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Performance degradation of photovoltaic power system: Review on mitigation methods

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ABSTRACT

Solar photovoltaic (PV) is one of the renewable energy (RE) technologies that offers a fast option for deployment. It is rated according to its maximum DC power output (W_p) which is obtained under Standard Test Condition. However, this is seldom encountered when under actual operating condition where it is sturdily influenced by surrounding climate; hence, it affects performance of the PV module. Soiling is a factor caused by the accumulation of dust and dirt on the PV surface and limiting the penetration of solar energy; hence, reduces the energy output. This paper discusses in details on the types of soiling and presents some mitigation techniques which have been studied and developed. The advantages and disadvantages on the mitigation techniques were also explained. The comparison of each method were simplified and summarized in details into two tables so that they can be a guide in selecting the most appropriate method for soiling mitigation.

Contents

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1. Introduction

The world energy consumption is currently accelerating at 9% from the year 2013 to the year 2014 according to British Petroleum Statistical Review of World Energy in June 2015. Among the factors that contribute to this is the rapid growth in population at the growth rate of 1.5 million people per year [1] and fastest increased of global urbanization. As reported by International Energy Agency (IEA) in World Energy Outlook (WEO) 2014 Edition, 7200 GW of energy capacity is required by 2040 to comply with the increasing energy demand. The increasing usage of energy demands also raises greater concerns on the effect of fossil-fuel towards the environmental pollution. Realising this, independence power producers (IPPs), government and policymakers particularly throughout the world are making efforts to be less dependent on fossil-fuel energy sources by exploiting other sources of energy such as solar, wind, biomass, geothermal and ocean. Also, according to WEO 2014 Edition, these resources will increase their contribution in global power generation to one-third of the total generation which is above 10,000 GW by 2040. Up-to-date photovoltaic (PV) is the third largest power generator (18%) of renewable energy (RE) comparing to wind power (34%) and hydropower (30%). Based on the 'Renewables 2015 Global Status Report', the total global capacity of PV power systems has grown exponentially from 3.7 GW in 2004 to about 177 GW in 2014, and 40 GW was contributed solely at the end of 2014 which is more than 60% accretion.

Recently, PV industries is boosting up, escalate by module production cost reduction, lower regional price levels, and weaker-than-expected demand (especially in China) that cause the average module prices fell, began on 2014. Due to this scenario, many countries are promoting their own solar based power supply by introducing specific policies that favours solar [2] and funding for increasing the energy generation capacity, including technology enhancement.

The PV module performance is generally rated under standard test conditions (STC): irradiance of 1000 W/m^2, solar spectrum of AM 1.5 and module temperature at 25 °C. However, this condition is seldom encountered when exposed under actual operating conditions due to surrounding climate and environment. The two factors which are solar irradiance and temperature play an important role in determining the energy yield from the module. It is found that low irradiation level will result in low output current meanwhile for a high module temperature will reduce the output voltage and vice-versa. For example in the tropical country, the irradiation and temperature levels are irregular. Hence, it will leads into inconsistency of the energy yield. In addition to the two main factors, other pollutants such as dust, grime, pollen, debris, sand, bird dropping and particulate matters also able to settle on the solar panel surface. This will further reduce the energy yield. Besides all the factors mentioned, the settlement might come from the sprout of moss, fungi and lichen which are referred as vegetation [3,4]. The presence of soiling on the module surface prevents solar radiation from impinging directly on the surface [5], hence reduce the reliability that expected from PV, since it depends on sunlight and the surrounding environment. This may leads to the irregularity of energy generation [6]. Thus, to increase the reliability of the system, avoiding system degradation and financial losses, mitigation techniques need to be developed and improved to overcome the soiling affect. Studied done by [7] found that the efficiency of PV systems increased convincingly with the soiling mitigation by regular cleaning.

Studies conducted by [5,8–13] showed that there are significant percentage losses on the energy output from the installed PV systems due to soiling affect. On the other hand, it is also observed that the economic loss from the reduced energy output percentage is higher as have been studied by [10,14]. For example, a study conducted by [10] on the soiling effect for two 1 MW_p rated PV plants which consists of 60 units crystalline modules on each plants, showed that the power losses determined are from 1.1–6.9%. These losses will give great impact to the plant's income. Their observations from the findings are summarized in Table 1 [10]. It showed that plant 2 has a 1.1% output reduction due to soiling with the equivalent loss of €6,600.00 per year. Meanwhile, plant 1 that was also operated by the same company, experienced losses due to soiling 5.8% more than plant 2 at an equivalent loss of €41,400.00 which is 84.06% more than plant 2. In conclusion from the findings, the economic loss from the system yield is much higher compared to the maintenance cost to clean the module.

