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Improving Efficiency of Dust Removal from Surfaces to Maximize Output of Photovoltaic Cells

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Abstract— The series of experiments documented in this paper was aimed at determining, analyzing and comparing different solar panel cleaning systems. Output in all experiments was measured in terms of Potential Difference, Current and Power. Readings were taken under three circumstances: (i) when the solar panel was clean, (ii) when a measured amount of material was deposited on it, and (iii) after cleaning action was performed. It was observed and concluded through performed experiments that (i) Of materials used (talcum, dust, sawdust, and leaves), dust was most difficult to remove and led to a maximum drop in the overall output of solar panel after cleaning action was performed, (ii)Dust particles are charged in nature and stick to solar panel screens, rendering current mechanical cleaning methods inefficient, and (iii) Electrodynamic sheet comprising of Indium Tin Oxide improved efficiency to up to 98% whereas other methods witnessed a power drop to a maximum of 25% of original power output, making it better than mechanical cleaning methods by a significant margin.

Keywords—Photovoltaic Cells, Dust Removal Efficiency, Mechanical Cleaning of Solar Panels, Electrodynamic Sheet, Indium Tin Oxide

I. INTRODUCTION

Due to the planetary dust storm on Mars in 2018, the *Opportunity* Mars Rover ceased communications on June 10 and entered hibernation on June 12, 2018. It was hoped it would reboot once the weather cleared, but it did not, suggesting that a layer of dust had covered its solar panels. The team remained hopeful that a windy period between November 2018 and January 2019 might clear the dust from its solar panels, as had happened before. More than 835 recovery commands were transmitted since losing signal in June 2018 to the end of January 2019 with over 1000 recovery commands transmitted before NASA finally declared the mission over on February 13, 2019. The rover is just one of the hundreds of examples of a mission costing over 820 million dollars being soiled by dust.

While we don't see dust as much more than a small annoyance in our day to day lives, it interferes with the workings of a lot of technology and systems and contributes to the failure in working in numerous. It interferes with measurements often leading to inaccuracies in readings, resulting in fatal miscalculations and errors.

Dust accumulation on solar panels can lead to significant losses in the power being generated. Currently, solar panel manufacturers advise domestic users to use an ordinary cloth and soapy water to clean the surface of the panel in 6-8 moths. This process can be extremely tedious for users who have solar panels installed in inaccessible areas such as roofs. On an industrial scale, most users rely on wind to clean the surface of the panel, which due to its unpredictability, proves to be very inefficient. Recent advances made in the field use light dependent resistors and mechanical wipers to wipe off the dust. This method, although better compared to the others, cannot remove more than 30% of the dust in deserts and dusty regions which is why the increase in power does not compensate for the increased investment costs.

II. RELATED WORK

M.K Mazumdar, in his paper 'Self-Cleaning Transparent Dust Shields for Protecting Solar Panels and Other Devices', proposes the use of electrodynamic sheets to minimize obscuration of solar panels by the deposition of dust. Mazumdar proposes the use of single and triple phase excitations through applications of single and multi-phased AC currents to lift the dust off the surface of the solar panels. 'Particle Removal by Electrostatic and Dielectrophoretic Forces for Dust Control During Lunar Exploration Missions' by C.I.Callea, C.R. Buh1er, J.L. McFalIb, and S.J. Snyder" focuses on particle removal during lunar exploration activities for the success of robotic and human exploration of the moon. The paper discusses the use of dielectrophoretic forces to develop a dust removal technology that prevent accumulation on dust on surfaces of photovoltaic cells, with a thrust on its applications during outer space missions. It makes use of electrostatic and dielectrophoretic forces to move charged dust particles off surfaces and to prevent dust particles from getting deposited on those surfaces.

III. EXPERIMENTAL

Three different sets of experiments were performed, on the basis of which different, yet correlating conclusions were drawn. For all experiments, the output was measured in terms of the following:

1. Potential Difference (V)
2. Current (I)
3. Power (P)

The readings for the Potential Difference and Current were taken using a multimeter. The Power was calculated using the formula:

$$P = VI$$

We measured this output under three circumstances:

i. When the solar panel was clean
ii. When a measured amount of material was deposited on it
iii. After the cleaning action had been performed

Experiment 1

The first of the series of experiments was aimed at determining how different materials affected the output of the photovoltaic cells and how effective mechanical cleaning was in their removal.

