Need for Automation in Solar Panel Cleaning Systems – A Comprehensive Review

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Abstract

Solar energy is abundant and may be easily collected using solar cells and solar panels that are maintained on a regular basis. However, variables like as panel orientation, shading, wind speed, ambient temperature, precipitation, and dust deposition all impact solar cell efficiency, which is already poor. The maintenance of solar panels is difficult due to soiling. To remove the material that has collected on the panels, manual and water-based cleaning treatments are commonly utilised. A complete analysis of soiling avoidance approaches is offered in this research with the goal of increasing solar panel energy collection. Following that, the technical specifics of an indigenously created automated water-free cleaning mechanism for removing soiling from solar panels are explained. The energy collection for PV panels cleaned using an automated solar panel cleaning solution over the course of a month is compared to the energy capture for filthy panels in a local solar panel installation, and the enhanced yield is calculated.

Keywords
Solar panel cleaning, Soiling, water-free Surface roughness, Yield increase, cleaning robot

1. Introduction
The accumulation of dust on the surfaces of photovoltaic modules reduces the solar cell's incoming irradiance, obscures solar flux, and results in power loss. According to studies conducted in arid places, these losses might amount to up to 15% of total generation capacity each day. Water-based cleaning is expensive in large-scale PV systems, especially when water is scarce. Solar photovoltaic (PV) systems are predicted to provide 25% of the world's total electrical power demands, however they are more likely to be found in non-agricultural, semi-arid, and desert areas. According to projections, the whole world energy demand can be satisfied with close to zero CO2 emissions even if PV facilities are installed in only 4% of the net feasible dry regions.
Cleaning solar photovoltaic panels requires autonomous solutions because manual and semi-automated cleaning methods use excessive amounts of water and are labour intensive, reducing their cost effectiveness and environmental friendliness. The use of an electrodynamic screen (EDS) atop a PV panel to remove dust using an electric field created by a high voltage supply to the EDS electrodes is described further. Due to their hefty weights and uneconomical services, these screens may not always be effective, lowering commercial viability.

2. Solar energy generation
In 2007, global solar PV market installations reached a new high of 5.95GW (Figure 1). By 2017, China will have reclaimed the total annual PV demand lead. Solar power could account for 11% of global electricity production by 2050 and 60% by 2100, according to the International Energy Agency (IEA) (Kaliappan et al., 2004). China's photovoltaic business is developing at a quicker rate than any other country on the planet. In 2016, solar PV accounted for 43.3 percent of newly installed renewable energy capacity. China had the largest PV market, with 77.5GW of installed capacity (Yang et al., 2003). The theoretical reserves of worldwide solar Photovoltaic resources total 208 EWh/a, according to estimates based on global horizontal irradiance statistics for solar energy. Africa is the continent with the highest TR 63,505.48 PWh/a, which accounts for 31% of the global total (Tang et al., 2003).

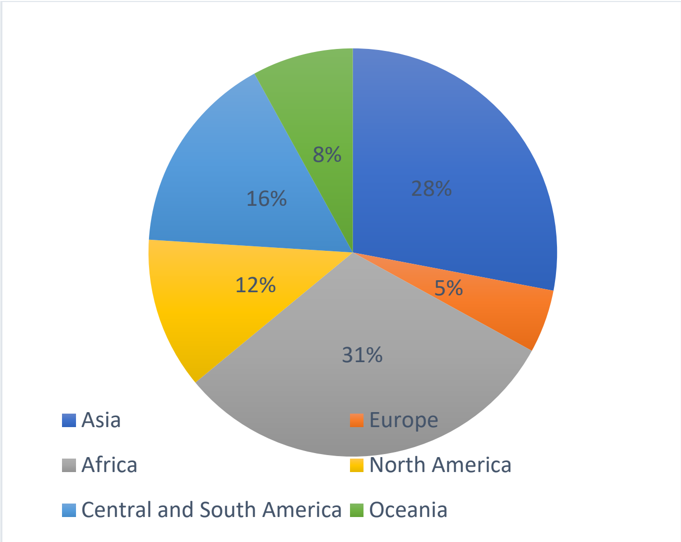

Figure 1. Solar energy usage all over world.

