An overview of cleaning and prevention processes for enhancing efficiency of solar photovoltaic panels

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The energy produced by solar photovoltaic (SPV) modules is directly connected with the solar accessible irradiance, spectral content, different variables like environmental and climatic components. Dust and bird droppings are considered as the real challenges for SPV performance. This article covers dust-related challenges and advanced improvements made on the automated cleaning system, by providing a brief framework on strategies such as mechanical, electrical, chemical and electrostatic. The environmental impact of cleaning processes has also been evaluated, which is directly related to the ultimate performance of overall conversion.

Keywords: Automated cleaning process, dust, electrodynamic screening, particle removal, solar photovoltaics.

SOLAR energy is considered as the main solution for the energy demand of the world when non-renewable sources of energy are declining[1]. Solar-based energy systems are convenient due to their easy installation, maintenance and longer durability.

Utilization and conversion of solar energy is a complex photochemical process, requiring optimization of several parameters for an acceptable level of efficiency, where the process is directly controlled by surface characteristics and its cleaning. Solar photovoltaic (SPV) cleaning and prevention from dust are two main aspects of maintenance required for enhanced and longer yield. Other parameters such as increase in temperature, overheating[2–4] and physical hindrance of sunlight may cause its scattering from the SPV surface resulting in low absorption[5].

Although cleaning of solar panel has been a defining challenge for researchers mainly for balancing the cost with performance and durability, continuous efforts in this direction seem to be a positive step towards enhancing the efficiency of the devices. Dust is a fine, dry powder comprising miniature units of earth or waste material[6]. Dust settlement for the most part depends on numerous components like compound properties, size, weight, shape, site, tilt point surface completion, stickiness, wind speed, etc.[7–11]. Dust exposure affects many parameters of SPV; so several attempts have been made to address this issue (Tables 1 and 2). However, there are a variety of approaches for cleaning depending on weather or on power generation capacity (Tables 3 and 4).

Cleaning techniques

There are several challenges and benefits related to the cleaning techniques. All the techniques are mainly focused on reducing the adhesion bond between dust particles and the panel by controlling electrostatic repulsion (ER)[12–18]. This strategy is aimed at incorporating materials or system designs that use non-contact, continuous techniques which require little or no labour for cleaning.

Electrostatic biasing

This is mainly directed at SPV cleaning in space application. Apart from the traditional/conventional cleaning techniques, special ones are required for space related conditions. The process should be non-contact type, which reduces manpower. As the space environment (explored so far) is dry or non-humid, and since the dust particles are ionized due to lack of atmosphere around them, suitable techniques were applied earlier[13–17,19–21]. An electrostatic biasing film consists of rows of transparent, conducting, parallel electrodes sandwiched between two transparent dielectric layers. This film is integrated with SPV module on its optical surface to maintain high transmission efficiency without the need for water. To remove dust particles deposited on an electrostatic biasing film surface, the electrodes are activated by applying low-frequency, high-voltage pulses. The dust particles are then electrostatically charged and removed

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Table 1. Factors affecting the reaction to dust

Parameters	Details
Frequency of dust settlement incidents	Generally a community is equipped to withstand an incident once a month; however, the community needs to prepare for repetitive incidents at frequencies of once or twice a week.
Amount of dust deposited	Dust deposition has an inverse relationship with distance of the dust source and is one of the major factors for determining the level of complaint.
Affected area of deposition	If the emissions upsurge, then there is a probability for larger area therefore will increase the probability of complaint.

by Coulomb force[22]. Electric field distribution and dust particles charge acquired during removal play an important role during the cleaning process and evaluation of electrostatic performance.

Standing wave: The electric curtains contain a series of parallel electrodes planted in a dielectric layer[19]. Providing AC voltage supply along one electrode and grounding the other electrode creates a unidirectional electric field, with amplitude oscillating at the imposed frequency. The charged particle oscillates along with the field line (Figure 1).

Ionized gas below the inception voltage shows intense agitation[23]. This phenomenon in combination with tribo-charging[13] is used for removing dust from SPV surface by providing voltage supply (called dielectric barrier discharge voltage) less than the agitation voltage.

Multiphase electric curtain: Similar to the standing wave, to generate travelling nature of the wave at a direction normal to the electrode axes, three-phase supply including phase shifts of $2\pi/3$ and $4\pi/3$ has been provided to electrodes (non-uniform electric field distribution). Two types of force components act over the charged particles[24], which include an outward component along O_z (normal to the plain of the curtain) and a component along O_x (parallel to the plain of the curtain and normal to the axis of the electrodes). The resulting force (called dielectrophoretic (DEP) force[25,26]) is relative to the particle charge, field, field gradient and frequency and help for lift to the charged particle to sweep of the field (Figure 2). Above mentioned technique of multiphase electric curtain is been used by Masuda *et al.*[24] developed a layer of electric curtain which prevents the charged particles from reaching the SPV surface, and further lifting and transporting the charged particles.

The above-mentioned clearing of SPV surface using electrostatic biasing shows the following unique characteristics: (a) expulsion of dust is proportional to the applied voltage; (b) dust expulsion performance decreases with respect to applied pressure on the surface and (c) cleaning efficiency decreases with relative increase in humidity.

