IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 3, 2020, accepted July 21, 2020, date of publication July 23, 2020, date of current version August 4, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3011553

Current Practices of Solar Photovoltaic Panel Cleaning System and Future Prospects of Machine Learning Implementation

NASIB KHADKA[1,2], AAYUSH BISTA[1,2], BINAMRA ADHIKARI[3], ASHISH SHRESTHA[1,2], (Member, IEEE), DIWAKAR BISTA[1,2], (Member, IEEE), AND BRIJESH ADHIKARY[1], (Member, IEEE)

[1]Department of Electrical and Electronics Engineering, Kathmandu University, Dhulikhel 45200, Nepal
[2]Centre for Electric Power Engineering, Kathmandu University, Dhulikhel 45200, Nepal
[3]Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, SK S7N 5C9, Canada

Corresponding author: Nasib Khadka (nasib.khadka@ku.edu.np)

This work was supported by the Center of Electric Power Engineering (CEPE), Kathmandu University, through the support of EnergizeNepal Project Office Kathmandu University, Nepal, under Project ENEP-CEPE-18-01.

ABSTRACT Solar Photovoltaic System (SPV) is one of the growing green energy sources having immense penetration in the national grid as well as the off-grid around the globe. Regardless of different solar insolation level at various regions of the world, SPV performance is also affected by several factors: conversion efficiency of PV cell technology, ambient temperature and humidity, soiling and seasonal/weather patterns. The rise in PV cell temperature and soiling is found to be detrimental issues regarding power plant performance and life expectancy leading alterations in the levelised cost of energy (LCoE). In this paper, authors present a short glance about factors affecting the performance of photovoltaic modules and re-discuss their usability in cleaning intervention decision-making models. With some highlights on the essence of cleaning to mitigate the soiling issues in PV power plants, this paper presents the existing cleaning techniques and practices along with their evaluations. The need for an optimal cleaning intervention by using advanced scientific tools rather than by visual inspection is drawing the attention of PV experts. The authors finally suggest a schematic of a decision-making model which involves the use of probable parameters, data processing techniques and machine learning tools. The implementation of data science and machine learning in a solar PV panel cleaning system could be a remarkable advancement in the field of renewable energy.

INDEX TERMS Solar photovoltaics, green energy, performance, soiling, cleaning system, machine learning.

I. INTRODUCTION

Globally, low carbon dioxide (CO2) emission from energy conversion has been a major concern and the use of renewable energy is expected to be a prime solution. According to the Sustainable Development Scenario developed by International Energy Agency [1], it has been projected that till 2050, 32% of carbon emission shall be reduced by making the use of renewable energy sources replacing the fossil fuels. Hydropower and renewable energy sources are the major concerns for energy experts to promote green energy. As reported by Key World Statistics (2019), out of the total global energy production in the year 2017, hydropower has a share of 4,197 Twh; wind electricity has a share of 1,127 Twh and that by solar electricity of 444 Twh [2]. The demand side has equal importance as the production, when renewable energy comes into a picture. Many political and technical challenges are expected to arise, while replacing non-renewable energy sources. In order to double the share of renewable energy, its end use in the industrial sectors: mainly in manufacturing, is considered to be a crucial step [3]. The harvest action of wind energy and solar energy are the two strengths in the field of renewable energy to meet the expected plant capacity in the future. The applicability of solar PV system is almost everywhere in the globe due to accessibility of sunlight, which is a major advantage over the wind energy system, where power generation is characterised by a largely varying source, wind. Solar PV is expected to be one of the renewable

The associate editor coordinating the review of this manuscript and approving it for publication was Dwarkadas Pralhaddas Kothari.

energy sources having a 25% share in total energy demand as forecasted in the year 2050 by deploying more than 8,500 GW capacity [4]. The forecasted generation capacity of Solar PV in the future entails that there will be a rapid installation of PV plants, more than 10-fold rise in comparison to the present scenario. The operation of the projected capacity of PV plants will be a challenging job, mostly regarding its reliable, economic, and sustainability. As of 2020, the largest solar farm in operation, Tengger Desert Solar Park has a peak generation capacity of 1,574 megawatts [5]. The use of uncultivable and unused landscape has been a focal point to the energy investors and governments for the installation of new PV plants.

A photovoltaic cell is the smallest unit which harnesses solar energy into the electrical energy. The energy conversion efficiency of a solar cell is dependent on semiconductor technology involved during the manufacturing process. Silicon-based technology is the most commonly used technology whose conversion efficiency ranges from 5 to 15% [6]. With the rapid development of thin-film semiconductor technology, the conversion efficiency of solar cells is increasing. Every solar module has its specified output power at Standard Testing Condition (STC); however, the exact operating condition of solar cell differs from that specification and results in varying output power. The performance of solar cells might also differ by some other site-specific influencing parameters like temperature, humidity, dust density, air mass, panel orientation. Additionally, these parameters might differ drastically in different seasons. Different forms of precipitation, clouding, and wind also affect year energy production from solar plants. Despite these factors, soiling is considered to be one of the major issues which block solar cells and reduces energy conversion efficiency directly. Moreover, dust accumulation most often leads to cell temperature rise resulting in the decrement in the efficiency indirectly. Various studies have concluded that there lies a negatory effect of soiling on the output of solar panels mostly explained reduced solar intensity and rise in cell temperature [7]–[11]. The effect of performance degradation in turn affects the economics of larger PV plants more prominently thereby increasing the LCoE. Different dust preventing as well as cleaning technologies have been evolved ever since PV plants have come into its use. Robotic cleaners, electrostatic removal, self-cleaning layer, automated water cleaning are the current technologies which have been practised so far and the selection of appropriate cleaning mechanism is a crucial task for the specific plant size and location. Beside the cleaning mechanism, the essence of the optimal time for cleaning is a concern which needs to be dealt with since visual inspection for decision making of cleaning shall not be appropriate in terms of energy economics. With the advancement of data science and machine learning, their application for decision making for cleaning operation can be a major leap in the advancement of solar PV energy systems. Such an optimized cleaning decision would certainly help to reduce the LCoE.

This review paper reflects a complete capsule covering from the existing product/idea based solar photovoltaic panel cleaning systems to the prospects that could optimize the cleaning procedure. The paper contributes a cleaning interval scheduler schematic, which can be a starting point for further research in the domain of PV systems. With regard to the articles reviewed, the suggested decision-making framework encompasses the requirement of technical as well as cost-based parameters in an automated solar PV panel cleaning system. This study first introduces the trend of solar photovoltaic power generation in the global context. In Section 2 of this article, an idea is presented about the influencing parameters for a particular PV module and some of which can be useful while determining the cleaning intervention. Section 3 is mainly focused on the review of different types of cleaning mechanisms adopted in the current scenario, in addition to which, the evaluation along with their pros and cons are discussed in the subsequent section. As stated in Section 5, the authors suggest machine learning implementation for the advancement of the solar PV cleaning system. Finally, in Section 6, the major conclusions are enlisted.

II. SOLAR PHOTOVOLTAIC SYSTEM AND ITS INFLUENTIALS

Solar Photovoltaic system consists of PV modules connected appropriately to form the solar arrays, and the combination of solar arrays form the generating unit. The solar generating unit can be a single module to a large solar farm sizing thousands of megawatts depending upon the requirement. Solar Photovoltaic system is operated to its maximum power point, the point where adjusted photovoltaic voltage with output current gives the maximum power output in that particular instant, and the technology is normally termed as Maximum Power Point Tracking (MPPT) system. The generated power is fed into the control system, most often known as the charge controlling device, which controls the flow of electric current (power) to the different loads. Charge controllers balance the generation and demand in an optimal way such that loss in the system is minimized and provide an environment to operate equipment safely. In order to feed AC load, PV systems are provided with the inverter which changes the nature of current from direct current (DC) to alternating current (AC). A typical solar photovoltaic system with different kinds of loads: dedicated load, battery energy storage system and interconnection with grid supply, are collectively shown in Figure 1. Photovoltaic Systems with these various loads are controlled with the programmed prioritization by a control system embedded within the inverter unit. Different constraints are also shown along with the same figure which affects the output power of the generating unit. These constraints mostly include: the surrounding temperature [12]–[17], humidity [18]–[22], solar irradiance [12], [23], [24], panel orientation [25]–[28], dust [29]–[36]. Nonetheless, some variations might be observed in all of these environmental factors collectively due to seasonal changes and weather perturbations [23], [37]–[39].