For this experiment, we used one solar panel of dimensions 19cm x 19cm, connected to a mechanical wiper consisting of a brush, operated by an Arduino board. The solar panel had a Light Dependant Resistor to automate the working of the wiper. The solar panel was connected to a Light Emitting Diode (LED) on a breadboard. A multimeter was used to measure the output through the positive and negative terminals of the LED. A digital weighing scale displaying up to 3 decimal places was used for measuring the material. Care was taken to ensure that the experiments were conducted in a controlled environment: in a closed dark room, with a mercury bulb as a constant light source to prevent changes in the light falling on the photovoltaic cells. The room had no fans or similar sources of air current, which could interfere with the experiment and lead to inaccuracies in the readings.

Methodology

The voltage and current produced by the solar panel when no material was deposited over the panel were recorded in the observation table. This was taken as the maximum potential difference and current being generated by the solar panel.

Twenty grams of sawdust were deposited on the solar panel. Used the multimeter, the voltage and current being supplied to the LED was measured, and this reading was recorded in the observation table under the ‘Readings with Material Deposition’ column.

The mechanical wiper was operated to remove the material. We measured the voltage being generated by the system after the cleaning by using the multimeter across the two terminals of the LED. The same experiment was performed with talcum, husk, and dust.

Observation

A drop in the potential difference was observed in all 4 cases i.e., with all four materials, once the material was deposited on the solar panel.

As can be seen from Table 1, we were able to restore potential difference being produced by the panel back to normal in the case of leaves, talcum, and husk once the cleaning was performed. However, there was no significant improvement in the potential difference after cleaning in the case of dust, where we were unable to restore the production back to normal.

Table 1

OBSERVATION TABLE				
Substance	*Amount*	*Maximum Voltage*	*Voltage With Exposure To Substance*	*Voltage After Mechanical Cleaning*
Leaves	*20g*	*1.92V*	*1.76V*	*1.91V*
Husk	*20g*	*1.92V*	*1.34V*	*1.91V*
Talcum	*20g*	*1.92V*	*1.54V*	*1.92V*
Dust	*20g*	*1.92V*	*0.714V*	*1.02V*

Experiment 2

The second set of experiments aimed at determining the reduction in power output and the overall efficiency of the photovoltaic cells caused due to dust accumulation alone.

For this experiment, we used three solar panels, each of the dimensions 19cm X 19 cm. The three panels were equipped with a mechanical wiper, a roller screen, and a robotic arm, respectively, all operated by an Arduino board *(Refer to Figure 1*). The solar panels had light dependent resistors to automate the working of the systems. The resistors activated the systems on encountering an obstruction of light irradiated on the panel caused due to the accumulation of dust on the panel. Just like in Experiment 1, the solar panels were connected to 3 Light Emitting Diodes (LED), which in this case radiated three different colours. A multimeter was used to measure the output through the positive and negative terminals of each of the three LEDs. A digital weighing scale displaying up to 3 decimal places was used for measuring the amount of dust taken in each case. All experiments were conducted in a dark room, using a mercury lamp to prevent inaccuracies, which may have resulted due to variation in the intensity of sunlight. The room had no fans or similar sources of air current, which could interfere with the experiment and lead to inaccuracies in the readings.

After each step, the solar panels were cleaned manually using a cloth to make sure that no dust particles would interfere with the reading of the following experiments.

Figure 1. Experimental setup

Methodology

The objective behind employing three different techniques of cleaning was to increase the surface area of the panel, which was being cleaned. This was done to improve power efficiency. As evident in figure 2, the mechanical wiper traversed the minimum area, whereas the roller screen traversed the maximum.

To conduct our experiment, we measured 5g, 10g, 15g, and 20g of dust using a digital weighing scale. The four measured quantities of dust were stored in 4 different beakers.