India's solar power potential is enormous, projected to be several times the country's annual energy needs of around 5000 trillion kWh (Pandey et al., 2012), (Sharma et al., 2012) (Figure 2). India's daily solar radiation incident is 4–8 kWh per square meter, with a yearly radiation range of 1200–2300 kWh per square meter (Veeraboinaand Ratnam, 2012), (Mohan et al., 2018). The government's initial effort to encourage grid-connected solar power facilities was the Generation Based Incentive (GBI) scheme introduced in January 2008 (Srivastava and Srivastava, 2008).
The Table 1 shows the number of megawatts of solar power installed in India per state as of March 2013 (Venkatakrishna andRengaraj, 2014). (www.mnre.gov.in)

Table 1. The number of megawatts of solar power installed in India per state

State	Installed Capacity (MW)
Andhra Pradesh	23.15
Arunachal Pradesh	0.025
Chhattisgarh	4.00
Delhi	2.525
Goa & UT	1.685
Gujarat	824.09
Haryana	7.8
Jharkhand	16
Karnataka	14
Kerala	0.025
Madhya Pradesh	11.75
Maharashtra	34.5
Odisha	13
Punjab	9.325
Rajasthan	442.25
Tamil Nadu	17.055
Uttarakhand	5.05
Uttar Pradesh	12.375
West Bengal	2.00
Total 1440.605	

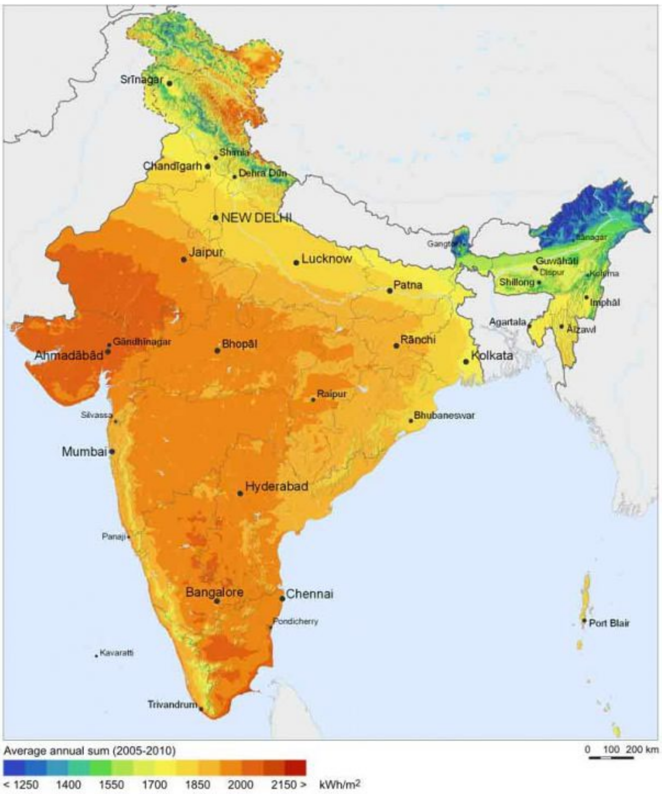

Figure 2. Solar resources in India (Kumar and Hussain, 2018).