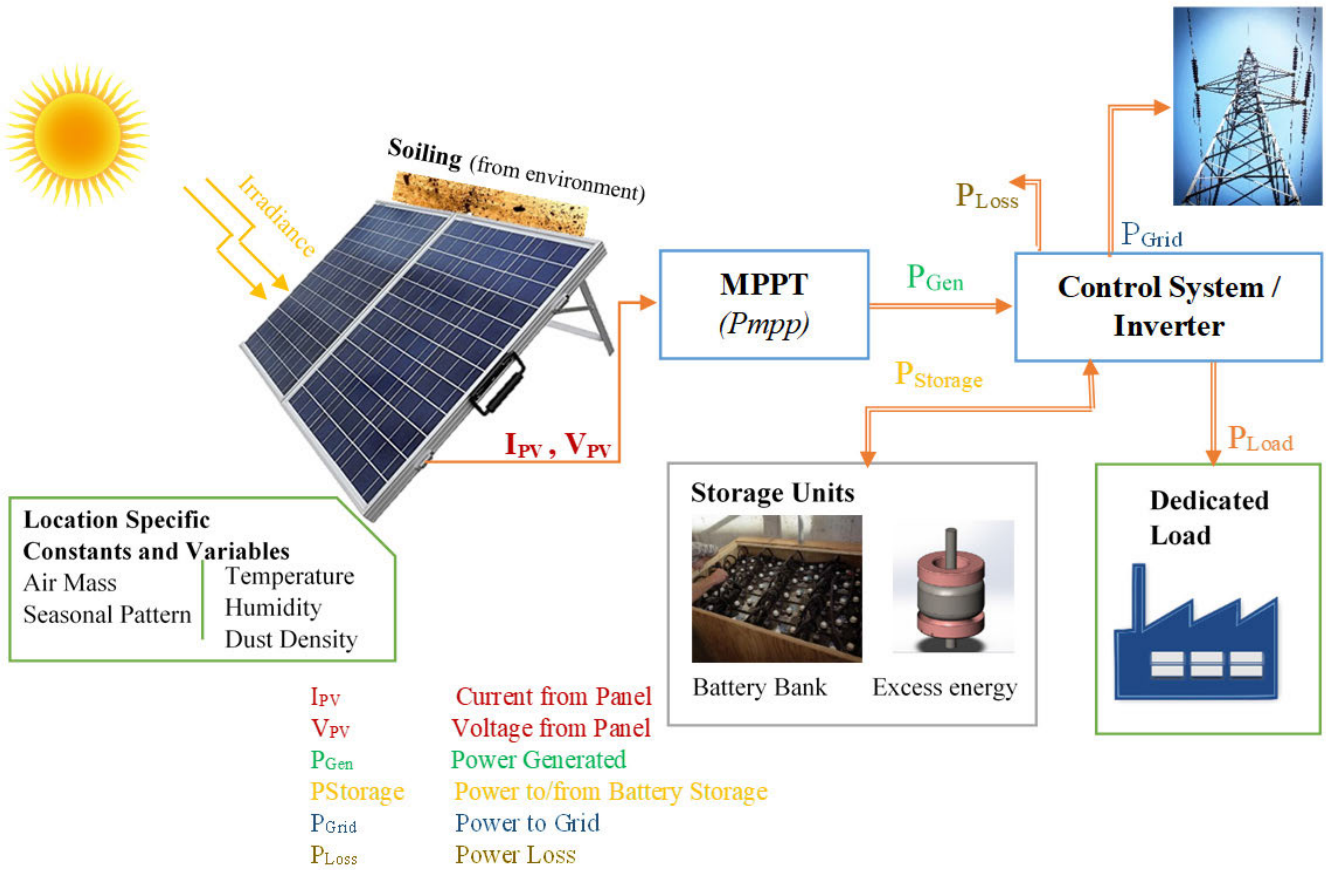

FIGURE 1. A typical block diagram of Solar PV system.

In this section, the underlying reasons for the deviation of the output power are explained along with the deductions made from the experimental observations done in the respectively referenced research. Out of these factors, the temperature of the solar cell is found to be a prominent factor harming energy harvest action from PV cells. Some of the researchers suggest different cooling methods of PV modules to be an effective solution [13], [40]. Similarly, soiling is considered to be another major issue in efficient solar PV operation. Accumulation of foreign particles over the panel surface not only block the entering solar radiation but also increases the cell temperature thereby having a double effect. Soiling issues can be addressed by cleaning the panel; however, the effective way of cleaning is still a major concern.

A. MANUFACTURING TECHNOLOGIES AND CONVERSION EFFICIENCIES

Theoretically, the solar irradiance that strikes on the PV cells is called as the input power. Whereas the output power can be defined as the multiplication of its developed current and induced-voltage as per cell's impedance at a particular instant. The ability to convert input solar energy into electrical energy is known as conversion efficiency of that particular solar cell. Based on a different semiconductor substrate, doping material, manufacturing processes used, solar cells can be characterized into different types such as monocrystalline, polycrystalline, thin-film amorphous, perovskite, organic or plastic solar cell [41] and the conversion efficiency varies accordingly. As per a study [42], the efficiency of a cell can be increased significantly by doping some amount of organic polymers as luminous-down-shifting (LDS) materials. It was found that the application of LDS technology reveals that there can be an increase of 10-20% efficiency in Cd-Te devices having CdS buffer layer whereas the most commonly used silicon wafer-based technologies are benefited up to 0.5 -3% [42], [43]. Table 1 shows various kinds of PV technologies with their respective efficiencies. Among all technologies listed, mono and polycrystalline technology have more than 40% market share due to material availability and economic constraints [44]. In recent advancement of thin-film technology, solar cells having higher efficiency are commercialised with the pricing in the same range that would have cost for conventional wafer-based technology [45].

B. ENVIRONMENTAL CONDITIONS AND PV PERFORMANCE

A particular PV module is characterised based on Standard Testing Condition (STC) [46], and is considered to be a

TABLE 1. Different solar technologies with their efficiency [6].

PV Technology	Efficiency (%)
Carbon nanotubes (CNT)	3-4
Amorphous silicon	5-7
Polycrystalline silicon	8-12
Dye synthesized	11.1
Monocrystalline silicon	15-18
Other thin film (CdTe, CIS, etc.)	16-20
Triple junction under concentrated Sun	up to 37.4
Hot carrier solar cell	66

reference point from which the performance would deviate concerning the environmental factors it is subjected to. The atmospheric condition and the radiation profile vary from place to place, and the performance of a solar PV plant in a particular place is solely dependent on such environmental constraints. The changes observed in temperature, humidity and solar radiation vary either of parameters: short circuit current (Isc) or open-circuit voltage (Voc) or Fill Factor (FF) which in turn happen to decrease the maximum power point from STC characterization. Solar radiation is the source of energy harvest action, which is composed of energy carrying photons thereby releases electron from PV cells through the photoelectric effect. The intensity of the solar radiation entering into the PV cell determines the output current so as the output power. The solar energy input to the PV cell is measured in the term of a watt per meter square area, often termed as Solar Irradiation. Solar irradiation varies from place to place and mostly for a particular place, it varies along the time of day. With the increase of solar irradiance, both short circuit current parameter and open-circuit voltage parameter increases resulting in the increase of maximum power point [24]. However, the change in short circuit current is found to be more prominent than that to open-circuit voltage [12], [23]. Despite specific air mass of any particular place, the resultant solar irradiation also varies with the number of atmospheric particles: dust and water vapour content present [19]. Besides this, the orientation and tilt angle of the solar module also affects the amount of incident light intensity falling upon it and it is suggested to face the module at an optimal angle defined by the latitude of the site minus ten degrees [25]. Even though the optimum tilt angle might vary seasonally or monthly according to the location, the feasibility of a two-axis tracking system must be done before implementation [26]. Subsequently, the temperature of the solar PV cell is one of the performances determining parameters. The ambient temperature to which the PV modules are exposed, does not have a direct impact on the performance metrics of PV cell, rather the rise in the cell operating temperature concerning laws of thermodynamics explains it. The PV cell parameters: open-circuit voltage (Voc), short circuit current (Isc) and fill factor (FF) vary almost linearly with the temperature variation explained by the decrease in the bandgap [14]. However, it is seen that the decrease in the power of PV cell is mostly explained by the decrease in Voc and FF with the increasing temperature [47]. Similarly, high humid environment also has an adverse effect in PV cells performance. From the experimental results obtained in [21], it is found that the short circuit current (Isc) decreases significantly with high relative humidity and which is explained by the current leakage due to increased moisture content. Additionally, water vapour contents in high humidity cause the scattering of solar radiation and as a consequence, the performance of the module reduces with the reduced short circuit current [48]. According to the experimental observation made at Karachi, Pakistan (305K) [18], with the increase of humidity by 25%, the output power seems to be reduced approximately by 29.92%. Likewise, from a case study of Sohar City-Oman, significant reduction of 44% was seen in the output current, when RH was increased from 67% to 95% [20]. Although, places with high wind velocity seem to provide a better environment for PV energy harvest action, as it reduces relative humidity and lowers the cell temperature [19]. The above-discussed parameters: solar radiation, ambient temperature, relative humidity, do also exhibit variations during different seasons of the year as well as due to weather perturbations like precipitation, change in wind pattern and cloudiness. Spectral gain/loss of PV cell technology (a-Si and CdTe) with stronger sensitivity at shorter wavelength can be seen with several percent with the seasonal variation [37]. From a study of Sohar-Oman [49], increment of solar intensity by 101.6% was seen in the summer season in comparison to the winter. Adversely panel temperature was reduced by 97.6% due to decrease in ambient temperature during the winter. Similarly, in a study of seasonal effect in a si-PV technology [38], the change of about -3% in temperature effect, 16% in spectral effect and 2.5% of irradiance effect was seen in summer as compared to winter season.