We first carried out experimentation by determining the voltage and current output when the solar panels were clean and free of dust. These readings were taken as the maximum values of voltage and current. 5g of dust was then uniformly spread on the surfaces of each of the three panels, thus making the amount of dust per cm^2 approximately 0.013g *(Figure 2b)*. The voltage and current output of the mechanical wiper were recorded using a multimeter. The power being generated in each case was then computed using the equation:

$$P=VI$$

The other two setups were devoted to the estimation of dust removal efficiency, also taking into account the effective surface area being cleaned in each case.

The same experiment was conducted for dust quantities 10g,15g, and 20g.

The two important factors that we kept in mind to determine which system was the most efficient were:

1. The difference between power being generated with dust and once the solar panel had performed its cleaning action.
2. Amount of dust left of the panel after the cleaning action had been performed (measured by the digital weighing scale).

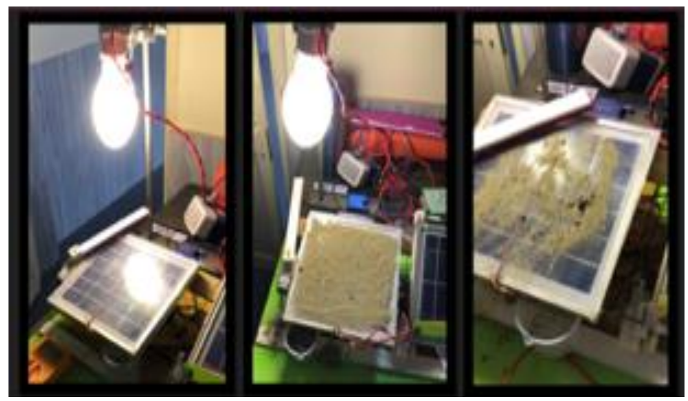

Figure 2a. Three circumstances of mechanical cleaning.

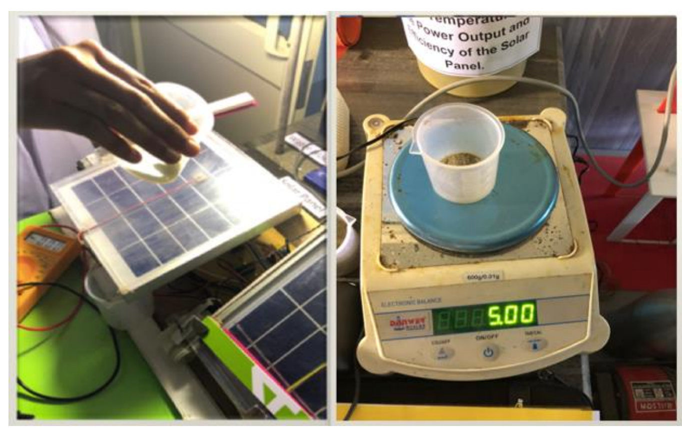

Figure 2 b.

Observation-:

The solar panel was producing 1.92V and 5.49mA of current when it was free of any dust particles.

1. *Mechanical Cleaning*

- The deposition of the 5g dust decreased the reading to 1.86V and 3.02mA, thus bringing down the power efficiency to 53.2% of what it was produced earlier. The operation of the mechanical wiper successfully removed

3.86g of dust, thus restoring efficiency to 69.5% of the initial value *(Refer to Figure 3a)*.

- The deposition of 10g dust reduced the efficiency to 35.77%. The operation of the wiper successfully removed 7.66g of dust, thus restoring the efficiency to 63.8% of the initial value *(Refer to Figure 3b)*.
- The deposition of 15g dust reduced the efficiency to 9.02%. The operation of the wiper successfully removed 12.00g of dust, thus restoring the efficiency to 36.5% of the initial value (*Refer to Figure 3c)*.
- The deposition of 20g dust reduced the efficiency to 7.97%. The operation of the wiper successfully removed 12.10g of dust, thus restoring the efficiency to 35.9% of the initial value (*Refer to Figure 3d)*.
- We observed that, as the amount of dust on the solar panel increased, the power generated by it decreased. Furthermore, an increase in the amount of dust reduced cleaning efficiency as well.

Table 2. Data observations for 5g of dust.

OBSERVATION TABLE				
	Dust on the Panel	***Voltage***	***Current***	***Power***
Clean Panel	*0 g*	*1.92V*	*5.49 mA*	*0.01054W*
A panel exposed to dust	*5 g*	*1.86V*	*3.02 mA*	*0.00562W*
After mechanical cleaning	*1.14 g*	*1.89 V*	*3.88 mA*	*0.00733W*

Table 3. Data observations for 10g of dust.

