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Electrostatic dry cleaning of solar panel Surfaces: how to make it cost effective?

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Abstract

The recent unprecedented advancements in solar panel deployment worldwide have also aroused much interest in various dry-cleaning methods to tackle soiling-related problems. A more recent work of MIT, USA, is based on cleaning through Electrostatic Induction by coating the top of the panel with an AZO layer and moving an EHT (Extra High Tension) biased metal electrode over it. The present approach we suggested eliminates the need for the top of the solar panels to be electrically conducting and optically transparent, simultaneously making the entire process simple, economically feasible, and sustainable. Moreover, this work proposes an additional enhancement to this cleaning process. After applying an EHT supply for cleaning, a short burst of air can be introduced to improve the effectiveness of dust removal further, ensuring even more satisfactory results.

1. Introduction

With the ever-increasing deployment of Solar PV technology worldwide, the problem of keeping the panels clean has received focused attention in recent years. Numerous studies have established that the efficiency of PV cells/modules in generating energy is reduced due to the accumulation of dust particles on their exposed surfaces, commonly referred to as the soiling effect. This phenomenon significantly impacts the optical, thermal, and electrical properties of PV systems, particularly in the spectral range of 450–500 nm, where the optical intensity peaks. According to research by Aritra Ghosh [1], it has been highlighted that a soiled PV system in

India can experience daily performance losses of up to 0.6%. Furthermore, data from literature studies and experiments indicate that approximately 4 to 7% of global PV generation is lost due to dust accumulation. Looking at the larger picture, it is projected that by 2023, the global monetary losses incurred in PV generation, solely due to the soiling effect, could amount to around 3 to 5 billion euros [2,3].

Deluge washing is the most common way to keep solar panels clean, which requires copious amounts of clean water. In many areas with high solar insolation, like in deserts and arid zone areas, water availability for sustaining life is a problem. Alternative ways to clean, now used for large Solar installations, is robotic cleaning using brushes. In recent years, contactless cleaning by Electrodynamic Screen (EDS), which, in fact, is an Electrostatic cleaning technique based on dielectrophoresis, has been investigated a lot, mainly by Boston University, USA group (BU) [4-6,7]. This involves inducing a charge polarization on otherwise neutral dust particles by exposing the same to a non-uniform electric field. This is schematically shown in Fig 1. The necessity of such a device was first felt by NASA back in 1967 for their space missions. During a collaborative program with BU and IIEST, Shibpur, we had many exchanges with the Boston University group led by Prof. Malay Mazumder and with M/s Sol Clarity, a BU start-up, and the only EDS manufacturer. Due mainly to these interactions, we now appreciate the problems related to this technology. S. Patel et al. [8] have recently reviewed this device and related technologies. An EDS is powered by a pulsed high-voltage supply that removes the dust particles, first by energizing them, lifting them, and then gradually swiping them away from the panel. Their work mainly focuses on 3 Ph EDS. IIEST, Shibpur has reported extensive research on the single-phase EDS fabricated by Laser scribing of transparent conducting oxide-coated glass samples [10]. Though single- and three-phase EDS systems have given substantial dust removal efficiency, scaling them up to industrial panel level remains difficult. Moreover, environmental variables like humidity also play detrimental role in reducing their efficiency for practical operation.

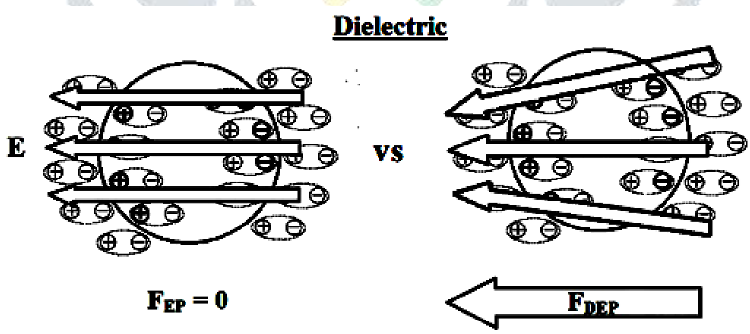


Fig. 1. Dielectrophoresis phenomenon: Particles being dragged or pushed in a non-uniform electric field.

The dielectrophoretic force, F_{DEP}, exerted on a spherical particle of radius r by dielectrophoresis is described by the equation (1) [11],

$$F_{DEP} = 2\pi r^3 \varepsilon_L R_e\left(\frac{\varepsilon_P^* - \varepsilon_L^*}{\varepsilon_P^* + 2\varepsilon_L^*}\right)\nabla|E|^2 \qquad (1)$$

in which 'r'is the radius of the particle, ε_P^* & ε_L^* are the complex permittivity of the particle and the surrounding medium, respectively, and E is the electric field strength.

H. Kawamoto & Megumi Kato in the year 2018 reported "Electrostatic Cleaning Equipment for Dust Removal from Solar Panels of Mega Solar Power Generation Plants" [12]. This is, again, seen as a variation of EDS. In another interesting manifestation of Dielectrophoresis, Nami et.al [13] experimented with so called moving EDS, where one opaque EDS made on a PCB of small size, was made to move over a large enough solar panel, with a finite air gap in between. It can, thus we called the first example of contact less electrostatic dust cleaning. However, in their cited paper no mention of exact air gap distance is mentioned. The fact that EDS could be moved, and dust cleaned one can estimate that the gap distance may at least be a few millimeters. Deviating from all these MIT, USA group in an important publication entitled "Electrostatic dust removal using adsorbed moisture–assisted charge induction for sustainable operation of solar panels" by Sreedath Panat and Kripa K. Varanasi reported a very detailed investigation of dust cleaning based on forces of Electrostatic Induction [14], details of which are described in the patent U.S. application no. 62/859,654, international patent application no. PCT/US20/36829 [15]. This differs from EDS in the sense that such cleaning efficiently works also on higher humidity levels. For such cleaning to work the researchers require to have a thin transparent conducting AZO layer, on the top glass cover. It is, however, felt that depositing a thin AZO layer on commercially sold Silicon Solar panels will be prohibitively expensive proposition. A conservative estimate from industry sources Rs 5000/Sq meter in India.

However, for the particle sizes not too small, the analysis presented by Panat & Varanasi states that electrostatic force appears to be sufficient for the experimentally observed removal of particles from charged surfaces [14, 15]. The net force acting on the dust particles according to their analysis is given by the equation (2) [14, 15],

$$\begin{aligned} F_{net} &= F_E - F_A - F_G \\ &= (4\pi\varepsilon_0\varepsilon_r E^2)R^2 - \left(\frac{A}{6d_0^2}\right)R - \left(\frac{4}{3}\rho\pi g\right)R^3 \end{aligned} \qquad (2)$$

F_{net} = Net Force exerted on a dust particle under removal, F_E = Electric Force of induction, F_A = Total forces of adhesion, F_G = Force due to gravity, R = Radius of the particle, A = Hamacker's Constant, d_o = distance between the particle and the surface, ρ = density of the particle, g = gravitational constant, ϵ_o = absolute permittivity, ϵ_r = relative permittivity.