C. SOILING ISSUES

Atmospheric dust and soiling both happen to reduce the performance of solar module. However, soiling is found to be more degrading one. Atmospheric dust is likely to absorb the solar radiations which would otherwise hit on module surface whereas soiling is an issue caused by the deposition of dust and other opaque particles over the module surface. Hard shading and soft shading are the two kinds of shading caused by soiling effect. Hard shading is a phenomenon where small patches of accumulated particle block the PV cell and cause a reduction in Voc of the module, whereas soft shading is the uniform deposition of soiling particles all over the solar module, causing a reduction in Isc [7], [50]. Researches have concluded that soiling issues can be a detrimental factor reducing energy harvesting capability of solar power plant [51]. An average of 1% with a peak of 4.7% in two-month observation period was observed in the United States [52], 40% degradation in 6 months in Saudi-Arabia [53], 11% decrease in efficiency in the tropical climate of Thailand [54], 29.6% in Kathmandu, Nepal and from 33.5% - 65.8% reduction in efficiency from a study conducted in Egypt [55]. On long term perspective, soiling can result in degradation of the expected life of PV modules and seasonality in spectral response [8]. The impact and rates of soiling differ tremendously place to place in a different part of globes. Places with low rainfall, high dust density and relative humidity are likely to have particles accumulating for a long time and result in poor energy harvest action from PV plant [56]. Similarly, as the size of soiling particle goes on increasing, the efficiency of the solar panel decreases [57]. According to a case study of 186 PV sites in USA, it has been observed that by cleaning a solar PV plant half the way of dry summer without rainfall, 0.81% to 4.7% improvement can be seen in energy harvest action throughout a year, and up to 9.8% by implementing an automated cleaning system [9]. To coverup, the losses experienced by PV plants due to soiling issues, different solar panel cleaning techniques have been implemented. The subsequent section explains about the recent technologies that have been evolved for performance restoration of PV plants by cleaning modules constituting them, and different market-based products have also been highlighted.

III. CURRENT TECHNOLOGIES AND PRACTICES OF SOLAR PANEL CLEANING

Megaprojects of energy generation from Solar PV panel can be built in semi-arid or desert which receives plenty of solar radiation throughout the year. But with higher possibility comes a bigger challenge. In these deserted places having a higher concentration of atmospheric dust with seldom rain, soiling in the surface of the panel is inevitable. For maximum harvesting of energy from solar cells, cleaning of these panels is a must. Different manual and automatic technologies are available for cleaning of the solar panel. Cleaning expenses in a solar plant accounts for almost half of the O&M cost.

A. CURRENT TECHNOLOGIES

Rainwater has been a medium for a long time for cleaning of solar panels. Harness of energy from sunlight is more from a clean panel which in return generates more electricity. With the advancement in material science and robotics, manual cleaning of the solar panel is slowly being eradicated. Much new technology like EDS, Robots, cleaning kits is available to clean a panel effectively. Some of the practices and technologies are discussed in the sub-sub sections below:

(i) Manual cleaning: Different tools and techniques are available to clean the solar panel manually by an operator. A cleaning kit is the most common manual cleaning tools which include multiple extension poles, carrying bags, brushes, cloths, hose connections, and more [58]. Many companies produce manufacturing brushes and hose system for cleaning of the solar panel and can be found readily in the market. Figure 2 shows manual cleaning of the solar panel in Kathmandu University Hospital with a cleaning kit by an operator. This method efficiently cleans a panel but increasing

FIGURE 2. Manual hand cleaning system.

the size of the solar plant size, it will be impossible to clean manually as it increases O&M cost drastically requires large manpower.

(ii) Piezoelectric system: Piezoelectric actuators are being used in various optical adjustments, biomedical manipulation, space explorations and other areas due to higher torque to volume ratio, flexible structure and high positioning precision. The piezoelectric system is being used in the cleaning of solar panels. The acoustic piezoelectric system with water as a cleaning agent, spread 0.1 to 1 mm depth of water around the surface of the solar panel cleans during the rarefaction cycle of the compression waves. A vacuum is created in liquid during the rarefaction called an ultrasonic cavity, and this cavity cleans the panel by sucking the dust present in the solar panel surface. for the medium of air, the mechanism is similar to change in the cleaning medium only. Linear Piezoelectric actuator based solar PV panel cleaning system has a proper pressure force between the wiper and solar panel is adjusted where the actuator can drive the wiper to effectively clean and wipe a dust layer by vibrating the dust away from the solar panel's surface [59], [60]. Figure 3 shows a linear piezoelectric system

(iii) Electric curtain system: Places with dry dust can be dealt with a phenomenon explained by the application of suitable electric field to the dust particles residing on the module surface. This phenomenon of charging dust particle is an electrostatic concept where charged dust particles are bound to form a standing wave-type electric curtain [61] such that at any point there exists an electric field with an amplitude and a direction oscillating at the imposed frequency. Frequency of oscillation is set in such a way that dust particle moves along the line of an electric field to one of the edges of the module thereby cleaning the surface. Uncharged particles failing to form the electric curtain are soon charged through either polarisation or electrostatic induction process and hence removed from the module [62]. An Electro-Dynamic Screen (EDS) is one of a kind which uses the same principle of standing wave-type electric current. High voltage

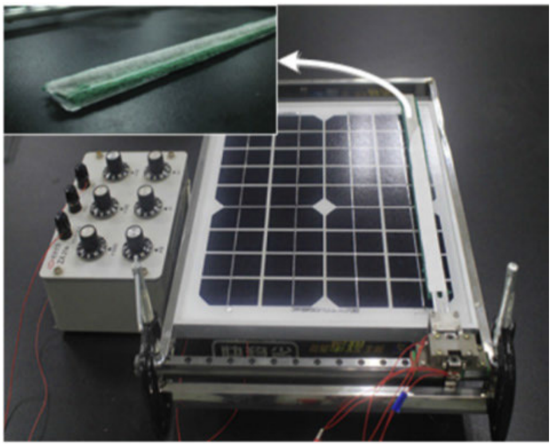

FIGURE 3. Linear Piezoelectric system [61].

three phase electric source is used instead to form a travelling wave with strong translational energy [63]. The application of different phases to the substrates of a module and respective lines of force is visualized in Figure 4.

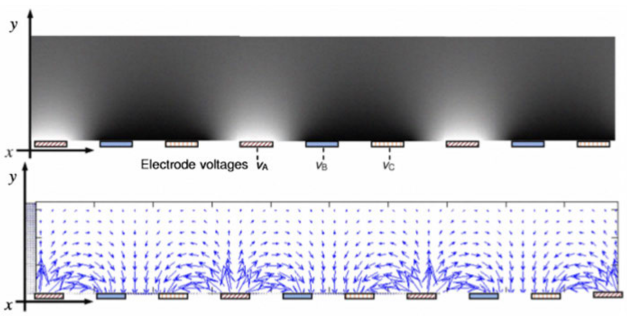

FIGURE 4. Electrodynamic screen [64].

This kind of cleaning mechanism requires dry module surface which would avoid any vapour based bonding of dust particle with the module and it has been suggested to use such systems where humidity is extremely low and almost negligible precipitation. From a study based on concentrated solar power plants, it has been reported that its applicability is limited to the places where relative humidity is less than 60% and such system is expected to have 90% efficiency in regaining the reflectance lost due to soiling [65]. The dry condition as such of MARS is suitable for the application of this technology [64].

(iv) Self-cleaning mechanism: A translucent self-cleaning nano-film can be coated to the surface of a solar panel to avoid deposition of dust in the panel. The self-cleaning nano-film is made of super hydrophilicity material or super-hydrophobic material. In the super-hydrophilicity method, the rainwater gets scattered throughout the solar module and cleaning the dust. Thus, this method is not popular and various research is going on. In case of super-hydrophobic material, the water droplets quickly fall off carrying dust particles with them like in the leaf of a lotus plant. Various researches are going on to realize superhydrophobic surfaces by forming microstructures or nanostructures. Usage of these materials in the surface of the solar panel would be questionable as solar farms are situated where seldom rains are present. Thus, in the case of solar panel, these materials need to be studied in depth [66], [67].

(v) Robotic system: The robotic system is the most demanded technology in comparison with all other technologies being discussed above since it has a wide range of applicability in small as well as large PV systems. The robotic system consists of actuators, drives, gears having some movement above the module surfaces, and is a virtual operator which cleans the module even much better than manual hand cleaning. Advancement in 3D printing, nanotechnology is aiding to make very complex robots which can operate as efficiently as a human would do the work. The recent development in the field of automation is making the cleaning job even easier so that complexity between the robot and the operator is reduced. Integration of automation in the robotic system has given the ability for a robot to self-decide and perform an action when needed lowering the human-machine interfacing time and humanitarian aid for the entire cleaning operation. The use of microcontrollers and programmable logic controllers to ease the solar panel cleaning process can be seen in most of the robotic cleaners [68], [69]. The fuzzy logic controlled algorithm discussed in [70], [71], deals with the fuzzification of the solar irradiance value and the output current value such that defuzzification would result in decision making whether to clean or not.

The rising topic Internet of Things (IoT) in the technological field can give a substantial turn in the solar panel cleaning process. Distant monitoring of the PV system can be achieved by employing required sensors which shall feed the real-time data to the operator through the cloud. Such an IoT enabled system reduces the cost for inspection and cleaner team can go with their robots only at the time of need. With the application of IoT, even site visits can be avoided such that human intervention in cleaning process shall only be limited to the supervision of completion. This can be achieved by employing decision making automation with pre-installed robots mounted over the solar array/s. This idea has been demonstrated in the prototyping of a system named after Smart Solar Photovoltaic Panel Cleaning System as depicted by Figure 5 [72]. This system consists of two major units: Robotic and Autonomous unit, functioning cleaning and decision making respectively. The autonomous unit takes solar radiation as an input parameter and generated power as an output parameter and compares with the calibrated model to decide whether to perform cleaning action or not. Consequently, robotic units act as the slave unit and perform the cleaning as commanded by the autonomous unit. The whole system can be supervised by a person located at any part of the world if only both the cleaning system and the supervisor are in the access to internet connectivity.

