sustainability

MDPI

Article

The Study of Dust Removal Using Electrostatic Cleaning System for Solar Panels

Murat Altıntaş [1] **and Serdal Arslan** [2,*]

[1] Department of Electrical Engineering, Faculty of Engineering, Harran University, Şanlıurfa 63290, Turkey; murat@mualmuhendislik.com.tr
[2] Department of Electrical, Organized Industrial Zone Vocational High School, Harran University, Şanlıurfa 63290, Turkey
* Correspondence: serdalarslan@harran.edu.tr

Abstract: This study explores the use of electrostatic cleaning to remove dust from the surface of photovoltaic solar panels. First of all, existing systems used for dust removal from solar panels were evaluated. Then, the effects of dust on the panel were investigated for Şanlıurfa province in Turkey. In addition, the elemental content of the powder was analyzed. A new device for electrostatic cleaning has been designed and implemented. The cleaning performance of this device has been tested considering the electrode designs. The electric field value was determined by analytical and numerical methods in the conventional model (parallel electrode) model. Electric field distribution was investigated using Ansys Maxwell simulation software. The printed circuit boards of the proposed model and the conventional model were produced. The traditional model with positive and negative waveform is widely used in electrostatic cleaner studies. Dust removal efficiencies and electrical losses for different frequency and voltage values were compared for both cards. It has been shown that the proposed model can perform cleaning with high efficiency despite similar loss variation.

Keywords: dust; dust removal; electrostatic; solar panel; solar energy

Citation: Altıntaş, M.; Arslan, S. The Study of Dust Removal Using Electrostatic Cleaning System for Solar Panels. *Sustainability* **2021**, *13*, 9454. https://doi.org/10.3390/su13169454

Academic Editor: Yoshiki Shimomura

Received: 13 July 2021
Accepted: 20 August 2021
Published: 23 August 2021

1. Introduction

With the increasing use of energy and climate change resulting from the use of fossil fuel sources, there is growing interest in sources of renewable energy, which includes direct use of the radiation from the sun through photo-voltaic cells (solar panels) [1]. However, these are subject to degradation in their efficiency through factors including location, environment, and weather conditions. Other conditions include dust accumulating on panels, shading from structures such as trees and buildings, seasonal changes, meteorological impact as snow, rain, cloud, and migration routes of animals (birds, etc.) near the production site [2,3]. The contamination of panels caused by these factors affects the output voltage of the panel and therefore the energy generation [4]. The impact of several of these factors, such as panel degradation, location, and annual average sunlight, can be estimated at the planning stage of a project stage. However, solar power plants (SPP) need data monitoring [5]. This is particularly important in areas (such as the North Africa and Middle East) with high accumulations of dust, which will cause significant loss of energy [6,7]. For example, an accumulation of 4 g/m^2 of dust can result in a 40% reduction of electricity generation [8]. In the last decade, the effect of dust and approaches to reduce the dirt and grime on solar panels has been the subject of research. One study focused on the 2013–2015 period [9], with an update for 2012. The work was expanded and updated to cover 2016 to 2017 [10].

An electrostatic system was implemented in this study to determine the effect of electrode design, voltage, and frequency. The study includes: (a) simulation analysis and (b) experimental results. The study was undertaken in three stages: a literature review on atmospheric transported particulate matter and especially dust-induced panel contamination and cleaning; the effects of atmospheric-transported particle material on solar panels; an analysis by Finite Element Modelling (FEM); and the application and evaluation of a dust removal system.

2. Dust-Induced Panel Pollution and Cleaning Systems

2.1. Dust-Induced Panel Pollution

The output of photovoltaic panels has been found to decrease by up to 85% due to dust, sand, and algae-like substances that occur on their surface, requiring that they are cleaned at regular intervals to maintain production values [11]. The effect of different types of dirt on the surface on the output has been investigated [3]. The masking due to contamination can be grouped into two categories: soft shading due to air pollution and hard shading due to others [12]. Light transmittance changes with physical parameters and the type of the dust, such as grain size, which causes changes to the performance of the photovoltaic (PV) panel [13].

Dust consists of particles of various elements and sizes [14]. Some of the dust particles cause particle clustering in the dust layer and can affect adhesion to solid surfaces due to ionic charges [15]. As a result, the effort and power required to remove dust particles from surfaces can increase significantly [15].

2.2. Cleaning Systems

Passive methods applied to cleaning solar panels include modification of the dust layer to minimize surface adhesion, thereby assisting in the cleaning process [16]. Dust can be removed by spraying the panels with compressed air, however, this can result in dust hanging in the air and resettling [6].

The angle of inclination of the PV modules has a strong influence on dust accumulation, and as the angle of inclination of the solar panel increases from horizontal (0 degrees) to vertical (90 degrees), dust accumulation decreases [16]. Dust accumulation is highest in the horizontal position due to gravity. The dust that accumulates on a vertical surface will mainly consist of fine particles [16]. When a panel inclined at 30 degrees is cleaned daily, weekly, and monthly, the highest output power is obtained from daily cleaning [17]. In addition, the accumulation of dust can be reduced by changing the angle of panels early in the morning or late in the evening, but this is a laborious process [6]. The angle of incidence also affects the voltage generated by the panel.

The effects of dust can be reduced and the performance of the solar panel increased by coating the surface against contamination and by reducing the amount of light that is reflected from the panel glass [18]. It has been shown that an increase in wind speed increases the accumulation of dust on PV modules; however, increasing the height of the modules above the ground reduces the accumulation of dust at increased wind speeds [18]. The height at which solar panels can be positioned is limited by the need for structural support, cleaning, and precaution against high-speed winds [16]. Dust accumulation and removal depends on a number of factors, including the force of the wind, gravity, rain, the time of day, and the inclination of the solar panel [19].

A number of technologies have been adopted as cleaning methods for PV panels and where conventional cleaning methods are inefficient or harmful, new methods are being developed. Natural forces such as wind and rain will remove dust. Mechanical methods, self-cleaning nano-film, and electrostatic tools are employed [19]. These are referred to as active cleaning methods and are applied directly or indirectly to the solar panel [7,12].

2.3. Wet Cleaning

Wet cleaning is performed with ionized distilled water, which is preferred for this task [20]. Cleaning PV panels with pure water has significant advantages; it completely removes the contaminating particulate matter on the surfaces and does not leave residue, which increases panel output voltage [20,21].

Cleaning with ionized distilled water has the following further advantages [20,21]:

- It has low conductivity, which increases the electrical occupational safety (electric shock) of the employees during cleaning.
- It provides no nourishment to plants or unwanted weeds, which can cause shade on the PV panels, as normal water would.
- It leaves not leave a residue, so there is no need for drying after the cleaning process.
- Cleaning does not damage the PV panel surface.
- It does not cause corrosion.
- Regular periodic cleaning increases the efficiency of the panels.
- It is commonly available.

Coating the panel surface with a hydrophobic material after cleaning prevents contaminants such as dust and pollen from adhering to the panels following rain fall on the panel surface.

Mechanical methods have proven to provide excellent dust removal and are compatible with the environment; however, they are bulky and heavy due to the driving components [22]. The water or other chemicals used in the wet cleaning system will dissolve the salts and other residues in the dust layers that have accumulated on the panel surface and rinse away the remainder. For small-scale panel cleaning, hand washing (wet method) is still preferred. For large-scale panels, cleaning is performed with hoses [23]. The effectiveness of cleaning of PV panels using water and surfactants using a system for spraying and collecting water has been investigated [24].

2.4. Dry Cleaning Systems

Although dry cleaning methods are not as effective as wet cleaning technologies, they do not require as much labor and water. In addition, although the glass surface of the panel has greater hardness than any brush that may be used, dust particles can scratch the panel surface in dry conditions [18]. Brushes of different material have different effectiveness in removing dust particles, which varies according to the cleaning frequency, weather conditions, and region [18]. A brush-disc configuration [25] showed that the cleaning efficiency (increased to over 90%) of dry dust particles was independent of the applied load.

In rainy dusty areas, PV panels are covered with a layer of mud, which requires excessive cleaning [23]. In areas with little rainfall, the dry cleaning method proves to be a cost-effective and self-sufficient process that does not require a water supply [23]. The efficiency of the brush-disc configuration can be increased in a humid environment by using a higher applied load; the higher the sweeping force, the greater the cleaning efficiency [23]. The efficiency of the PV panels cleaned with nylon brushes was compared with uncleaned panels, and it was found that light transmittance increased in the cleaned panels [18,25]. A nylon-brushed, flicker-free, multi-row cleaning system has been proposed in which the water can be reused [26].

Dry cleaning using nylon brushes has been shown to have no significant or lasting effect on the optical properties of the glass surface [18]. Deterioration of solar panel surfaces where dust is removed by dry brushing in outdoor conditions is an important factor that reduces the energy efficiency of solar energy systems [27].

2.5. Autonomous Cleaning Systems

Solar panel cleaning can also be performed by autonomous cleaning systems. Vehicles or robots can inspect, clean, and monitor solar panels [28]. Many developments have occurred in automatic cleaning systems since 2000, including electrostatic cleaning systems developed for extraterrestrial missions [29]. In another system, a bi-axial tracking system was used to reduce dust accumulating on the solar panel surface [30].

Robotic cleaning machines can reduce the amount of water used and increase the efficiency of the panel by 15% [23]. However, machine operation and maintenance are required and so the future labor cost is uncertain [31]. A tracking cleaning robot was designed to move in the horizontal plane, while the cleaning brush, detecting the panel length in the vertical axis, would clean it [32]. The movement of the Gekko Solar robot [29] is based on vacuum technology and cleans with a rotating brush and water. It can also move flexibly in any chosen direction. Hector [29] is equipped with various sensors that allow it to navigate autonomously day and night, and it does not require an external power or water source to operate. Solarbrush [29] is a wireless robot that can move on the panel similar to other products. Drones have been developed as autonomous cleaning systems to clean the panels. Greenbotic's robot cleans panels effectively with pressurized water perpendicular to a wiper system and uses very little water [29]. It is possible that panel cleaning can be more effective using robotic systems. In addition, the use of video can facilitate cleaning the panel surface and remotely monitoring surface conditions [33].