We in this communication, critically examine their findings and suggest a more cost-effective electrostatic cleaning, without any TCO coating applied on the top cover glass of the panels, which is made of toughened Borosilicate glass, again further AR coated by the glass manufacturers themselves. Applying, therefore, any AZO or any TCO coating on already AR coated glass will interfere with the AR action. This will require, if at all desired, the development of a coating recipe which is at the same time transparent and electrically conducting and demonstrates an anti-reflection behavior. We have, through a detailed investigation being reported here have tried to examine how efficiently dust can be removed from a solar panel which does not have a TCO coating at the top. In our case we have conducted most of experiments from dust samples obtained from Jodhpur, Rajasthan, India. This is a hot and arid region with high solar insolation and a suitable area for dry cleaning of Solar panels. India's largest Solar PV plant of 2.2 GW capacity, Bhadla Solar Park, is also in Rajasthan. A microscopic image of a typical sample is given in supplementary information S1. There is much distribution in particle size as can be seen from the photographic images captured.

2. Methods

In this method, we utilized a digitally controlled movable platform equipped with an activated electrode to charge and subsequently remove dust particles deposited on any type of surface. To conduct our experiment, we constructed an in-house cleaning platform using acrylic sheet material. This platform is designed to accommodate a 1 ft x 1 ft solar PV panel as the substrate to be dry cleaned. To enable the cleaning process, we incorporated a trolley with a variable height adjustment mechanism, allowing the activated electrode to move along the surface that requires cleaning. Additionally, the setup includes provision for housing various electrical and electronic components, which are required for sensing and motion control. The components of the dust cleaning setup, referred to as **ESPDC** (**E**lectrostatic **S**olar **P**anel **D**ust **C**leaner), are illustrated in the schematic provided below (Figure 2).

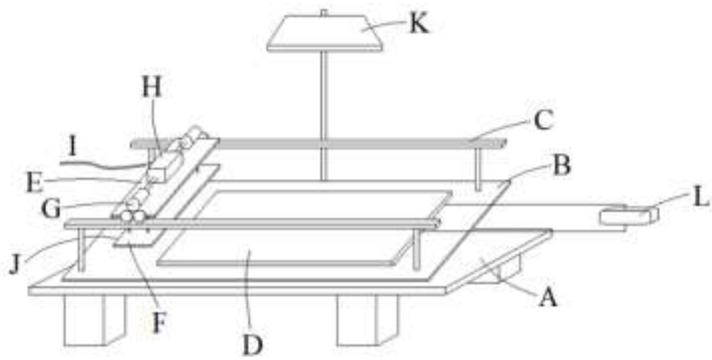


Fig. 2. Schematic design of the cleaning set up **ESPDC** (**E**lectrostaic **S**olar **P**anel **D**ust **C**leaner) along with its components

Lab-scale prototype of **ESPDC** (**E**lectrostatic **S**olar **P**anel **D**ust **C**leaner) is shown in Figure 3.

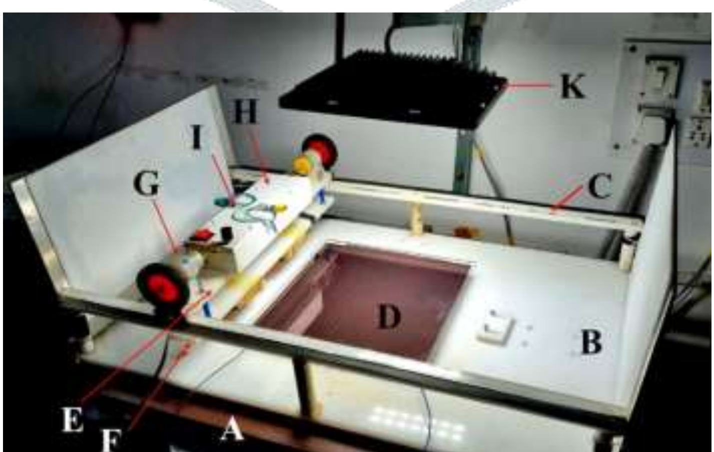
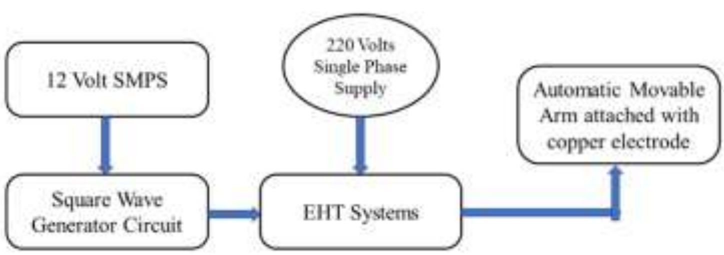


Fig. 3. ESPDC (**E**lectrostatic **S**olar **P**anel **D**ust **C**leaner): Lab-scale prototype.

Here **A** is the cleaning Table. **B** is the base for the cleaning substrate. **C** is the mechanical rails on which the trolley moves. **D** represents the cleaning substrate or the PV cell Module. **E** in the figure denotes the wheeled moving trolley**. F** is the attached metallic plate to it. G here represents the DC stepper motor that runs the wheels of the moving trolley, where H is the microcontroller unit block for the two stepper motors**. I** denotes the power supply to the controller block & the metallic plate, respectively. **K** is the high-intensity light source that powers the PV module/cell under cleaning**.** A digital panel meter records the real-time difference between the short circuit current of the PV cell/ module at pre- and post-cleaning conditions, thus, gives the Dust Removal Efficiency (DRE).

Under our scheme dust was deposited manually through a metallic sieve of gap ~ 50 µm. For the electrical components, an 11kV external DC supply was used to generate high electric field on deposited dust. A micro-controller based movable electrode system is used in this cleaning process. The speed of the movable electrode can be varied on a real time basis, with respect to the thickness as well as type of the deposited dust. A schematic of the system is given in Fig.4 and a video of the demonstration model of movable electrode made of Arduino, IR sensor module, and Centre shaft DC motor can be found in the supplementary information S2.



Once the activated electrode is powered with the 11 kV supply, it is allowed to move two and from over the cleaning substrate and ,thus, achieving the dust removal. For removal studies we have mainly used dust from Jodhpur, as a representative of dust prevailing in Indian conditions. However, it has also been validated with dust samples brought from Haridwar as also that collected from Solar panels at IIEST roof top.

Dust type	Approx.maximum diameter(µm)	Approx. Minimum diameter (µm)
Rajhasthan Dust	284.82	118.03
Haridwar Dust	192.95	89.59
IIEST roof top Solar PV Dust	45	11.21

Table 1 Brief details of different type of dust samples used for present investigations.

2.1. Dest cleaning using a very sensitive electronic balance on a variety of substrate types.

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The DRE or dust removal efficiency was estimated with a commercially available electronic balance (FC 50) ,which gives a resolution of 0.001 mg. For the experiment, two commercially available Si-wafers, and two glasses (one bare and one ITO-coated) have been used. The weight values were measured for the bare substrate (w_b), the substrate with manually deposited dust (w_d), and the substrate after dust removal (w_c), respectively. The DRE or dust removal efficiency was estimated by the following equation (3).

$$\text{Dust Removal Efficiency } (\%) = \frac{w_d - w_c}{w_d - w_b} \times 100 \qquad (3)$$

We obtained three readings for each type of substrate and calculated the Dust Removal Efficiency (DRE) values, subsequently determining their averages. This process was repeated for four different substrate types, resulting in four DRE values. Additionally, microscope images of the dust particles ,used in the experiments, can be found in supplementary information S1.