For removing dust from SPV surface under Martian environment, generally voltage in the range of 10 kV and frequency range 10–100 Hz are required[13]. Mazumder *et al.*[27] and Bock *et al.*[28] used electrodynamic screens to patent technology for the Mars Rover. Biryukov *et al.*[29] further developed the electrostatic biasing approach, including dielectrophoretic prototype device to attain a dust removal efficiency of 90%. Clark *et al.*[30] explored an electrostatic tool called 'SPARCLE' to deal with lunar dust, where an electron beam has been used to control the electrostatic potential.

Electrostatic repulsion (ER) techniques are innovative; however, cost competitiveness is still a key issue for their feasibility and commercialization.

Autonomous cleaning techniques

There are a few techniques accessible in industrial grade that could be utilized in real time through robots for cleaning, where the existing solutions are subject to geographical terrain, application area, cost of device, sophistication and performance ratio. On the basis of cost, ease of utilization, performance rate, water consumption, etc., robotic solutions have emerged as an attractive option for SPV surface cleaning.

Solar panel cleaning robot is a two-body structure for SPV module cleaning[31]. It comprises a mobile robot which carries the cleaning payload and cleaning head, which actually does the cleaning work. The cleaning head undergoes horizontal motion with the help of motorized trolleys at the edges of panels, while the belt-driven system attached directly with the cleaning head undergoes vertical motion. Cleaning head comprises rotating anti-scratch cylindrical brushes to scrub the SPV surface and a scraper to remove the dirt solution (Figure 3).

Moreover, robotic cleaning mechanisms such as 'Gekko Solar'[32] and 'Gekko Solar Farm'[33] (Serbot Swiss Innovations) developed for mobile deployment onto SPV (Figure 4) have shown good potential. The robot works through a revolving brush using demineralized water. Vaccum cup-based feet are used for its movement over the SPV panel, which in turn revolves on two

Table 2. Summary of selected reports of dust effects on solar photovoltaic device performances[10,11]

Location	Type of solar device	Period of study	Observations	Reference
Boston, MA, USA	Solar–thermal collectors	3 months	Maximum degradation during the test period is 4.7%. A correction factor of 0.99 (for a 45″ tilt angle).	10
New York, USA	Glass samples	3 months	At tilt angles between 0″ and 50″, the reduction in solar radiation due to dirt is 5%.	79
Cleveland, OH, USA	PV modules	1 year	Degradation is site-dependent. Washing does not eliminate all degradation, permanent loss in maximum power reaches a steady value after several hundred days. Local condition is most damaging.	80
California and south-western USA	PV system (grid-connected)	1 year	'Soiling' study for utility-connected PV system. Efficiency and energy losses (typical 0.2% per day without rainfall).	81
Lexington, MA, USA	PV module (glass)	18 months	Measurement of soil accumulation and model cleaning using gloss meter.	82, 83
Oregon, USA	Solar module array (glass)	6 years	Unwashed solar cell array degrades at the rate about 1.4% per year. Fluctuations in degradation (rates) do exist and long-term testing of degradation is needed.	84
Saudi Arabia	Solar collectors	25 days	Heat-collection reduction of 30% after three days without wiping.	85
Saudi Arabia	Concentrated photovoltaic	1 month	Open-circuit voltage does not change, and short-circuit current and cell efficiency show a large change with dust deposition.	86, 87
Saudi Arabia	PV modules (glass)	6 months	33.5% and 65.8% reductions in efficiency after one and six months respectively.	88
Saudi Arabia	Solar collectors and PV modules (glass)	6 months	26% and 40% reduction of efficiency from solar collector and PV panels respectively.	89
Riyadh, Saudi Arabia	PV module (glass)	1 year	Efficiency decreases by 5.73–19.8% depending on the type of module, when presented to the outside environment. Compared Module specifications are compared with the manufacturer's claims (differences). Hot, arid conditions.	90
Saudi Arabia	Solar collectors and PV modules (glass)	1 year	7% reduction per month for PV panels and 2.8–7% for solar collectors.	91
Kuwait	PV modules (glass)	6 days	17% reduction in the efficiency of modules.	92
Laboratory tests and Kuwait	Solar cells (large-area)	10 days	Current losses of greater than 13% and voltage losses of greater than 0.86% (5–15% loss in peak power).	93
Helwan, Cairo, Egypt	PV cells and glass	7 months	Decrease in PV output of about 17.4%/month. Provides information as a function of tilt angle.	94
Israel	PV modules (glass)	Laboratory work	Fine dust deposition on the cell has significant effect on power output. Considered effects of due to air-borne dust concentration and wind velocity. Reported losses in solar intensity on cells, open-circuit voltage, fill factor, short-circuit current and power as a function of accumulation time. Power losses greater than 95%.	11
India	PV modules (glass)	Laboratory work	Loss of power due to accumulation of dust and increase in temperature of the panel can be significant.	95

(*Contd*)

Table 2. (*Contd*)