Air pollution is another major source of dust. It is caused by pollutants from industries (chemical waste), automobiles, and other sources. Air pollution sources in urban and rural environments include stationary, mobile, and region-specific emissions. Motor vehicles represent the most rapidly growing source of air pollution in cities and urban neighbourhoods. Using GIS-based methods, nearly 55% of the population in Delhi resides within 500 m of roads. PM2.5 concentrations are at least 1.5 times higher in vehicles than ambient air pollution. Local dust sources such as areas with a little green cover, construction sites, and resuspension of road dust are major contributors to PM levels. The use of biomass for heating is thought to account for up to 30% of PM pollution in winter (Gordon et al., 2018). It's alarming to learn that thirteen of the world's top twenty most polluted cities are in India. They include Allahabad, Agra, Lucknow, Kanpur, Amritsar, and others. Other significant towns in India's neighbours, such as Karachi, Rawalpindi, Peshawar in Pakistan, and Beijing in China, are also on the list. On PV surfaces, high relative humidity (RH) causes the production of sticky and cementing dust layers (Adinoyi and Said, 2013), (Piliougine et al., 2013). For example, in nations around the Mediterranean Sea, such as Spain, humidity levels are high, resulting in a significant level of dust particle adhesion on the surface of the modules. In terms of numbers, an increase in relative humidity from 40% to 80% increased adhesion by roughly 80% (Saidand Walwil, 2013), (Said et al., 2018).

3. Efffects of dust accumulation

Environmental elements such as humidity, wind speed, precipitation, and temperature, as well as non-environmental factors such as air pollution, dust build-up, and bird droppings, all contribute to solar modules' low power production efficiency (Farrokhi et al., 2021).

Environmental factors, notably solar irradiation and ambient temperature, have a substantial influence on photovoltaic panels' ability to generate electricity. Sunlight can be reflected, scattered, and absorbed by dust particles on the surface of PV modules and in the surroundings. Dust particles can be as little as a few micrometres and as large as hundreds of micrometres. Dust particles create optical loss or a reduction in the amount of light absorbed by PV cells and converted to electric energy (S. Oh, 2019). The majority of published research on flat-plate collectors has focused on performance-related factors like (a) geological and climatological factors, (b) collector alignment, inclination, and geometrical parameters, (c) the nature, rate, and pattern of the working fluid, (d) collector fabrication and materials, and so on.

The deposition and build-up of flying dust affect the efficiency of solar cells by limiting sunlight transmission. They observed a 10.4% drop in efficiency for 30° slanted panels after 16 weeks of exposure and a 9.7% reduction for 55° inclined panels after 16 weeks. When compared to clean panels, the power output of dirty panels was

lowered by 21.57 percent. Dust collection causes the modules' output power to be reduced (Lasfar et al., 2021), (Oh et al., 2020).
EFFECT OF GEOGRAPHIC CHANGE AND ORIENTATION:
The geographical location of the solar plant, as well as its orientation, has a significant impact on its power generating efficiency (Figure 3).
In India the various geographic locations are:

- cold
- warm and humid
- hot and dry
- composite

As indicated in the picture, the type of dust deposition and cleaning duration vary depending on geographic location. Because dust build-up is low in cold climates, the cleaning cycle is repeated every six months. Due to the humidity in the atmosphere, both dry and wet dust accumulate in warm and humid climates, and the cleaning cycle is repeated regularly. The dust build-up in hot and dry locations is higher, and it is dry powdery dust. The cleaning cycle is repeated weekly since the dust accumulation is more than in other regions. In contrast, the cleaning procedure in composite regions is performed every three months.