Over the years, several of mitigation methods have been developed to address the issue of soiling on PV module surface. They were designed and implemented on the real situation to either restore the PV module surface back to its clean condition or reducing the accumulation of dirt on the module. Despite the large number of works written regarding this matter, there are fewer efforts to compile all the available information about soiling mitigation methods into a single article. The information dispersed in various articles and journals will complicate the searching. Besides, the researches on soiling mitigation methods are performed at different geographical condition with different climate, weather, pollution, traffic and economic activity. Therefore, the soiling rate and atmospheric condition for each region is different and hence, the proposed soiling mitigation methods are developed based on the specific region. This situation will create the difficulty in understanding, comparing and evaluating the available soiling mitigation methods. Currently, only two papers have been published on these topics. A review paper by [15] is discussing on the self-cleaning methods including natural cleaning, mechanical cleaning, super hydrophobic surface, super hydrophilic surface and electrodynamics screen (EDS) but it was discussed briefly and no comparison between the methods were performed. Meanwhile, researcher in [15] is compiling and investigating the impact of dust for the application in solar energy without focusing in the soiling mitigation approaches.

This paper discusses in depth the types of soiling and compiles in details the advantages and disadvantages of different (or various) mitigation methods. Besides, it also highlights the differences in rating of mitigation methods studied and simplified them for easy understanding. Hence, with the growing interest on the subject discussed and also in order to improve the PV system performance that leads to increase energy output, this paper compiles detail information on the types of soiling, properties and factors affecting the dust settlement, up-to-date mitigation techniques as an aid to the researchers in the same field. Finally, a proposed suitable technique in enhancing the energy output from the installed PV system is introduced.

2. Dust properties and factors

Dust settlement is the regular cause of soiling. Mekhilef et al.

Nomenclature

MW_p	Mega Watt Peak, unit for plant maximum rating capacity according to the output power
€	Currency symbol for Euro
µ	Prefix used to represent the measurement in micro (10^{-9})
g/m^2	gram per square meter, a unit regularly used by researchers to indicate the dust density as the dust mass per area of the PV module
NIL	Nothing
W_p	Unit used to measure maximum electrical power
m^3	Symbol to represent cubic meter, a unit used for volume measurement
g/ℓ	Gram per litre, unit used to for chemical surfactant concentration in water
T_{cell}	Module's temperature
T_{amb}	Ambient average maximum temperature during PV module's operation
G_{amb}	Average maximum irradiance measured in Watt per square meter (Wm^{-2}) at T_{amb}.
NOCT	Normal operating condition temperature for PV module
T_{cell_NOCT}	PV module's temperature in normal operating condition and it depends on the type of PV modules. The value is usually provided by the manufacturers in the module specification datasheet
δx	The variation of parameter x
x	A parameter can be used to represent V_{oc}, I_{sc}, V_{mp}, I_{mp} or P_{mp}
V_{oc}	PV module's open circuit voltage
I_{sc}	PV module's short circuit current
V_{mp}	PV module's maximum module output voltage
P_{mp}	PV module's maximum module output power
γ_x	Temperature coefficient of x (% per temperature change)
T_{stc}	PV module's operating temperature at STC
PLC	Programmable Logic Control
PIC	Peripheral Interface Controller.
AC	Alternating Current
MOSFET	Metal oxide semiconductor field effect transistor
Wh/m^2	Watt hour per square meter, a unit to quantify the energy used to clean the area of PV module's surface
θ	Symbol to represent the contact angle of water droplet to a surface, measured in degree (°) or radius (radians)
cosθ	Cosinus of θ in mathematical trigonometry theory
Y_{sv}	Solid-gas interfacial free energy
Y_{sl}	Solid-liquid interfacial free energy
Y_{lv}	Liquid-gas interfacial free energy
θ_1, θ_2, θ_3	water contact angle of water droplets (as in Fig. 13 only)
θ_4, θ_5,	Ultra-violet
UV	Ultra-violet
MPP	Maximum Power Point
µC	Symbol used to represent micro-controller term.

identified that besides humidity and air velocity, dust is one of the natural factors that affect the PV systems performance [16]. Another studied by [12], considered dust as an environmental stimulus, third importance factors after irradiance and air temperature, which give a significant impact on the PV systems performance. According to Mani and Pillai, dust is a term generally applied to solid particles with diameter less than 500 µm [17]. They summarized the factors influencing dust settlement on PV modules in a framework as in the Fig. 1.

2.1. Dust property

Dust can be characterized by its chemical, biological, electrostatic and physical properties. The latter is related to its size, shape and weight. Different property of dust will have difference condition of dust settlement. As example, finer dust particle (diameter less than 1 µm) tend to settle more than the coarser dust (diameter more than 5 µm) [18]. Besides, it may also come in the different electrostatic property whether it is neutral, positively charged or negatively charged [19,20]. The charged particles tend to accumulate more than the neutral particles due to the coalescence between the differently charged particles. This is known as physics Coulomb force [21]. Rationally, positively charged dust particle will attract to the negatively charged particle while the particles with the same electrostatic property will repel again each other's. Apart from that, dust consist variety of chemical composition as reviewed by [15]. The dust chemical or mineralogy composition will be different from one location to another depending on the surrounding environment [15,22]. Elminir et al. by

Table 1
PV Plants income and expenditure due to soiling loss [10].

