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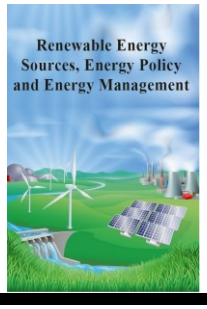

Original Review Article

Photovoltaic panels: A review of Cleaning Systems

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ABSTRACT

Efficiency of photovoltaic panels varies depending on various factors such as environmental factors, soiling on the panel, design and tracking mechanisms. By paying attention to the aforementioned factors, to achieve the highest level of efficiency is possible. The desired level of electrical energy can be obtained from the panels that are maintained and cleaned properly. Dust and dirt formed by environmental contaminants adheres to the panels and prevents the sun rays from penetrating the surface. Efficiency is seemed to reduce 30% due to uncleaned solar panels. Therefore, panels need to be cleaned periodically.
This paper presents an overview of soiling problem and the robots developed for cleaning of photovoltaics. The main goal of the study is to review the literature on automated cleaning techniques for solar photovoltaic modules in order to find out the most effective method developed up to now and identify research gaps in the cleaning systems.

Keywords: Photovoltaic performance, dust deposition, cleaning robot, PV cleaning

1. Introduction

Organization for Economic Cooperation and Development (OECD) 3rd Turkey Environmental Performance Review attracts attention to investment incentives help double the renewable energy use within ten years while the country remains heavily dependent on coal, oil and gas.

The annual gross electricity consumption in Turkey has risen by 2,5% to 304,2 TWh in 2018. Whereas electricity production increased by 2,5 % to 304,8 TWh. In 2018, 37,3 % of electricity production in Turkey was made from coal, 29,8% from natural gas, 19,8% from hydraulic energy, 6,6% from wind, 2,6% from the solar, 2,5% of them are from geothermal energy, and 1,4% are from other sources [1].

According to the International Energy Agency (IEA), solar energy falling on the earth in 90 minutes is enough to meet the world's annual energy demand. IEA predicts that 11% of global electricity generation will be provided by solar energy in 2050, and by 2030 renewable energy sources will be the fastest growing energy sources with an annual growth rate of 7.6% [2].

Coal, natural gas and oil power plants have local and global threats. When fossil fuels are burned, carbon dioxide, dust and soot appear resulting in pollution in the environment and affect on climate change. Solar energy falling on Earth is at least twenty thousand times of Earth energy consumption. So, a small part of the energy arriving from sun can solve Earth's energy problem.

Photovoltaic modules are obtained by connecting solar cells in parallel or in series. When two solar cells are connected in parallel, the voltage doubles while the voltage remains constant, and when the series is connected, the voltage doubles while the current remains constant. In this way, it is possible to increase the voltage

to 14-16 volts. Photovoltaic modules are designed for harsh outdoor conditions. The modules are encapsulated to protect solar cells and electrical connections from the outside environment. Photovoltaic panels are obtained by connecting the photovoltaic modules in parallel or in series. In this way, it is possible to obtain a voltage between 12-600 V [3].

The main factor that reduces the efficiency of photovoltaic (PV) power plants is the soiling of PV panels [3]. Soiling losses in a site was observed to have a decrease in efficiency from 7.2% to 5.6% during a 108 day dry period in the summer at which point a rain event occurred that recovered most of the lost efficiency going back to 7.1% [4]. In rainy areas dust on the panels is removed by rainfall. However, as shown in Figure 1, the PV plants in dusty regions are covered by dust and soil which reduces generated power [5].

Figure 1 Soiled PV panels installed in Doha, Qatar [5]

Many techniques have been developed in order to clean photovoltaic panels to decrease the negative effect of dusty air on them. In this study cleaning methods developed for photovoltaic panels are analyzed in three groups as mechanical, electrostatic and manual cleaning.

2. Photovoltaic Panel Cleaning Systems

Cleaning of solar panels is important for maintain efficiency. In panel cleaning, pure water and some alcoholic cleaners are used. Especially in the winter season, alcohol-based cleaners are preferred to prevent freezing on solar panels under the influence of cold. This type of cleaning agent is often used to prevent frost, even though it leaves water on the panel and hits the sun's rays. Regardless of the seasonal conditions, cleaning the panels with pure water stands out as the most common cleaning material. Unlike alcoholic cleaning agents, pure water does not stain the panels. Thus, after cleaning, there is no obstacle to the sun's rays reaching the panel and absorbing. Cleaning in this way also provides solid safety. Since pure water is not conductive, the risks of high voltage are eliminated while cleaning the panel. Corrosion hazard is also eliminated.