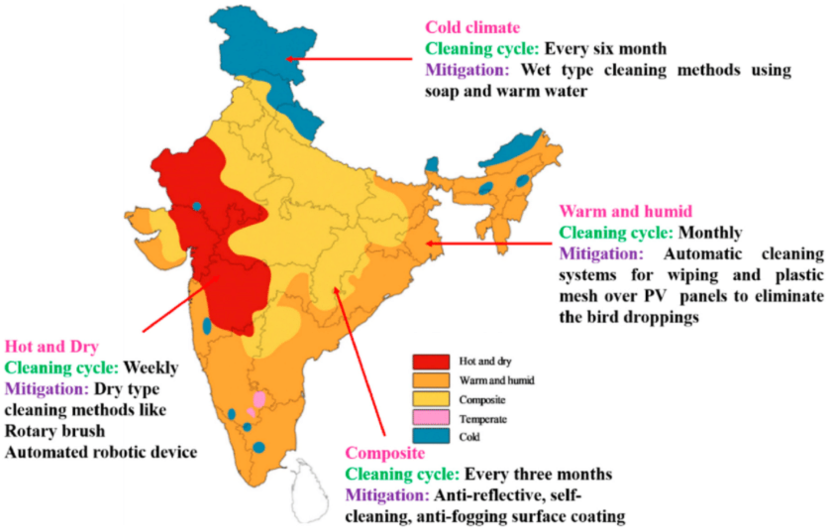

Figure 3. Types of dust in different regions over the country and cleaning systems that are used (Parida and Ghosh, 2015), (Gulia et al., 2021).

Dust accumulation on a glass plate slanted at 45° was found to reduce transmittance by an average of 8% after a 10-day exposure period (Garg, 1974). After 38 days of exposure to the environment with tilt angles of 0°, 15°, 30°, 45°, and 60°, Sayigh et al. found a 64, 48, 38, 30, and 17 percent decrease in glass plate transmittance, respectively (Sayigh, 1978). When the collector is kept dirty for a year, however, the collector's performance plummets by 70% (El-Nashar, 1994), (Hegazy, 2001). Weekly cleaning kept performance losses to a minimum of 2 to 2.5 percent (Maka, 2012), ((ICDCS, 2016).

4. Sources of dust

The sources of dust can be classified into two major categories:
(a)anthropogenic sources (man-made sources)
(b)natural sources.
Industries, transportation, and agricultural systems are examples of anthropogenic sources of dust, whereas soil erosion, storms, pollen, and bird droppings come under natural sources of dust. Environmental causes such as volcanic eruptions – such as the recent Taal volcano activity, soil and salt deposition, air pollution, etc can also cause dust to build (Solaric, 2022). Soft shading and hard shading are the two main types of shading. Soft shading is caused by pollution, mist, or fog affecting the irradiance received by the panel. Hard shading is caused by dust particles, dirt particles, and bird droppings (ICPRE, 2017).
Many of the biggest sources of dust are found in over-dry areas with an average precipitation of less than 100 mm, according to Total Ozone Mapping Spectrometer (TOMS) images (Kermani et al., 2016). The Sahara Desert is the world's largest source of dust. The emission volume of dust is estimated to be between 1,000 and 3,000 million tonnes per year, with 500 to 1,000 million tonnes per year on average, originating from the Sahara

Desert. In other words, the Sahara Desert produces roughly half of the world's dust. The Sahara desert's dust is carried south, to the Caribbean, Bermuda, and America. Sahara dust has the potential to travel over Europe, the Middle East, and even thousands of kilometres (up to 20,000 km) (Kermani et al., 2016).

5. Methods of cleaning systems

a) Natural cleaning: Natural forces such as wind, gravity, and the scour of precipitation are used to remove the dust. This procedure does not produce a good result. When it's early morning, late evening, night, or a rainy day, the solar cell array can be adjusted to a vertical or slant position to conveniently remove dust. The rotation of the big solar cell array, on the other hand, is extremely challenging (Bari et al., 2018) (Figure 4).
b) Self-cleaning:

- Nano hydrophobic: The features of the material that repels water, solid particles, and viscous liquids are known as superhydrophobic AR coating. It functions primarily as an anti-dust coating and renders the surface very water-resistant (superhydrophobic) with a water contact angle (WCA) greater than 150 degrees. If water droplets land on the AR-coated surface, they begin to roll down, dragging dust particles with them. Similarly, the primary property of the medium, namely its refractive index (RI), influences the proportion of light transmission. Furthermore, high transparency is important for boosting the performance of solar devices and optical equipment like solar panels, lenses, and windows (Sahoo et al., 2019).