	Plant # 1	Plant # 2
Cash inflow (€/year)	600,000.00	600,000.00
Losses due to pollution (%)	6.9	1.1
Money lost because of the pollution (€/year)	41,400.00	6600.00
Washing cost (€)	2500.00	2500.00
Average hidden washing cost (€)	1644.00	1644.00
Total washing cost (€)	4144.00	4144.00

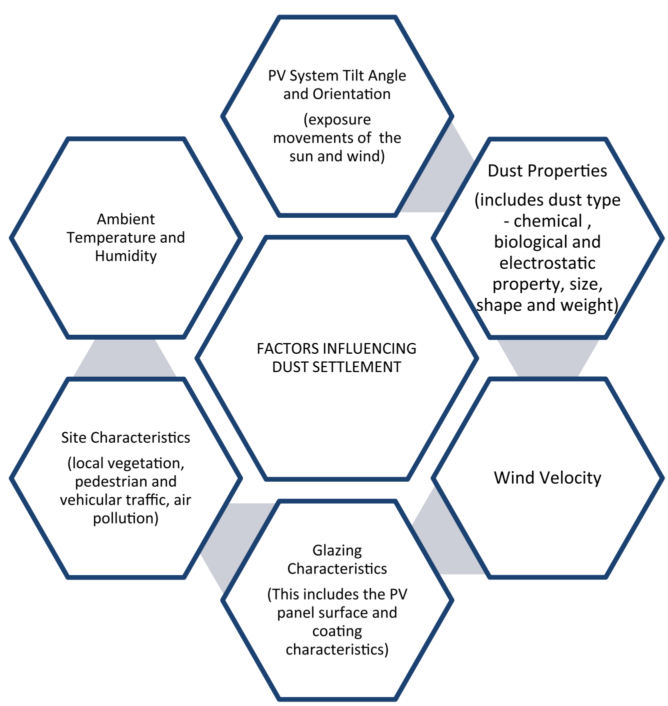

Fig. 1. Factors influencing dust settlement [17].

using X-ray diffraction (XRD) method in identifying the chemical composition of the dust sample collected in Cairo, Egypt found that majority consist of quartz and calcite, with smaller amounts of dolomite and clay minerals [22]. Krueger et al. used scanning electron microscopy techniques (SEM) found that high concentration of calcium from the mineral dust collected from China and Saudi Arabia [23], whereas Wake et al. indicated very high levels of Calcite, Sulphate and Chloride in the tropospheric aerosol from the north-eastern region of the Tibetan plateau [24]. Fujiwara et al. discovered the presence of Ferum, Aluminium, Calcium and Magnesium in their collected dust sample which were obtained nearby the automotive industry area [25]. Meanwhile, Cabanillas and Munguia indicate the organic composition such as clay, sand, soot, fungi, spores and plant fibres in their collected dust [26].

2.2. Wind velocity

Wind is the transporting agent of dust. Airborne dusts get carry by wind from various locations depending on the wind direction and settle down at any surface in the end. Influence of wind on the dust settlement rate can be different from location to location. It depends on the concentration of airborne particle carried by wind and its velocity. Wind that carry high concentration of airborne dust, the dust settlement rate will be higher compared to the one which have low airborne dust concentration. On top of that, higher wind velocity will result in higher soiling rate than the lower speed wind [27]. The influence of wind speed over dust settlement is best described at the PV system installed in the desert area where the soiling problems are much serious.

2.3. Surface property

The property of a PV module surface also plays an important role in influencing the dust settlement rate. These include the surface apparent texture and additional coating on it. Not only that, even the different surface material can have a different surface property. Kalogirou et al. indicated that a protective layer above the PV module surface which is fabricated from glass is less affected by soiling, compared to the layer made from tedlar [9]. In addition, for different surface texture will result in difference surface property such as the surface which was coated with the super hydrophobic [28] or hydrophilic [29]. It indicates that these coated surfaces are less accumulated by dust compared to the uncoated surface.

2.4. Tilt angle and orientation

Despite of wind influence, another factor that relates to the dust settlement rate is the module tilt angle (inclination) and orientation. As indicated by Cano et al., the presence of dust has no significant relationship with the degree of tilt angle and orientation, where the surrounding environment is the main factor that influence of the dust settlement rate [30]. However, dusts are more favourable to settle on the horizontal surface rather than tilted surface because of gravitational force. As explained by [31], some of the larger dust particles will roll from the upper parts to the lower parts of the tilted module due to the gravitational force. Hence, the influence of gravitational force to dust settlement increases as the incremental of tilt angle. Also, the module orientation is important to consider in determining the dust settlement rate. In this case, module that facing the wind directly will get the most of wind influence in dust settlement compared to the module which is less exposed to the wind as have been discussed in [17,27,32].