Location	Type of solar device	Period of study	Observations	Reference
India	PV modules (glass)	1 year	Reduction in current value due to dust is up to 30%.	96
Malaysia	PV modules	Laboratory experiment	18% reduction in peak power when depositing dust on PV module. 6% power reduction difference between mud and talcum deposition.	97
China	PV modules (glass)		Dust deposition layer 0–22 g/cm^2; PV efficiency decreases by 26% (linear relationship). No difference between cell types.	98
Ghana	PV system (glass)	4 years	Effect of dust particles in the atmosphere generally lessens the solar irradiance and vitality yield from the PV array. Time of day data reported. Cleaning by wiping of module surface.	99
Nigeria	Silicon solar cells	4 months	Poor efficiency due to scattering of incoming radiation by dust particles.	100
Tokyo, Japan	PV modules (glass)	Laboratory experiment	Varying the aspect ratio of PV cells used for PV modules results in depletion in energy yield of 80% or less with 3% of spot dirt on the module area.	101
Spain	PV modules (glass)	1 year	During dry season, energy losses exceed 20% over a three-month period. Annual average loss in PV output is 4.4% (with natural cleaning by rainfall). Proposed regular, periodic cleaning scheduled for modules. A simple model has been provided stimulated with ray-tracing methods to explain the behaviour of dust-induced loss in solar PV modules. Both fixed and tracking systems of PV panels have been considered. Time-of-day losses have been evaluated.	102
Italy	PV system (1 MW)		Two 1-MW PV systems have been investigated. Soil type and washing technique control the losses. There is 6.9% loss with sandy soil and 1.1% with more compact soil.	103
Libya	PV modules	Outdoor testing	PV modules exposed for a period from February through May in Sahara environment. Reported significant though gradual reduction in power. Weekly washing (water) kept power losses in the 2–5% range.	104

Table 3. Proposed cleaning techniques for different weather conditions

Weather/area	Cleaning technique applied
Desert	Vibrating the surface and aerodynamic streamlining[40,104–107].
Dry	Electrostatic biasing[105], autonomous/robotic cleaning[107,108], sprinkler[105,109,110]
Rainy, humid	Special techniques are not required, but can be combined with anti-reflective coating[67,111,112].
Cold, moist	Autonomous/robotic cleaning[108], sprinkler[113] and anti-reflective coating[67,111,112].
Snow	Stowing/ inverting[76,78], anti-reflective coating[67,111].
Hot, arid, sunny	Electrostatic biasing[29,76,114], autonomous/robotic cleaning[107], sprinkler.
Cloudy, shaded	Autonomous/robotic cleaning[107,108], sprinkler[115], aerodynamic streamlining.

trapezoid-formed geared belt drives, providing the robot good flexibility in any desired direction. It can likewise be radio-controlled with a joystick for bigger applications.

Solar panel cleaning robot from WashPanel[34] is completely autonomous, with double programmable operation through a rain sensor using water, whereas jets help in providing a steady and uniform cleaning. This framework is isolated, with conceivable supervision and administration from remote site and does not require any additional frame, support and added guides. It can be introduced on ground systems, buildings, peaked roof or shed roof. A text message sent from mobile phones, can permit command control from remote sites (Figure 5).

Heliostats Cleaning Team Oriented Robot (HECTOR) for heliostats can be used for SPV cleaning (Figure 6)[35].

It is a self-sufficient mobile SPV cleaning robot, which contains a cleaning solution tank. It is fused with sensors to work autonomously and navigates on its own over the SPV panel surface. Due to its autonomous nature, it does not require external power supply and has been made wireless and rechargeable. HECTOR is intended for night and day operations. Its execution is moderate and the weight of HECTOR is over the surface of panel. 'Solar brush' is also a robotic cleaning system for SPV panels, which moves over the panels up to a slant of 35° (Figure 7)[36]. Solar brush is compact in size, wireless, and rechargeable with light weight (2.5 kg), which makes it apt for SPV cleaning; however, its performance rate is

Table 4. Proposed cleaning techniques for different power generation capacities[107]

Power generation	Cleaning technique proposed
Up to 1 kW	Human labour
1–10 kW	Water sprinkler
10–100 kW	Autonomous technique
More than 100 kW	Hybrid technique (coating + autonomous technique)

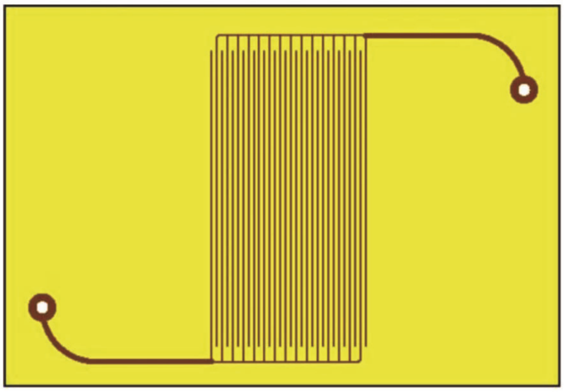

Figure 1. Single-phase electric curtain to create standing waves[19].

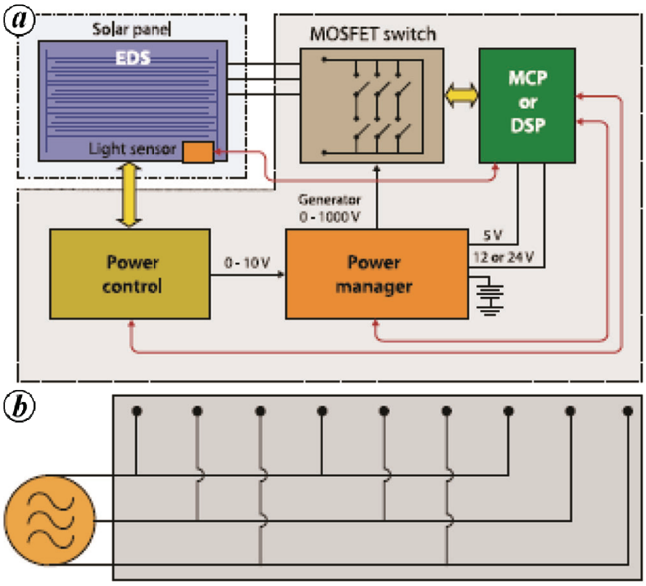

Figure 2. Electrodynamic screen with SPV array system: ***a***, Block diagram. ***b***, Three-phase electrode configuration[28].