2.6. Self-Cleaning Technologies

Self-cleaning PV technologies are based on nanotechnology materials. These remain in research and development and are currently expensive to deploy. Self-cleaning methods that prevent the accumulation of dust on the solar panel surface are seen as the best method both in terms of preventing loss in efficiency and extending the life of the solar panel [27]. FluroSurf and PTFE are fluorine-based hydrophobic anti-dust coatings [29,31] that make the glass surface non-adhesive to dust and easy to clean. Cleaning can be accomplished through simple washing with clean water or mild detergent and wiping with a soft towel [29].

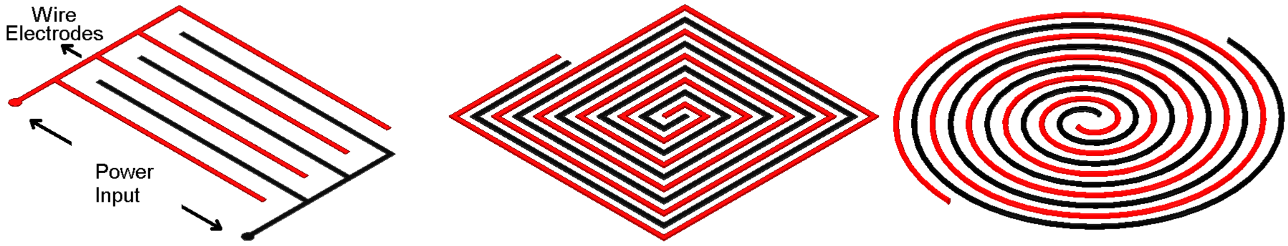
The effects of three types of rain repellent on the solar panels have been studied in our previous paper [34]. In comparing panels with rain repellent on their surface to the panels with no rain repellent, performance increased in the panels with rain repellent [34]. Recent developments have emerged in coatings with superhydrophilic and superhydrophobic materials that can operate in both dry and wet dusty conditions [29].

2.7. Surface Acoustic Wave (SAW) Technologies

SAW technologies are widely used for precision surface cleaning and particle channeling applications [27]. SAW interactions can create gaseous micro-air flows by penetrating into sloping panel surfaces, causing the surfaces associated with the acoustic areas to vibrate; this effect contributes to the cleaning of the surfaces and areas normally inaccessible to other cleaning methods [27]. Although this cleaning (sweeping) technique is considered as an advantage in energy consumption when evaluated for panel applications that continuously clean itself, a sound intensity of 90 dB that accompanies SAW is not a desired feature for a continuously operating systems [27].

2.8. Electrostatic Cleaning and Electrode Design

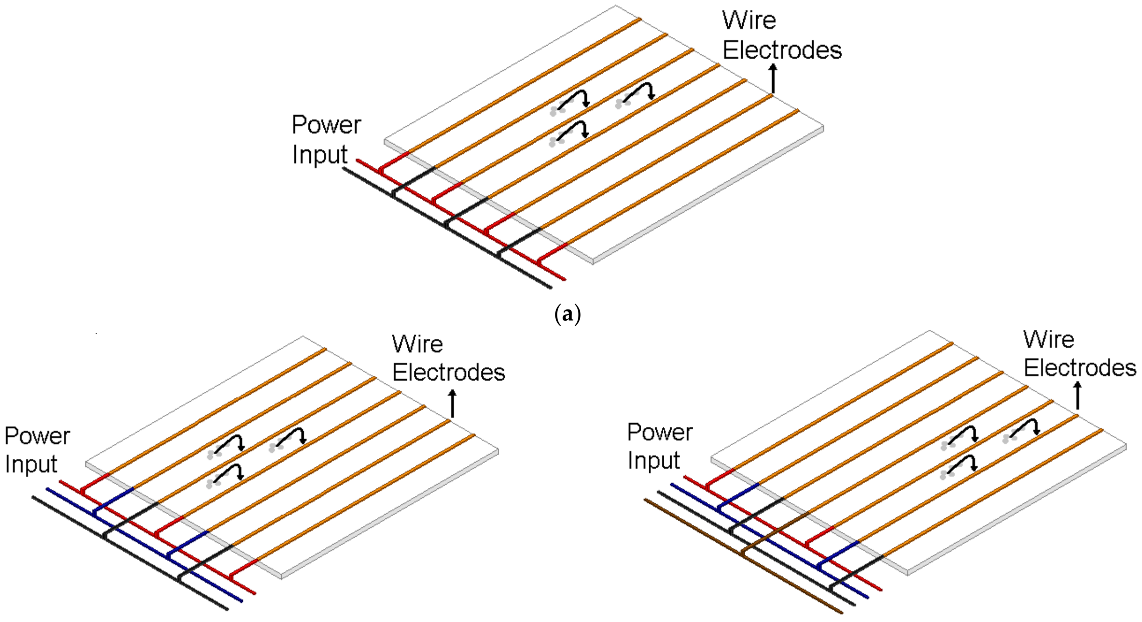
A photovoltaic panel cleaning method has been developed based on moving wave electric charge on small particles suspended in liquid [35], which can remove dust and similar dirt (except algae) formed on the surface of solar panels [36,37]. One electrode is charged with a very high negative voltage, and the other electrodes are positively charged, causing the dust particles to be ejected from the panels [36,37]. In a different mechanism, dust was removed by an electric curtain, with the distribution of the electric field density [38]. This mechanism was analyzed as a Finite Element Model (FEM) using the ANSYS software taking the electrode width as 0.5 mm and the electrode spacing as 1.3 mm [38]; the distribution of the electric field in the vertical direction and horizontal direction was studied. In this system, the electric field density varies over the plate, creating a force on the dust that moves it off the plate [38]. Figure 1 shows the alternative electrode designs that were studied.



(**a**) (**b**)

Figure 1. Alternate electrode designs [38,39]: (**a**) Interdigitated, (**b**) Concentric.

Coating Alternate approaches to using electrostatic cleaning apply one- [40], two- [31], and four-phase [39] low frequency and high voltage to parallel electrodes placed under the glass plate of the PV panel. Whilst generally effective, performance was found to be poor for extremely small dust particles. Figure 2 shows examples of the arrangement of electrodes on the solar panel with the excitation states for one-phase (Figure 2a), three-phase, and four-phase cleaning systems (Figure 2b).



(**a**)

(**b**) (**c**)

Figure 2. Multi-phase electrostatic cleaning methods [19,31]: (**a**) one phase, (**b**) three phases, (**c**) four phases.

Figure 3 shows the arrangement of electrodes on the solar panel. This consists of parallel electrodes embedded between two transparent dielectric films. The top, sun-facing layer is ultra-thin flexible glass (Corning Willow Glass) to protect the electrodes. The electrodes are buried in a transparent film that bonds the top layer of glass to the glass of the solar collector [41].

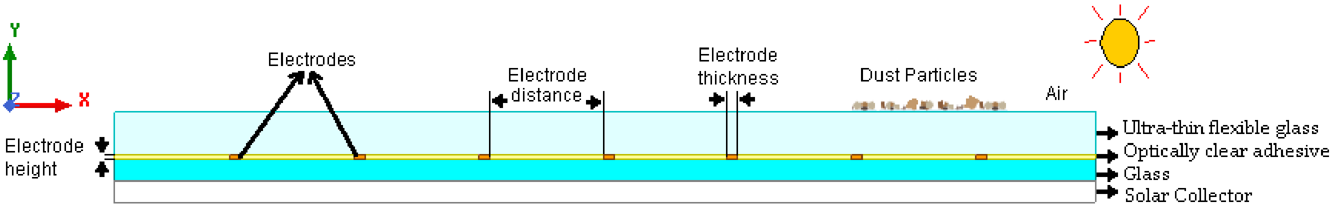


Figure 3. Cross section of parallel plateelectrodes with material [40,41].

The system in [42] was operated with a 1.2-kV, three-phase, pulsed voltage [42], however, the performance could be increased by applying a higher voltage to reduce the adhesion force and exploit the natural wind and greater regularity of use before dust accumulates [31]. The effect of frequency on cleaning performance and power consumption are described in detail in [31,42]. The electrostatic cleaning technology could potentially increase the efficiency of solar power plants built at low altitudes in deserts [31,42]. Other similar systems using three-phase high-voltage electrodynamic principles to remove dust particles from solar panels have been developed [8,41].

Electrostatic cleaning, as an electrodynamic screen (EDS), is seen to have significant advantages: it reduces the energy loss caused by the contamination on PV modules and the use of freshwater resources required for conventional cleaning [41,43]. Moreover, it is effective at cleaning, removing more than 90% of the accumulated dust within 2 min without the need for water or other mechanical materials and can use energy being generated by the panels [43]. An investigation of the optimal voltage to remove particles determined 2.8 kVp-p for low voltage, while 11.8 kVp-p was sufficient to continually move particles [44]. Dust transport was observed to decrease as the cycle frequency increased from 0.5 to 10 Hz [44]; however, other studies determined the greatest transport rate occurred at 1 Hz [45].

In another design [42,46], high voltage pulses were applied to the parallel electrodes. The lower part of the electrodes was placed on a dirty PV panel and the electrodynamic force was used to affect the particles under the lower electrode (Figure 4). This initiates a downward movement of some of the particles along the inclined panel due to the gravitational force passing between the electrodes and through the openings of the upper screen electrode due to the electrodynamic force; the dust accumulated on the panel is cleaned in this way [46].