2.5. Ambient temperature and humidity

Mekhilef et al. indicated that dust, humidity and wind are commonly dependence on solar irradiation and surrounding environment [16]. For example, at high ambient temperature and low RH like the condition of the arid climate, dust can easily be transported by wind. In addition, during dawn the relative humidity (RH) is getting higher, hence, the concentration of water vapour in the ambience will amplify. In this condition where the temperature is low, water vapour will condensate to form water droplets on surface. This leads to the surface becoming more adhesive [33] and attracts more dust from airborne [34].

All of the above factors discussed are known to influence the dust settlement rate. Actually, dust settlement is a complicated phenomenon, which influenced by site's specific environmental condition. The above factors and their effects on dust accumulation rate can be different from one site to another. Studied by [30] showed that the site characteristic mainly determine the dust settlement rate in the specific area in concurrence with the site activity such as air pollution, nearby industry, transportation facility, nature act (volcanic eruption, haze from forest burning, sandstorm, etc.). In addition to that, wind can be added up as one of the most important factors that contribute to the quantity of soiling settlement apart from ambient temperature and RH. Studied by [35–39] showed that, wind is the main transporting agent of dust such as particulate matters (airborne dust) that presence in the air before it settle down.

3. Degradation of performance

Several studies on the impact of dust have highlighted the significance of losses in the PV system energy generation. Jiang et al. investigated the correlation between PV system efficiency degradation and dust accumulation for different types of PV module in the laboratory. They found that when the dust deposition density increased from 0 to 22 g/m^2, there is a reduction of PV output efficiency from 0% to 26% [40]. Hence, it can be concluded that there is correlation between these two parameters. Zorrilla-Casanova et al. of Spain, attempted to quantify losses caused by the accumulation of dust on the surface of photovoltaic modules. They identified that the mean daily energy loss within a year caused by dusty PV module was around 4.4% and could be more severe in long dry season without rain, where it can rise up to more than 20% [8]. Adinoyi and Said in Dhahran, Saudi Arabia, discovered more than 50% power output is reduced for their installed PV systems after six month been exposed without prior cleaning [11]. Studied conducted by [9] at the urban coastal area of Cyprus indicated the significant reduction of 43% for the installed PV system performance due to airborne pollutants and dust. Although it was claimed that with heavy rain (acts as nature's cleaning agent) will reduce the dust accumulation but unfortunately it adds more adhesive affect which makes it difficult to clean. Apart from these, most of the studies raise concern on the soiling impact on PV system's performance. All of them highlight the performance loss due to soiling [3,12,25,26,33,41–44], however, the impacts were experienced relatively vary from site to site.

There have been a lot of researches on the impact of obscuring elements on solar PV modules but there is no similar study done in hot and humid tropical countries. In addition, the phenomenon of moss growth on the PV modules has not yet been studied [45]. Sulaiman et al. investigated dirt accumulation in the tropical climate where both soiling and vegetation problems are found. An indoor experimental was conducted by using a clean panel and a panel covered with talcum, dust, sand, moss and water droplet (by spraying water evenly on to the module surface) irradiated by

Table 2
Result of PV system performance degradation (Sulaiman et al., 2014) [45].

Type of dirt	Power output degradation	
	Radiation at 310 W/m^2	Radiation at 250 W/m^2
Talcum	9–31%	25–31%
Dust	60–70%	65–74%
Sand	70–80%	
Water droplet	NIL(water is easily evaporated)	0.5–4.3%
Moss	77–83%	15–86%

spotlights to study the degradation cause by different type of dirt accumulation. The finding is tabulated in Table 2 where it indicates that the output power of the solar panel reduced significantly with the presence of dust, sand and majority when the presence of vegetation (moss). It was concluded that particles like dust and sand can be reduced naturally (by rain), except for moss which requires a proper cleaning.

Apart from the above, system cost-effectiveness is another important issue to consider prior the installation of PV system and three factors that have to be fulfilled according to [46] are listed below:

i. minimizing system cost
ii. maximizing initial performance, and
iii. minimizing loss of performance over time.

In conclusion, dirt and soiling accumulation on the PV panel surface can cause significant impact on the PV systems performance which later leads to its efficiency, reliability and cost of deployment. Hence, this concern leads to the development of various methods for soiling and dust mitigation. They are discussed in the next section.

4. The mitigation methods

The awareness to keep the PV panel clean has resulted in the development of various methods for soiling and dust mitigation. The classification of soiling mitigation methods is shown in Fig. 2. The cleaning methods can be categorized into two; one is by manual cleaning which is done through labour, and secondly is the self-cleaning by integrating a cleaning feature to the PV system. Self-cleaning methods in this article are further classified into two categories. The first category is to let the panel static so that it can be cleaned by rainfall, which is also known as natural cleaning. However, due to the shortcoming of natural cleaning, another two methods were developed which are by altering the morphology of PV module surface for more improvement by introducing the super hydrophobic surface and super hydrophilic surface. The second category in self-cleaning methods is active restoration methods by using water cleaning, mechanical cleaning and electrodynamics screen.