OBSERVATION TABLE				
	Dust on the Panel	***Voltage***	***Current***	***Power***
Clean Panel	*0g*	*1.92V*	*5.49mA*	*0.01054W*
A panel exposed to dust	*10g*	*1.83V*	*2.06mA*	*0.00376W*
After mechanical cleaning	*3.34g*	*1.88V*	*3.58mA*	*0.00673W*

Table 4. Data observations for 15g of dust.

OBSERVATION TABLE				
	Dust on the Panel	***Voltage***	***Current***	***Power***
Clean Panel	*0g*	*1.92V*	*5.49mA*	*0.01054W*
A panel exposed to dust	*15g*	*1.76V*	*0.54mA*	*0.00095W*
After mechanical cleaning	*3g*	*1.85V*	*2.08mA*	*0.00384W*

Table 5. Data observations for 20g of dust.

OBSERVATION TABLE				
	Dust on the Panel	***Voltage***	***Current***	***Power***
Clean Panel	*0g*	*1.92V*	*5.49mA*	*0.01054W*
A panel exposed to dust	*20g*	*1.75V*	*0.48mA*	*0.00084W*
After mechanical cleaning	*8.90g*	*1.85V*	*2.05mA*	*0.0037W*

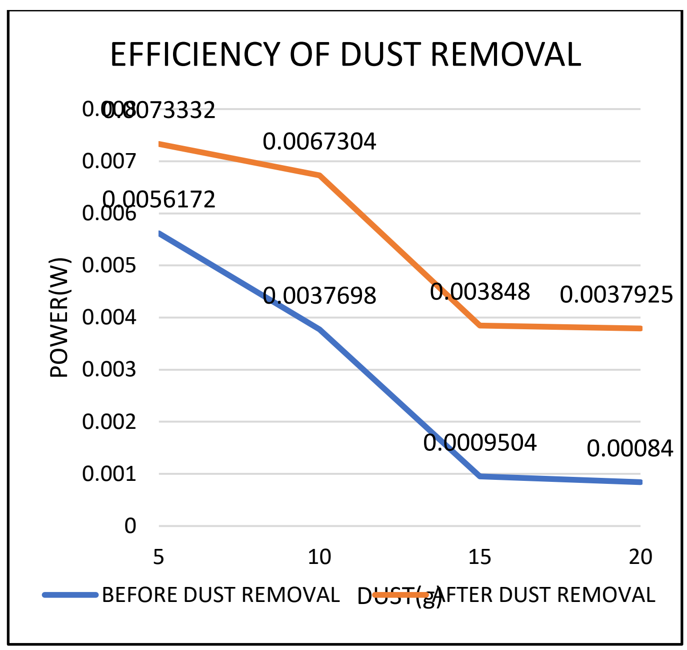

Figure 3. Comparison of power output before and after mechanical cleaning.

2. Robotic Cleaning (Using automated arm)

In this experiment, we solely focused on the dust removal efficiency of the system. This was estimated by measuring the quantity of dust deposited, and the dust left, once the cleaning action had been performed. The data we obtained are presented in Figure 4.

Table 6. Data observations for the robotic arm

OBSERVATION TABLE	
Dust Added	***Dust Removed***
5 g	*3.73 g*
10 g	*7.55 g*
15 g	*11.85 g*
20 g	*12.15 g*

3. Roller Screen

This experiment was devoted to the estimation of dust removal efficiency when the entire surface of the panel was in contact with the cleaning material. We measured the amount of dust deposited on the panel, after which the roller screen was operated. Once the cleaning action had been performed, the dust stuck to the surface of the panel was measured. The data we obtained are presented in Figure 5.

Table 7. Data observations for roller screen

OBSERVATION TABLE		
Dust Added	***Dust Removed***	***Dust Left***
5g	3.63g	1.37g
10g	7.45g	2.55g
15g	11.76g	3.24g
20g	12.01g	7.99g

Conclusion

Despite our efforts, we were unable to remove dust from the surface of the panel beyond a certain extent, and an increase in the surface area being cleaned did not have a significant impact on the power being generated. We concluded that due to its charged nature, dust was getting stuck on the solar panel, thus explaining our inability to remove it beyond a certain extent *(Figure 6)*. This made it impossible to achieve a dust removal efficiency greater than 90%.