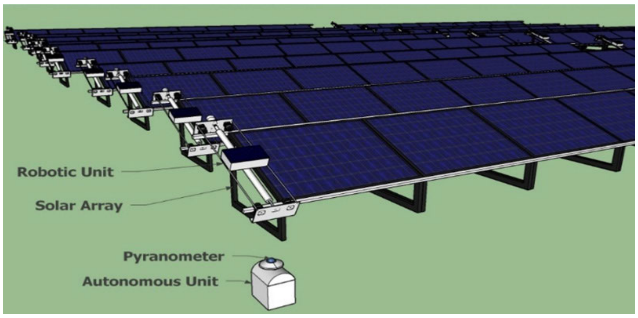

FIGURE 5. Smart solar photovoltaic panel cleaning system [72].

B. CURRENT PRACTICES

Cleaning of any PV glass surface is done in two ways: either using water with water solvent cleaning agents and without water using special brushes. Most of the cleaning practices involve the use of a robotic system with either of the above two practices. Whereas, some of the PV sites with abundant water resources are cleaned by the sprinkled water time to time to avoid the soiling issue. The selection of cleaning mechanism is dependent on geographical location, seasonal variations and weather perturbations, plant size, array configurations and others, so that the economics of cleaning process sticks in a good agreement with that of the worth achieved after cleaning.

(i) Water-based robotic cleaning systems: Water-based cleaning systems use water as their primary component as their cleaning agent. The water-based cleaning system is best suited in an urban and tropical climate where water is abundantly available. Water-based cleaning is the best cleaning system in terms of cleaning efficiency. It can remove hard stains and bird excrements from the surface of the panel.

The Serbot Swiss Innovations developed a cleaning mechanism for mobile deployment onto SPV panels which are shown in Figure 6 (a, b). This system cleans through the rotating brush and demineralized water. The robot moves in the solar panel with vacuumed feet which are rotating on two trapezoid-shaped geared belt drives. This system can be radio controlled and is easy to move from one place to another. Whereas, for a larger application, 'Gekko Solar Farm' has been used, which is designed for utility-scale solar farms [73], [74].

Similarly, Greenbotic's robotic cleaning system (GB1) is a wireless and rechargeable robotic cleaning system for SPV panels. It comprises rotating cleaning brushes perpendicular to the axis of the panel and a wiper system, such that not only does it clean the panel, but also clears the dirty water residing over the module surface. Hence, it is found to be effective for all types of dust and bird droppings [75]. Hector is a wireless mobile robot carrying water solution tank, which can navigate itself throughout the modules without human intervention [76]. Many other systems like these are available in the market with similar techniques of using a robotic system with water to perform the cleaning action. The only difference in these systems is their usage of water delivering and swiping method and the movement along with the panel. Based on their specification, there applicability in different types of array configuration and different sizes of power plant is determined accordingly.

(ii) Waterless robotic cleaning systems: Though water-based cleaning is most effective cleaning method, in dry places like the desert where water is not available and the soiling in the surface of the panel is only due to dust accumulation, it is effective to use water-less cleaning technology. In waterless cleaning technology, a brush typically dust repellent is rotated or moves along the surface of the panel to swipe the dust away. This method is efficient in dry places. The robots cleaning without the use of water is less complicated as it does not store water and doesn't need to pump high-velocity water into the panel and the robots are consequently of lightweight. Solar Brush is an example of a robotic cleaning system for SPV panels without the usage of water. The robot 'solar brush' walks over the solar PV panel up to an inclination of 35 degrees. It is wireless and rechargeable. It is having a cleaning brush which swipes the dust. With the increasing advancement in drones, companies are also introducing cleaning system by drone, which is very applicable and handy for streel light solar panel.

Aerial Power's SolarBrush drone is targeting desert regions of the world to introduce their product of drone cleaning technology [77]. Similarly, Boson solar farm cleaning robot shown in Figure 7, is a fully automatic robot that can clean the surfaces of the panel without the use of water. This is an IoT connected system which cleans the panel at night with its solar-powered unit. This robot also features gap spanning, i.e., it can overcome the problem of other robots that get struck in gaps of the panels in a solar farm. Also, an automatic cleaning feature is added in this system for making the system reliable [78]. Many other products are available in the market with waterless techniques to clean the panel with more efficient ways by the usage of dust repellent or attracting brushes and wipers.

(iii) Automated water sprinkler system: Places with an abundant amount of water can have a system that performs a routine cleaning system making the use of water alone. Automation regarding the routined cleaning shall be required to perform cleaning time to time such that no soiling particles or bird excreta are allowed to stay for a long time. These systems virtually create a rain-like an environment in the solar plant as hoses spray the water directly in the panel, the panel due to its inclination washes the dirt along with water to earth due to gravity. It automatically washes and rinses the solar panels by nozzles attached to the solar panels. These systems consist of a controller which automatically provides wash and rinse cycles, the controller programming can be changed as per seasonal requirements. Figure 8 shows a nozzle spraying high-velocity water into solar panels. This type of fully automated system was first designed and introduced by Heliotex [79].

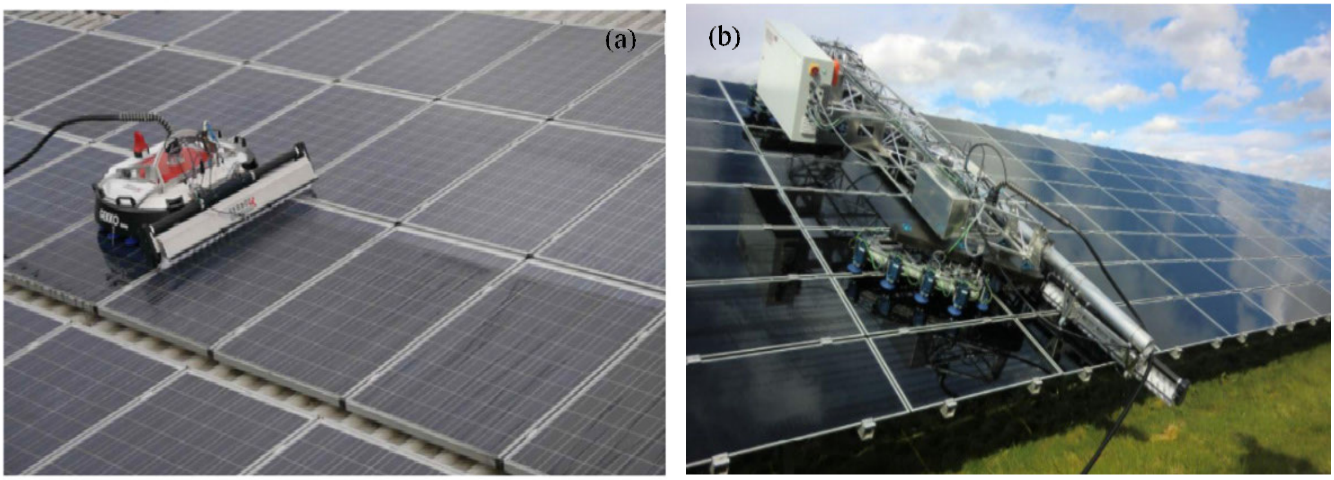

FIGURE 6. Gekko solar robot, and (b) Gekko solar farm robot [73], [74].

FIGURE 7. Boson robotic panel cleaning system [78].

FIGURE 8. Automatic water sprinkler [79].

IV. EVALUATION OF DIFFERENT EXISTING SOLAR PV PANEL CLEANING SYSTEMS

With various technologies and practices available to clean the solar panel, it is necessary to choose the right one based on environment, seasonal and weather patterns and dust density level to ensure the selected method to be economically and technically feasible. Manual cleaning is feasible in small plants which are on the ground level and easy to reach. Manual cleaning for street poles requires a skilled operator having high manpower cost. Similarly, in large solar farms robotic system is considered to be best as it requires less manpower and has high efficiency in cleaning. Solar farms in a tropical region where it is wet and humid having plenty of rainfall may install waterless robotic system as the dew in the solar panel at morning can act as a cleaning agent. So, is also useful for desert areas where the soiling is only of dust particles. However, sites which are prone to sticky specks of dirt and bird excretes, might require water and cleaning agent to clean the panel effectively. In such places, water-based robotic cleaning is found to be more appropriate. In case of desert and places like the surface of Mars (for dry areas) having few module/s for the special purpose can have EDS and piezoelectric based systems which are featured with light weighed and have a compact structure. The different solar panel cleaning technologies evolved so far has been structured in Table 2, which also details the features, effectiveness and the disadvantages respectively.

V. DISCUSSION AND RECOMMENDATIONS

With the rapid development of a robotics system for the solar panel cleaning, the essence of optimal cleaning instant has been a research interest for the PV experts. The scheduling of solar panel cleaning is the challenging task for the smooth operation of PV plants. It is even more essential, if the plant size is in the range of hundreds and thousands of megawatts. The investment made for cleaning purpose must have a good rate of return in terms of restoration of energy harvesting

TABLE 2. Evaluation of different solar PV panel cleaning system.