4.1. Manual cleaning by labour

This is the traditional way of cleaning dirt settlement on the PV panel surface. The method is efficient if arranged in a proper schedule [47], as it enables removal of even hard soiling like bird droppings or cemented dust from the PV panel efficiently by manpower. However, there are two disadvantages for this method. First, the labour cost for cleaning may be quite expensive especially for large scale PV plants [48,49]. Also, there are several aspects of labour that need to be considered, such as salary, occupational safety and health matters, welfare and even government

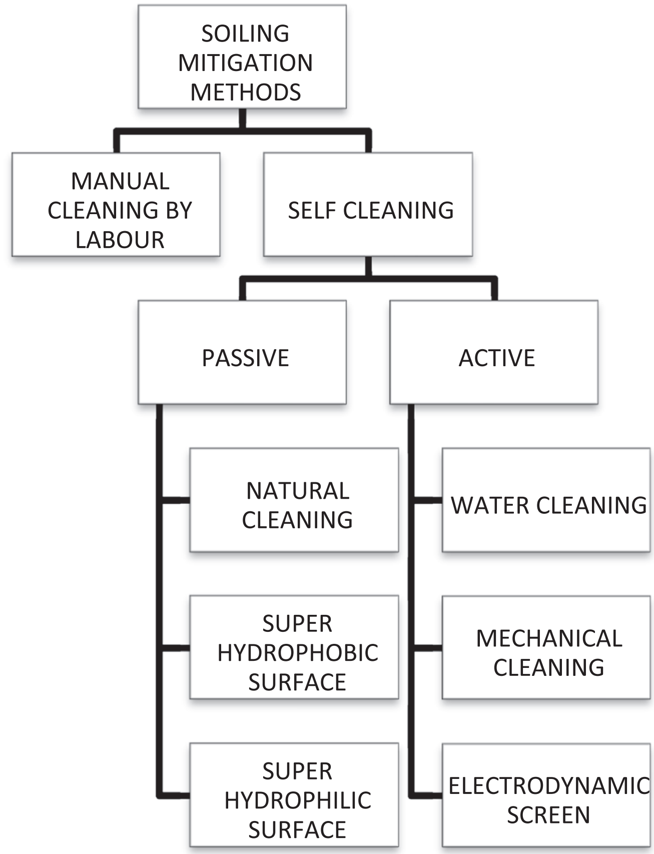

Fig. 2. Classification of soiling mitigation methods.

related issues on labour requirement [49]. Not only that, there is still expenditure such as water, tools (including cleaning and maintenance tool) and detergent used for cleaning purposes to consider because manual cleaning also have various methods similar to the self-mechanical cleaning systems. Nevertheless, labour type of cleaning method that used tools or other cleaning equipment might expose the PV panel surface to the abrasive damage or crack if the handling is not done properly. Secondly, this method may not be suitable as the PV modules are often at elevated heights or offshore dangers.

4.2. Self cleaning methods

Self-cleaning methods are developed to solve labour cost and the unreachable area of cleaning which cannot be obtained through labour. By applying the automation auxiliary system for cleaning as an additional feature for the system, the usage of labour can be replaced or reduced. A variety of self-cleaning methods have been developed for dust and soiling mitigation. Other than natural cleaning method by rainfall, the water cleaning system, mechanical cleaning system, electrodynamics screen and super hydrophobic surface have been developed.

4.2.1. Natural cleaning

Natural cleaning of the PV modules is usually done by rainfall. This cleaning method is suggested for PV locations with sufficient precipitation to do the cleaning. The PV panel needs to be mounted at certain tilt angle accordingly [44,50,51]. The tilt angle must be planned well to obtain not only the cleaning effect by the rainfall but also the best performance of a PV system [52–54]. Using natural cleaning, tilt angle is one of the crucial parameters in this method, because the horizontal surface is hardly possible to be cleaned by the rainfall [43]. Moreover, it is common sense that the higher tilt angle causes dust to fall easily due to the gravitational force [55].

Actually, the result for this type of cleaning method related to PV system efficiency after the cleaning process is not promising and less effective. According to Smith et al., through their observation on the effects of the manual cleaning and natural cleaning by rainfall, they found that the natural cleaning by rainfall was only capable to restore PV power output by 1% of the manually cleaned panel after the reduction of 4% due to the dust settlement [56]. Kalogirou et al. conducted a study in Cyprus reported that with frequent heavy precipitation its able to keep the PV panel clean; however, the rainfall after dust settlement its creates adhesiveness of the panel surface, hence more dust will settle on the surface [9]. Likewise, the light rain only able to partially wash away the dust and accumulate some of it at the lower edge of the PV panels [57]. Appels et al., meanwhile, proved that nature cleaning by rainfall only caters large dust particles, more than 10 μm rather than smaller ones (2–10 μm) [41].