There are three methods used for cleaning of photovoltaic panels: mechanical cleaning, manual cleaning and electrostatic cleaning. The studies conducted to develop robots in order to clean photovoltaic panels by using these methods are given in this section.

2.1. Mechanical Cleaning

Mechanical cleaning system is one of the most used methods among solar panel cleaning systems. In these systems, generally brush or compressed air is used to clean the panel surface. Brush may scratch the glass on the panel surface and damage it.

- As a result of micro-controller based dust cleaning study for photovoltaic systems made by Al-Qubaisi et al., power losses were calculated and the application of the designed micro technology is concluded to be insufficient in terms of panel output energy efficiency [5].

Figure 2 Mechanical cleaning system [6]

- A new design and implementation of a Portable PV Cleaning Robot System (PPVCRS) is developed in United Arab Emirates which is surrounded with deserts. In order to remove dust from the photovoltaic panels a solar cleaning robot is developed with an object-based sensor design. The robot is composed of a cleaning brush moved by a motor. The latter rides along the top and the bottom of each panel to vertically move through the whole array. System is expandable to adapt easily different sized systems. The system structure of robot is given in Figure 3.

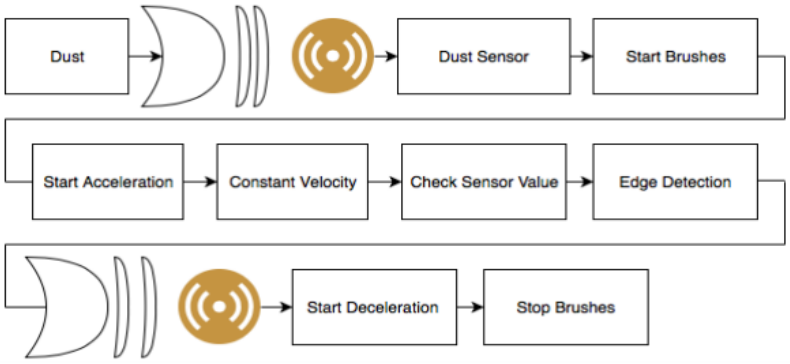


Figure 3 System structure of Solar Panel Cleaning Robot [7]

As seen from Figure 3, dust sensor activates the system. Once the dust sensor detects the dust, brushes (via motor) start cleaning. The robot is then positioned. At the end, the robot slows down and stops and system changes direction in order to find new dust particles [8].

- Another study conducted in The Middle East region which is a very suitable region for harvesting solar energy besides has too much sand and dust and water scarcity problem. In this study a novel “dry” cleaning’ method is developed. Cleaning is carried out with compressed air spray instead of using liquids. A foam roller and a polywool synthetic duster removes dust from surface. Servo motors and a stepper motor is installed on the assembly to rotate and guide the cleaning structure [7]. Mechanical design consists of the robot includes a cylinder with nozzles to spray compressed air, a Polyurethane foam and a synthetic duster roller. Components are fixed on a triangular plate. The triangular assembly is rotated by 60° at the end of each cleaning stage by a stepper motor. Design of the cleaning robot is given in Figure 4.