2.2. Dust Cleaning Experiments with Silicon solar PV module:

Manufacturer rating of silicon module (manufactured by HBL Power system Ltd): Model No. HB-06503, PV Module HB-3, Maximum Power (Pmax) 3 W, Open Circuit Voltage (Voc) 10 V, Short Circuit current (Isc) 0.40 A, Voltage at maximum Power (Vmp)8.50 V, Current at maximum Power (Imp) 0.36 A.

2.3. Dust Cleaning *Experiments with Amorphous silicon solar cell panel obtained from M/s HHV, Bangalore of 30 cm x 30 cm size, without any frame:*

The solar panel consists of 24 solar cells, connected in both series and parallel configurations. The panel's efficiency was approximately 7%. It was developed as an experimental prototype to highlight the technology and is not commercially available.

Most of our experiments, conducted at IIEST, Shibpur, were performed under varying humidity levels ranging from 35% to 65% and sometimes even higher (maximum 88%) due to the institute's proximity to the bank of River Ganges in Howrah. In the case of experiments 2 and 3, we recorded the device I-V characteristics and stored the data on a computer for analysis. Among all the device parameters, we particularly focused on changes in Pm (maximum power) with dust accumulation and subsequent removal to estimate the Dust Removal Efficiency (DRE). Additionally, we propose a novel idea where a short air pulse is utilized to facilitate the cleaning process before or after applying Extra High Tension (EHT) to the conducting copper plate, F, in the system.

To analyze the I-V characteristics, we used a specially designed I-V tester provided by M/s Synchro electronics, Kolkata. It can display the complete I-V characteristic of the solar cell/panel and gives numerical values of Short-circuit current (I_{SC}), Open circuit voltage (V_{oc}), maximum power point related parameters, V_m, I_m & P_m. The intensity of light source used in these experiments was kept at 41731 Lumens (320 Watt/m^2). The intensity of light was measured using a Daystar meter.

In the following only Pmax (Pm) variation has been tabulated to ascertain DRE changes. It is to be noted we observed a similar trend for changes in I_{SC}.

3. Results and Discussion

3.1. of substrate types:

Dust deposition Substrate type	weight without dust (gm)	weight after dusting (gm)	weight after dust removal (gm)	DRE %	**mean DRE %**
Bare p-type Si wafer without coating *(with Jodhpur Dust)	2.29	2.567	2.29	100	**100**
	2.285	2.583	2.285	100	
	2.284	2.515	2.284	100	
p-type Si wafer with conducting coating (Sheet resistance 212.95 ohm/sq.) *(with Jodhpur Dust)	2.264	2.529	2.265	99.62	**99.6**
	2.264	2.51	2.266	99.18	
	2.263	2.5	2.263	100	
Bare glass*(with Jodhpur Dust)	21.594	21.89	21.6	97.97	**98.75**
	21.599	22.404	21.608	98.88	
	21.599	22.781	21.606	99.4	
Bare glass With Haridwar dust	22.857	23.091	22.861	98.29	**96.98**
	22.857	23.021	22.863	96.34	
	22.857	23.048	22.864	96.33	
Bare glass With IIEST Roof top dust	22.8614	22.934	22.864	95.89	**93.95**
	22.861	22.925	22.868	89.06	
	22.861	22.926	22.863	96.92	
Glass with TCO coating *(with Jodhpur Dust) (Sheet resistance 9.64 ohm/sq.)	40.892	42.334	40.914	98.45	**98.67**
	40.892	42.395	40.911	98.73	
	40.892	42.305	40.908	98.85	

Table 2 DRE (Dust Removal Efficiency) data from weighing of dust with a sensitive electronic balnce before and after ESPDC accutaion.

It is to be noted irrespective of the substates used DRE values are more than 98% ,meaning there by TCO substates behaved the same way as a plain uncoated glass substated .

3.2. Experiment with Silicon solar PV module:

In these experiments solar panel with contacts was placed at a suitable distance from the moving powered copper plate and I-V curve obtained with the tracer and stored in a computer. Subsequently, it was dusted, then the powered electrode was energized and moved over the solar cell and dust removed and the I-V curve again taken. Experiments repeated the same way with an additional uncoated glass plate kept over the solar panel in one case in other case the glass plate replaced with a TCO coated glass.

3.2.1. With bare module:

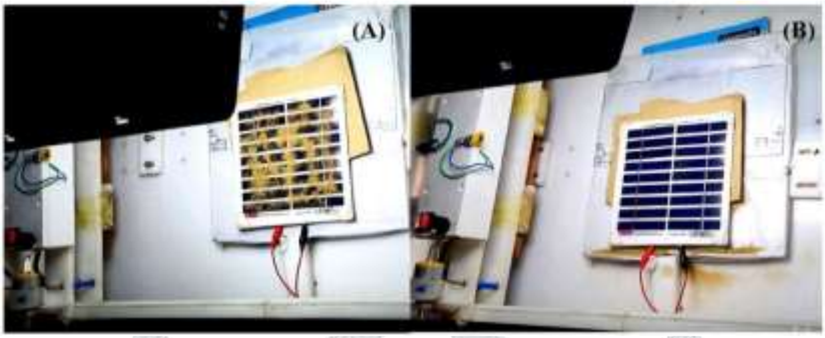

Fig. 5. 5**(**A) Bare Si solar module with dust, 5(B) Bare Si solar module after dust removal

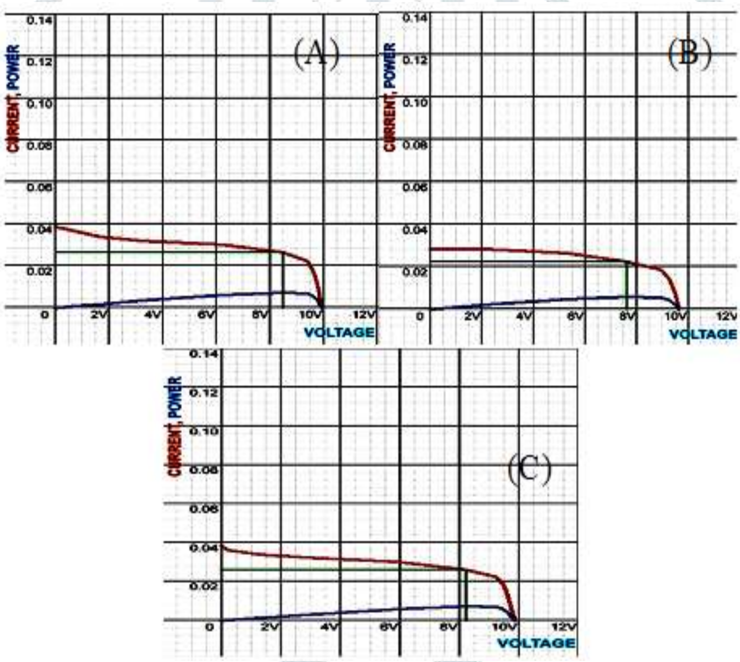

Fig. 6. represents the power output (IV curve) gain aftrer dust removal (A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temp. (^oC)	Humidity (%)
0.224	0.172	0.216	96.43	***98.13***	32	50
0.203	0.172	0.202	99.50		34	51
0.196	0.131	0.193	98.47		35	49

Table 3 DRE from the set up at specific temperature and % RH.