4.2.2. Water cleaning

Water is a common cleaning agent used for dust cleaning. Even though the cleaning effect can be obtained from the rainfall, it cannot be always effective [41] compared to the water cleaning either manually or automatically [58] because during the long period without rain, the modules will get dirty [34,59] and the prolong untreated soiling will be difficult to mitigate as mentioned by [60]. A research conducted by K.A Moharram et al. [19] state that mixture of water with some kind of chemical is used to improve the cleaning efficiency for the hard soiling.

Fig. 3 shows the cleaning experiment set up and conducted at the German University, Cairo, Egypt. The cleaning structures consist of six main parts were installed at the tested PV modules and as listed below:

1. Six PV modules of 185 W_p output each.
2. An aluminium water tank of 0.16 m³ capacity.
3. A water pump of 0.5 horse power.
4. One stage industrial transparent water filter.
5. 120 units of water nozzles for spraying water over the panels.
6. Drain pipe

In this study, the cleaning operation was performed every 10 min daily for 45 consecutive days by a controlled water flow at 12 ℓ/minute. This system was activated in the early morning to avoid water evaporation. The cleaning process as indicated in Fig. 2 is a closed loop system, which began with the pumping up of water from the tank to the filter. From the filter, the water would be flushed through the nozzles onto the panels. Due to the tilted

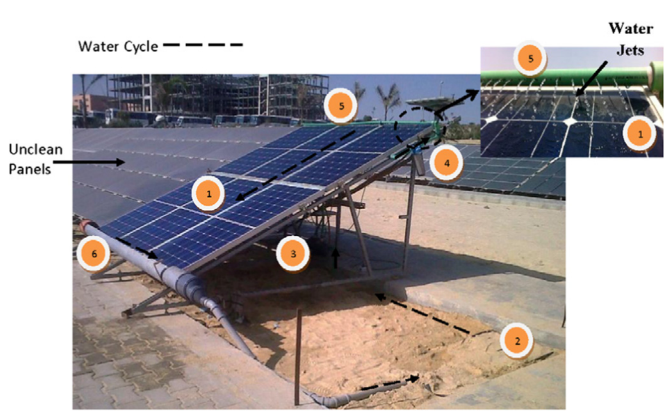

Fig. 3. PV system with non-pressurized water cleaning structure [19].

position, the water is passing through the drain pipe at the bottom of the panel and finally to the tank again.

In the experiment conducted by [19], the PV modules efficiency decreases at 0.14% daily with the accumulation of dust settlement and also when the non-pressurized water without any surfactant addition is used to clean the modules. On the other hand, by using a mixture of two surfactants in 1:1 ratio of Sodium Dodecyl Sulphate, the anionic type and Cetylpyridinum Bromide [61] which is the cationic type at concentration of 1 g/ℓ of water, the result showed that the modules efficiency which was kept constant at 12% during the experiment, giving better result. Additionally, ionic surfactants tend to attract dust particles, which might come into two different forms, negatively charged or positively charged, due to the electrons imbalance. The anionic surfactant would remove the positively charged dust particles that stick on the panels' surface. This ionic reaction cleaning process is much efficient when compared to using water only. On the other hand, Mohamed and Hassan managed to maintain the PV system performance loss due to soiling effect from 2% to 2.5% only by the manually frequent water cleaning [62].

Therefore, from that research, it is agreed that cleaning of PV panels with non-pressurized water and with the support of ionic surfactants is the most practical method applied to the experimental set-up site. Nevertheless, some weaknesses are indicated such as:

i. The water consumption is greater when pressurized method is applied compared to non-pressurized. This is due to the splashing when spraying towards the panel surface and this method is not suitable option if the system is installed in the desert where water is difficult to obtain.
ii. Although the use of surfactants to improve the cleaning efficiency can minimize the water usage is possible but in hot climate, the water evaporation rate can be very high most of the time. This might drain the water supply and increase the concentration of those surfactants. Hence, it may lead to sticking of the surfactants on the panels which caused soiling effect.
iii. Water cleaning able to introduce thermal shock [63–65] incident on the modules' surface. A study by [66] indicated that the sudden temperature change of the PV panel surface will cause extension and retrenchment of material, which leads to the crack of the surface if it occurs frequently. Panel's surface crack can also happens immediately when there is big temperature gap between cleaning water and the module. Therefore, in order to apply this kind of soiling mitigation solution; the cleaning schedule needs to be verified accordingly so that the lifespan of the panel is extended. Cleaning can be performed either in the early morning or evening to avoid thermal shock On the other hand, dry cleaning methods like electrodynamic screen (EDS) can be proposed in soiling mitigation along with thermal shock prevention.
iv. Using water pump itself in the cleaning system consumes more electricity, although PV system is constructed initially for power generation. Attaching such cleaning system consumes electricity from the external source to operate is not practical for stand-alone PV systems because the power output generated is to be used by the designated load rather than by the cleaning system. It might be worse, when there is insufficient power generated by the PV system, the cleaning system cannot be activated. Pressurized water cleaning system is more suitable for grid connected PV system where the pump can always get the supply from the grid to mitigate soiling. However, a study by [67] found that the power consumed by the pump can be considered less if being compensated by the benefit of panel cleaning and cooling that improve or recover the systems efficiency.