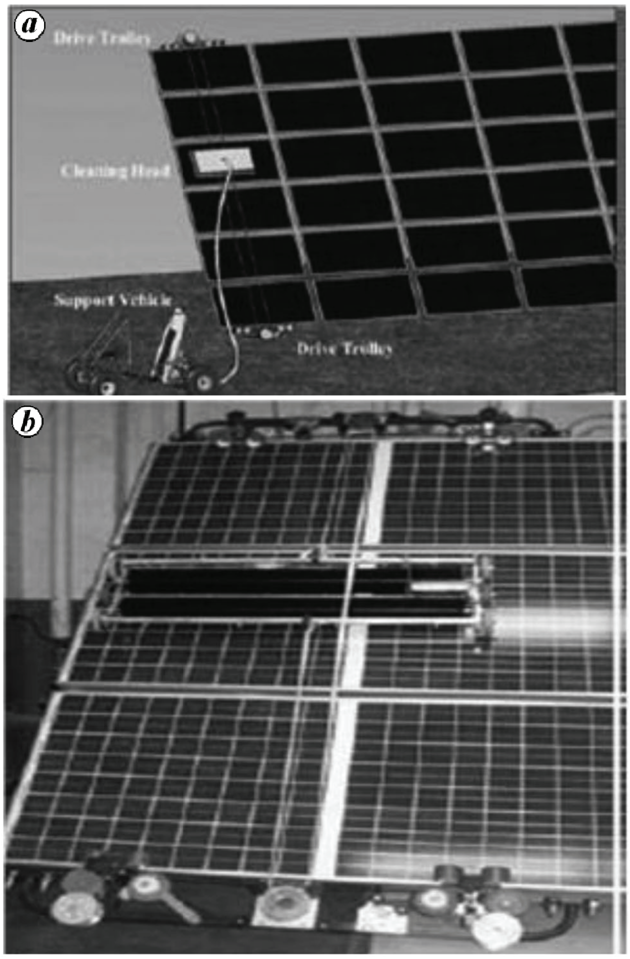

Figure 3. ***a***, Simulated operation of SPV cleaner[31]. ***b***, Cleaning of solar photovoltaic module using PV cleaner[31].

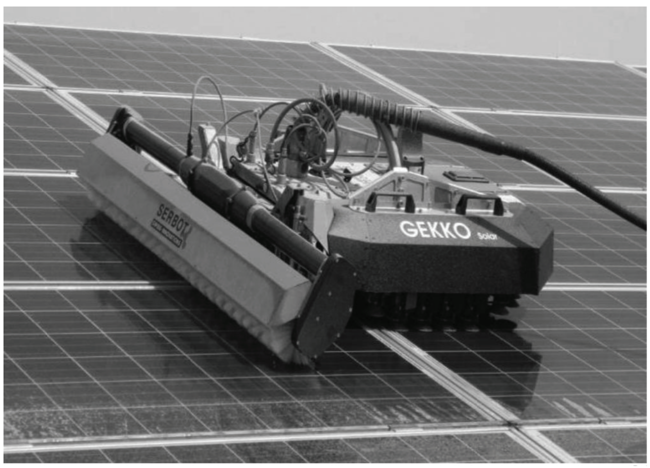

Figure 4. Gekko Solar for cleaning of SPV module[32].

very slow. 'GB1' from Greenbotics (now SunPower) is another robotic cleaning system for SPV panels (Figure 8)[37]. It involves rotating cleaning brushes normal to the axis of the panel and a wiper arrangement, useful for cleaning the panel as well as parallel cleaning of grimy water. It is therefore effective for all types of dust and bird droppings. Likewise, effective for single-axis tracking of SPV panels, GB1 moves at the edges of the frame of the panels (Figure 8). This is an added benefit as the direct weight of the set-up does not exceed that of the SPV panel.

Demo-based studies have been conducted, where PIC[38] microcontroller and PLC[39] were used for controlling the cleaning process (Figures 9 and 10). These set-ups use sensor data as input for navigation of cleaning head

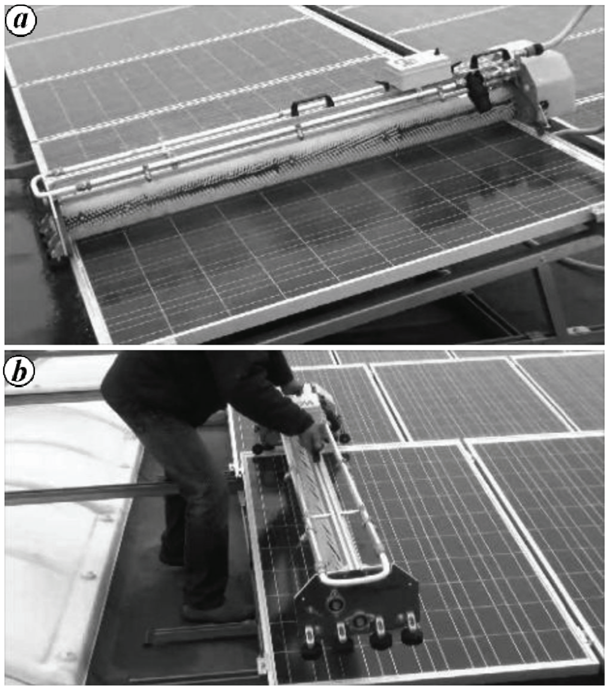

Figure 5. ***a***, WashPanel cleaning over SPV[34]. ***b***, Placement of wash panel over SPV module[34].