Figure 4. Picture depicting rolling down of water droplets carrying dust particles on a superhydrophobic surface (PV cells, 2017).

- Nano Hydrophilic: Super hydrophilic materials are essential for their self-cleaning properties, which has become a hot research area, especially in photovoltaic (PV) applications. By changing the shape of ZnO, we describe hydrophilic and super hydrophilic ZnO for use as a self-cleaning coating for PV applications. Hydrothermal techniques were used to create three distinct ZnO microstructures: ZnO nanorods (R-ZnO), ZnO micro flowers (F-ZnO), and ZnO microspheres (M-ZnO). R-ZnO, FZnO, and M-ZnO were found to have average crystallite diameters of 28.95, 11.19, and 41.5 nm, respectively. The bandgap values for R-ZnO, F-ZnO, and M-ZnO were computed from the UV-vis absorption spectra and found to be 3.6, 3.3, and 3.1 eV, respectively (Figure 5).

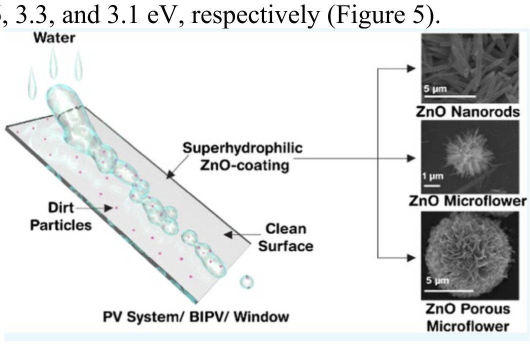

Figure 5. Hydrophilic and super hydrophilic self-cleaning coating by morphologically varying ZnO microstructures for photovoltaic modules (Nundy, 2020).

c) Manual cleaning: This approach necessitates the use of a mop or other wipers with appropriate support structures to clean manually. The operator himself judges the cleanliness of the cleaned surface using a visual technique for a sufficient level or until all dust particles have been wiped off entirely. Solar power facilities have many panels erected at a height of 12 to 20 feet or more from the ground, making the operation laborious and difficult. The person's and panel's safety, as well as the time necessary, are at risk. Manually cleaning the panels requires the use of fluids such as cleansers or gels, which act on the panel and degrade the surface transparency if not done properly. Physical damage to PV panels is a distinct possibility that cannot be prevented (Hudedmani et al., 2017).

d) Automatic cleaning:

- Electrostatic cleaning system (ECS): One of the automated techniques for cleaning a solar cell panel is an electrostatic cleaning system (ECS). The parallel screen electrodes positioned on the solar panel are subjected to a high alternating current (AC) voltage in this approach. The electrostatic force that results in acts on the particles that are close to the electrodes (Bock et al., 2008) (Figure 6).