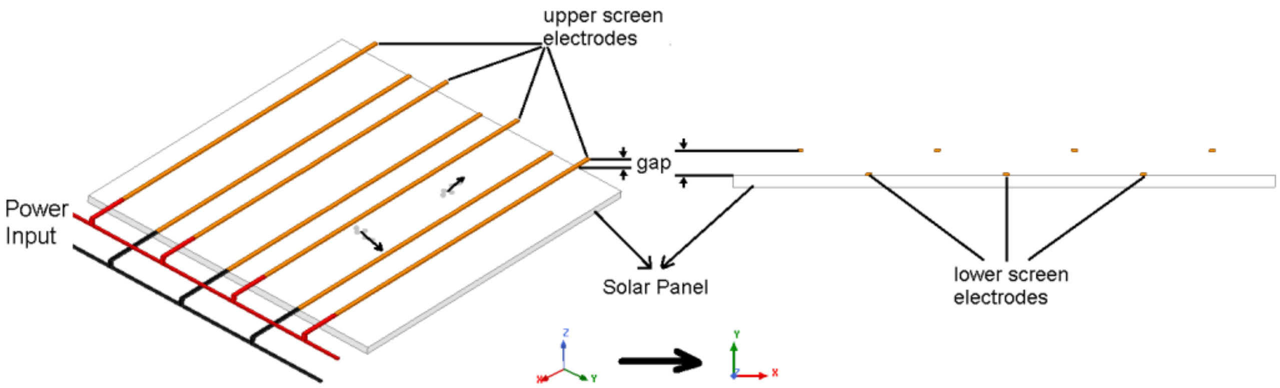


Figure 4. Schematic diagram of a detachable electrostatic cleaning device [46].

The shape of electrodes has been investigated [47] by comparing the performance of planar, thick-toothed comb-shaped, and fine-toothed comb-shaped electrodes to remove dust (Figure 5). Comb-shaped electrodes were found to provide better electric field distributions compared to the common planar electrodes. Dust removal was not related to the thickness and the shape of the electrode or the material of the insulation film [47].

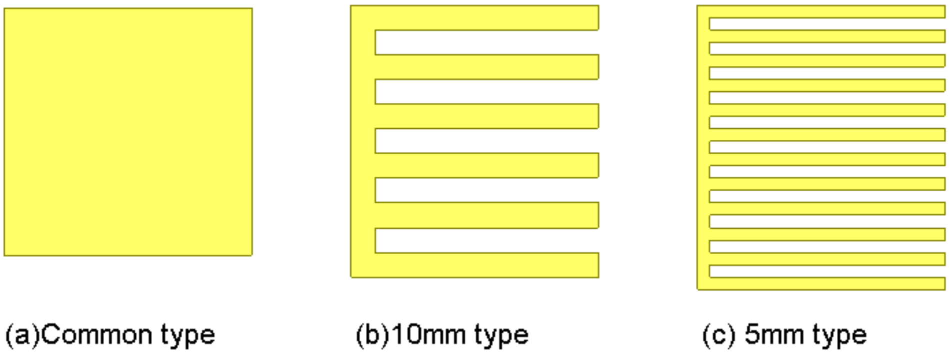


Figure 5. Dust removal electrodes with the same area [47].

3. Effect of Atmospheric-Transported Particulate Matter on Solar Panels

PV panels located next to an unlicensed solar power plant site with a production capacity of 1 MW, located in Akziyaret, Şanlıurfa province in Turkey, were used as a test case. The production values were measured for a six-month period for one CWT270 60P PV panel that was cleaned monthly and for a second that was left uncleaned [14]. The open circuit voltage is 38.84V. The short circuit current is 9.10A. The contamination on the panel surface had significant impact on the reduction in the performance of the panel. The open-circuit voltage measured in the solar panel is given in Figure 6 [14].

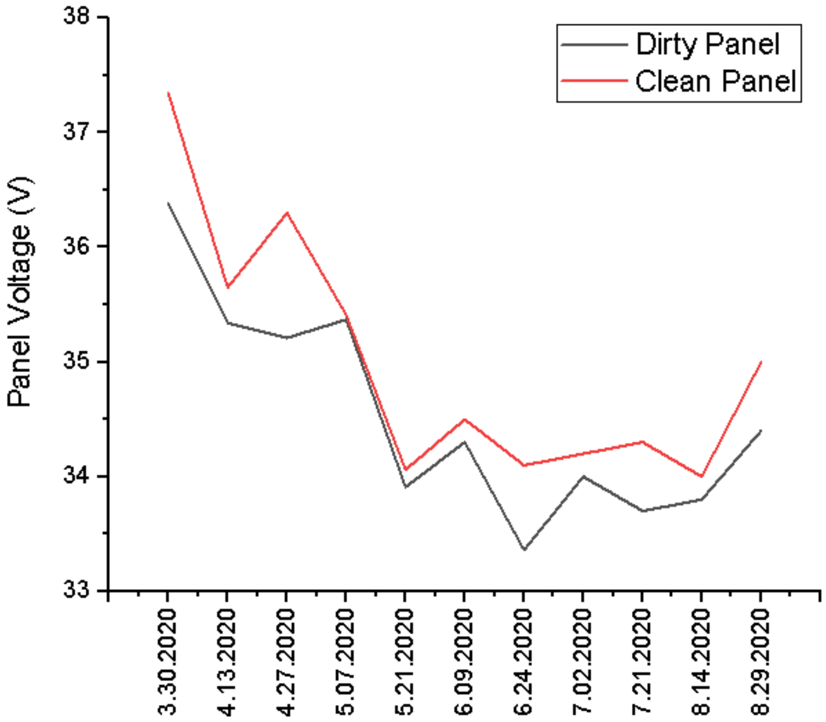


Figure 6. Six-month variation of voltage measured on cleaned and uncleaned PV panels.

The contaminating dust was collected from the panel surface for analysis in the HÜBTAM Laboratory at Harran University, and the type and amount of particles were determined by energy dispersive spectroscopy (Figure 7). The particles comprised the oxide forms of Si, C, O, Ca, S, Na, In, K, Mg, Al, and Fe. Images from a scanning electron microscope (SEM) of the dust particles were used to determine the size and shape of the particles. Figure 8 shows a typical sample of dust collected during May. The powder contains a mixture of large and small particles. Dust particles have a complex shape. For example, they can be spherical, ellipsoid, angled, etc. Regionally, the composition and amount of dust is not constant throughout the year; the particle size is large during March, April, and May, smaller in June, July, August, September, October, and November, and high in December [14].

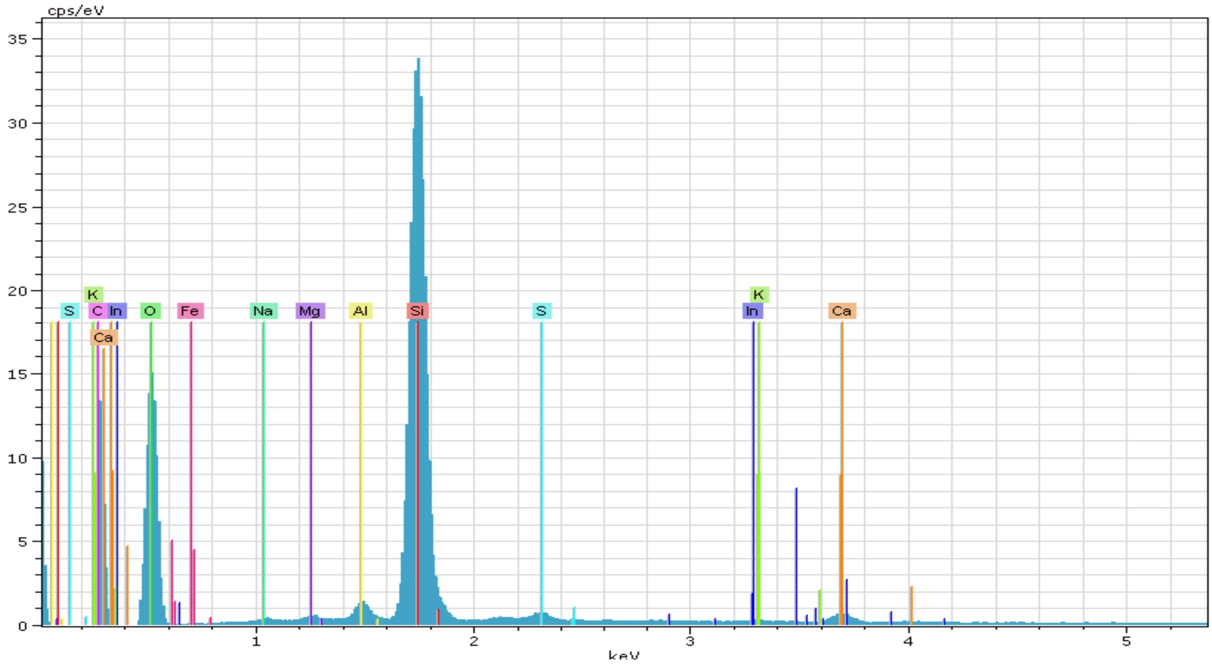


Figure 7. Elemental composition of dust.