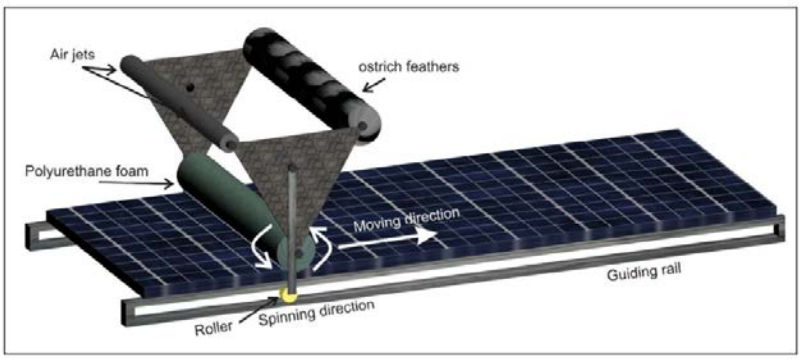
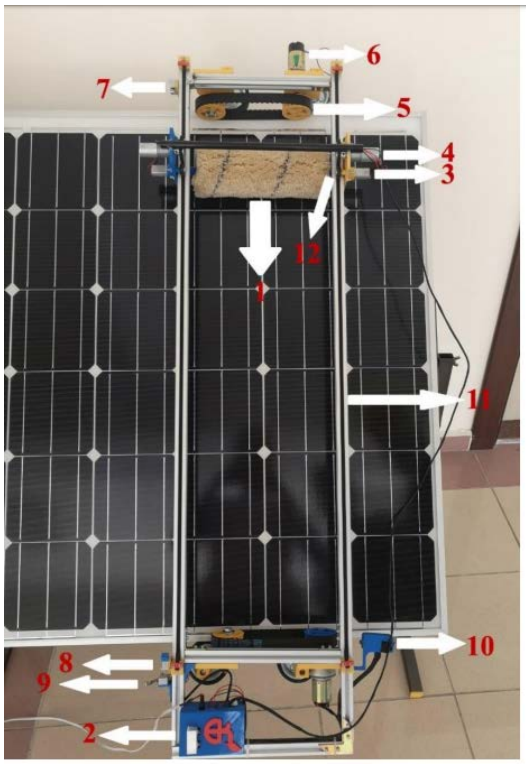


Figure 4 Design of dry cleaning robot[8]

- A microcontroller based solar panel cleaning robot has been designed and developed in a study conducted in Trabzon, Turkey. System contains dual-motor and crawler robot that moves horizontally whereas the cleaning brush runs on the vertical axis. Aluminum sigma profiles already contained in photovoltaic panels are used as frame and rail system to provide the advantage of lightness to the device. System parts with descriptions is given in Figure 5 [9].



1) Cleaning brush.
2) Control unit
3) 9V DC motor for rotating the brush (2 pieces).
4) DC motor that allows the brush to move up and down.
5) Special design pallet. It provides the right and left movement of the device without rail (2 pieces).
6) DC motor for rotating pallets.
7) Limit sensor used to check if the brush is at the top.
8) Limit sensor used to check if the brush is at the bottom.
9) Limit sensor used to check if the device is at the parking/charging station.
10) UItrasonic distance sensor used to check whether the panel array of the device is finished.
11) Rail of the mechanism with up and down movement of the brush.
12) Movement mechanism connected to rail.

Figure 5 System parts with descriptions

- Another study conducted in United Arab Emirates improved a solution to reduce the effect staining on PV modules on offshore platforms. Microcontroller technology was used as the electrical basis for the design. Abu Dhabi Marine Operating Company (ADMA-OPCO) is an oil company located in Abu Dhabi, UAE. ADMA-OPCO uses PV panels on offshore facilities to supply electricity demand. Although located in the middle of sea, dust, birds' droppings, and nests around the panels reduce efficiency of panels. The system improved the staining on the offshore PV plant cleans and deters the birds from getting close to the panels [10]. Designed circuit and developed cleaning equipment are given in Figure 6. Wiper is pulled upwards by two motors that are attached to the rails. Circuit designed to power and control the mechanical section.
- In addition to academic studies there are some robots developed in commercial sector. The robots developed to clean photovoltaic panels in commercial sector are given in Table 1 with some of their distinctiveness.

Figure 6 Circuit design (left) and cleaning device (right)

Table 1 Some commercial cleaning robots developed for photovoltaic panels

Company	Distinctiveness	Photo
GEKKO Solar [11]	• Robot-efficiency reaches up to 400 m^2/h • Cleans rigorously by rotating brushes, executing a constant pressure on the panels and the use of demineralized water • Operator can lift the robot comfortably to the roof and control it by radio using a joystick	
HECTOR-HEliostats Cleaning Team Oriented Robot [12]	• The cleaning system by wet brushing ensures, in comparison with water jet cleaning, a high cleaning efficiency in one pass while minimizing the water and fuel consumption, being the most effective cleaning method to maintain the average reflectivity factor of the field in an optimum level. • HECTOR robot carries a suite of various sensors and software which permit it to navigate autonomously upon the heliostat's surface without any human supervision, including surpassing steps and separations among the different facets or panels. No external power or water supply is necessary for its operation. HECTOR carries its own batteries and water tank, and its consumption is so low that a considerable cleaning capacity and autonomy is achieved. ◦ It is wireless, rechargeable and carries water solution tank with itself ◦ It is fused with various sensors which permit it to navigate autonomously without any human supervision ◦ It requires no external power or water supply for its operation; it carries its own batteries and water tank	 
SunBrush [13]	• The solar cleaning plant with its mobile cleaning brush can be used for dry cleaning in desert regions as well as for wet cleaning using demineralized water – or tap water with the additional "SunBrush blue". Also the solar cleaning plants can be used for the snow removal in winter.	
Heliotex™ Automatic Solar Panel Cleaning Systems [14]	• Once the system is installed and programmed, it requires no further attention except the occasional refilling of the soap concentrate and replacement of the water filters.	