Moreover, the benefit obtained by water cleaning is it helps to cool down the panels and increase the electricity generation. Krauter stated that water can reduce PV cell temperatures until 22 °C and sunlight reflection by 2–3.6% [68]. Also, Bahaidarah et al. observed that the PV panel temperature is reduced to 20% and the panel efficiency rise up to 9% through back surface water cooling system [42]. In addition, Odeh and Behnia also found that by applying the surface cooling system, it showed 15% increment of the output power during maximum irradiation [69]. Kim et al. also found that their PV system achieved a maximum power enhancement of 11.6% by the development of surface cooling system for their model validation study on energy balance and heat and mass transfer relationships [70], while Cazzaniga et al. obtained a better result for the PV system output power when the open loop water cooling systems is applied compared to Moharram's [71].

Theoretically, the solar cell is less effective with the increase of module temperature. For this reason, lots of cooling methods need to be studied, identified, researched and improved. It has been proven that the increase of solar cell temperature will degrade the energy yield [72–76]. The change of module temperature can be expressed by the following equation [77]:

$$T_{cell} = T_{amb} + \left[\left(\frac{T_{cell\_NOCT} - T_{amb}}{G} \right)_{standard} \right] \times G_{amb} \tag{1}$$

$T_{cell\_NOCT,}$ which is the module temperature in normal operating condition temperature, depends on the type of PV modules and the value is usually provided by the manufacturers in the module specification datasheet. Sometime, Eq. (1) can be more specific according to the type PV module and the local authorized standard as in Eq. (2):

$$T_{cell} = T_{amb} + \left[\left(\frac{NOCT - 20}{800Wm^{-2}} \right) \right] \times G_{amb} \tag{2}$$

In Eq. (2), *NOCT* for the PV module is being tested at the irradiance level of 800 W m^{-2}. T_{cell} is always related to the basic parameters of the PV module in measuring the module performance. They can be related through the following equation:

$$\delta x = \gamma_x \times \left(T_{cell} - T_{stc} \right) \tag{3}$$

This equation shows how the change in the module temperature due from cooling effect can contribute to the PV module output.

4.2.3. Mechanical cleaning systems

There are a lot of mechanical systems being developed for PV panel cleaning and they come in various designs depending on the purpose of the PV systems, preferences, and the site condition Most of the systems are equipped with either wiper, brush and usually move either horizontally or vertically, accordingly to the dirt detection [78–82], and some of them are designed as a robotic cleaner. The system can be activated manually, automatically by using electrical or electronic control device or both [83]. Usually, they are attached to the PV panels as an auxiliary for cleaning purpose. For example, a system can also be developed from a combination of rotating sun tracking PV panels and sliding brush [84,85] where water is not required. However, different installation configuration has been proposed by [85] that is by mounting the panels vertically and perpendicular to sunlight. Somehow, with the tilt angle at 90° also did not guarantee no dust settlement on the panel surface, because studied by [30] that dust is present anyway and it is influence from the surrounding environment despite how the module is installed.

Lamont and El Chaar [86] combined most of the elements mentioned in the above paragraph. They developed two separated systems (refer Fig. 4). The first system comprised of wipers, night sensor and motion sensors (for prevention from bird's dropping) and automatically controlled by a PLC device. Meanwhile, the second system comprised of roller brush, sirens (for prevention from bird's dropping) and also automatically controlled by a PLC device (also for prevention from bird's dropping). The wiper cleaner system is controlled by a PIC microcontroller. Both systems require water for cleaning.

With regard to this field, several robotic cleaning systems have been developed [87–92]. Although equipped with the specification almost similar to the non-robotic mechanical cleaning systems, the robots work totally independent through the designed programming algorithm. In other words, they are just a mechanical cleaning system with the same purpose but have an 'artificial brain' and act accordingly to the sensors and programs [93]. The advantages of robotic cleaning are the extra inbuilt features such as fast response, low power consumption, real time strength, high stability and reliability than the ordinary mechanical cleaning systems, whenever the highly unmanned control is required [94] and to solve the problems of labour cleaning (Fig. 5).