Figure 6. HECTOR robot cleaning SPV module[35].

Figure 7. Solar brush cleaning SPV module[36].

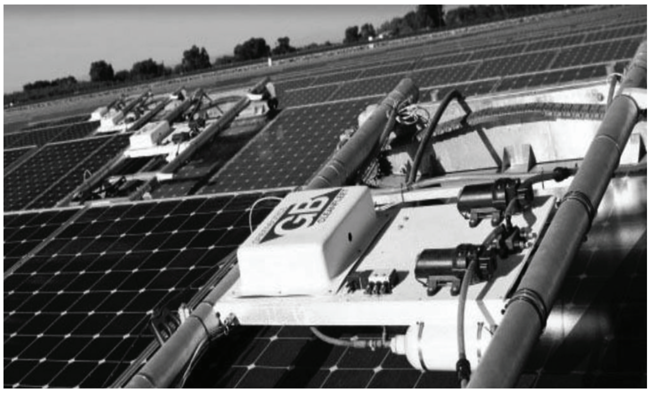

Figure 8. SPV cleaning robot from Greenbotics[37].

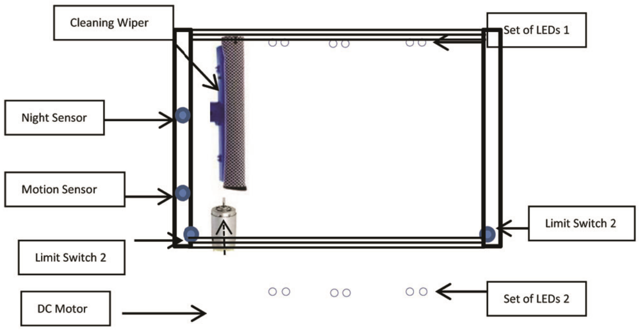

Figure 9. Mechanical design for cleaning SPV using PIC microcontroller[38].

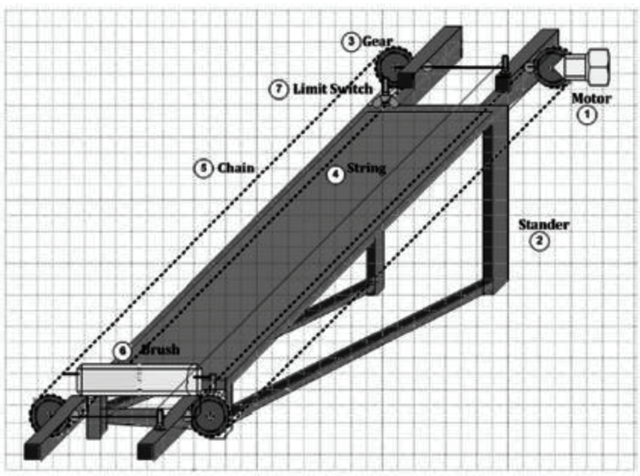

Figure 10. Mechanical design for cleaning SPV using PLC[39].

Table 5. Various types of cleaning systems[107]

Cleaning system	Advantages	Challenges
Heliotex's 'automatic solar panel cleaning system'[116]	Water spreads to every part of the SPV modules. Aids in the cooling of SPV module, which enhances the efficiency.	Treated water required. Filter has to be changed periodically. Huge wastage of water.
Gekko Solar[32]	Self-regulating and flexible, uninterrupted cleaning process.	Limitation of angle of tilt of SPV modules up to 45°. Added stresses on the surface due to gear, belt and vacuum arrangement.
Gekko Solar Farm[117]	Self-regulating and flexible, uninterrupted cleaning process.	Limitation of angle of tilt of SPV modules up to 30°. Complex gear, belt arrangement.
Solar brush[118]	Automated robot Works up to an angle of tilt of 35° It is rechargeable and wirelessly controlled.	Heavy weight. Initial investment cost is high. Requires human intervention. Very slow performance speed.
PIC microcontroller[38] and PLC-based cleaning[39]	Self-regulating and flexible. Continuous cleaning operations.	Complex chain, sprocket-based structure. Single SPV panel-based design.
HECTOR[35]	Compatible, integrated with all supplies. Operational day and night.	Slow performance. Regular feeding needs to be done.
Solar panel cleaning robot[31]	Both washing and wiping processes are present.	Chances of skid due to horizontal shifting of the robot over the SPV module. Causes stress on the surface of SPV module due to its own weight.
WashPanel's solar panel cleaning robot[119]	Able to clean dust and bird droppings.	Human intervention is required to start the operation and while shifting from one row to another.
Sunpower-Greenbotic's GB1 118 (ref. 120)	Able to clean dust and bird droppings.	Human intervention is required to start the operation and while shifting from one row to another.