3.2.2. With transparent TCO coated glass plate over Si Module:

Fig. 7. 7(A) & 7(B) represents TCO glass plate Covered Si Solar module, with Pre and Post dust removal condition

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temp. (^oC)	Humidity (%)
0.176	0.154	0.180	97.78		32	50
0.175	0.121	0.181	96.68	**97.963**	34	51
0.176	0.134	0.175	99.43		35	49

Table 4 DRE from the set up at specific temperature and %RH.

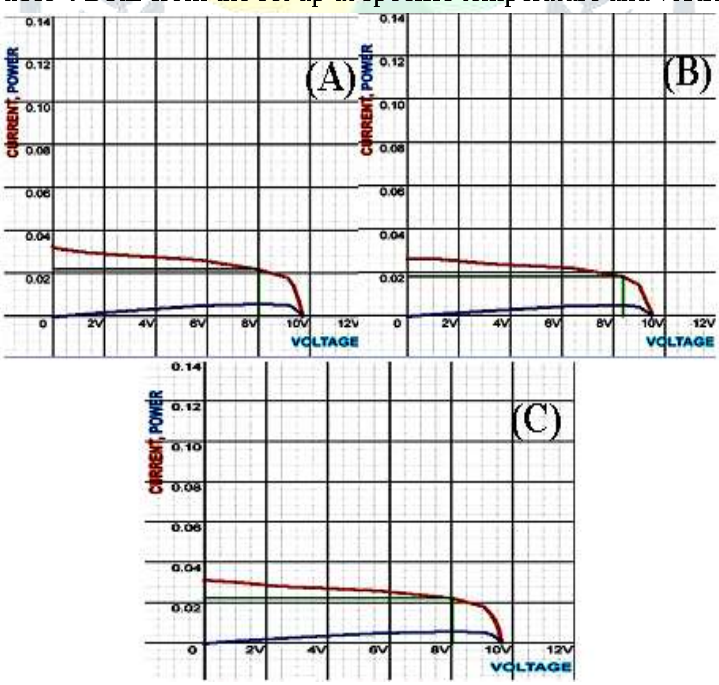

Fig. 8. represents the power output (IV curve) gain aftrer dust removal (A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

3.2.3. With bare glass plate over Si module:

Fug. 9. 9(A) & 9(B) Bare glass plate covered Si solar module at pre and post dust removal condition respectively.

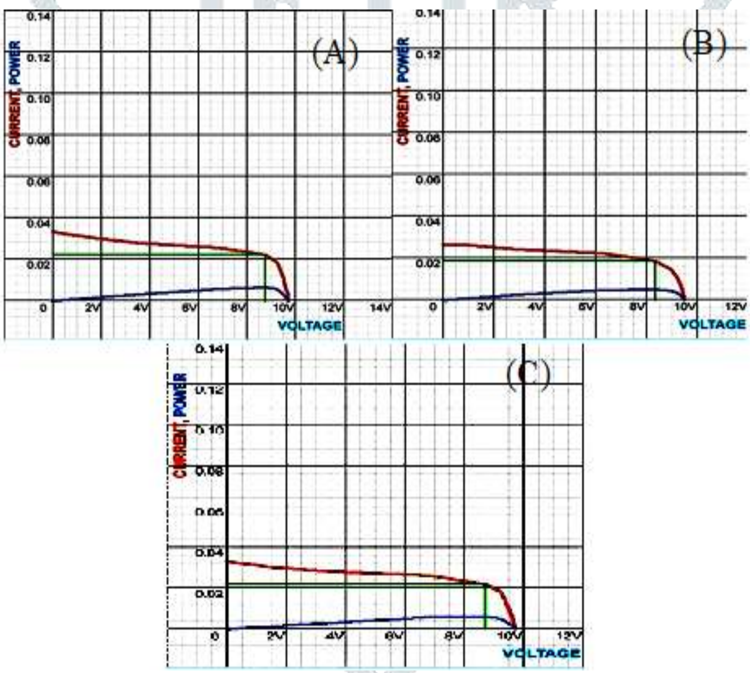

Fig. 10. represents the power output (IV curve) gain aftrer dust removal (A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temperature (^oC)	Humidity (%)
0.195	0.156	0.193	98.97		32	50
0.185	0.154	0.186	99.46	**97.85**	34	51
0.185	0.126	0.176	95.14		35	49

Table 5 DRE from the set up at specific temperature and % RH.

3.3. Experiments with a:Si PV module: On an amorphous silicon solar cell panel obtained from M/s HHV, Bangalore of 30 cm x 30 cm size, without any frame:

Experiments were conducted the same way as for Si solar panel.

3.3.1. With Bare module:

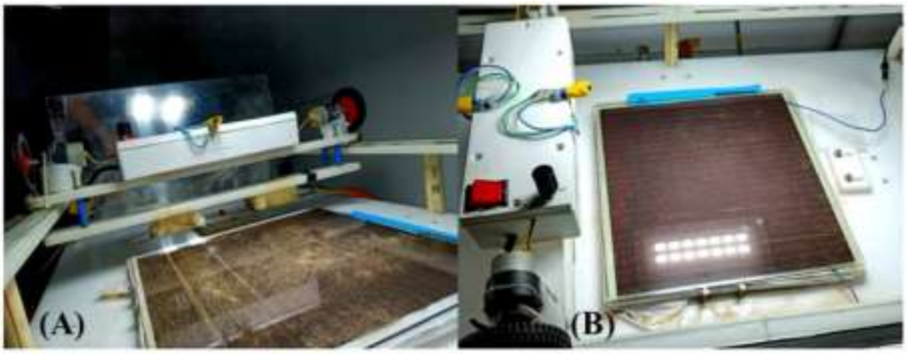

Fig. 11. 11(A) & 11(B) represent bare **a:Si PV module** at pre and post dust removal condition, respectively.

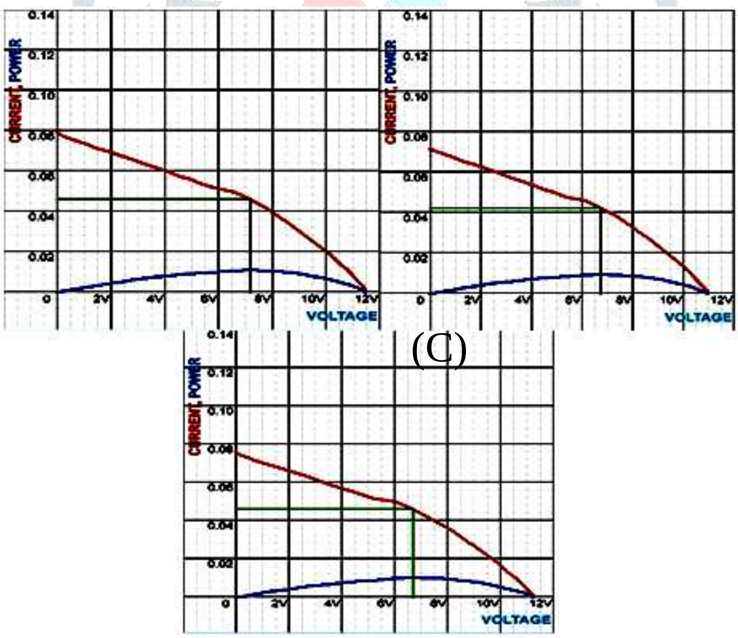

Fig. 12. represents the power output (IV curve) gain aftrer dust removal
(A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temperature (°C)	Humidity (%)
0.383	0.328	0.366	95.56		35	32
0.33	0.284	0.308	93.33	**94.84**	34	36
0.322	0.292	0.308	95.65		34	38

Table 6 DRE from the set up at specific temperature and % RH.