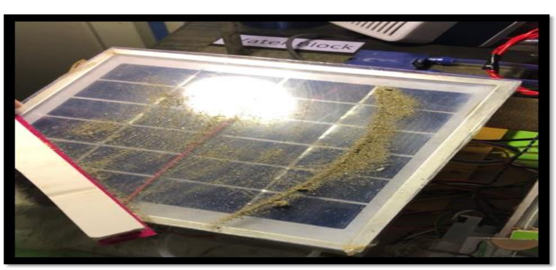

Figure 4. Charged dust particles stick to the surface after cleaning

IV. PROPOSAL

Keeping in mind the physical nature of dust particles, we looked towards our knowledge of electrostatic waves and electric fields for inspiration. We took a few aspects like standing waves, traveling waves, and effects of electric field on particles with intrinsic and extrinsic dipole moment to find a way in which we could repel dust.

An Electrodynamic Sheet with a conductive Indium Tin Oxide, which on applying a potential difference, produced either a standing wave, which could help levitate them above the solar panel or traveling wave, which could help levitate and move the particles by providing a translational velocity, was ideal for this purpose.

Figure 5. Electrodynamic Sheet

Experiment 3

Setup

Standing waves are produced using single-phase excitations, while traveling waves are produced using multi-phase excitations. Both single-phase and multiphase excitation require a very high voltage. We would like to thank Dr. Ambuj Tripathi, researcher, scientist, and teacher in the field of Materials Science at the Inter-University Accelerator Centre, New Delhi, for his guidance.

Using Indium Tin Oxide

We needed a conductive sheet for this purpose, and we selected Indium Tin Oxide coated sheet due to its transparent and adequately conductive nature, which makes it ideal for use in solar panels.

Since we did not have access to an ITO sheet, we decided to create our own. With the help of the Materials Science researchers at IUAC, we used an ITO cathode to coat PET with Indium Tin Oxide using the Physical Vapour Deposition technique. We then tested it and found that we were successful in obtaining a conductive sheet.

We created strips from the ITO sheet we obtained (by scraping off the ITO coating) at equidistant points, making sure they were parallelly arranged.

Working

The Indium Tin Oxide electrodes can be placed over the solar panel and embedded into the glass sheet, which covers it. These electrodes can be connected to an AC source. When dust falls onto the solar panel, these electrodes can be energized using a single-phase excitation and will, in this case, produce a standing wave.

A standing wave is a superposition of two traveling waves traveling in opposite directions at an angle of 180 degrees from each other. The waves generated between the positive and negative terminal on each electrode have nodes and antinodes, the variation between which causes the particles to levitate.

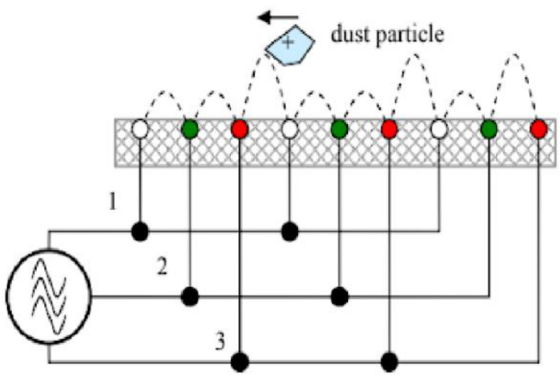

Figure 6. A Three-Phase Excitation [2]

Any asymmetry or perturbation in the AC electric field, the presence of harmonics in the applied field, and any air current on the top surface of the screen produce a drift velocity to transport the dust particles levitated from the surface to move away from the screen. [1]

In general, the net force of repulsion on the particles, which levitates them above the surface, can be expressed as the contribution from the electrodynamic force, the viscous force, and the gravitational force:

$$M\frac{d2r}{dt2}=qE\,cos\omega t-6\pi\eta\frac{dr}{dt}-mg$$

where m is the particle mass, r is the particle's position, η is the viscosity of the fluid in which the particles move, q is the particle charge, and g is the acceleration due to gravity. [2]