Technology	Method of cleaning	Effectiveness of cleaning	Unique Features	Disadvantages	Remarks	References
Manual Cleaning	Hand cleaning	Cleans all type of dust including bird excreta, grease layers, etc.	Human laboured cleaning	i)Manpower required ii)Not effective in large solar farms iii)Can damage the surface of solar panel	Implementable for small solar home systems	[80]
	Cleaning kit		i)Additional shaft and special cleaning agent ii)Maintains smoothness of surface		Can be used in large sized roof top solar plants with random array configurations	
	Spraying water	Cleans dust particles	Water hose applied manually		Better used in sites with abundant water	
	Rainwater cleaning	Cleans dust particles	i)Natural cleaning ii)No manpower required	Ineffective for the places with inadequate rainfall	PV sites situates in tropical regions	
Piezoelectric System	Water/air components carrying dust material; vibration and actuator drives the dust away from the panel	Cleans dust particles	Light weight and compact structure	Inapplicable for a larger number of modules.	Applicable for astronautic and aeronautic applications	[59, 60]
Standing Wave Electric Curtain System	Electric Field makes a path for dust to move along the solar panel and fall off	Cleans dust particles	Completely static cleaning method with no moving mechanical parts	Dry state of module is required (RH <60%)	Can be used in a harsh dusty environment like deserts or even in Mars	[61-65]
Robotic System	Water-based Cleaning	Cleans hard dirt and dust deposits	Smoothness of panels surface remains intact after cleaning	i)sophisticated and complex systems ii)Restricted to particular module configuration iii)additional costing of water	Applicable for large scale solar plants abundant with water resources	[73-76]
	Waterless Cleaning	Cleans dirt and hard dirt without the use of water	Low operational cost	i) Restricted to particular module configuration ii)Ineffective in cleaning tough dirt and bird's excretes	Applicable for large scale solar plants with scarce water	[77, 78]
	Robotics with IoT integration	Can comprise of both water-based or waterless techniques and cleaning effectiveness depends on technique used	i)Distant monitoring of real-time plant conditions ii)Requires no human intervention iii)Cleaning supervision can be done distantly	i)Complex system ii)High initial investment iii)Skilled and trained supervisor is needed	Applicable for semi-arid areas and far to reach large solar plants	[72] [78]
Self-Cleaning Method	Translucent Coating of Nano Film	Cleans more effectively than rainwater natural technique	i)Thin film coating does not affect the efficiency of a panel ii)no operator required	i)Low reliability of the system for different site condition ii) Inapplicable for dry places	Can be used for PV powered sensor networks installed in remote locations	[66, 67]
Automated Water Cleaning	Automated Water Sprinkler	Cleans dust particle and bird's excreta (if cleaned before it gets dry)	i)Easy installation ii)frequent water rinses avoid sticking of accumulated dirt	Inapplicable for water-scarce places	Can be used at roof top solar plants	[79]

capability of the solar cells thereby decreasing the LCoE. Cleaning decision made just concerning the visual inspection by a human being might not be effective in terms of power plant economics and plant health. With the advancement in the field of data science and machine learning, their application in some of the parameters associated with the power

TABLE 3. Methodologies for the decision-making model.

Components for Methodology Selection			
Data Selection	**Data Processing**	**Model Selection**	**Evaluation of Performance**
➢ Parameter Selection ➢ Computational Delay	➢ Time Series ➢ Feature Extraction ➢ Feature Selection	➢ Logistic Regression ➢ Support Vector Machine ➢ Artificial Neural Network ➢ Random Forest ➢ Transfer Learning ➢ Deep Learning	➢ Accuracy Index

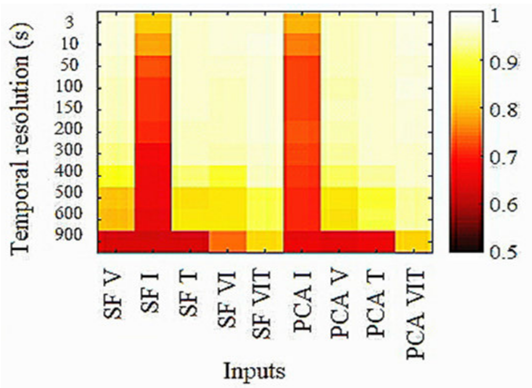

FIGURE 9. Average accuracy classification for random forest technique [81].

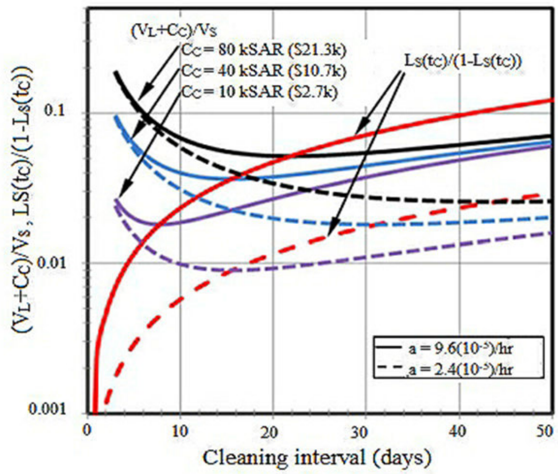

FIGURE 10. Cleaning interval based on Cost of Energy (CoE) [82].

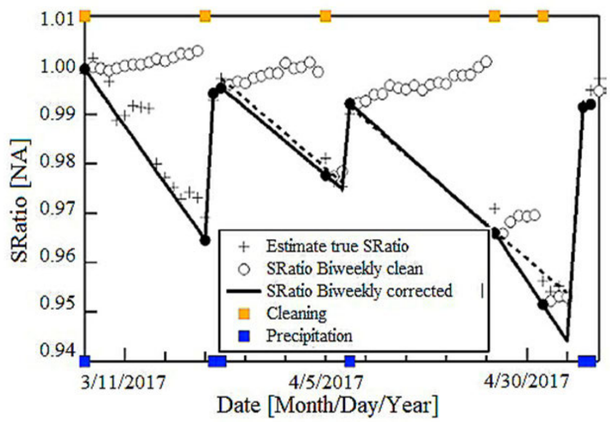

FIGURE 11. Cleaning interval based on soiling accumulation [83].

production from the solar arrays, can be proven as the most advanced scientific tool to decide the cleaning intervention of the solar power plant.

A. SCHEDULING OF SOLAR PANEL CLEANING INTERVENTION

According to the study done for solar pumping system of 600 Wp in [81], it is found that the logistic regression model can give greater than 90% system accuracy for temporal resolution smaller than 300 seconds whereas for greater than 300s, complex tools like the random forest (RF) or artificial neural network (ANN) are needed. In the same system, the combination of the array voltage, the array current and the module temperature with Random Forest model gave the most accurate classifier (90%) which can be visualized by Figure 9. In a research done at 100 MW Solar PV plant at Saudi Arabia, an optimal cleaning interval of the plant is evaluated using simple exponential loss model [82] where the minimization of the total cost (cost of energy loss due to soiling plus cost of cleaning) over the value of energy sold during that interval [82] is achieved. The cleaning interval from this technique is evaluated by finding the abscissa of the point of intersection between the line plot of the value of energy represented by either of the black, blue or purple (depending on the cost of cleaning) line to that of soiling as represented by the red line in Figure 10. Likewise, an analysis done in Chile suggests that, an optimal cleaning program can be designed from a robust statistical representation of power generation characteristics of a PV plant using correlation of the obtained data from the real PV plant to that of ideal power based on geographical data.

In an experiment performed in the Southwestern United States [83], cleaning schedule is optimized as shown in Figure 11 by using the Soiling Ratio (Sr): defined by the ratio of the short circuit currents of naturally soiling PV cell to that of intended to be cleaned cell. Along with the use of precipitation data, the corrected Sr ratio over the time is drawn as per the changes obtained in the consecutive instances.

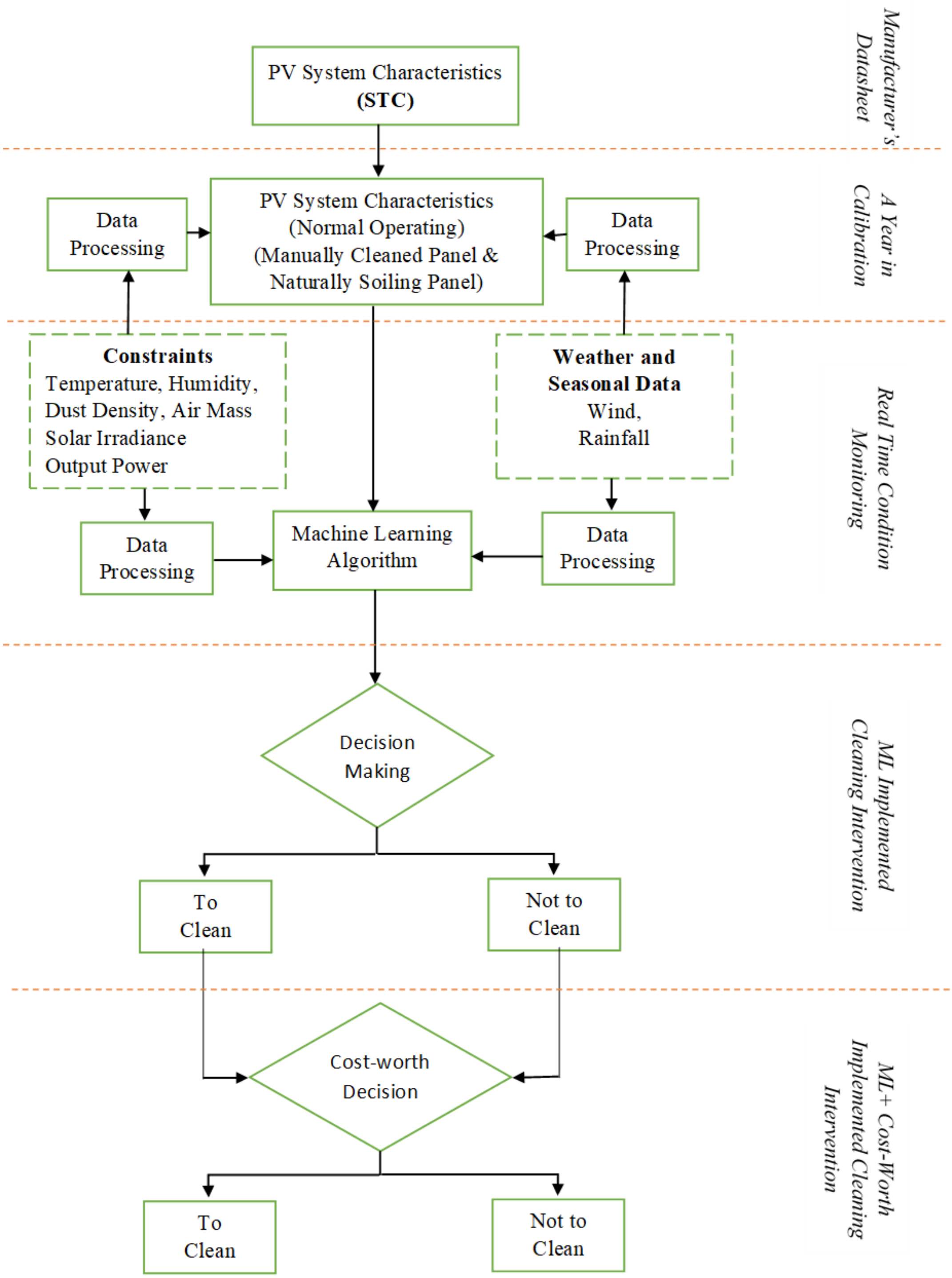

FIGURE 12. Suggested model for scheduling the cleaning intervention.