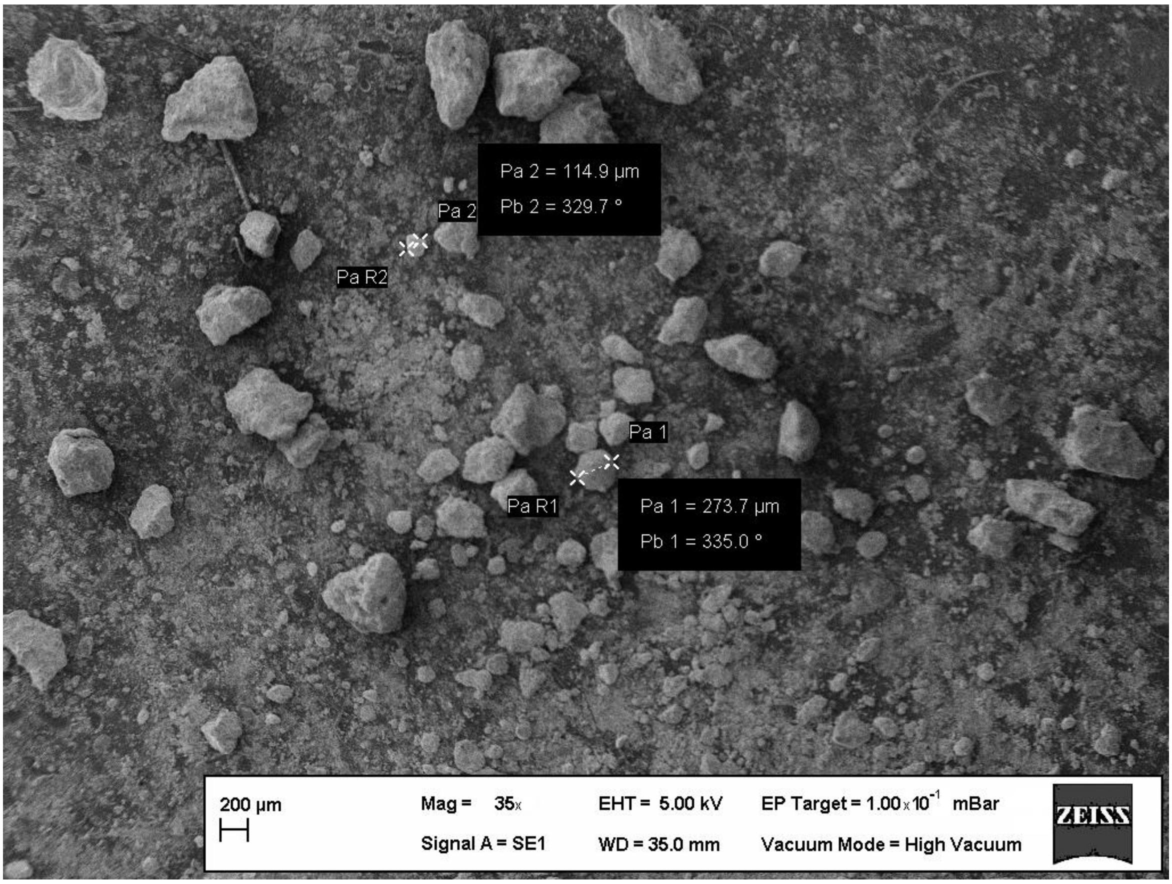


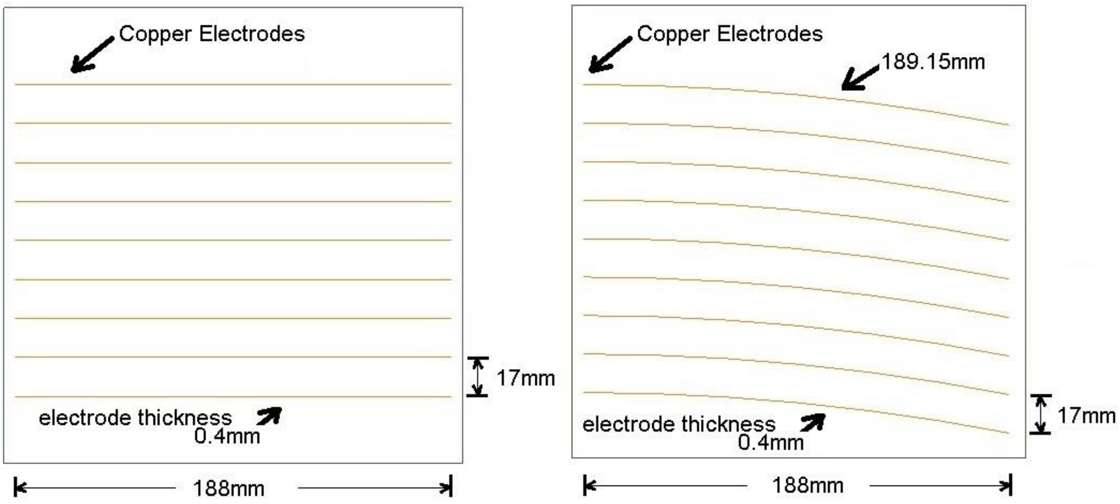
Figure 8. Appearance of the microstructure of particulate matter in SEM analysis for May.

4. Electrostatic Cleaning Systems

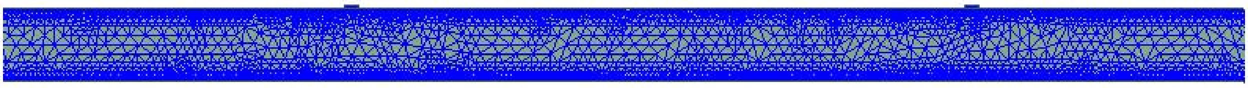
4.1. D and 2D Numerical Analysis of Electrode Arrays

Ansys Maxwell, a computer-aided analysis software, is widely used in the numerical solution of electromagnetic problems. From the modeling point of view, the electrostatic problem under consideration basically has a three-dimensional geometry. However, it has been discussed to examine the results of both a 2D and a 3D analysis. Firstly, the dimension to be designed for the machine geometry is selected, and the model is drawn. Then, the voltage definition and the boundary conditions are defined to the energized parts of the model. As model parameters, capacitance and electrostatic force definitions are made. Mesh identification, although it may seem small in the program algorithm, is very important for the machine to produce a sufficient solution. In order to increase the sensitivity of the solution, a denser mesh is assigned by the user or the program to the small sub-parts of the designed model. In these regions, the finite element mesh may not be symmetrical, and the narrow angle-pointed corners in the mesh make the solution difficult and also negatively affect the results obtained. Inside the solution area, the inside mesh is defined. We did not restrict the number of elements. The finite element mesh is automatically created in the system to be modeled before the analysis. After the first pass of the analysis, Ansys Maxwell calculates the delta energy (%). Solver performs error analysis over the completed solution to a file. The meshes are improved until the percentage energy error is below the target percent error specified by the user. The solution continues until the error criterion is met. As a result, important parameters (electrostatic force, electric field, etc.) are obtained.

The distribution of the electric field around electrode arrays can be determined using the Finite Element Method (FEM) and can be used to find the maximum electric field in a complex system. The electric field between parallel electrodes can be determined analytically using E = V/d as the uniform electric field between the plates of a parallel plate capacitor, where d is the distance between the electrodes, and V is the applied voltage. The electric field value is 6.47×10^5 V/m for an applied voltage of 11 kV when the distance between the electrodes is 17 mm (Figure 9a).



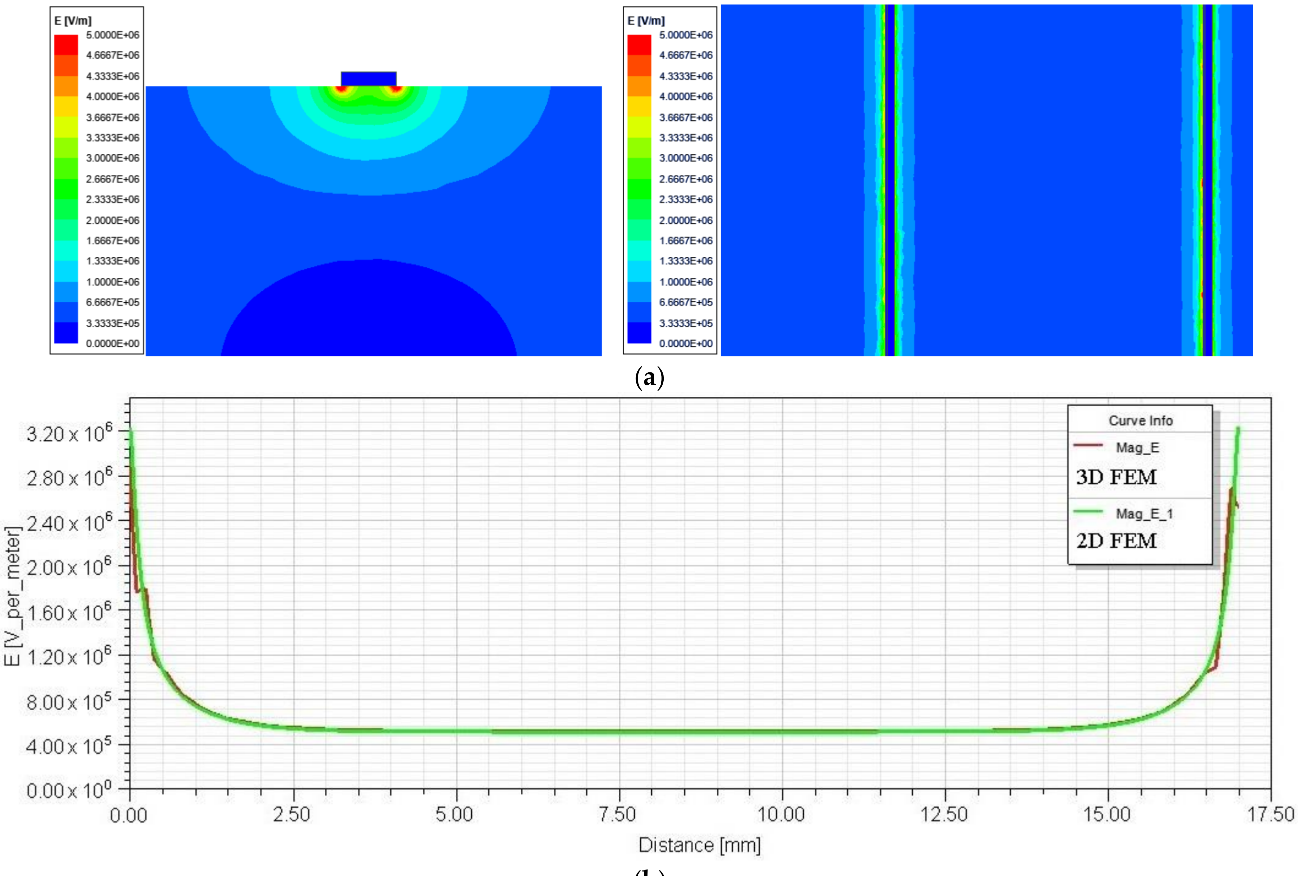
(**a**)



(**b**)

Figure 9. Electrode models: (**a**) N1 traditional model (left) and N2 model (right); (**b**) The mesh views of N1 model in the 2D analysis.