Although the forces responsible for the levitation of the particles are highly dependent on their charge, polarizable particles can be levitated using these techniques. [3]

Since many larger neutral particles contain nearly equal amounts of positive and negative charges on their surface, these particles possess an extrinsic electric dipole moment. If this dipole moment is exposed to a spatially non-uniform electric field, the particles will experience a force. Likewise, particles with intrinsic electric dipole moments or containing polar materials like water will also experience a force. The force which causes the movement of particles with internal electric dipole moments in a non-uniform electric field is called the *dielectrophoretic force.* [3]

Particles with lower dielectric constant than the surrounding medium will automatically be repelled from the screen. If the particles have a higher dielectric constant than the surrounding medium, they will be attracted to the curtain's electrodes. In this case, a neutral particle traveling along the insulated screen acquire a charge through *triboelectrification* and would then be lifted from the screen by the stronger qE force. [2]

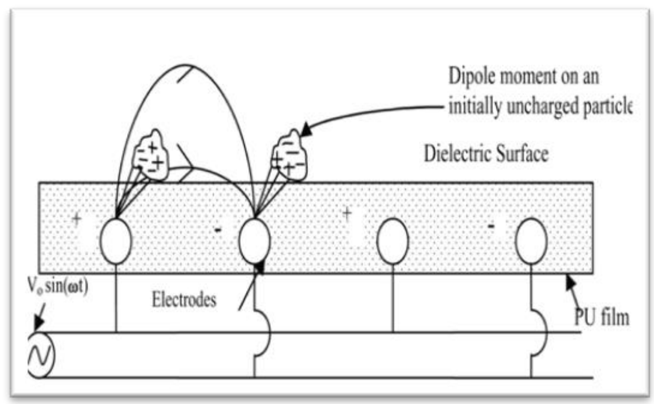

Figure 7. An uncharged dielectric particle deposited on the surface of the dielectric film is experiencing a dielectrophoretic force because of the induced dipole moment on the particle by the applied electric field. Since the applied electric field oscillates, the particle experiences a force proportional to the square of the field gradient and moves along the field lines on the dielectric surface and is triboelectrified to a significantly high charge [1].

Experiment

We carried out our testing for this system with slightly smaller amounts of dust as permitted by the equipment available to us.

Strips from the ITO sheet created were obtained (by scraping off the ITO coating) at equidistant points, making sure they were parallelly arranged *(Figure 10)*. We connected alligator clips and an AC source to provide the potential difference to these ITO strips *(Figure 11).*

Dust was spread across the Indium Tin Oxide Electrodes. We then provided a potential difference across each ITO electrode and recorded our observations. Potential Difference was supplied as per the specifications in "Particle Removal by Electrostatic and Dielectrophoretic Forces for Dust Control During Lunar Exploration Missions", published by the scientists and researchers of the NASA Electrostatics and Surface Physics Laboratory, Kennedy Space Center [2].

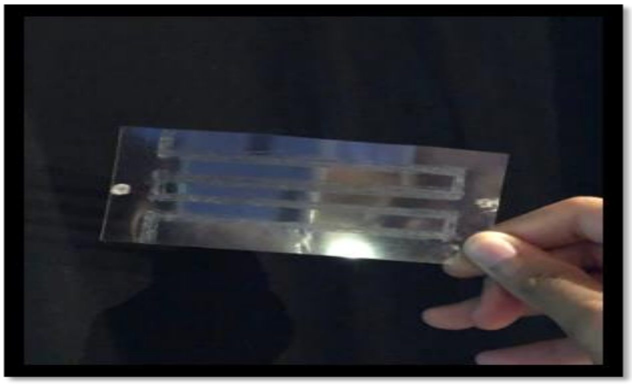

Figure 8. Electrode formation

Figure 9. Set up

Observation

1. We observed movement in the dust particles. The dust gradually moved off the photovoltaic cells. *(Figure 12)*
2. After 2-3 minutes, no dust remained on the solar panel. All of it was cleaned off.
3. The efficiency of the solar panel improved to 98%, and power output was very close to normal.