3.3.2. With a bareglass on top of the module

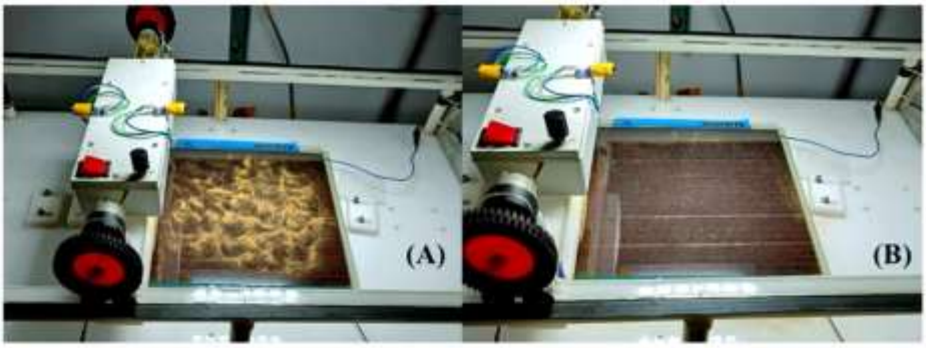

Fig. 13. 13(A) & (B) represent bare glass covered **a:Si PV module** at pre and post dust removal condition respectively.

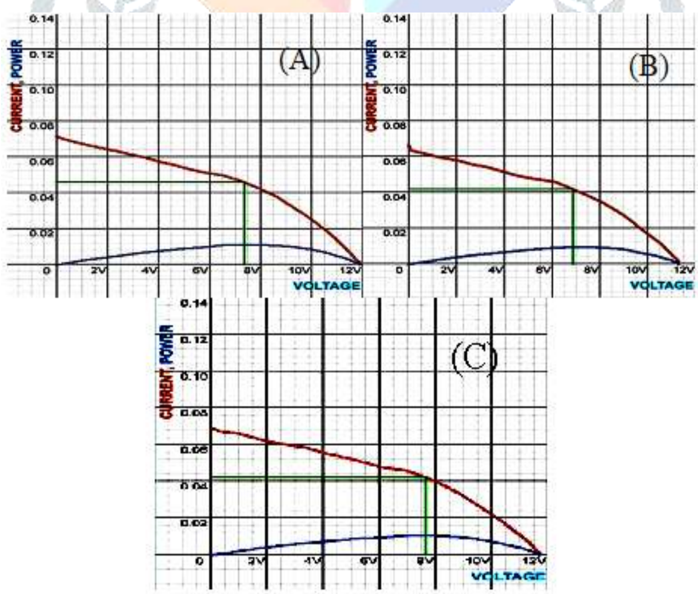

Fig. 14. represents the power output (IV curve) gain aftrer dust removal (A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temperature (°C)	Humidity (%)
0.331	0.276	0.313	94.56		35	32
0.334	0.303	0.321	96.10	**95.60**	34	36
0.338	0.288	0.325	96.15		34	38

Table 7 DRE from the set up at specific temperature and % RH.

3.3.3. With an ITO coated glass on top of the module

Fig. 15. 15(A) & 15(B) ITO coated glass covered **a:Si PV module** at pre and post dust removal condition respectively.

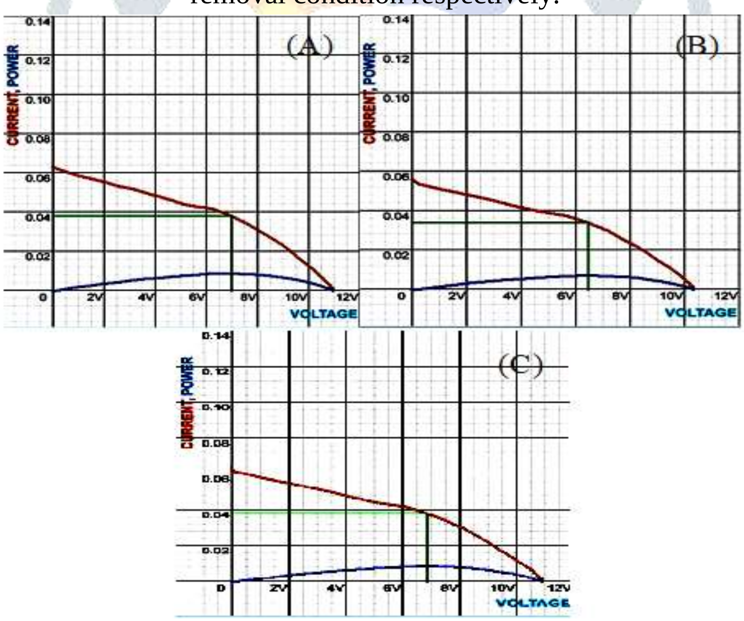

Fig. 16. represents the power output (IV curve) gain aftrer dust removal
(A) Pre-dust deposition, (B) Post deposition & (C) Post tremoval

P_m of Cell without Dust	P_m of Cell with Dust	P_m of Cell after Dust Removal	DRE (%)	**Mean DRE (%)**	Temperature (°C)	Humidity (%)
0.346	0.264	0.327	94.50		35	32
0.33	0.294	0.324	98.18	**97.34**	34	36
0.314	0.267	0.312	99.36		34	38

Table 8 DRE from the set up at specific temperature and % RH.

We find that ,in case of solar panels of different types , when bare or aditionally TCO coated glass or glass without any coating put above the solar panels ,DRE vales are at least 95%.This aging goes to show that coating the solar panel glass with TCO does not appear to have any distinct advantage.

3.4. Exeriments with short Air blast after electrostatic cleaning:

After the electrostatic dust removal process, a brief compressed air blast is typically applied to further enhance the efficiency of dust removal. Below, we present mathematical estimates for the required air blast velocity, denoted as Vair [16, 17].

$$\mathbf{V_{air}} = \sqrt[1.8]{\frac{2V_{Sheer}^2}{0.0592}\left(\frac{x_l}{v}\right)^{.2}} \qquad (4)$$

Here v = kinetic viscosity of air, x_l = length of the panel surface along the direction of the airflow, V_{sheer} = Shear velocity of air.