For example, in the 2D analysis of the electrode array, the total number of mesh elements was 921,635, the energy error value was 0.02%, and the analysis time was 3.32 min. In the 3D analysis, the total number of meshes was 1,772,735, the energy error value was 0.378%, and the analysis time was 24.04 min. Figure 10a,b indicate similar electric field values were determined for 2D and 3D FEM.



(**a**)

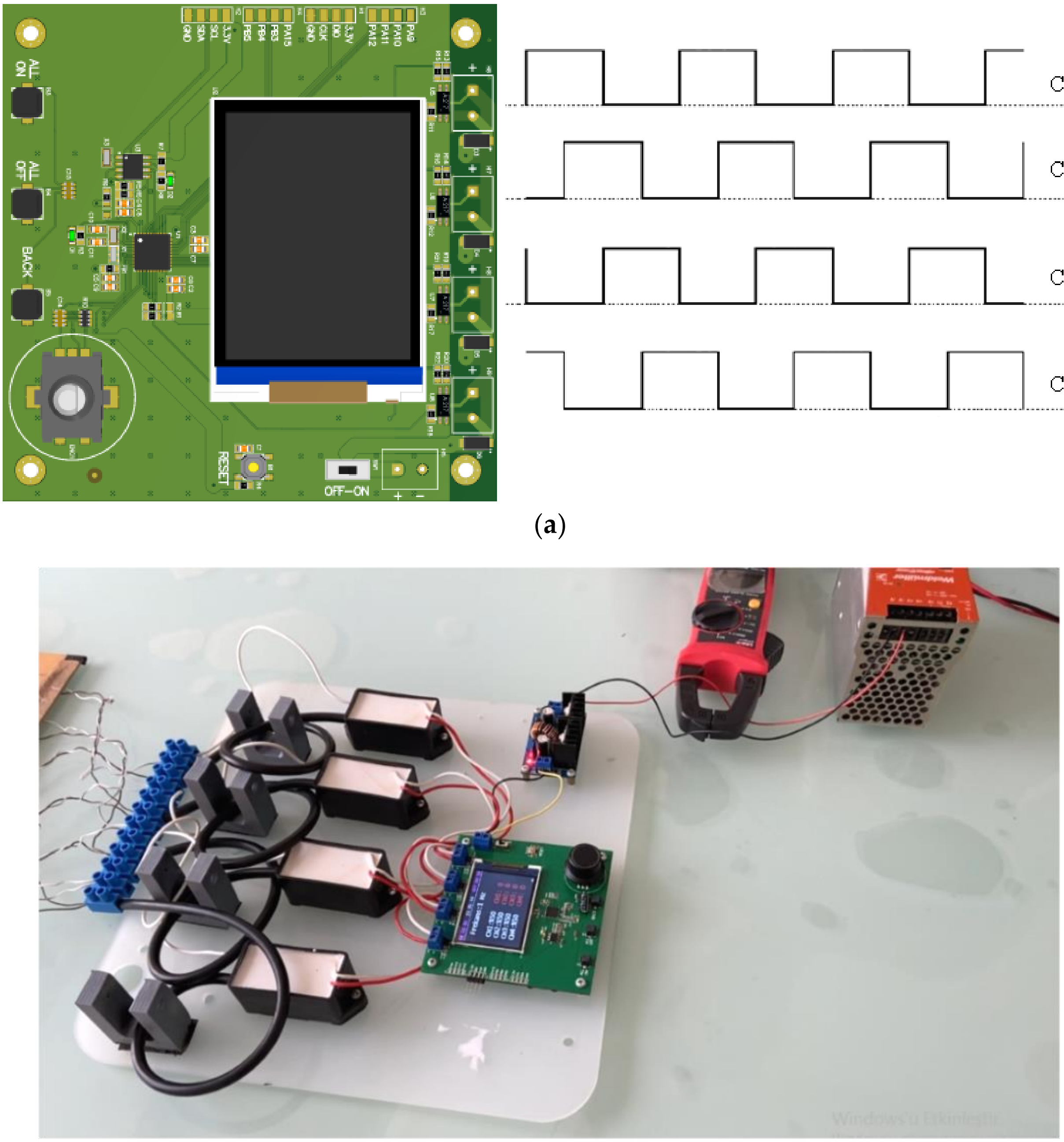
(**b**)

Figure 10. Electric field between two electrodes: (**a**) 2D FEM (top left) and 3D FEM field distributions (top right); (**b**) 2D and 3D numerical results.

Due to the relatively large distance between the electrodes (17 mm) compared to the area between them as plates of a capacitor, the distribution of the electric field is not uniform, and the greatest value occurs in areas close to the electrodes, as seen in Figure 9b. Note that there was close agreement in the results between the 2D and 3D analyses. For example, the electric field value in the 2D analysis at 8.5 mm was 5.14×10^5 V/m and the electric field value in the 3D analysis was 5.20×105 V/m for an applied voltage of 11 kV. The difference between the 2D and 3D analyses results was 1.28% and acceptable for FEM analysis.

4.2. Experimental Electrostatic Cleaning System

An electrostatic cleaning system was designed to drive four channels of high voltage transformers at a desired frequency (1 Hz–3 Hz) and voltage (3 kV–11 kV). Figure 11 shows the (a) controller card, (b) the signal output, and (c) the experimental system.



(**a**)

(**b**)

Figure 11. Electronic card images: (**a**) Printed circuit appearance and channel outputs, (**b**) Experimental system.

The system is designed to drive four channels at a desired frequency between 1 Hz and 3 Hz and with an output voltage between 3 kV and 11 kV. Each channel gives a square wave output, as in Figure 11b. The frequency and duration of the duty cycle can be set for each channel. It can program each channel independently, as well as actively operate four channels in the desired time interval. Even if the system is energized, it continues to work from where it left off with the battery. The processor (STM32F411CEU6) works by switching the high voltage set by the user with the help of an encoder or by using the information received from the RTC chip. All the information can be followed in color on the TFT LCD screen, and the sequence of operations is displayed. Details of the circuit developed for these experiments are given in the Appendix A. The flow diagram for the operation of the system is given in Figure 12.

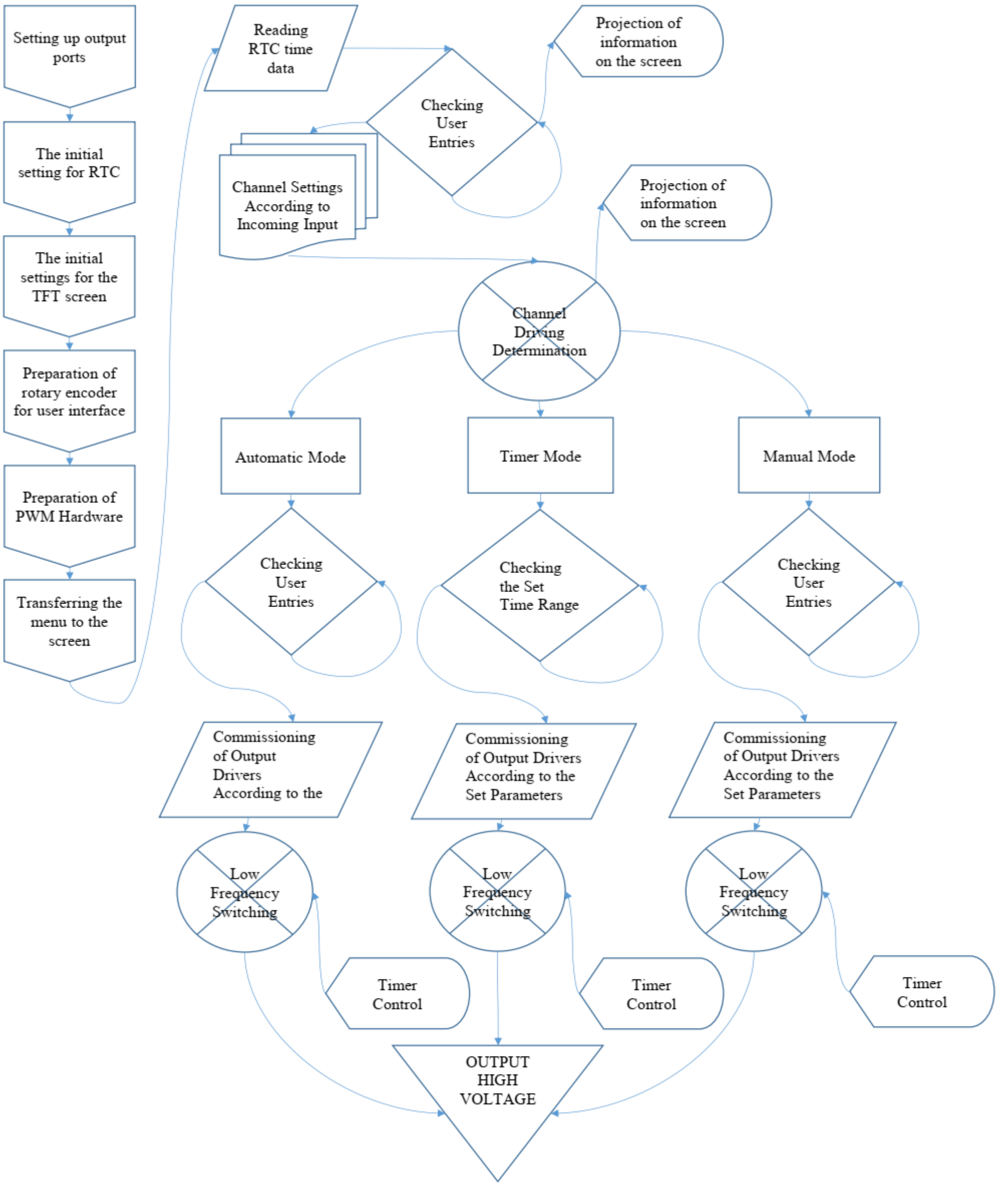


Figure 12. Flow diagram of system operation.