B. SUGGESTED SCHEMATICS FOR MACHINE LEARNING IMPLEMENTATION IN PV CLEANING SYSTEM

Machine learning's ability to inherit certain behaviour, the tendency of the dataset and the ability to classify or predict the similar behaviour that it has learned through, with high confidence makes it most suitable to cater this particular problem. Table 3 presents the different methodologies to design a decision-making model.

(i) Data Selection: There are several parameters associated with the efficiency of a solar photovoltaic module as discussed in the previous sections. Module Temperature (Tpv), Ambient Temperature and Humidity, Dust Density, Air mass are the influencing parameters. Array Voltage (Vpv) and Array Current (Ipv) are the output parameters whereas Solar irradiance (Gpv) is the measure of solar energy input and termed as the input parameter. The more the parameters included, the more accurate the model might be and consequently, the more sophisticated and costly the system shall be. In the study performed at middle east countries [80], [83], due to different soiling conditions at different months of a year, it is experienced that seasonal meteorological data have paramount importance in determining the cleaning intervention.

(ii) Data Processing: Before casting the calibration model for the decision making, it is necessary to process the data collected which seems to be erroneous. Time series is the simplest data processing tool which takes each input of a parameter as a single entity, whereas simple featuring defines a set of data inputs as a statistical interpretation (mean, mode, median, variance) and groups the multiple numbers of data having a common feature to a single one. Principal Component Analysis (PCA) is complex than the other two, and mostly used if there are a large number of parameters included, where accuracy is a must. Similarly, there are more complex data processing techniques which can be used suitably.

(iii) Model Selection: Logistic Regression is one of the simplest calibration modelling techniques used which defines the linear relation between the parameters. According to the quality of the processed data, parameters involved and accuracy required, various complex tools of machine learning like: support vector machine, artificial neural network, random forest, transfer learning and deep learning can be tested and best among them shall be implemented.

(iv) Evaluation of Performance: Once different machine learning models in a combination with the various data processing tools have been tested, evaluation is done to select the best combination among all, which is solely dependent on the system accuracy, costing, energy consumption and computational time, particularly as per demanded by the specification of the solar photovoltaic system.

Figure 12 is the suggested model to schedule a cleaning intervention using a machine learning tool, additionally with cost worth analysis. Regardless of using every parameter included in the dotted box, only selected parameters through optimisation techniques of feature extraction are selected for the calibration and decision-making process. The robustness of the model is solely dependent on the accuracy index as per the requirement of the solar power plant and the location where it is situated. Most of the plants situated in the Middle East countries where soiling is the major issue are compulsion to have a detailed prerequisite before designing the cleaning system. The larger the system is, the more accurate the model has to be, and the more complex tools of machine learning need to be implemented. Beside the cleaning intervention determined from the ML tools alone, it is suggested to use the cost worth based model [82], additionally to achieve the expected LCoE.

VI. CONCLUSION

This review discusses the effects of various parameters on the solar photovoltaic panel, and various cleaning systems that are developed and being used up to the present days. The key points of the topics discussed are:

1. The rise in cell temperature and soiling of the module are the two major issues of the PV systems.
2. Places with extensive temperature rise can be dealt with by active and passive cooling techniques, whereas soiling can be dealt with by cleaning the surface of modules.
3. Cleaning can be achieved by natural rainfall, manual hand cleaning, water jet/sprinklers and most effectively by robots.
4. Standing wave-type electric curtain system can be applied in the areas with water-scarce, like for solar panels in Mars.
5. To obtain optimum cleaning instant for a particular case scenario, machine learning application can be implemented to develop a decision-making model with the use of parameters affecting the performance of PV plant: solar irradiance, output power, temperature, humidity, air mass, dust density, seasonal and weather patterns. The complexity and accuracy of the system are defined mainly by power plant size, vulnerability to soiling, seasonal patterns and weather perturbations.
6. For distant solar farms with no rainfall and prone to frequent sand/dust deposition, the IoT based cleaning system with a pre-installed robot in the solar array [72] can be used, which shall avoid the multiple site visit costs.

It is suggested that for the large solar farms, solar panel cleaning shall only be done, if the efficiency is reduced below the critical level and the investor must make sure that the investment made on the cleaning purpose have a tolerable rate of return. Further research and development on a decision-making model considering cost worth evaluation are essential for the evolving solar panel cleaning technology.

ABBREVIATIONS

SPV	Solar Photovoltaic
PV	Photovoltaic
LCoE	Levelised Cost of Energy
CO_2	Carbon dioxide
GW	Giga Watt
MW	Mega Watt
Twh	Terawatt hour
STC	Standard Test Condition
MPPT	Maximum Power Point Tracking
AC	Alternating Current
DC	Direct Current
LDS	Luminous Down Shifting
CNT	Carbon Nano Tubes
CdTe	Cadmium Telluride
CIS	Copper Indium Selenide
I_{SC}	Short Circuit Current

V_{OC}	Open Circuit Voltage
EDS	Electro-Dynamic Screen
O&M	Operation and Maintenance
3D	3 Dimensional
IoT	Internet of Things
RH	Relative Humidity
ANN	Artificial Neural Network
Sr	Soling Ratio
T_{pv}	Module Temperature
G_{pw}	Solar Irradiance
I_{pv}	Array Current
V_{pv}	Array Voltage
PCA	Principal Component Analysis

REFERENCES

[1] *World Energy Outlook 2019*, IEA, Paris, France, 2019.

[2] *Key World Energy Statistics*, IEA, Paris, France, 2019.

[3] *Renewable Energy Options for the Industry Sector*, IRENA, Abu Dhabi, United Arab Emirates, 2015.

[4] *Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects*, IRENA, Abu Dhabi, United Arab Emirates, 2019.

[5] (2020). *The World's Biggest Solar Power Plant*. [Online]. Available: https://www.power-technology.com/features/the-worlds-biggest-solar-power-plants/

[6] A. K. Mondal and K. Bansal, "A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels," *Adv. Robot.*, vol. 29, no. 8, pp. 515–524, Apr. 2015.

[7] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, "Power loss due to soiling on solar panel: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1307–1316, Jun. 2016.

[8] J. R. Caron and B. Littmann, "Direct monitoring of energy lost due to soiling on first solar modules in california," *IEEE J. Photovolt.*, vol. 3, no. 1, pp. 336–340, Jan. 2013.

[9] F. A. Mejia and J. Kleissl, "Soiling losses for solar photovoltaic systems in california," *Sol. Energy*, vol. 95, pp. 357–363, Sep. 2013.

[10] F. Mejia, J. Kleissl, and J. L. Bosch, "The effect of dust on solar photovoltaic systems," *Energy Procedia*, vol. 49, pp. 2370–2376, Oct. 2014.

[11] B. R. Paudyal and S. R. Shakya, "Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of kathmandu," *Sol. Energy*, vol. 135, pp. 103–110, Oct. 2016.

[12] D. M. Tobnaghi and D. Naderi, "The effect of solar radiation and temperature on solar cells performance," *Extensive J. Appl. Sci.*, vol. 3, no. 2, pp. 39–43, 2015.

[13] S. Sargunanathan, A. Elango, and S. T. Mohideen, "Performance enhancement of solar photovoltaic cells using effective cooling methods: A review," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 382–393, Oct. 2016.

[14] O. Dupré, R. Vaillon, and M. A. Green, "Physics of the temperature coefficients of solar cells," *Sol. energy Mater. Sol. cells*, vol. 140, pp. 92–100, 2015.

[15] T. Salmi, M. Bouzguenda, A. Gastli, and A. Masmoudi, "Matlab/simulink based modeling of photovoltaic cell," *Int. J. Renew. Energy Res.*, vol. 2, no. 2, pp. 213–218, 2012.

[16] Y. Jiang, J. A. A. Qahouq, and I. Batarseh, "Improved solar PV cell MATLAB simulation model and comparison," in *Proc. IEEE Int. Symp. Circuits Syst.*, May 2010, pp. 2770–2773.

[17] V. J. Fesharaki, M. Dehghani, J. J. Fesharaki, and H. Tavasoli, "The effect of temperature on photovoltaic cell efficiency," in *Proc. 1st Int. Conf. Emerg. Trends Energy Conservation*, Tehran, Iran, 2011, pp. 20–21.

