the particles are removed. We define this threshold voltage as the dust removal voltage.

Using the expression for force balance, we derive an expression for dust removal voltage as shown in Eq. 3, where \(g \cos (\theta)\) is the normal component of gravity due to the tilt \((\theta = 20^\circ)\) of the plate we introduced, and \(s\) is the separation/gap between the plates \((\sim 1.2\) cm\) (see Materials and Methods).
Particle size. We assume material properties of silica. The net vertical force acting on a dust particle in contact with an electrode as a function of

\[ F_{\text{net}} = F_A + F_G \]

\[ (4\pi \epsilon_0 \epsilon_r E_{\text{th}}^2) R^2 = C_\text{r} \left( \frac{A}{6 d_0^2} \right) R + \left( \rho \frac{4}{3} \epsilon_r \cos(\theta) \right) R^3 \]

\[ E_{\text{th}} = \frac{V_{\text{th}}}{s} \]

\[ V_{\text{th}} = \sqrt{\left( \frac{C_\text{r} A s^2}{24 \pi \epsilon_0 \epsilon_r d_0^2} \right) \frac{1}{R} + \left( \frac{\rho \epsilon_r \cos(\theta) s^3}{3 \epsilon_0 \epsilon_r} \right) R} \]

Notice that we also introduce a roughness correction factor \( C_\text{r} \) in front of the van der Waals force term based on modified Rumpf model (see the Supplementary Materials) \( 44, 45 \). This factor accounts for the rough surface topology (see scanning electron microscopy image in fig. S4A) of the dust particles, which is shown in the atomic force microscopy (AFM) image of Fig. 4D. Nanoscale roughness reduces the force of adhesion significantly \( 50 \) and must therefore be considered in this force balance. We estimate \( C_\text{r} \) by measuring the value of surface roughness using AFM \( (\sigma_{\text{RMS}} \approx 25 \text{ nm}) \) and plugging in the value for particle radius \( R \) and parameter \( d_0 \) in eq. S11. The observed value of surface roughness and the estimated values of \( C_\text{r} \) that we use in our force balance model are in alignment with those estimated by the modified Rumpf model. The exact value of \( C_\text{r} \) is dependent on the size of particle \( R \) as described in eq. S11. Since our particle sizes vary by a factor of \( 40 \) (from \( \approx 7.5 \text{ to } 327 \mu m \)), the estimated \( C_\text{r} \) values also vary significantly (by a factor of \( \approx 30 \) from largest particle size to the smallest). The effect of adhesion force is predominant in small particles, and large particles are mostly influenced by only gravitational force. Therefore, \( C_\text{r} \) is more relevant for smaller particles \( (<30 \mu m) \). For particle size on the order of 10 \( \mu m \), the estimated value of \( C_\text{r} \) is \( \approx 10^{-2} \), meaning that the force of adhesion compared to that of a smooth surface could be reduced by up to two orders of magnitude, as suggested by models and experiments in literature \( 45, 51, 52 \).

We nondimensionalize the horizontal axis of Fig. 4C by normalizing the measured voltage with \( V_{\text{th}} \) and plot it in Fig. 4E \( (V^* = V/V_{\text{th}}) \). We see that all curves collapse onto a single nondimensional curve, suggesting that our simple model captures the essential physics of the induction-based dust removal process. Thus, \( V^* = 1 \) defines the nondimensional criterion for dust removal.

**Effect of humidity**

Moisture adsorption on dust particles changes with the relative humidity of the ambient environment, which fluctuates in outdoor conditions depending on the time of the day and the season.
Because charging depends on moisture adsorption (38), we expect that dust removal will also depend on humidity. To study the effect of changing humidity, we devised an experimental setup (Fig. 5A) where electrodes were placed inside a sealed acrylic chamber with two inlets, one for nitrogen purging to decrease the humidity and another for flow of humid air to increase the humidity. A wireless humidity sensor placed inside the chamber measured the realtime humidity.

The bottom electrode was made of smooth rectangular silicon cut from silicon wafer to minimize the effect of surface irregularities on adhesion. On application of voltage (10 kV), dust particles were removed, which was quantified using optical microscope imaging of the remaining dust on silicon wafer (Fig. 5B). Figure 5C shows a microscope image from one of the experiments with remaining dust particles (~30 um) appearing as white dots on the silicon wafer, which appears black. We use the percentage area of the wafer covered by particles as a measure of dust removal.