2.2. Electrostatic Cleaning

Solar power plants are generally built on arid lands, however environmental factors such as dust and sand in these lands decrease the panel output power.

Another method of solar panel cleaning is electrostatic cleaning method. These systems consist of a sand repellent sheet consisting of parallel electrodes embedded under the solar panel glass. Sand particles moving down from the panel creates a flip-flop movement in the device and thus dust particles are removed from the panel surface.

I) In a study conducted in Japan, high cleaning performance is realized by the application of low frequency high voltage, and high inclination of the panel and low initial dust loading. Low amount of residual dust accumulates after repeated cleaning. The power consumption of the system is rather low. Developed technology is expected to significantly increase the efficiency of mega solar power plants constructed in dusty regions [15].

System structure of the proposed electrostatic cleaning system is given in Figure 7. When a high AC voltage is applied between the parallel screen electrodes of the device, the resultant Coulomb and dielectrophoresis

forces act on the dust particles near the electrodes. Dust particles are activated by the alternative electrostatic field near the electrodes, and some particles pass through the opening in the upper screen electrode due to their inertial forces.

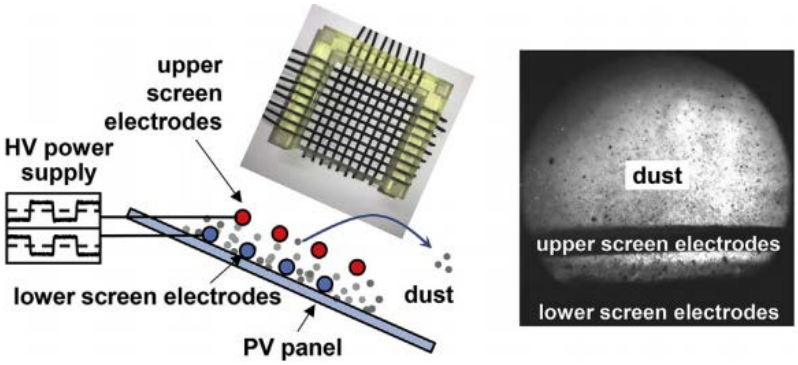


Figure 7 System structure of the electrostatic cleaning system [15]

In this study, small, wide and long cleaning devices were produced. The small device is used to investigate the basic performance of this system, and large and long devices are used to demonstrate practical performance for the real large panel as given in Figure 8.

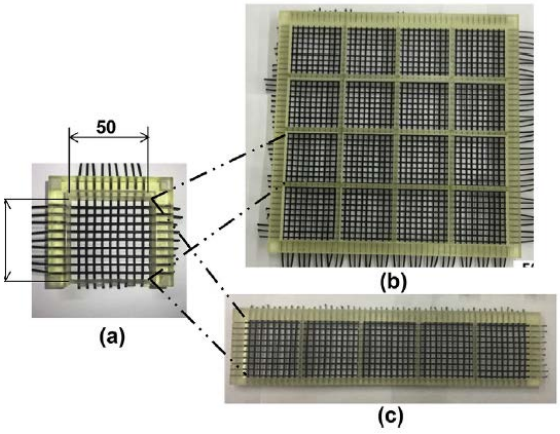


Figure 8 Cleaning devices. Parallel screen electrodes are attached in plastic frames in lattice geometry.
(a) small device (b) wide device (c) long device [5]

II) Mitigation of soiling losses on a photovoltaic cell using the electrodynamic screen (EDS) is investigated in Boston University in laboratory environment. An EDS sample has been integrated into a solar cell for dust mitigation during the study. Restoration of the short-circuit current (Isc) is resulted in more than 90% of the pre-dust value after 10 trials using standard test dust and EDS cleaning. Photos of different procedures followed in development of EDS-PV sample are given in Figure 9 [16].