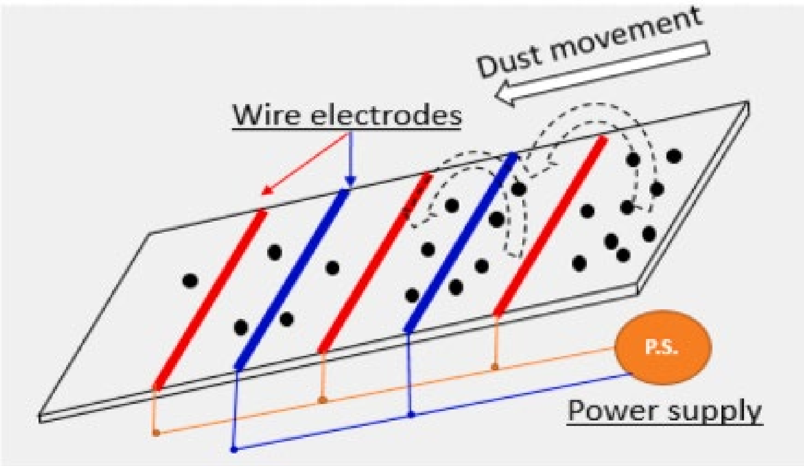

Figure 6. Electrostatic cleaning system

- Heliotex cleaning system (HCS): Nozzles are fitted to the corners of the solar panels in the heliotex cleaning system (HCS). The HCS may be tailored to any panel array design, whether it has ten or ten thousand panels. To power the controller, you'll need a 110-volt AC outlet. The system is supplied with water from an easily accessible source, such as a private home's water bib (Farrokhi et al., 2021) (Figure 7).

Figure 7. Heliotex cleaning system

- Robotic cleaning system (RCS): The robotic cleaning systems are used in conjunction with two different cleaning processes. The first is dry cleaning. The alternative option is wet cleaning, which involves cleaning with water or other water-based substances. A robotic cleaning system (RCS) is made up of two-body structures, which implies that two driving modules run in opposite directions (e.g., x and y) to move the cleaning head over the panel's surface. To enable the robot to function autonomously without connecting to an external computer device, most robots use an Arduino controller or a Raspberry Pi as the main control unit. Infrared (IR) sensors are used as dust sensors because they are effective at detecting dust on PV panels (ICDCS, 2016) (Figure 8).

Figure 8. Robotic cleaning system

- Brush cleaning system (BCS): A brush cleaning system (BCS) is a dust-removal device that uses a mix of electro-mechanical components controlled by an electronic controller to remove dust off solar panels without using water. It functions automatically by sensing its present state and following the pre-programmed instructions. The cleaning system is made up of a brush and a cleaning and driving device that works in both x and y directions (Deb and Brahmbhat, 2018) (Figure 9).
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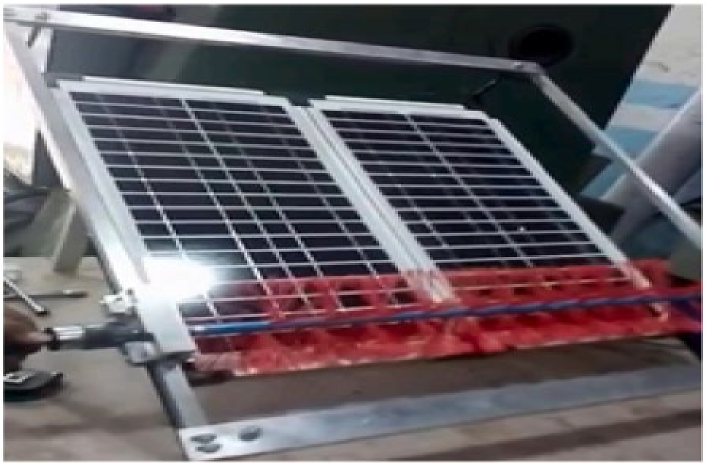

Figure 9. Brush cleaning system

Table 2. Comparison of different methods of cleaning systems (Farrokhi et al., 2021):

	Manual Cleaning System	Automated Brush Cleaning	Robotic Cleaning
Mechanism	Involve humans to clean manually with a mop or other wipers with adequate support systems.	Electronic components regulate a gadget that does not require water.	Either the Arduino UNO or the Raspberry Pi is used to operate a robotic gadget. DC motors and wheels make up the system.
Pros	Very less maintenance cost. Equipment cost is very less compared to other cleaning systems.	It is portable and easy to manufacture compared to other advanced cleaning systems.	It is lightweight and highly efficient. Water waste is also very less compared too other cleaning systems

Cons	Human interference makes it very less efficient compared to every other cleaning system. Humans sometimes must have clean the panels in the scorching sun. Wastage of water is also more.	It is ineffective for sticky type of dirt and the corners of the solar panels cannot be cleaned effectively. The brushes also need to be changed frequently which increases the cleaning cost.	It is a very slow cleaning process and requires high maintenance. It also requires human intervention.
Efficiency	Least efficient of all the cleaning systems.	It is approximately 30% more efficient than manual cleaning system.	It is also nearly 30% more efficient than manual Cleaning system.