Relative humidity was varied between ~10 and ~95% (see Materials and Methods) for dust particles of different sizes, as shown in Fig. 5D. At low relative humidity values (<30%), dust particles remained stuck to the silicon surface due to a lack of moisture-assisted charging. However, for relative humidity values above 30% and even as high as 95%, dust removal was highly effective. Desert regions typically experience daily fluctuation in humidity, where during the daytime, relative humidity tends to be low (below 30%), and during night, the humidity rises followed by the cooling of atmosphere and sometimes even results in humidity saturation (18, 53). Therefore, our electrostatic dust removal technique can be deployed and used as part of a daily cleaning when the humidity rises. For other geographic regions where there is moderate (~50%) or high (>75%) relative humidity, our approach works well to remove most of the dust particles as we demonstrate in Fig. 5D. This makes our induction-based approach robust and widely applicable for various geographical locations.

We further confirm the humidity-based charge induction by performing experiments using silica beads. We find that pristine silica beads get charged and completely repelled off from electrodes on application of voltage (fig. S5A and movie S5). The hydrophilic nature of silica makes it possible for the particles to adsorb sufficient moisture to experience sufficient charging. However, silica particles coated with OTS [trichloro(octadecyl)silane], a molecule with hydrophobic end group, are made hydrophobic and cannot adsorb sufficient moisture even at 55% relative humidity. Therefore, OTS-coated silica beads are not completely repelled off from the electrodes (fig. S6A and movie S6). These observations indicate that charging is governed by the hydrophilic nature of particles that result in sufficient moisture absorption, which results in charge induction.

**Lab-scale prototype**

Last, we designed and fabricated an electrostatic dust removal system for a lab-scale solar panel. The glass plate on top of the solar panel was coated with a 5-nm-thick transparent and conductive layer of

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**Fig. 5. Dust removal with varying humidity.** (A) Schematic of the humidity chamber experimental setup with nitrogen purge for reducing humidity and compressed air bubbler for increasing humidity. There were two ports for connecting the electrical leads and one port for gas exit. (B) Schematic of optical microscope imaging of dust particles that remained on the bottom electrode after applying voltage. (C) Microscope picture of remaining particles (size ~30 µm) after applying 10 kV across the parallel plates spaced by 1.5 cm. (D) Percentage area of the surface covered by particles for different particle sizes across varying humidity. Although dust particles do not get removed at low humidity, electrostatic repulsion works for a wide range of relative humidity values.
aluminum-doped zinc oxide (AZO) using atomic layer deposition (ALD) (see Materials and Methods) and forms the bottom electrode (Fig. 6A). The top electrode (made of aluminum) is mobile to avoid shading the solar panel and is translated along the panel during cleaning using a linear guide stepper motor mechanism (Fig. 6B). When a voltage ~12 kV is applied across the electrodes (calculated from our model to satisfy $V^* > 1$), dust particles are removed from the solar panel surface as the top electrode passes by the surface (movie S7). The output power was measured before and after cleaning for different dust particle sizes (Fig. 6C), and we measure a 95% recovery in the lost power after cleaning for particle sizes greater than ~30 µm.

For real solar farms, dust particle size distribution is dependent on the geographic location. It has been shown that the size distribution varies from 0.8 to 1000 µm, and for many locations, the mean dust particle size is above ~30 µm, making our approach highly practical (54). There are also several locations where the mean particle size falls below ~30 µm. However, it must be noted that the total optical loss by soiling is due to a combination of absorption, reflection, and scattering of light by dust particles. Unless the particle size is on the order of wavelength of light (submicron), absorption and reflection (shadowing) losses are predominant, which increases proportional to the surface area of the particle (55). Our approach can effectively remove the larger particles (>30 µm) in a particle size distribution with mean size <30 µm that can potentially contribute to more severe soiling loss and provide significant improvement to the efficiency and reduction in the water usage.