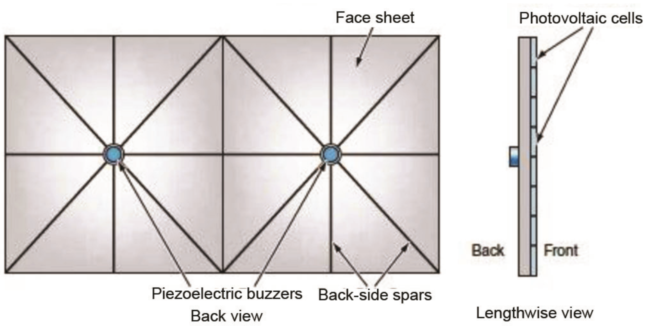

Figure 11. Placement of piezoelectric actuators at the back side of SPC panels (back view and lengthwise view)[40].

over the SPV surface. The difference lies in the driving and controlling mechanism. While the PIC-based system uses direct motor coupling with the cleaning head for motion, PLC uses a chain belt-driven system. Table 5 provides a summary of the cleaning techniques.

Surface vibrating

Tilted SPV panels are vibrated to loosen the accumulated dust on the surface[40]. Piezoelectric actuators are used to create this vibration by placing the cross-sections of structural spars (say nodes), connected to the back of SPV panels (Figure 11). Computational simulations by finite element method were used to optimize the exciting vibrations required for the SPV panel. Williams *et al.*[41] found that excitations up to 5000 Hz gave best response for dust removal as the travelling waves of the dust get excited. Additionally, they remove dust and restore power by 95% of the power-generating capacity.

Washing

Washing of SPV panels is traditionally known for effective cleaning using centralized cleaning facilities. For optimizing the performance, it is better to clean the panels early in the morning and using pressure-induced demineralized water[42,43]. As the SPV surface is wet due to dew, it can be rinsed easily. Meanwhile, when SPV panel temperature becomes high (mid-noon), it requires more water and human effort to get the desired result.

The main prohibitive factors in this cleaning method are high volume of water consumption for each cleaning cycle, transportation of desalinized water to the solar plant and labour cost. However, using environment-friendly chemical agents[42,44] (passive surface treatments such as (super)hydrophobic, (super)hydrophilic and anti-soiling coatings[45–49]), human effort and of water consumption could be reduced.

Although availability of water is a major concern to implement this method at an industrial scale, washing solutions should possess the following attributes: non-toxic and biodegradable and easily mixable, handy and able to reduce surface tension.

Automatic solar panel cleaning system

Heliotex's automatic solar panel cleaning system automatically washes and rinses the SPV panels[50]. It attaches nozzles to SPV panels (Figure 12), along with a reservoir for concentrated cleanser. There is a silt channel containing water softner media. This system has an additional anti-siphon valve to prevent backwashing step, which comprises a controller for automatic wash and rinse cycles. The controller programming can be changed to suit seasonal needs. Such systems are beneficial for areas with limited manpower. Literature survey and laboratory tests show that high-pressure water sprays in the range 500–10,000 psi can recover 95% of the original reflectance[42,43,51].

Prevention technique

Prevention of dust deposition may help avoid the use of cleaning systems in SPV panels. This will help reduce the overall cost of energy production. The strategies to achieve this are discussed below.

Surface modifications

Figure 13 shows the various types of SPV panel materials. To minimize the shortcomings of each material, specific surface modifications have been applied. Surface recombination can significantly affect both the short-circuit current and open-circuit voltage, where high recombination rates at the top surface have a particularly harmful effect on short-circuit current. Since the charge generation depends on the light intensity which reaches near the junction and but the defects in the semiconductor mostly occurs at the surface which is a dominant recombination process and may affect SPV properties. Cutting down the high top-surface recombination is normally refined by reducing the amount of dangling silicon bonds at the top surface via passivation. Many electronics industries rely on the usage of thermally created silicon dioxide as well as silicon nitride layers to passivate the surface on account of low surrender states at the interface[52]. Since the passivating layer for silicon solar cells is normally an insulator, any region which has an ohmic metal contact cannot be passivated using silicon dioxide. Rather, under the top contacts the effect of surface recombination can be minimized by extending the doping, especially in situations where a high recombination surface is near the junction. The most reduced recombination option is to maximize doping. However, extreme doping can degrade the diffusion size. Subsequently, the effect on transporter accumulation becomes irrelevant. Presently, TiO_2 nanotube layer based dye sensitized solar cells (DSSCs) are receiving more attention due to the favourable physical, optical and electrical properties of TiO_2. Kang *et al.*[53] focused on developing ZnO coatings onto the TiO_2 nanotube. They observed ~20% improvement in efficiency after ZnO coating, which might be due to suppression of electron loss owing to straight electron flow and hindrance of charge recombination in the TiO_2/electrolyte. Mohamed *et al.*[54] demonstrated the operational efficiency of an organic/ inorganic hybrid SPV cell through interface alteration with organic ligands. Jiang *et al.*[55] also reported the amalgamation and portrayal of CdS–thiophenol (CdS–PHSH) prepared by synthetic route.