[18] M. K. Panjwani and G. B. Narejo, "Effect of humidity on the efficiency of solar cell (photovoltaic)," *Int. J. Eng. Res. Gen. Sci.*, vol. 2, no. 4, pp. 499–503, 2014.

[19] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, "Effect of dust, humidity and air velocity on efficiency of photovoltaic cells," *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 2920–2925, Jun. 2012.

[20] H. A. Kazem and M. T. Chaichan, "Effect of humidity on photovoltaic performance based on experimental study," *Int. J. Appl. Eng. Res.*, vol. 10, no. 23, pp. 43572–43577, 2015.

[21] C. M. Tan, B. K. E. Chen, and K. P. Toh, "Humidity study of a-Si PV cell," *Microelectron. Rel.*, vol. 50, nos. 9–11, pp. 1871–1874, Sep. 2010.

[22] F. A. Touati, M. A. Al-Hitmi, and H. J. Bouchech, "Study of the effects of dust, relative humidity, and temperature on solar PV performance in Doha: Comparison between monocrystalline and amorphous PVS," *Int. J. Green Energy*, vol. 10, no. 7, pp. 680–689, Aug. 2013.

[23] R. Gottschalg, T. R. Betts, D. Infield, and M. J. Kearney, "Experimental investigation of spectral effects on amorphous silicon solar cells in outdoor operation," in *Proc. 29th IEEE Photovoltaic Spec. Conf.*, Dec. 2002, pp. 1138–1141.

[24] M. N. Islam, M. Z. Rahman, and S. M. Mominuzzaman, "The effect of irradiation on different parameters of monocrystalline photovoltaic solar cell," in *Proc. 3rd Int. Conf. Develop. Renew. Energy Technol. (ICDRET)*, May 2014, pp. 1–6.

[25] Ì. Portolan dos Santos and R. Räther, "Limitations in solar module azimuth and tilt angles in building integrated photovoltaics at low latitude tropical sites in brazil," *Renew. Energy*, vol. 63, pp. 116–124, Mar. 2014.

[26] M. Kacira, M. Simsek, Y. Babur, and S. Demirkol, "Determining optimum tilt angles and orientations of photovoltaic panels in sanliurfa, turkey," *Renew. Energy*, vol. 29, no. 8, pp. 1265–1275, Jul. 2004.

[27] M. Lave and J. Kleissl, "Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental united states," *Renew. Energy*, vol. 36, no. 3, pp. 1145–1152, Mar. 2011.

[28] B. Elhab, "Optimizing tilt angles and orientations of solar panels for Kuala Lumpur, Malaysia," *Sci. Res. Essays*, vol. 7, no. 42, pp. 3758–3765, 2012.

[29] D. Goossens and E. Van Kerschaever, "Aeolian dust deposition on photovoltaic solar cells: The effects of wind velocity and airborne dust concentration on cell performance," *Sol. Energy*, vol. 66, no. 4, pp. 277–289, Jul. 1999.

[30] H. K. Elminir, A. E. Ghitas, R. H. Hamid, F. El-Hussainy, M. M. Beheary, and K. M. Abdel-Moneim, "Effect of dust on the transparent cover of solar collectors," *Energy Convers. Manage.*, vol. 47, nos. 18–19, pp. 3192–3203, Nov. 2006.

[31] M. S. El-Shobokshy and F. M. Hussein, "Effect of dust with different physical properties on the performance of photovoltaic cells," *Sol. Energy*, vol. 51, no. 6, pp. 505–511, Dec. 1993.

[32] M. J. Adinoyi and S. A. M. Said, "Effect of dust accumulation on the power outputs of solar photovoltaic modules," *Renew. Energy*, vol. 60, pp. 633–636, Dec. 2013.

[33] M. Saidan, A. G. Albaali, E. Alasis, and J. K. Kaldellis, "Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment," *Renew. Energy*, vol. 92, pp. 499–505, Jul. 2016.

[34] F. M. Zaihidee, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, "Dust as an unalterable deteriorative factor affecting PV panel's efficiency: Why and how," *Renew. Sustain. Energy Rev.*, vol. 65, pp. 1267–1278, Nov. 2016.

[35] H. Qasem, T. R. Betts, H. Mällejans, H. AlBusairi, and R. Gottschalg, "Dust-induced shading on photovoltaic modules," *Prog. Photovolt., Res. Appl.*, vol. 22, no. 2, pp. 218–226, Feb. 2014.

[36] Z. A. Darwish, H. A. Kazem, K. Sopian, M. A. Al-Goul, and H. Alawadhi, "Effect of dust pollutant type on photovoltaic performance," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 735–744, Jan. 2015.

[37] D. Dirnberger, G. Blackburn, B. Müller, and C. Reise, "On the impact of solar spectral irradiance on the yield of different PV technologies," *Sol. Energy Mater. Sol. Cells*, vol. 132, pp. 431–442, Jan. 2015.

[38] J. Merten, "Clear separation of seasonal effects on the performance of amorphous silicon solar modules by outdoor I/V-measurements," *Sol. Energy Mater. Sol. Cells*, vol. 52, nos. 1–2, pp. 11–25, Mar. 1998.

[39] Y. Hirata, T. Inasaka, and T. Tani, "Output variation of photovoltaic modules with environmental factors-II: Seasonal variation," *Sol. Energy*, vol. 63, no. 3, pp. 185–189, 1998.

[40] J. Siecker, K. Kusakana, and B. P. Numbi, "A review of solar photovoltaic systems cooling technologies," *Renew. Sustain. Energy Rev.*, vol. 79, pp. 192–203, Nov. 2017.

[41] B. Parida, S. Iniyan, and R. Goic, "A review of solar photovoltaic technologies," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1625–1636, 2011.

[42] E. Klampaftis, D. Ross, K. R. McIntosh, and B. S. Richards, "Enhancing the performance of solar cells via luminescent down-shifting of the incident spectrum: A review," *Sol. Energy Mater. Sol. Cells*, vol. 93, no. 8, pp. 1182–1194, Aug. 2009.

[43] M. Tilli, M. Paulasto-Krockel, T. Motooka, and V. Lindroos, *Handbook of Silicon Based MEMS Materials and Technologies*. Norwich, NY, USA: William Andrew, 2015.

[44] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. Selvaraj, "Progress in solar PV technology: Research and achievement," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 443–461, Apr. 2013.

[45] B. van der Zwaan and A. Rabl, "Prospects for PV: A learning curve analysis," *Sol. Energy*, vol. 74, no. 1, pp. 19–31, Jan. 2003.

[46] *Photovoltaic Devices. Part 1: Measurement of Photovoltaic Current-Voltage Characterisitics*, Standard IEC 60904-1, 2006.

[47] F. Dinçer and M. E. Meral, "Critical factors that affecting efficiency of solar cells," *Smart Grid Renew. Energy*, vol. 1, no. 01, p. 47, 2010.

[48] B. A. L. Gwandu and D. J. Creasey, "Humidity: A factor in the appropriate positioning of a photovoltaic power station," *Renew. Energy*, vol. 6, no. 3, pp. 313–316, Apr. 1995.

[49] M. T. Chaichan and H. A. Kazem, "Experimental analysis of solar intensity on photovoltaic in hot and humid weather conditions," *Int. J. Sci. Eng. Res.*, vol. 7, no. 3, pp. 91–96, 2016.

[50] A. Rao, R. Pillai, M. Mani, and P. Ramamurthy, "Influence of dust deposition on photovoltaic panel performance," *Energy Procedia*, vol. 54, pp. 690–700, 2014.

[51] L. Dorobantu, M. Popescu, and C. Popescu, "Yield loss of photovoltaic panels caused by depositions," in *Proc. 7th Int. Symp. Adv. Topics Electr. Eng. (ATEE)*, 2011, pp. 1–4.

[52] H. Hottel and B. Woertz, "Performance of flat-plate solar-heat collectors," *Trans. ASME Amer. Soc. Mech. Eng.*, vol. 64, Oct. 1942.

[53] B. Nimmo and S. A. Said, "Effects of dust on the performance of thermal and photovoltaic flat plate collectors in Saudi Arabia-preliminary results," *Alternative energy Sour.*, vol. 1, pp. 145–152, Oct. 1981.

[54] G. A. Mastekbayeva and S. Kumar, "Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate," *Sol. Energy*, vol. 68, no. 2, pp. 135–141, Feb. 2000.

[55] A. Hassan, U. A. Rahoma, H. K. Elminir, and A. Fathy, "Effect of airborne dust concentration on the performance of PV modules," *J. Astron. Soc. Egypt*, vol. 13, no. 1, pp. 24–38, 2005.

[56] H. Khonkar, A. Alyahya, M. Aljuwaied, M. Halawani, A. Al Saferan, F. Al-khaldi, F. Alhadlaq, and B. A. Wacaser, "Importance of cleaning concentrated photovoltaic arrays in a desert environment," *Sol. Energy*, vol. 110, pp. 268–275, Dec. 2014.

[57] S. A. Sulaiman, A. K. Singh, M. M. M. Mokhtar, and M. A. Bou-Rabee, "Influence of dirt accumulation on performance of PV panels," *Energy Procedia*, vol. 50, pp. 50–56, Oct. 2014.

[58] (Apr. 16, 2000). *Solar Panel Cleaning Kit*. [Online]. Available: https://www.windowcleaningstuff.co.uk/water-fed-pole-systems/911-solar-panel-cleaning-kit.html

[59] P. Vasiljev, S. Borodinas, R. Bareikis, and A. Struckas, "Ultrasonic system for solar panel cleaning," *Sens. Actuators A, Phys.*, vol. 200, pp. 74–78, Oct. 2013.