4.3. Test Results for Electrostatic Cleaning System

In measurements in Sanliurfa, a 270-W solar panel with dimensions of 1.64 m × 0.99 m = 1.624 m^2 accumulated 16.24 g of dust during November, giving a daily average accumulation of 10 g/m^2.

Model electrode arrays were developed to investigate the cleaning efficiency when applied to the 270-W panels and had a size 0.20 m × 0.20 m = 0.04 m^2. The equivalent amount of dust x_d that would accumulate during November was determined as Equation (1).

This is example 1 of an equation:

$$x_d = \frac{A_k \times x_m}{B_k} \quad (1)$$

where A_k is the surface area of the electrode array (m^2), B_k is the surface area of the 270-W panel (m^2), and x_m is the mass of dust (g) that fell on the 270-W panel in November. The amount of dust x_d was determined as 0.4 g. Thus, 0.4 g of dust with size 100 µm–300 µm was applied to the N1 model representing traditional straight electrodes with 17 mm spacing (Figure 13) and to the proposed N2 model with modified electrodes with 17 mm spacing (Figure 14). The efficiency of dust cleaning was compared for 1 Hz, 2 Hz, and 3 Hz and various voltages (Figure 15a,b). Power loss was compared for 1 Hz, 2 Hz, and 3 Hz and various voltages (Figure 16a,b).

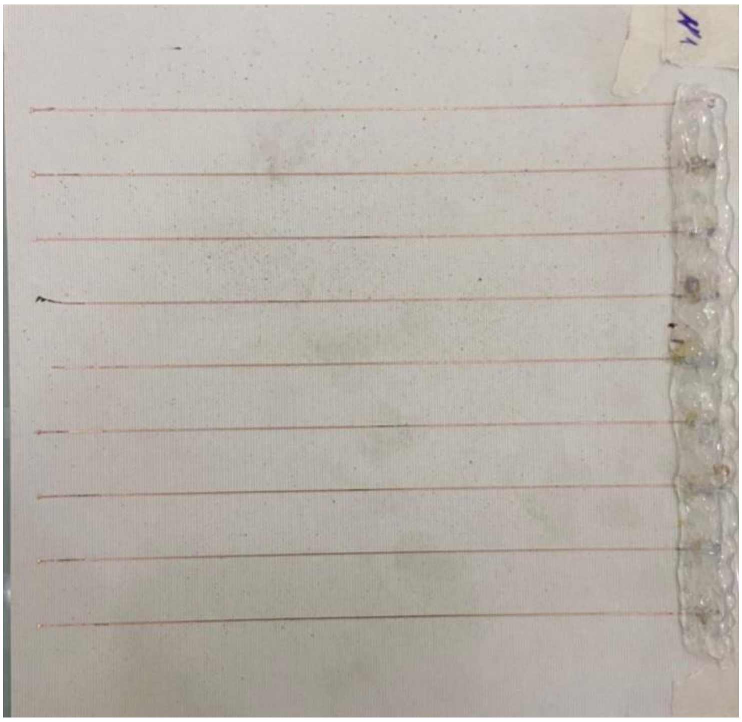
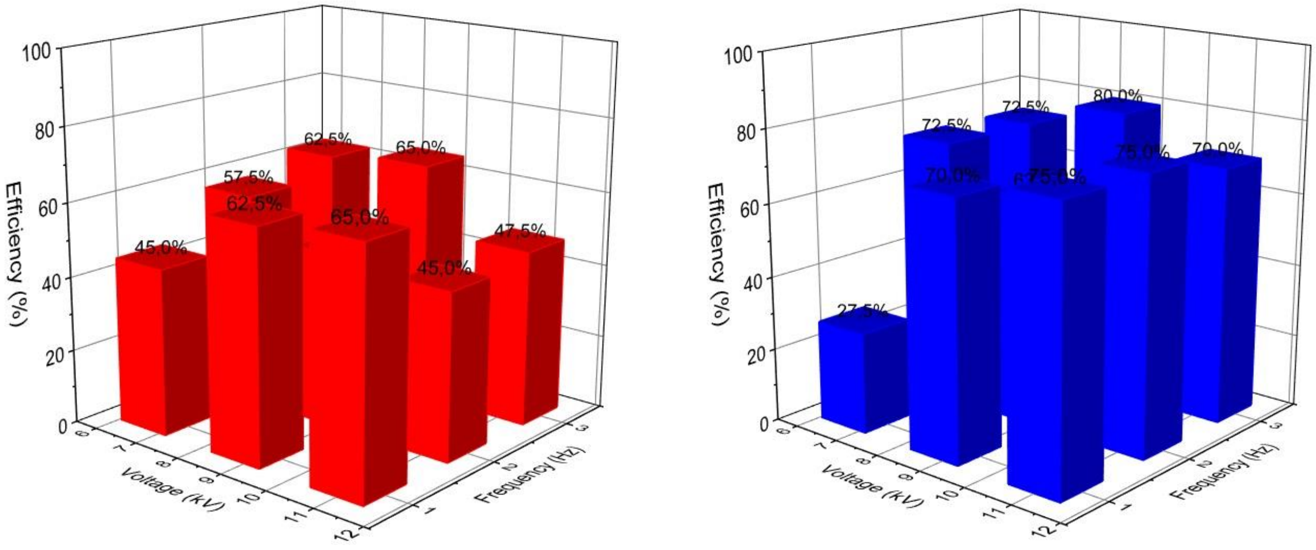


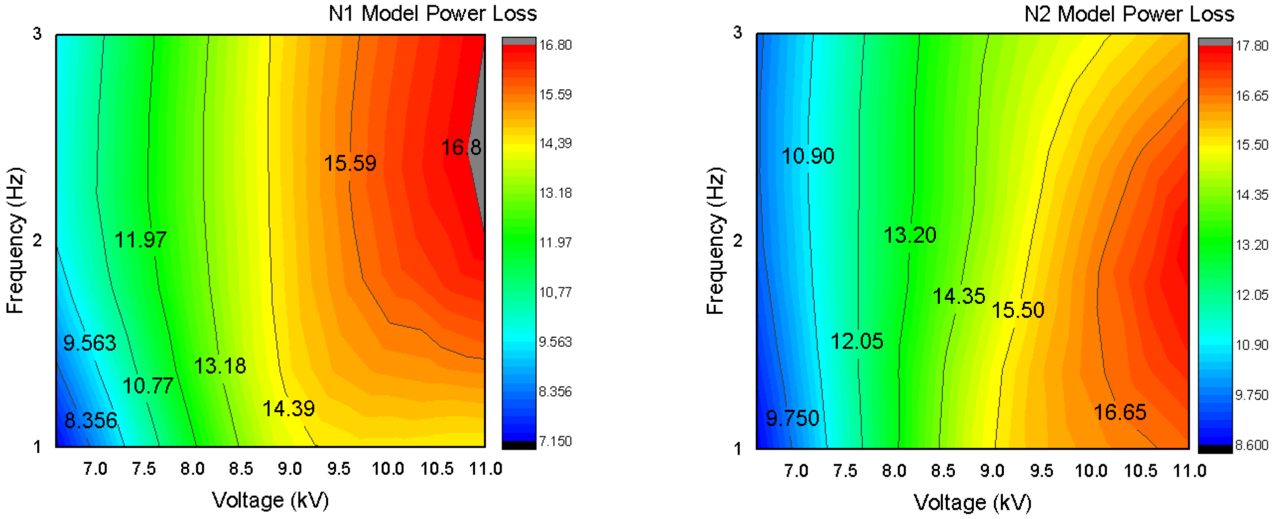
Figure 13. N1 traditional model with 17 mm spacing with 100–300 µm dust distribution.

Figure 14. N2 model with 17 mm spacing with 100–300 µm dust distribution.



(**a**) (**b**)

Figure 15. Efficiency of cleaning: (**a**) N1 model, (**b**) N2 model.



(**a**) (**b**)

Figure 16. Power loss maps in various model: (**a**) N1 traditional, (**b**) N2 recommended.

The cleaning efficiency of panels is commonly expressed as the ratio between the weight of sand on the panel before cleaning and that removed by the cleaning [25,31].

Although increasing the voltage initially increased the efficiency, this reaches a maximum value, beyond which no further increase was seen, and decreases in some instances. However, higher voltages will result in an increased current, and there is therefore an optimal value for cleaning efficiency and minimum power consumption. When the 11-kV 1 Hz value is compared in terms of power losses, the N1 model has a power loss of 14.4 W, and the N2 model has a power loss of 16.8 W. When the panel is examined in terms of cleaning efficiency, the N1 model is 65% efficient and the N2 model is 75% efficient. Increasing the frequency above 1 Hz resulted in lower efficiency, and this value is deemed optimal. This is similar to the result from other studies [31,44], which concluded that 1 Hz was preferable. The proposed electrode geometry of the N2 model was found to give a significant increase to the efficiency of cleaning at the optimum voltage and frequency.

5. Conclusions

The electrostatic cleaning of PV panels has many advantages, albeit some disadvantages. The greatest advantage comes if electrostatic cleaning is built into the PV panel so that it is self-cleaning. Initially the disadvantage will be the cost of replacing existing cleaning techniques and retrofitting electrostatic cleaning panels to existing PV panels or replacing the PV panels.