For manufacturing transparent conductive surfaces, ALD technique is an already established industrial standard in PVs for smaller substrates. Also, there is quite a lot of interest to use transparent conductive oxides such as ITO for developing thin film solar cells (56). Since we provide a uniform coating, there are no complex microfabrication steps involved (unlike embedded microelectrodes in prior works), which eliminates significant portion of the cost, making our embodiment much practical to scale up. All we need to provide is a simple retrofit of a thin transparent film with an appropriate conductive coating on top of the solar panel. For high throughput, techniques such as roll-to-roll deposition can be used (57). Since we are not limited by the resistance of the thin film due to zero current flow between the electrodes, we can make the coating as thin as possible. The thickness of our current coating is ~5 nm. However, it could be as small as 1 nm or even subnanometric, which will significantly reduce the cost and minimize any potential optical losses.

DISCUSSION

In summary, we demonstrate a simple electrostatic induction–based approach for mitigating the dust accumulation problem on solar panels. Our method is based on the principle of electrostatic dust repulsion and utilizes a simple retrofit mechanism that can be easily integrated into existing solar panel arrays. The dust removal system is effective for a wide range of dust particle sizes, with a 95% recovery rate for particles greater than ~30 µm. This approach is highly practical for real-world solar farms, as it does not require complex modifications to the existing infrastructure. The use of transparent conductive oxides ensures minimal optical losses, allowing for high efficiency and reduced water usage. The simplicity of the mechanism also makes it scalable and cost-effective, making it a viable solution for improving the performance of solar panels around the world.
panels to recover the lost power output. We find that dust particles, although predominantly consisting of insulating silica material, can be made to repel from surfaces using moisture-assisted charge induction. We experimentally estimate this charge and show that the dust particles are electrically conducting. We characterize the dust removal process for different particle sizes and derive an expression for the voltage required for particle removal. Furthermore, we show that our approach can recover 95% of the lost power and is effective whenever the relative humidity of the ambient environment is greater than ~30%. We discuss how we can leverage ambient humidity fluctuation to make our approach widely applicable to solar installations around the world. Given the significant efficiency losses posed by dust fouling and the associated water footprint for cleaning the panels, we expect that our waterless electrostatic cleaning can provide an efficient and cost-effective approach for maintaining dust-free solar panels, contributing to sustainable operation of solar farms.

**MATERIALS AND METHODS**

**Equipment and materials**

1. DC high-voltage power source: Spellman, model no. SL30P600.
2. Mini solar panel: Adafruit, model: medium 6V 2W.
3. Stepper motor with linear guide: FUYU FSL40 Linear Guide Slide Stage Actuator motorized by Nema 23 Stepper Motor.
4. Stepper motor control: Adafruit Metro M0 Express with DRV8833 driver.
5. Optical microscope: Zeiss, model: Axio Zoom.
6. Multimeter: EXTECH, model: EX540.
7. Dust particles: Arizona Test Dust particles and iron particles of various mean sizes were obtained from Powder Technology Incorporated. Dust particles have an average density of 2.6 g/cm³ and consist of up to 77% silica (39). Particle diameters (means ± SD) of different size distributions that we used are the following: 15 ± 2, 30 ± 5, 50 ± 5, 79 ± 20, 159 ± 25, 256 ± 20, and 327 ± 12 µm.
8. Stainless steel microspheres 7.8 g/cm³ density of various sizes were purchased from Cospheric LLC.
9. Silicone oil (500 cSt) was purchased from Sigma-Aldrich.
10. Weighing scale for dust removal voltage measurement experiments: Hogentogler & Co. Inc.
11. Wireless humidity sensor: SensorPush.

**Charge estimation experiments using silicone oil bath**

The bouncing of dust particles between parallel plates occurs at uniform velocity when the electrodes are immersed in high viscosity silicone oil (500 cSt). Too low of a viscosity of the medium (air or low viscosity silicone oil) does not allow the particles to reach terminal velocity within the time duration that it takes for dust particles to travel from one plate to another. Theoretically, it should still be possible to estimate the charge on particles by balancing electrostatic, gravitational, inertial, and viscous forces. Inertial forces could be estimated by experimentally determining the acceleration using high-speed imaging. However, since dust particles are not perfectly spherical, particles rebound between the plates at random velocity depending on the orientation of impact (movie S2). This makes it difficult to extract useful information from the high-speed images of dust particle oscillation in low viscosity medium. Too high viscosity (>1000 cSt) is also not favorable, because the thin oil film between particle and the electrode surface takes long time to get displaced for dust to physically contact the electrode for getting charged. Thus, appropriate viscosity of silicone oil was selected such that inertia is negligible but displacing the oil film does not take long time.