[60] X. Lu, Q. Zhang, and J. Hu, "A linear piezoelectric actuator based solar panel cleaning system," *Energy*, vol. 60, pp. 401–406, Oct. 2013.

[61] H. Kawamoto and T. Shibata, "Electrostatic cleaning system for removal of sand from solar panels," *J. Electrostatics*, vol. 73, pp. 65–70, Feb. 2015.

[62] M. Mazumder, "Electrostatic removal of particles and its applications to self-cleaning solar panels and solar concentrators," in *Developments in Surface Contamination and Cleaning: Methods for Removal of Particle Contaminants*. Amsterdam, The Netherlands: Elsevier, 2011, pp. 149–199.

[63] M. N. Horenstein, M. K. Mazumder, R. C. Sumner, J. Stark, T. Abuhamed, and R. Boxman, "Modeling of trajectories in an electrodynamic screen for obtaining maximum particle removal efficiency," *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 707–713, Mar. 2013.

[64] G. A. Landis and P. P. Jenkins, "Dust mitigation for mars solar arrays," in *Proc. 29th IEEE Photovolt. Spec. Conf.*, 2002, pp. 812–815.

[65] M. Mazumder, M. Horenstein, J. Stark, J. N. Hudelson, A. Sayyah, C. Heiling, and J. Yellowhair, "Electrodynamic removal of dust from solar mirrors and its applications in concentrated solar power (CSP) plants," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2014, pp. 1–7.

[66] J. Son, S. Kundu, L. K. Verma, M. Sakhuja, A. J. Danner, C. S. Bhatia, and H. Yang, "A practical superhydrophilic self cleaning and antireflective surface for outdoor photovoltaic applications," *Sol. Energy Mater. Sol. Cells*, vol. 98, pp. 46–51, Mar. 2012.

[67] G. He, C. Zhou, and Z. Li, "Review of self-cleaning method for solar cell array," *Procedia Eng.*, vol. 16, pp. 640–645, 2011.

[68] S. M. Al-Dhaheri, L. A. Lamont, L. El-Chaar, and O. A. Al-Ameri, "Automated design for boosting offshore photovoltaic (PV) performance," in *Proc. IEEE PES*, 2010, pp. 1–6.

[69] E. Al-Qubaisi, M. Al-Ameri, A. Al-Obaidi, M. Rabia, L. El-Chaar, and L. Lamont, "Microcontroller based dust cleaning system for a standalone photovoltaic system," in *Proc. Int. Conf. Electr. Power Energy Convers. Syst.*, 2009, pp. 1–6.

[70] C. H. Huang, M. R. Lee, Y. F. Su, C. C. Huang, Y. T. Su, W. H. Su, and F. Z. Cai, "Development of intelligent solar panel cleaning system with fuzzy logic theorem," *Appl. Mech. Mater.*, vols. 479–480, pp. 565–569, Dec. 2013.

[71] G.-C. Hsieh, L.-R. Chen, and K.-S. Huang, "Fuzzy-controlled li-ion battery charge system with active state-of-charge controller," *IEEE Trans. Ind. Electron.*, vol. 48, no. 3, pp. 585–593, Jun. 2001.

[72] N. Khadka, A. Bista, B. Adhikari, A. Shrestha, and D. Bista, "Smart solar photovoltaic panel cleaning system," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 463, Apr. 2020, Art. no. 012121.

[73] *Gekko Solar Robot*. [Online]. Available: https://serbot.ch/en/solar-panels-cleaning/gekko-solar-robot

[74] *Gekko Solar Farm Robot*. [Online]. Available: https://www.serbot.ch/en/solar-panels-cleaning/gekko-solar-farm-robot

[75] *Greenbotic's Robotic Cleaning System*. [Online]. Available: https://www.greentechmedia.com/articles/read/sunpower-cleans-up-solar-with-acquisiton-of-greenbotics#gs.YzTxhJI

[76] M. Hardt, "HECTOR-heliostat cleaning team-oriented robot," in *Proc. Solar-PACES*, Granada, Spain, Sep. 2011, pp. 20–23.

[77] *Solar Brush*. [Online]. Available: https://www.aerialpower.com/solarbrush/

[78] (Apr. 15, 2020). *Intellegent Cleaning Robots*. Available:. [Online]. Available: https://bosonrobotics.com/en/products/robot

[79] Heliotex. (Apr. 17, 2020). *Automatic Solar Panel Celaning System*. [Online]. Available: https://www.solarpanelcleaningsystems.com/

[80] M. K. Smith, C. C. Wamser, K. E. James, S. Moody, D. J. Sailor, and T. N. Rosenstiel, "Effects of natural and manual cleaning on photovoltaic output," *J. Sol. Energy Eng.*, vol. 135, no. 3, Aug. 2013.

[81] M. Heinrich, S. Meunier, A. Samé, L. Quéval, A. Darga, L. Oukhellou, and B. Multon, "Detection of cleaning interventions on photovoltaic modules with machine learning," *Appl. Energy*, vol. 263, Apr. 2020, Art. no. 114642.

[82] R. K. Jones, A. Baras, A. A. Saeeri, A. Al Qahtani, A. O. Al Amoudi, Y. Al Shaya, M. Alodan, and S. A. Al-Hsaien, "Optimized cleaning cost and schedule based on observed soiling conditions for photovoltaic plants in central saudi arabia," *IEEE J. Photovolt.*, vol. 6, no. 3, pp. 730–738, May 2016.

[83] M. Muller, L. Micheli, and A. A. Martinez-Morales, "A method to extract soiling loss data from soiling stations with imperfect cleaning schedules," in *Proc. IEEE 44th Photovoltaic Specialist Conf. (PVSC)*, Jun. 2017, pp. 2881–2886.

NASIB KHADKA received the bachelor's degree in electrical and electronic engineering specialized in power and control from Kathmandu University, in 2018, A. D., with a thesis focused on the elimination of soiling issues in solar photovoltaic power plants. He is currently pursuing the M.S. degree by Research Program, in 2019, A. D., dealing with lightning protection of medium voltage distribution network, along with the Research Assistantship at Center for Electric Power Engineering (CEPE), Kathmandu University. He had once been awarded with the Erasmus Mundus Leaders grant for the student exchange program hosted by Frederick University, Cyprus, in 2016. He has been working in the field of solar photovoltaics, lightning protection systems, mini-grid, and high-voltage engineering. He has further interest in smart grid technology, the Internet of Things, and machine learning applications.

AAYUSH BISTA received the bachelor's degree in electrical and electronics engineering from the School of Engineering, Kathmandu University, Nepal, in 2018, where he is currently pursuing the master's degree in LED lighting. He was also an Erasmus Mundus candidate with the Department of Electrical Engineering, Frederick University, Cyprus, funded by European Union. He is also working as a Research Assistant with the Center for Electric Power Engineering (CEPE), Kathmandu University. His research interests include control and instrument systems, LED lighting, sensor technology, and renewable energies.

BINAMRA ADHIKARI received the bachelor's degree in electrical and electronics engineering specialized in power and control from Kathmandu University, in 2018, A.D., with thesis focused on elimination of soiling issues in solar photovoltaic power plants. He is currently pursuing the master's degree in electrical and computer engineering with the University of Saskatchewan. He is also working as a Graduate Research Assistant with focus on Resiliency in Distribution System. His research focuses on modeling the resiliency of distribution systems, microgrids, and DER. He has been working in the fields of renewable energy, microgrids focusing on solar photovoltaics, and applications in machine learning.

ASHISH SHRESTHA (Member, IEEE) received the bachelor's degree in electrical and electronics engineering from the School of Engineering, Pokhara University, Nepal, in 2014, and the master's degree in planning and operation of energy system from the School of Engineering, Kathmandu University, Nepal, in 2017. He was also an Erasmus Mundus candidate with the Department of Electrical Engineering, Frederick University, Cyprus, funded by European Union. He is currently working as a Lecturer with the Department of Electrical and Electronics Engineering, and a Researcher (Activity Leader) with the Center for Electric Power Engineering (CEPE), Kathmandu University. He is also involved in the problem-based learning project funded by Erasmus+ program of EU, and serving as a Co-Principal Investigator in a project funded by the Ministry of Foreign Affairs (MFA), Norway. He is also a professional member of the Nepal Engineering Association. Till today, he published around 23 peer-reviewed journal articles and international conference papers, and was assigned as a Reviewer for numerous international conferences and peer-reviewed journals from the IEEE, Springer, and Elsevier. His research interests include power systems, distributed generation resources, planning and operation of energy systems, and electric vehicle.

DIWAKAR BISTA (Member, IEEE) received the bachelor's degree in electrical and electronics engineering (specialization in power and control) and the M.S. degree from the School of Engineering, Kathmandu University, where he is currently pursuing the Ph.D. degree. He is also working as an Assistant Professor with the Department of Electrical and Electronics Engineering, Kathmandu University, where he is also the Project Leader of the Center for Electric Power Engineering (CEPE). His research interests include the lighting technologies, control and instrumentation, and renewable energy. In the past, he had coordinated number of projects funded by Royal Norwegian Embassy at Nepal, European Union, and Nepal Government. He is also working as a Coordinator from Nepal of problem-based learning project funded by Erasmus+ program of EU.

BRIJESH ADHIKARY (Member, IEEE) received the B.Sc. degree from Tribhuwan University, in 1988, Nepal, the B.E. degree from Karnataka University, India, in 1994, the M.E. degree from BITS Pilani, India, in 1998. He is currently working as an Associate Professor with the Department of Electrical and Electronics Engineering. His research interests include renewable energy, distributed generation, and power generators.