6. Components of cleaning systems- cleaning agents & their effects

Components:

I. Arduino UNO: It is open-source electronics prototyping platform that allows the user to generate interactive electronic projects. It is programmed using Arduino IDE by connecting it to a computer through a cable ((kute et al., 2008).
II. Motor Shields: It is a current amplifier used to convert the low-current signals to high-current signals (Chailoet and Pengwang, 2019).
III. Jump wires: Used for connections between the electronic components.
IV. Wheels and Support Wheels: The wheels and supported wheels are used to guide the robot all along with the solar panel.
V. Rechargeable Battery: It is charged using the solar panels and gives power to the robot during the cleaning of the solar panel.
VI. Sensors: Sensors like Ultrasonic sensors, Dust sensors are used to automate the robot.
VII. DC motors for driving wheels
VIII. DC motors for rotating brush
IX. Pump: The pump is used to pump water from the tank onto the solar panel while cleaning.
X. Nozzles: Nozzles are used to spray water that is been pumped onto the solar panel. (Mathew and Abraham, 2020), (Durmanwar et al., 2019), (Abdul et al., 2020)

Table 2. Cleaning Agents and their effect (Epa, 2020), (Chem, 2022):

Cleaning Agent	Specifications	Effects
Cyclohexene, 1-methyl-4-(1-methylethenyl)-, (4R)-(d-Limonene)	Primary Application: Cleaning and degreasing pH: 7.5 VOC: (g/L): 0 Foam: < 850 g/L NFPA: Pale yellow liquid Sizing: 5-gal	Removes glue, ink, scuff marks, grease, and any type of adhesives on the panel
n-Methylpyrrolidone(2-Pyrrolidinone, 1-Methyl-)	Primary Application: Solvent pH: 8 VOC: (g/L): 100 Foam: no foam NFPA: 1, 0, 0 Sizing: 5-gal	Removes paint stains, hard dust, sticky dust, etc.

7. Cost Analysis

This is a case study that covers a solar farm in Southern California with PPA values of USD 28/MWh and average daily soiling levels of 0.08%. By applying soiling monitoring and semi-automated cleaning systems, the solar plant achieves savings of 3.6 million dollars over the lifetime of the solar installation. Below you can see what options are available to clean a solar farm and their associated costs.

Solar Farm Characteristics (Table 3)

- 100 MW
- Region – Southeast CA, USA
- USD 28 / MWh
- Soiling Monitoring – Dust IQ by Ott HydroMet
- Annual Soiling Cost = USD $272,000
- Labor Rates = $35/hr

Table 3. 10 Year Financial Estimates in Southern California (Relysm.com, 2022).

	No Action	Manual	Semi-automated	
		Wet Brush	Linear Robot	Tractor
Cleaning frequency (per year)	0	l/yr	3/yr	3/yr
Cleaning CapEx	$ -	$ -	$ 160,000	$ 315,000
Cleaning OpEx	$ -	$ 2,000,000	$ 657,000	$ 185,000
Total Cleaning Cost	$ -	$ 2,000,000	$ 817,000	$ 500,000
Module soiling loss	$ 2,723,000	$ 1,626,000	$ 1,067,000	$ 998,000
Total cost of being dirty	$ 2,723,000	$ 3,626,000	$ 1,884,000	$ 1,497,000
Savings (compared to no action)	$ -	$ (904,000)	$ 840,000	$ 1,226,000
Total revenue (zero soiling)	$ 95,046,000	$ 95,046,000	$ 95,046,000	$ 95,046,000
Soiling cost (% of revenue)	2.9%	3.8%	2.0%	1.6%

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