This basic, low-cost technique transitions from using dangerous organometallic reagents to a new class of hybrid mixes of conjugated polymer (MEH-PPV)/CdS–PHSH nanoparticles. Similar work was done by others to improve efficiency. Some researchers observed an efficiency of 0.6% with well-allied CdS nanorods/MEH-PPV SPV cells[56]. A higher efficiency of 1.17% has also been demonstrated using multi-armed CdS nanorods/MEH-PPV SPV cells[57,58]. Shin *et al.*[59] studied the impact of thermal annealing of CIGS films in air, sulphur, or selenium climates, and examined the impact of compositional and bond structure changes on the photovoltaic properties of CIGS SPV cells. They found that Cu movement in the CIGS film amid thermal strengthening assumed an essential part in enhancing cell structure and the arrangement deformities in CIGS bulk. Li *et al.*[60] studied the surface alteration procedure to minimize surface recombination and manufacture productive, modern, dark silicon sun-based cells. In order to reduce surface reflectance, Ag-nanoparticles assisted etching was applied to form font surface nanostructures on silicon wafers. Over additional tetramethylammonium hydroxide (TMAH) treatment, the recombination at and close to the surface was stifled, which might be due to a lower surface dopant fixation after the surface change. The altered surface displayed

Figure 12. Heliotex's automatic solar panel cleaning system[50].

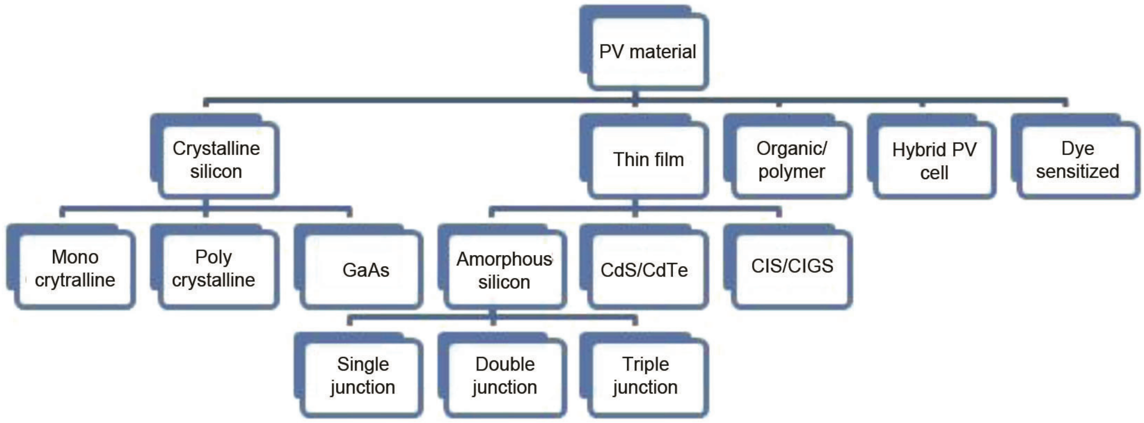

Figure 13. Different types of SPV materials.

low reflectivity in the range 350–1100 nm with an average conversion efficiency of 19.03%, when TMAH treatment was performed for 30 sec. TNAH modified solar cells were 0.18% more efficient compared to black silicon solar cells without TMAH modification. Yang *et al.*[61] utilized 3-phosphonopropionic acid (3-PPA), butylphosphonic acid (BPA) and 3-aminopropylphosphonic acid (APPA) as self-amassed monolayers (SAMs) to alter the surface of ZnO nanorods. The results showed that SAMs not only passivated the surface deformities of ZnO nanorods, but also tuned their surface operation capacity to change the band arrangement of solar-powered cells. Specifically, the 3-PPA change shows the best passivation impact and makes the surface work function of ZnO decreases by 1.04 eV to realize a better band alignment due to its electron-withdrawing tail group, which results in an enhancement in photovoltaic conversion efficiency of solar cells. Tang *et al.*[62] have critically studied the upgradation proficiency of ZnO-nanorods-based natural/inorganic SPV cells with turn covered P3HT: PCBM mix as dynamic layer. The performance of the fabricated device was enhanced by surface adjustment of ZnO with poly[(4,4′-bis(2-ethylhexyl)dithieno[3,2-b:2′,3′-d]silole)-2,6-diyl-alt-(2,1,3-benzothiadiazole)-4,7-diyl] (PSBTBT)[63]. Optimized device of ITO/ZnO nanorod/P3HT: PCBM/Ag device with PSBTBT surface adjustment and air introduction helped achieve an effectiveness of 2.02% with a short circuit current density including open-circuit voltage and fill component of 13.23 mA/cm^2, 0.547 V and 28%, individually, under AM 1.5 illumination of 100 mW/m^2. Compared to unmodified cells, a seven-fold increment in the productivity of the PSBTBT surface altered ITO/ZnO nanorods/P3HT : PCBM/Ag device was observed. Xiang *et al.*[64] altered nanoporous TiO_2 films with $ZrCl_4$/$TiCl_4$ blended arrangements, where a changed layer involving ZrO_2 and TiO_2 was framed onto the surface of TiO_2 photo-electrodes. They also observed an increment in conversion efficiency by 18.67% (from 6.21% to 7.37%), when TiO_2 films were modified with a mixed solution of 0.05 mol l^{-1} $ZrCl_4$ and 0.04 mol l^{-1} $TiCl_4$.

Surface coatings

Surface coatings deal with the glass covering surface of SPV panels and help prevent dust from sticking to the surface. There are several types of surface and helpful coatings available for the panels depending upon the major vulnerability of dust attack and type [65]: (i) hydrophobic type, which has less affinity towards ionic species[66,67], (ii) low surface energy type, which lowers the surface chemical reaction; (iii) chemical type, which reacts with sticky dusts and (iv) oil coatings.