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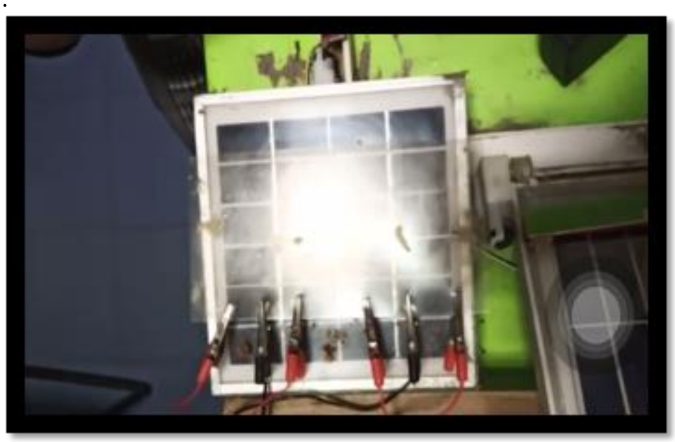

Figure 10. The dust removal efficiency of the ITO sheet

V. CONCLUSION

In the case of 20g of dust, the power generated dropped from $10.5408*10^{-3}$ W to $0.84*10^{-3}$ W when exposed to the dust. On applying a 3 phased AC current for 2-3 minutes, the power rose to $10.354*10^{-3}$ W. Similarly, for 15 g of dust, the reading dropped from $10.5408*10^{-3}$ W to $1.29*10^{-3}$ W, and on applying the three phase current, power rose to $10.319\ 10^{-3}$ W. The data we obtained by spreading different quantities of dust indicated a 98.23% restoration in the power being generated with respect to the initial value. It was observed that negligible amounts of dust now remained on the panel as compared to the data obtained in the other three methods.

Thus, in conclusion, electrostatic charges are much more successful in terms of dust removal efficiency. Efficiency in power generated rose up to 98.23%.

VI. FUTURE PROSPECTS

In the future, these self-cleaning solar panels can be integrated with Artificial Intelligence and IoT to create smart systems that can be used in domestic environments. In this case, a sensor determines the presence of dust on the solar panel and energizes the electrodes automatically.

This system also has a lot of potential in space missions and in environments where humans are unable to access surfaces that require cleaning.

It is a viable option for commercial centres and industries and can help solar panels recover their loss and fulfil energy requirements, thus helping contribute to a greener India by helping reduce the use of fossil fuels.

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AUTHORS PROFILE

Sancia Sehdev is a Medical student in Springdales School, Dhaula Kuan with a keen interest in Biology, Mathematics, and Applied Physics. She has conducted award winning research in the field of Biology, Mathematics and Physics, most of which have been targeted towards improving the healthcare system and promoting sustainable practices. Her paper documenting a mathematical model to optimize ambulance response has been published in an international journal. The model described in the paper was the Winner of the CBSE National Science Exhibition in the category Industrial Development. Sancia Sehdev is currently working on a project to increase the accuracy of prediction of tumor growth and efficiency of drug delivery to sites of malignant tumors.

Manya Gureja is presently a student of class XI at Springdales School, Dhaula Kuan, New Delhi. She has a keen interest in applied physics, mathematics and computer science. She has been conducting award-winning research in the fields of physics and mathematics, with the aim of using and applying scientific principles for sustainable development and progress in the future. Her work has been recognized by organizations such as the Central Board of Secondary Education and The Hindustan Times. Manya is currently doing research work on 'Increasing the accuracy and efficiency of prediction of tumor growth and drug delivery to sites of malignant tumors.'

Mandeep Kaur Sukhija pursued Bachelor's of Science and Master's of Science with major in Physics from University of Delhi, India. She specializes in Electronics and Communication. After her post-graduation she took up Masters in Environment and Ecology. She is currently working as a Post Graduate teacher at Springdales School, Dhaula Kuan New Delhi, India. With an experience of more than 25 years she has taken up research projects with her students in the field of STEM and Environment. In 2017, the Directorate of Education, Govt. of NCT of Delhi, honored her with the State Teachers' Award. She also received the Pied Piper Award by Springdales Education Society for her contribution for Project Based learning and for developing innovative mindsets amongst her students. Her students have won laurels and accolades at various National and International level competitions.