**Experiments for determining dust removal voltage**

The dust removal voltage was estimated by measuring the reading of the weighing scale against the applied voltage. Dust particles took off from the bottom plate placed on a three-dimensionally printed fixture on the weighing scale as applied voltage was increased. At a certain threshold voltage, most of the dust particles were removed. This shows up as a sudden jump in the $V$ versus $C$ curve as shown in Fig. 4C. Since a fraction of electric field lines starting from the bottom plate end up on the top portion of the top plate, few particles land on top of the top plate after taking off from the bottom plate (movie S1). Therefore, to avoid measuring the weight of these particles, the top plate was held separately in place without letting its weight fall on the weighing scale. Also, the parallel plates were tilted a bit to preferentially let most of the dust particles to fall onto one side assisted by gravity. We use the tilt angle ($\theta$ ~20°) to get effective normal component of gravity [$g \cos (\theta)$] in Eq. 3. The scale readings were taken only after switching off the high voltage, otherwise the electric field from the top plate pulls the bottom plate up, reducing the scale reading. Since this experiment is really weight sensitive, because the total weight of dust being removed from the plate is only ~1 g, the electrical wire that connects to the bottom plate was taped firm in its position to make it not move and perturb the measurement.

**Experiments with varying humidity**

Humidity was controlled in a sealed acrylic chamber by controlling the flow of nitrogen or compressed humid air. Nitrogen purging was very effective for achieving relative humidity as low as 10%. For increasing the humidity, a typical humidifier that creates mist was initially tried and was found to be not effective. This is because the droplets from the mist get deposited on the dust particles, and thus particles remain stuck on the silicon surface along with the water drops even after applying voltage, owing to the hydrophilic nature of the surface. Hence, we bubbled compressed air through a porous stone (aeration stone) into a water bath that resulted in humid air without entraining any water drops. This air was passed into the acrylic chamber to increase the humidity. Increasing the flow rate of air through the bubbling stone, in general, increases the relative humidity. However, there is a threshold flow rate (estimated by trial and error) of compressed air beyond which increasing the flow rate decreases the relative humidity owing to a smaller fraction of water vapor compared to air. By this method, we were able to push the humidity of the chamber up to ~80%. The flow rates of nitrogen or compressed humid air were controlled manually to attain different humidity values ranging from 10 to 80%. To achieve higher humidity values (from 80 to 95%), we used a wet sponge that was placed inside the fully sealed acrylic chamber and waited for evaporation to take place. It took up to 14 hours for the chamber to become 95% humid.

**ALD for fabricating transparent electrode**

ALD deposition of AZO on glass substrate was performed by coating ZnO and aluminum layer by layer at Center for Nanoscale Systems, Harvard University. The layer thickness of ZnO and Al is in the ratio of 40:1, such that the composite AZO coating has 2.5%
doping of Al in ZnO. We measure the transmittance of AZO-coated glass using an ultraviolet-visible spectrometer. The transmittance (~90%) is very close to that of a pristine uncoated glass (~92%) surface for most of the wavelengths of the visible spectrum (fig. S6).

**Translation mechanism for moving top electrode**

The top electrode is made of rectangular aluminum and is electrically grounded. The electrode is fixed on the moving stage of a linear guide actuator that makes the plate translate along the top surface of the solar panel. Lead screw rotation is controlled by a NEMA 23 stepper motor. To control the stepper motor, we make use of an “Adafruit Metro M0 Express” microcontroller coupled with a DRV8833 stepper motor driver. The microcontroller and driver need not be powered separately, as the power for the driver is taken from the microcontroller. To have precise input voltage and current control, we can power the microcontroller using a DC voltage source. Alternately, the microcontroller can be simply powered using a 9-V battery. Depending on the counter torque that is acting on the stepper motor, we will need to increase the input voltage as we find from operating the dust removal mechanism. In such cases, we make use of DC power supply at a fixed current but variable voltage setting.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at https://scienceadvances.maca.org/doi/10.1126/sciadv.abm0078

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