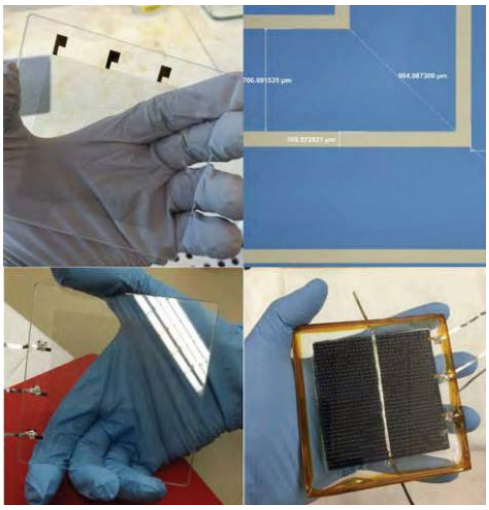


Figure 9 Different procedures followed in development of EDS-PV sample

III) Electrostatic removal of soiling particles and self-cleaning of solar panels are discussed in "Developments in Surface Contamination and Cleaning" published in USA. Dust removal by self-cleaning of solar panels in PV systems mainly in arid regions, their economic advantage is examined in the book chapter [17].

Automatic and continuous removal of dust from solar panels without requiring water or any moving parts can be supplied by integrated electrodynamic screen (EDS). Mathematical analysis provides an outline of the work of EDS for charged and uncharged particles vibrated by moving or standing wave voltages [17]. Basic principles of EDS are given in Figure 10.

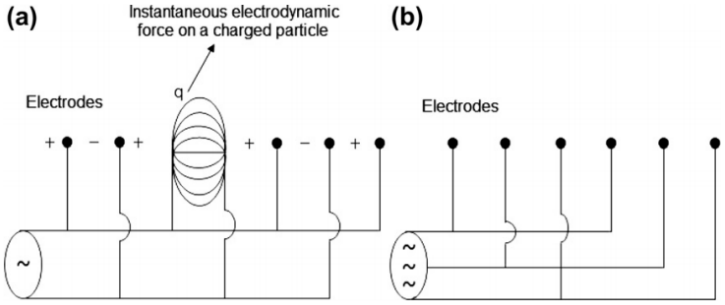


Figure 10 (a) single-phase EDS (b) three-phase EDS [17]

Figure 10 shows the free screen without any encapsulation by a dielectric film. The electrodes are energized by using a single-phase (a) and by a three phase (b) alternating current (AC) drive signal. The single-phase current produces a standing wave whereas a polyphase current produces a traveling wave. Traveling wave has a strong translational component that rapidly moves the dust particles from one end of the screen to the other [17].

2.3. Manual Cleaning

Manual cleaning is a widely used method for cleaning solar panels. In this cleaning method, the decision of dirtiness level of the panels is given by staff. Solar panel cleaning is done at least once a month using pure water. In Figure 11 a PV cleaning equipment completely controlled by a staff is given.

Figure 11 Manuel cleaning method [18]

The main disadvantage of manual cleaning systems is determination of cleaning time by staff. If the correct time is not determined electricity generated by PV panels decrease. Also this method has an extra cost payed to people who cleans the panels.

3. CONCLUSION

The dirt on PV panels thickens in layers over time in case not cleaned at regular intervals. In the long term, the opacity of the panel glasses causes loss of efficiency. Especially in the summer, the period of maximum electricity production and minimum rain, cleaning of panels result in significant increases of electricity production. The main source of dirt formed on the panels are dust and bird droppings. Although the rains wash the dust, it is not possible to remove bird droppings naturally. Therefore, PV panels should be cleaned in required time intervals. The required interval changes up to region. Due to the variable weather conditions a universal method can not solve the problem. There are several methods to clean PV panels. Automated cleaning systems with EDS technology is effective due to being active continuously and having low power consumption. Mechanical automatic cleaning systems are divided into two groups as wet and dry systems. Dust is the biggest problem in desert areas whereas lack of water is another main problem. Therefore, dry systems take more attraction. Researches are ongoing in this area. The main objectives of cleaning systems are low cost, low power consumption and high cleaning efficiency. Electrostatic cleaning is the method that seems to contain these objectives mostly. However, many studies are still in laboratory environment. Dry automated cleaning robots are also attractive due to being autonomous and water free. Another problem of cleaning robots is the power used by them and weight of battery. With a battery-free and renewable resource in the future, automatic cleaning robots could be more efficient and more mobile.

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