Li et al.in their paper regarding air blow studies have mentioned an air blower in the form of nozzles fitted at the top end of the slanted solar panel [17]. This falls in line with our proposition of injecting short air pulses, following the introduction of a suitable control scheme. The implanted airflow was through two nozzles, in their study, maintained at the top at a pressure of .1-1 MPa, with a solenoid controller of pressure level 1Mpa connected to a 0.34 m^3 tank. The flow rate was kept at 1370 L /m. The flow also helped the panel cool while cleaning dust. These results also help to establish our proposition. After 10-second air blowing, the PV panel showed a yield improvement of ~30%, with a cleaning to cooling ratio of 3:1. Extension of operation time to 15 s & the 20s further increased the power improvement by 33 % & 36 % respectively, while the cooling contribution to power improvement increased to 30.9% and 35.7%. They have also suggested that the blowing is effective on the particle having a diameter greater than 20µm. An air blow velocity of >25m/s will be required for particles of less than 20micron.

The blower used by Kawamoto et al. [18] had shown effective dust removal, while the nozzle mechanism with solenoid controller and timer as proposed by Li et al. and Whitefield et al. shows the possibility of air pulse ejection while cleaning and cooling the PV simultaneously. The incorporation of a modified R-L-C circuit by Anderson et al [19] showed promise of decreasing power loss while starting the blower as well as a reduced carbon footprint.

Combining all of them, an energy-efficient eco-friendly air blower that will be able to inject short high-pressure pulses while being charged by super-capacitors is proposed.

A air copressor working on 12 volt DC supply is commercially avialable for which a modest 150 Watt Solar panel will suffice .This panel can also energise EHT Dc supply and other electronics .

Therefore, in future designs of ESPDC these inovations nned to be integrated.

3.5. Discussion of results and its implications:

It is to be noted that the optical transmission of borosilicate glass without AR coating is usually at best 92%, whereas that of AZO-coated glass is around 85%. We, thus, will lose light intensity anytime we put a coated AZO Glasson Solar panel. Therefore, enhanced dust removal with CTO-coated glass will reduce optical intensity inside the panel. The dust removal process involves particle lifting, followed by corresponding particle swiping. The lifting can be proven from the camera footage and its removal from the panel. Any particle to be lifted off the net downward-acting force must be compensated and overcome by the net upward-acting force. If all the forces are to be considered, the composite force diagram would look as follows. (Figure 17).

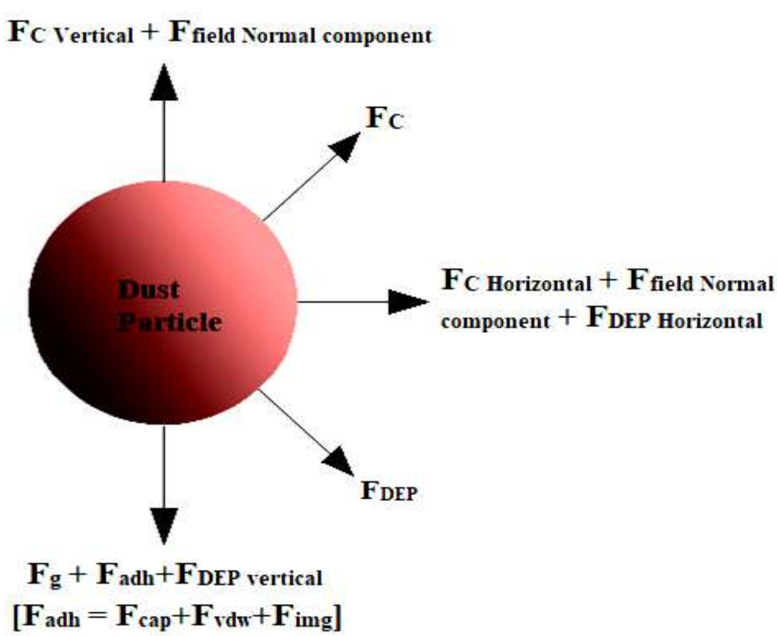

Fig. 17. Net forces acting on a dust particle at traditional EDS operation.

One of the two main acting forces is the electrical induction applied due to the charged electric plate. It is the force exerted by the electric lines (Fe) originating from the charged plate and terminating at the dust-deposited surface. In the present case, this has been identified as the electrostatic force of attraction due to induction (judging by the vertical movement of the particles).

It is emphasized here that dust particles consisting of Silica (sand) are mostly dielectric, and the fact that they have been removed from the glass plate surface of the solar panel, which has no TCO coating, reveals that they can also be primarily charged to facilitate their lifting and eventual removal. In this connection, the work of Y. Zhang et al. sheds much light. (Electric field and humidity trigger contact electrification [20].) We briefly reproduce their arguments in the following. "First, the insulators absorb water from a humid environment on their surfaces. Then, positively, and negatively charged ions dissolved in this water, which we believe to be hydronium and hydroxide ions, polarize, and thus gather at opposite sides of the insulators due to the electric field. On contact, they neutralize the respective other species around the contact domain. Finally, when separated, one insulator remains with the most positively charged ions and the other with the most negatively charged ions."

Given what has been said above, in the present case, both the requirements, i.e., the presence of a High enough electric field and humidity, are satisfied. In a departure from the MIT experiment, we have the following.

1. No AZO coating is on the solar panel glass surface. The surface is in contact with the ground of the moving Electrostatic cleaning setup platform.

2. The metal moving plate is kept at a + high potential of 11 KV. Changing the distance between the top plate carriage and Solar panel surface field strength is manipulated.

Even though our solar panel surface did not have any AZO (Aluminum-doped Zinc Oxide) coated glass, we achieved a dust removal efficiency of >95%. However, it is undeniable that the presence and influence of Electric Field Assistance are evident. Most of the arguments put forth by MIT researchers in their paper also apply to this scenario. Specifically, they mentioned, "The hydrophilic nature of silica makes it possible for the particles to adsorb sufficient moisture to experience sufficient charging." Additionally, they stated, "This confirms that charge accumulation occurs on the particle surface rather than in the bulk." [14].

Since our DC HT Supply was fixed at 11 KV, we could manipulate the electric field strength by adjusting the gap. The other vital force considered here is the dielectrophoretic force (F_{dep}). This is because the charged plate is of a much smaller area than the bottom test bed plate on which the 30 cm x 30 cm panel has been placed. Due to the movement of the plate, a non-uniform electric field will be experienced by a dielectric dust particle that is not precisely at the vertically downward location. The following figure represents the movement of the charged plate.

The diagrams illustrate the cleaning setup, where P represents the moving plate that is positively charged using a high-voltage DC source. The reference dust particle, D, is shown, and the electric lines of force are depicted in red. Two distinct areas, colored yellow and green, highlight the potential differences in the effect of the applied electric field concerning the movement of the plate. Further details regarding these areas are presented below.