Further advantages of electrostatic cleaning come from the unattended cleaning, lower cost, greater reliability, lower maintenance, no need for cleaning fluids (detergents) or water, avoiding the use of abrasive materials, increased panel efficiency, and extended life of the panels. Future research should include a detailed comparison between the costs of existing cleaning methods and electrostatic cleaning.

The data on the data accumulation gathered in Şanlıurfa show that effective cleaning methods for PV panels are essential in Turkey. Given that many areas in Turkey are already designated as areas with a shortage of water, methods that do not rely on water will become increasingly important, and electrostatic cleaning has an essential part to play. The results are summarized and listed as follows.

- It is known that the particle size and density of the powder varies regionally. This will also change the electrostatic cleaning performance. Regional dust conditions were evaluated and 80% of the dust was cleaned.
- The variation of the voltage applied to the electrodes changes the panel cleaning performance. The increase in the voltage, electrode distance, and electric field value should be determined using the finite element method for prevention of arcing.
- The change in the shape of the electrode in the electrostatic cleaning system changes both the cleaning performance and the power consumed.

It has been shown that the electronic card and the proposed electrode model can be used for electrostatic cleaning. The airflow contribution to dust removal is mentioned in [31]. In [39], dust removal from the solar panel by vibration is given. Both methods make a positive contribution to dust removal. However, since there is no study that deals with both cases, further work will include adding wind sensors to identify the optimum cleaning conditions and use of piezoelectric material.

Author Contributions: Conceptualization, S.A. and M.A.; methodology, S.A. and M.A.; software, S.A. validation, M.A., formal analysis, M.A.; investigation, M.A.; resources, S.A.; data curation, M.A.; writing—original draft preparation, S.A. and M.A.; writing—review and editing, S.A.; visualization, S.A.; supervision, S.A.; project administration, S.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This study was produced from the master's thesis prepared by the first author under the supervision of the second author. The software was obtained from the Harran University under Research Project (project no: 18060).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

This appendix contains the schematic diagram of the microprocessor and driver circuits.

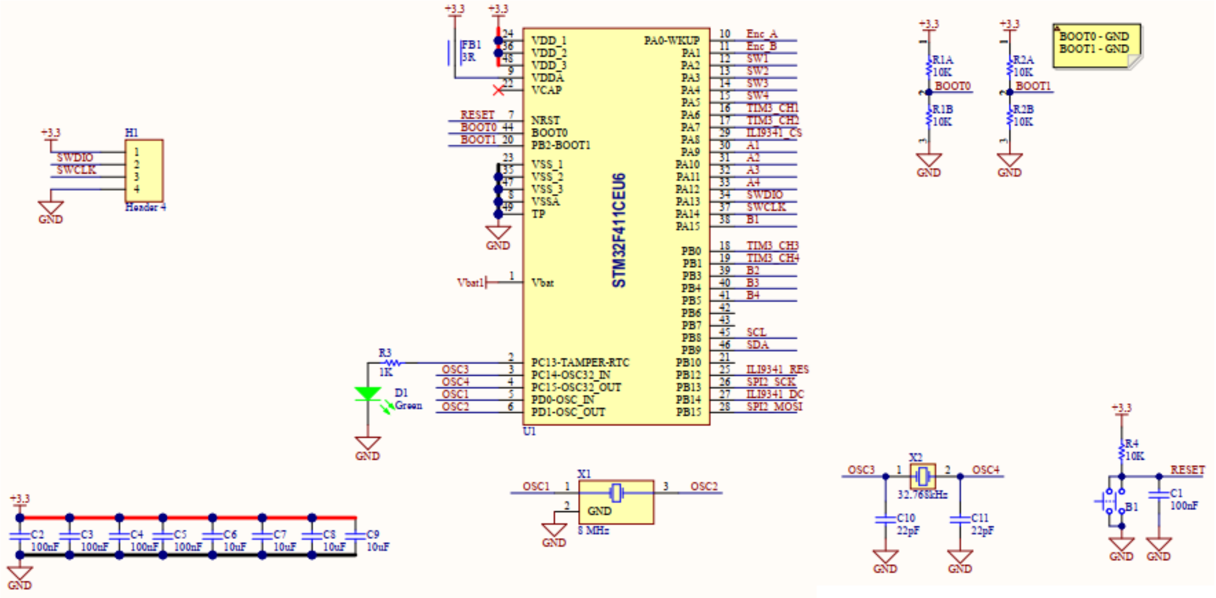


Figure A1. Microprocessor schematic diagram.

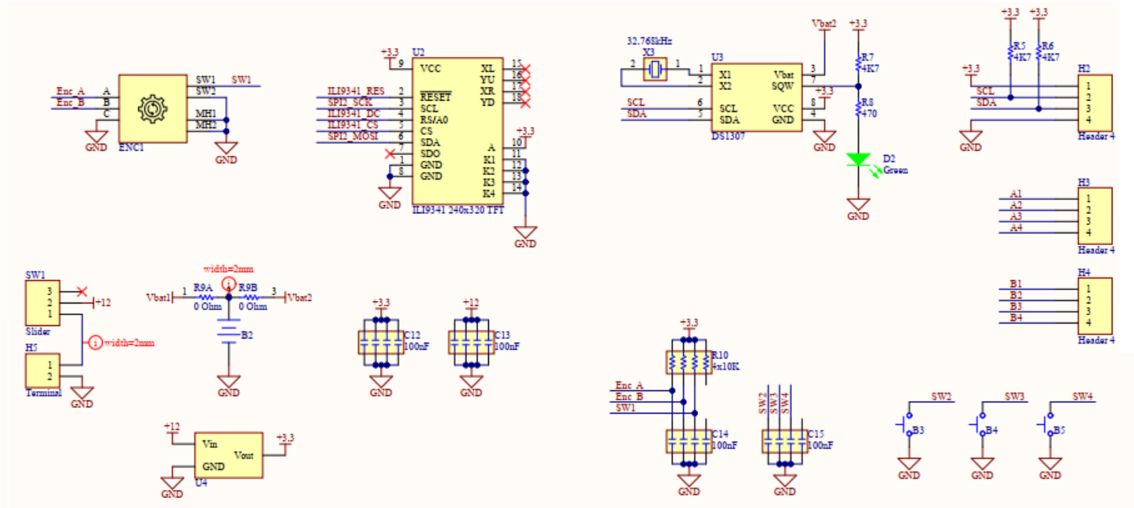


Figure A2. Display and control circuits schematic diagram.

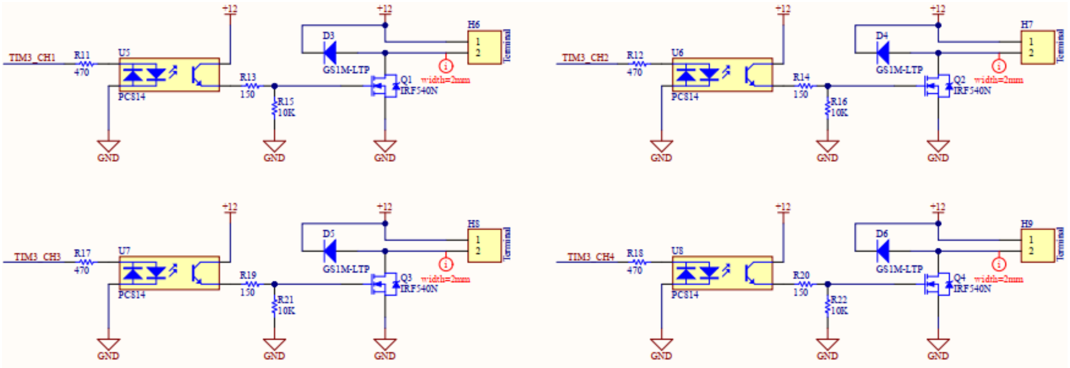


Figure A3. Output driver schematic diagram.