Hydrophobic coatings cause high contact angle between SPV surface and water droplets, making the droplets roll freely over the SPV surface, thus removing the dust. Chemical replacement of group I ion with groups II or III creates water-resistant solution or hydrophilic nature. Hydrophilic solutions are designed to resist dust accumulation and sheeting of water enables an effective cleaning of SPV surface (Figure 14). Various types of coating mixtures are now being explored. However, these are commercially unsuccessful as prolonged exposure to UV radiation causes permanent damage to the coatings[68,] affecting the durability as wind and sand can cause erosion.

Oil coatings like natural oil (sunflower) and mineral oil (vacuum pump oil), engine oil and brake oil are used to coat (>1 mm thick) the exposed surface of SPV panels. In fact, mineral oil coating shows 24% more transmissivity compared to normal glass[69]. Hence the same can be applied over SPV glass mounting with anti-reflection coatings[70].

Tuff Fab[71] is a coating solution which is easy to apply, making the glass surface non-sticky and effortless to clean. Tuff Fab does not require harsh chemicals and scrubbing to clean the SPV panels. Using this approach, clean water or mellow cleanser and an wipe with a soft

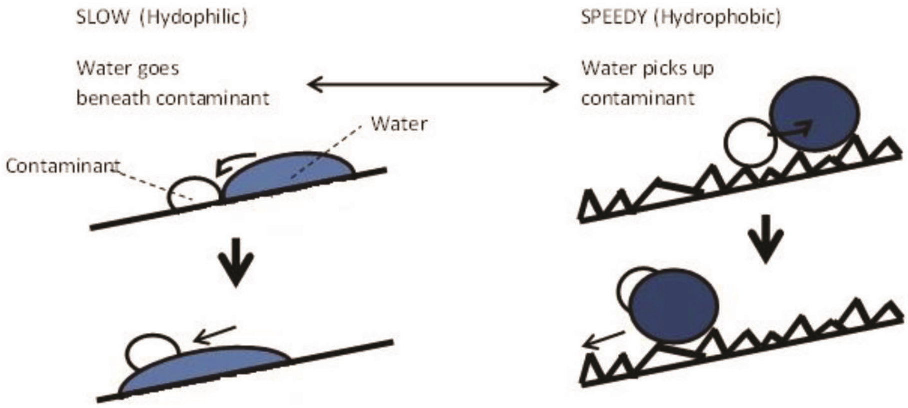

Figure 14. Hydrophilic and hydrophobic surface cleaning processes.

Table 6. Various types of industrial coating systems

Coating system	Advantages	Shortcomings
Tuff Fab's Nano Clear[71]	Long-lasting	Cleaning is required, but with less effort.
Asahi Kasei Corporation's SPV coating[121]	High transmittance capability	Cleaning is required, but with less effort.

towel will clean the SPV panels. Researchers[72,73] have implemented many other products similar to Tuff Fab (Table 6).

Aerodynamic streamlining

This uses air flow (preferable forced air) for removing dust from the SPV surface. In this method, special type of turbidity spoiler is positioned along SPV panels to create turbulent-flow due to an aerodynamic arrangement. This provides rotational and translational motion to impart scrubbing action to the gas flow, which can sweep off dust from the surface[74–77]. Key parameters like velocity, duration, angle of incidence and type of gas play a vital role in forced air cleaning.

Stowing/inverting of SPV

During night and dusty storm condition, tracking-enabled SPV panels can be inverted or stowed to prevent major dust accumulation[76]. Roth and Pettit[78] have shown that panel orientation at 180° (inverted) and 90° can reduce soiling.

Conclusion and future perspective

Cleaning and prevention are two main options to counter the deposition problem in SPV panels. Cleaning can be achieved by various manual processes, but they seem to be energy-intensive and time-consuming efforts. Automatic robotic system has been successfully employed, but the additional maintenance and energy consumption always remain a point of debate for commercial applications. In terms of prevention, coating seems to be a good approach, as it is effective in protecting the surface from harmful deposition. However, transparency of coating material is always a challenge for this approach. Additionally, impact of environment on the stability of coating is area of concern. Also, limited research on measurement and quantification of SPV coating limits the development of a successful system with long-term applications. Furthermore, coating-based research is currently at an experimental level and more studies are required for its effective commercialization. This is a challenging task and demands more precise structural engineering. Undoubtedly, there is need for a new, self-healing coating material with high flexibility, transparency for construction of stable and flexible SPV devices. The coating should also be impervious to oxygen and moisture. Dust deposition on SPV panels limits their efficiency and remains a challenging parameter to improve the performance of the overall system. In general, it may be concluded that dust will be a continuous challenge for SPV panels, particularly in desert areas. Lack of natural cleaning like rainfall and shortage of water resources increase the severity of the problem. Additionally, dew/moisture leads to cementation of dust. Stowing, inverting and vibration techniques could be considered as simple and robust approaches to prevent the build-up of dust. Adequately transparent, durable coating will be required for effective performance, preservation and enhancement of SPV panels. Sensors to detect the critical point for cleaning of surfaces are also required so that simultaneously hot point, partial shading, etc. can also be solved. Depending on the environmental and geographical requirements as well as solar plant capacity, hybrid (mixed) techniques are recommended.

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