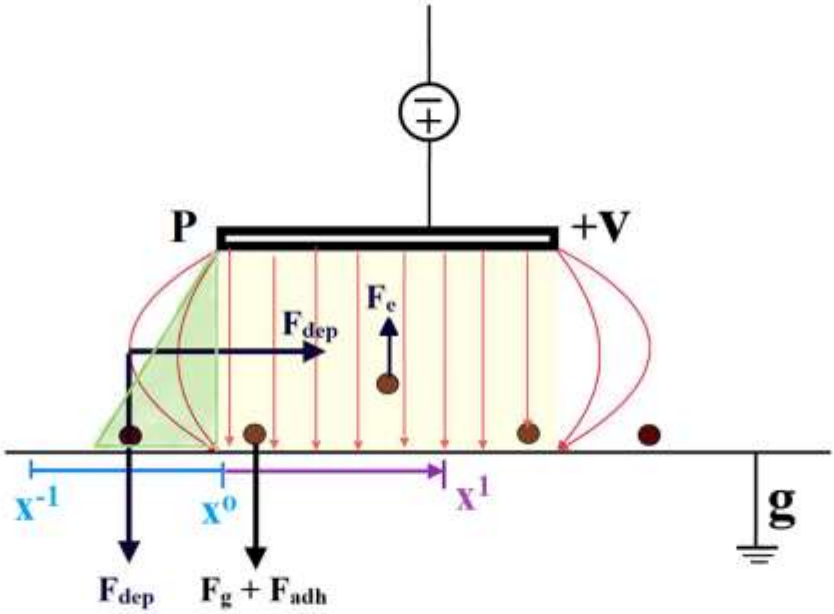

Fig. 18. The effect of the applied electric field concerning the movement of the plate.

From the above schematic (Fig. 18.), it is evident that from X^o to X^1, all the dust particles under examination, except one, come directly under the charged plate (denoted by yellow). Here, the electric field experienced by the particles is uniform. However, the particle at the left is away from the direct effect region (denoted by green). In this position, let us assume the total system is at a standstill and the time reference is $t = t_0$. Now, while the plate starts to move from x^0 to x^1, at $t = t_1$, the position of the charged plate on the particles will be as follows.

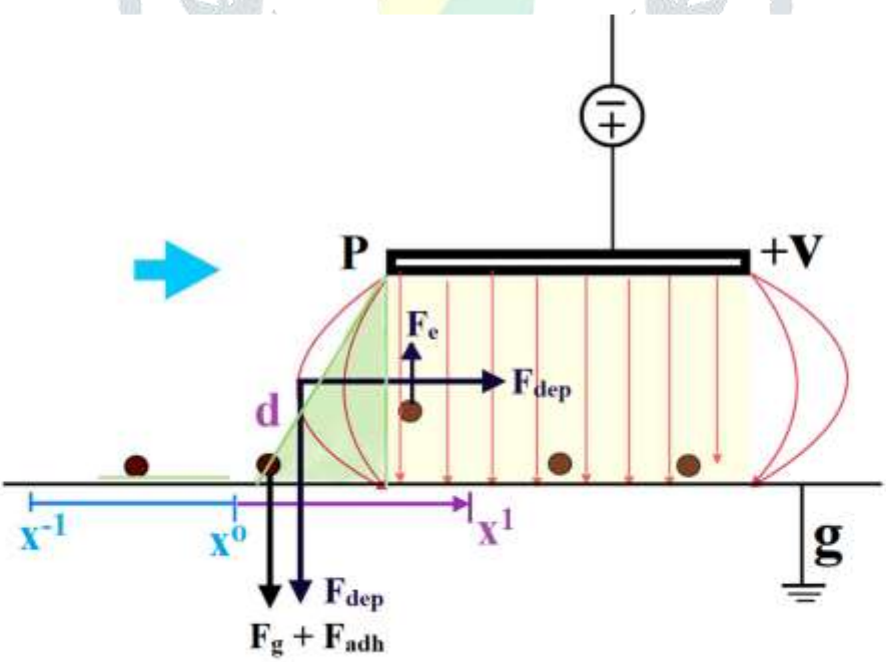

Fig. 19. Movement of the charged plate to the next position.

Based on the above Figure 19, it is evident that the charged plate has been moved to a new position. As a result, some particles previously experiencing a uniform electric field may now come under a non-uniform electric field, particularly in the green area, shifting along with the plate's movement. Consequently, the particles in this region are subject to a non-uniform electric field. While dielectrophoretic forces may not be as strong as induction forces, it is worth noting that experiments conducted by Nami et al. attribute dust cleaning to dielectrophoretic forces in their movable EDS system [13]. In our case, we have successfully operated the ESPDC at an air gap of 4 mm.

We know from literature studies that the net natural charge in a speck of dust suspended in the air is zero. However, they can acquire +/- charges upon impinged on the deposited surface. So, a net electrical charge can be accumulated in the deposited dust.

Considering the given conditions, three scenarios can be envisaged:

1. Suppose the settled particles on the panel's surface, resting on glass, are initially negatively charged upon impingement. In that case, they will be exposed to a uniform electric field generated by the high-voltage metallic plate. As a result of induction, charges will be stored inside the particles. When the charge reaches a sufficient level, the particle experiences an upward electrostatic force of attraction that overcomes the total downward forces acting on it (represented by F_g for its weight and Fadh for adhesive forces). Consequently, the particle is lifted, and then either swiped or rolled down the deposition surface due to the tilt introduced in the system. The charging process here is governed solely by triboelectrification and induction.

2. In an alternative scenario, the charge buildup in the particle may become sufficient while it is in the green zone and experiences a non-uniform electric field. In this case, the dielectrophoresis force of attraction becomes very effective. As depicted in the figure, this force has vertical and horizontal components. The vertical component acts against the downward forces, while the horizontal component causes the particle to swipe along the deposition surface. The particle can then move into the yellow zone and repeat the process or roll off the surface under the influence of gravitational pull.

3. A third possibility arises where the Coulomb force of repulsion acts on the particle. In such a scenario, a blowing mechanism comes into play, effectively removing the particle from the surface. The required blow velocity has been calculated and represented in the figure and the supplementary material.

Through these experiments and discussions, we have shown a method of Electrostatic dust cleaning of Solar panels, which does not require the top of the panel glass surface to be optically transparent while electrically conducting. This is seen as an auspicious development that makes the process cost-effective. Further, a timely short air blast can enhance cleaning efficiency. We are now designing a real-life system of ESPDC for outdoor deployment with data logging, etc., using a commercially available 300-watt solar panel so that our laboratory findings are further validated. We would also like to take necessary precautions in the design to use such high DC voltages.

4. Conclusions

From our studies, as documented above, we draw the following inferences: Electrostatic dust removal on a solar panel, with the glass coated with a transparent conducting coating (TCO coating) on top of the panel and without it has been critically examined from the viewpoint of its large-scale adaptation. In all cases, smaller dust particles are left behind after ESPDC actuation. It is seen that though dust particles are not entirely removed, their effect on the performance of solar cells or panels is not appreciable. Solar cell performance is comparable with and without a TCO coating. This makes the electrostatic dust cleaning technique cost-effective. Further, applying a short air blast after the electrostatic removal operation has been postulated to clear most of the remaining dust after ESPDC- EHT is switched off.