References

1. Ohunakin, O.S.; Adaramola, M.S.; Oyewola, O.M.; Fagbenle, R.O. Solar energy applications and development in Nigeria: Drivers and barriers. *Renew. Sustain. Energy Rev.* **2014**, *32*, 294–301. [CrossRef]
2. Mekhilef, S.; Saidur, R.; Kamalisarvestani, M. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2920–2925. [CrossRef]
3. Casanova, J.Z.; Piliougine, M.; Carretero, J.; Bernaola, P.; Carpena, P.; Mora-Lopez, L.; Sidrach-Cardona, M. Analysis of dust losses in photovoltaic modules. *World Renew. Energy Congr.* **2011**, 2985–2992. [CrossRef]
4. Adıgüzel, E. Effect of Dust Particles in Different Sizes on the Efficiency of the Photovoltaic Panels. Master's Thesis, University of Istanbul, Istanbul, Turkey, 2018. Available online: https://tezarsivi.com/farkli-boyutlardaki-toz-partikullerinin-fotovoltaik-panellerin-verimliligi-uzerine-etkisi (accessed on 1 November 2020).
5. Libra, M.; Daneček, M.; Lešetický, J.; Poulek, V.; Sedláček, J.; Beránek, V. Monitoring of Defects of a Photovoltaic Power Plant Using a Drone. *Energies* **2019**, *12*, 795. [CrossRef]
6. Ghazi, S.; Sayigh, A.; Ip, K. Dust effect on flat surfaces–a review paper. *Renew. Sustain. Energy Rev.* **2014**, *33*, 742–751. [CrossRef]
7. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. Dust and PV performance in Nigeria: A review. *Renew. Sustain. Energy Rev.* **2020**, *21*, 1–14. [CrossRef]
8. Mazumder, M.K.; Sharma, R.; Biris, A.S.; Zhang, J.; Calle, C.; Zahn, M. Self-cleaning transparent dust shields for protecting solar panels and other devices. *Particul. Sci. Technol.* **2007**, *25*, 5–20. [CrossRef]
9. Costa, S.C.; Diniz, A.S.A.; Kazmerski, L.L. A: Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015. *Renew. Sustain. Energy Rev.* **2016**, *63*, 33–61. [CrossRef]
10. Costa, S.C.; Diniz, A.S.A.; Kazmerski, L.L. B: Solar energy dust and soiling R&D progress: Literature review update for 2016. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2504–2536. [CrossRef]
11. Sulaiman, S.A.; Singh, A.K.; Mokhtar, M.M.M.; Bou-Rabee, M.A. The International conference on technologies and sustainability. *Energy Proc.* **2014**, *50*, 50–56. [CrossRef]
12. Maghami, M.R.; Hizam, H.; Gomes, C.; Radzi, M.A.; Rezadad, M.I.; Hajighorbani, S. Power loss due to soiling on solar panel: A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1307–1316. [CrossRef]
13. Abderrezek, M.; Fathi, M. Experimental study of the dust effect on photovoltaic panels energy yield. *Sol. Energy* **2017**, *142*, 308–320. [CrossRef]
14. Altıntaş, M.; Arslan, S. Analysis of Atmospheric Transported Particulate Matter and Investigation of Its Effects on Solar Panel. In Proceedings of the 9th European Conference on Renewable Energy Systems, Istanbul, Turkey, 24–25 August 2021; pp. 712–718.
15. Yilbas, B.S.; Al-Qahtani, H.; Al-Sharafi, A.; Bahattab, S.; Hassan, G.; Al-Aqeeli, N.; Kassas, M. Environmental dust particles repelling from a hydrophobic surface under electrostatic influence. *Sci. Rep.* **2019**, *9*, 8703. [CrossRef] [PubMed]
16. Sayyah, A.; Horenstein, M.N.; Mazumder, M.K. Energy yield loss caused by dust deposition on photovoltaic panels. *Sol. Energy* **2014**, *107*, 576–604. [CrossRef]
17. Doğan, G. Effect of Dirt and Dusting on Photovoltaic System Yield. Master's Thesis, University of Fırat, Elazig, Turkey, 2018. Available online: https://openaccess.firat.edu.tr/xmlui/bitstream/handle/11508/18284/492736 (accessed on 1 November 2020).
18. Al Shehri, A.; Parrott, B.; Carrasco, P.; Al Saiari, H.; Taie, I. Impact of dust deposition and brush-based dry cleaning on glass transmittance for pv modules applications. *Sol. Energy* **2016**, *135*, 317–324. [CrossRef]
19. He, G.; Zhou, C.; Li, Z. Review of self-cleaning method for solar cell array. *Proc. Eng.* **2011**, *16*, 640–645. [CrossRef]
20. Myenerjisolar. Available online: https://www.myenerjisolar.com/gunes-enerjisi-panel-temizligi/ (accessed on 1 November 2020).
21. Kurşun, M. The effect of natural dust accumulation on the efficiency of solar panels in Samsun climate conditions. Master's Thesis, University of Ondokuz Mayıs, Samsun, Turkey, 2019. Available online: http://libra.omu.edu.tr/tezler/131186.pdf (accessed on 1 November 2020).
22. Lu, X.; Zhang, Q.; Hu, J. A linear piezoelectric actuator based solar panel cleaning system. *Energy* **2013**, *60*, 401–406. [CrossRef]
23. Aly, S.P.; Gandhidasan, P.; Barth, N.; Ahzi, S. Novel dry cleaning machine for photovoltaic and solar panels. In Proceedings of the 3rd International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, Morocco, 10–13 December 2015; pp. 1–6. [CrossRef]
24. Moharram, K.A.; Abd-Elhady, M.S.; Kandil, H.A.; El-Sherif, H. Influence of cleaning using water and surfactants on the performance of photovoltaic panels. *Energy Conv. Manag.* **2013**, *68*, 266–272. [CrossRef]
25. Chen, E.Y.T.; Ma, L.; Yue, Y.; Guo, B.; Liang, H. Measurement of dust sweeping force for cleaning solar panels. *Sol. Energy Mater. Sol. Cells* **2018**, *179*, 247–253. [CrossRef]
26. Thomas, S.K.; Joseph, S.; Sarrop, T.S.; Haris, S.B.; Roopak, R. Solar Panel Automated Cleaning (SPAC) System. In Proceedings of the International Conference on Emerging Trends and Innovations In Engineering And Technological Research (ICETIETR), Ernakulam, Cochin, India, 11–13 July 2018; pp. 1–3. [CrossRef]
27. Alagöz, S.; Apak, Y. Removal of spoiling materials from solar panel surfaces by applying surface acoustic waves. *J. Clean. Prod.* **2020**, *253*, 1–11. [CrossRef]
28. Memon, N.K. Autonomous vehicles for cleaning solar panels. In Proceedings of the International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, Ouarzazate, Morocco, 30 June 2016; pp. 633–637. [CrossRef]
29. Mondal, A.K.; Bansal, K. A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels. *Adv. Robot.* **2015**, *29*, 515–524. [CrossRef]

30. Abbas, K.K.; Al-Wattar, A.J.; Kasim, N.K. New technique for treatment of the dust accumulation from pv solar panels surface. *Iraqi J. Phys.* **2010**, *8*, 54–59.
31. Kawamoto, H.; Guo, B. Improvement of an electrostatic cleaning system for removal of dust from solar panels. *J. Electrost.* **2018**, *91*, 28–33. [CrossRef]
32. Jaradat, M.A.; Tauseef, M.; Altaf, Y.; Saab, R.; Adel, H.; Yousuf, N.; Zurigat, Y.H. A fully portable robot system for cleaning solar panels. In Proceedings of the 2015 10th International Symposium on Mechatronics and its Applications (ISMA), Sharjah, UAE, 8–10 December 2015; pp. 1–6. [CrossRef]
33. Park, H.; Öztürk, A.; Park, H.; Khan, M. Utilization of robotics for solar panel cleaning and maintenance. *Konya Mühendidis. Biliml. Dergisi.* **2019**, *7*, 768–775. [CrossRef]
34. Altintaş, M.; Arslan, S. Yağmur Kaydıcırıların Güneş Panelleri Üzerindeki Etkilerinin İncelenmesi. In Proceedings of the 4th International Mersin Symposium, Mersin, Turkey, 22–24 October 2020; pp. 326–338.
35. Masuda, S.; Washizu, M.; Iwadare, M. Separation of small particles suspended in liquid by nonuniform traveling field. *IEEE Trans. Ind. Appl.* **1987**, *23*, 474. [CrossRef]
36. Biris, A.S.; Sanini, D.; Srirama, P.K.; Mazumder, P.K.; Sims, R.A.; Calle, C.I. Electrodynamic removal of contaminant particles and its applications. In Proceedings of the Conference Record of the 2004 IEEE Industry Applications Conference, 2004, 39th IAS Annual Meeting, Seattle, WA, USA; 2004; pp. 1283–1286. [CrossRef]
37. Hudedmani, M.G.; Joshi, G.; Umayal, R.M.; Revankar, A. A comparative study of dust cleaning methods for the solar PV panels. *Adv. J. Grad. Res.* **2017**, *1*, 24–29. [CrossRef]
38. Guangming, W.; Dan, L.; Guangjian, X.; Tianlan, Y. The mechanism study of dust removal with transparent interdigitated electrodes. *Integr. Ferroelec.* **2016**, *171*, 1–7. [CrossRef]
39. Kawamoto, H.; Uchiyama, M.; Cooper, B.L.; McKay, D.S. Mitigation of lunar dust on solar panels and optical elements utilizing electrostatic traveling-wave. *J. Electrost.* **2011**, *69*, 370–379. [CrossRef]
40. Kawamoto, H.; Shibata, T. Electrostatic cleaning system for removal of sand from solar panels. *J. Electrost.* **2015**, *73*, 65–70. [CrossRef]
41. Mazumder, M.K.; Horenstein, M.N.; Joglekar, N.R.; Sayyah, A.; Stark, J.W.; Bernard, A.A.; Griffin, A.C. Mitigation of dust impact on solar collectors by water-free cleaning with transparent electrodynamic films: Progress and challenges. *IEEE J. Photovolt.* **2017**, *7*, 1342–1353. [CrossRef]
42. Kawamoto, H. Electrostatic cleaning equipment for dust removal from soiled solar panels. *J. Electros.* **2019**, *98*, 11–16. [CrossRef]
43. Mazumder, M.; Horenstein, M.N.; Stark, J.W.; Girouard, P.; Sumner, R.; Henderson, B.; Sharma, R. Characterization of electrodynamic screen performance for dust removal from solar panels and solar hydrogen generators. *IEEE Trans. Ind. Appl.* **2013**, *49*, 1793–1800. [CrossRef]
44. Chesnutt, J.K.; Ashkanani, H.; Guo, B.; Wu, C.Y. Simulation of microscale particle interactions for optimization of an electrodynamic dust shield to clean desert dust from solar panels. *Sol. Energy* **2017**, *155*, 1197–1207. [CrossRef]
45. Faes, A.; Petri, D.; Champliaud, J.; Jonas Geissbühler, J.; Badel, N.; Levrat, J.; Roustom, B.; Hessler-Wyser, A.; Wyrsch, N.; Ballif, C.; et al. Field test and electrode optimization of electrodynamic cleaning systems for solar panels. *Prog. Photovolt. Res. Appl.* **2019**, *27*, 1020–1033. [CrossRef]
46. Kawamoto, H. Improved detachable electrodynamic cleaning system for dust removal from soiled photovoltaic panels. *J. Electrost.* **2020**, *107*, 103481. [CrossRef]
47. Jiang, J.; Lu, Y.; Yan, X.; Wang, L. An optimization dust-removing electrode design method aiming at improving dust mitigation efficiency in lunar exploration. *Acta Astronautica* **2020**, *166*, 59–68. [CrossRef]