5. Acknowledgements

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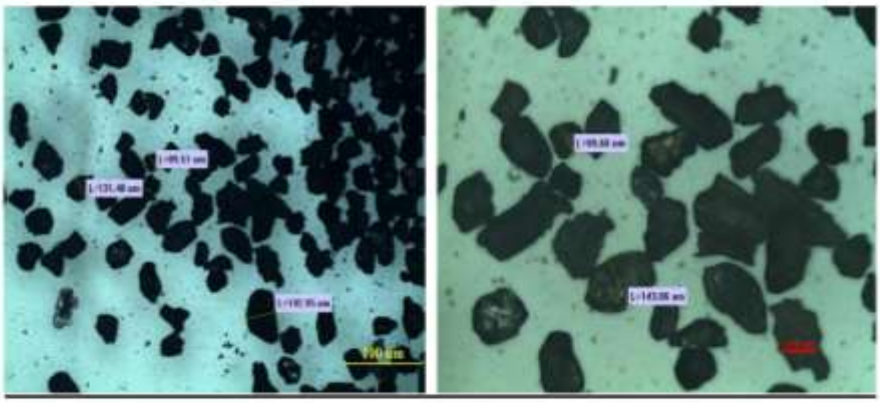
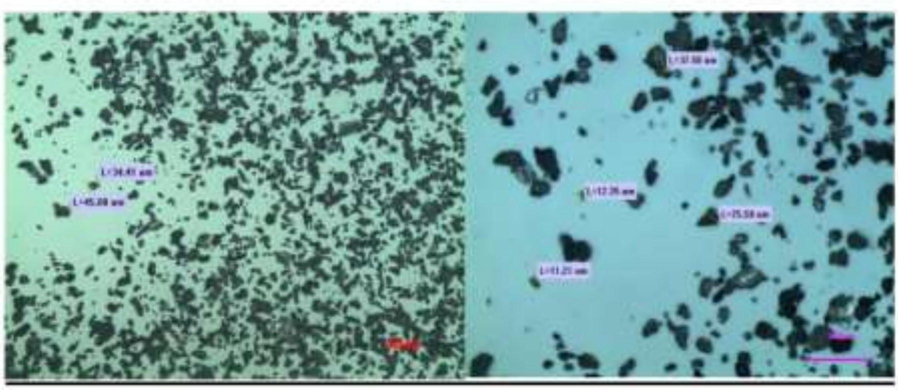
Supplementary Information- S1

Haridwar dust

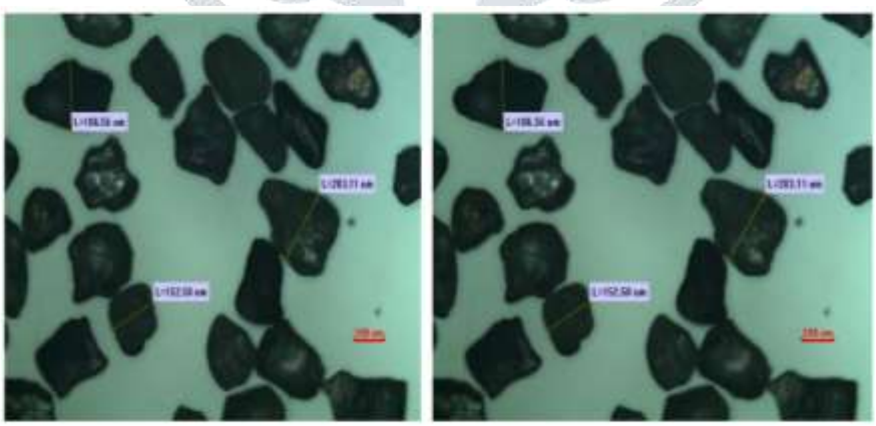


Haridwar dust with 5X magnification & 10X magnification respectively

IIEST solar PV rooftop dust



IIEST solar PV dust with 10X magnification & 20X magnification ,respectively



Rajasthan (Jodhpur) dust with 5X magnification

Supplementary Information-2:

Video of ESPDC

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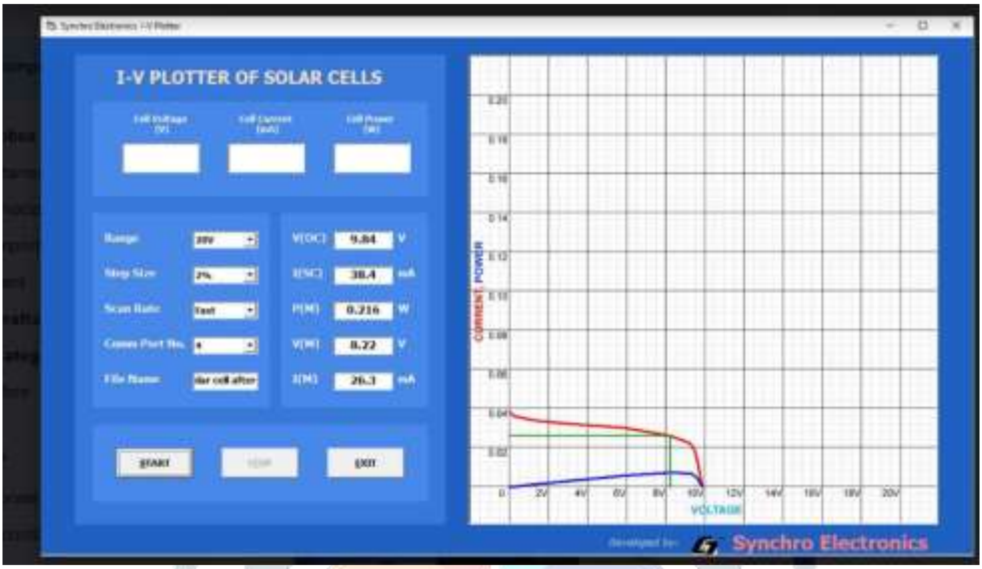
Supplementary information -3:

Typical I-V curve trace obtained from M/s Synchroelectronics tracer used in the experiments.



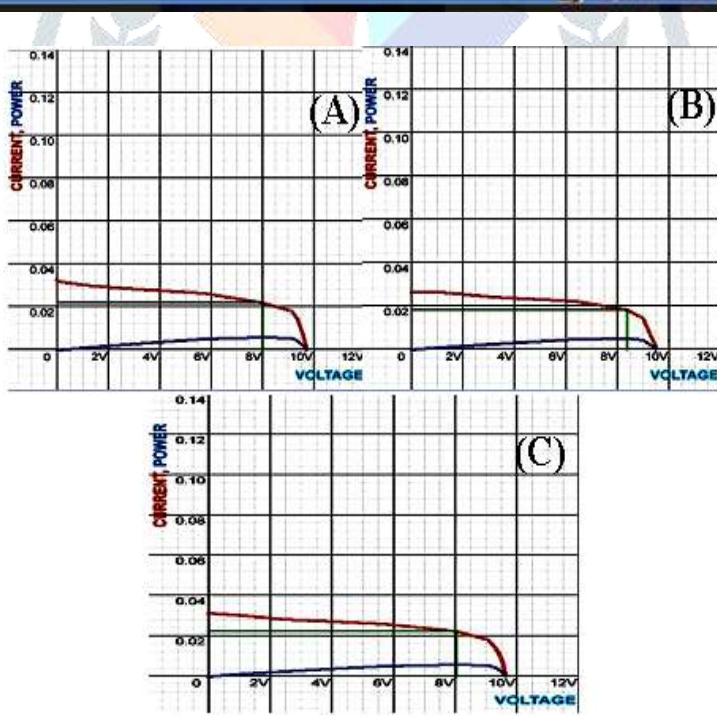


Fig represents the power output (IV curve) gain aftrer dust removal
(A) Pre-dust deposition, (B) Post deposition & (C) Post removal