The mechanical cleaning system was initially invented and developed to simplify the cleaning efforts by manual cleaning. Instead of reducing the labour cost or totally replacing the labour, this system can be reliable to do the cleaning job as similar as

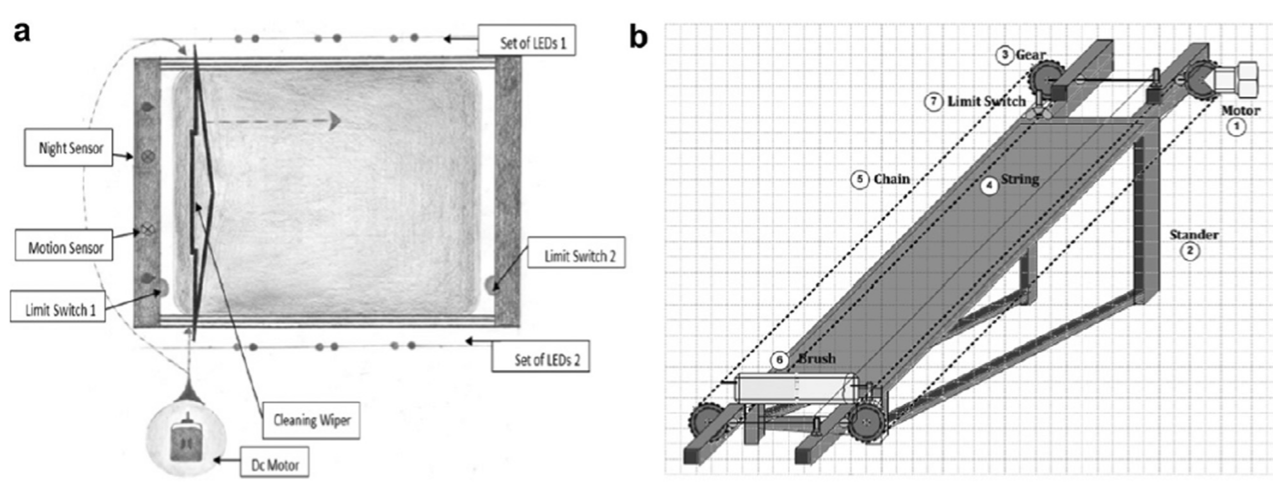

Fig. 4. Example of PV panel mechanical cleaning systems ((a) is the first system with PLC controller while (b) is the second system controlled by PIC microcontroller) [86].

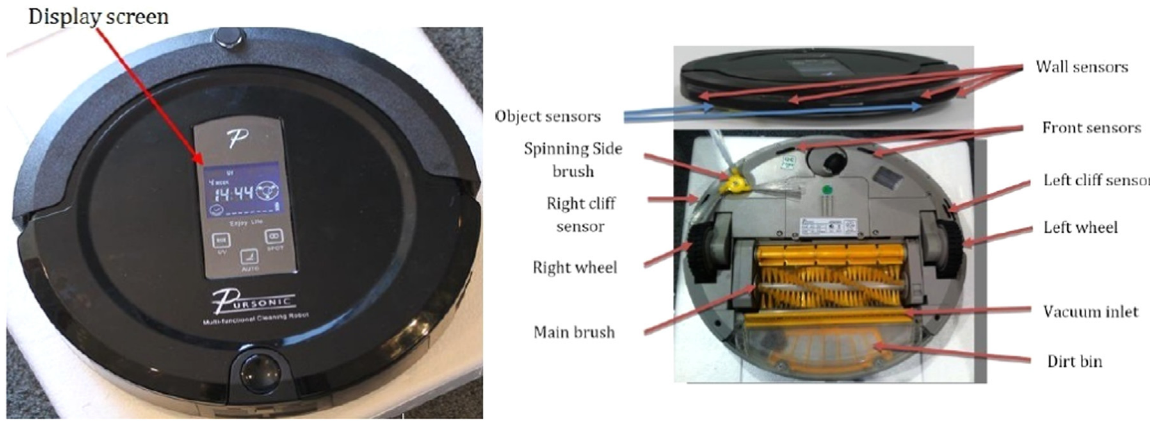

Fig. 5. Example of PV panel cleaning robot [89].

manly done. However, some aspects need to be considered before applying this kind of solution:

I) Mechanical cleaning system involves the use of various hardwares. Although it manage to remove or reduce the labour cost, the initial cost for this system is high, thus for a large scale PV plant will require more cost for the system installation.
II) The moveable mechanical parts of the device such as gear, chain and rotating feature need to be well maintained periodically for the system to work at its best. Similarly at this point, expenditure for maintenance needs to be included.
III) Most cleaning systems are equipped with wiper and brush that are moving along the panel. Thus, dirt will accumulate on the wiper, brush or the other parts which are in direct contact with the PV panel surface. Hence, if this prolong and without a proper maintenance, the cleaning efficiency will degrade.
IV) All the cleaning methods mentioned are the active cleaning system that can be automated or programmed and are electrically powered. Thus the power consume is either from external battery which need to be replaced or feedback power from the PV system itself which will limit the PV output during the cleaning. For example, studied by [95] showed that by using automated cleaning system, it consume 2.22% of the generated power from 1800 W_p PV system installed. However, in a large scale PV plant, the energy consumption required for cleaning will be higher. Therefore, the point to consider in designing of the automated cleaning system is to use the energy efficient equipment for example high efficiency motor.
V) Most parts of this system require contact with the PV panel surface to do the cleaning job. There is a probability that the panel surface might suffer abrasive damage during the dirt brushing or wiping, perhaps in the long period or high frequency of cleaning.
VI) For some module, the automated or robotic mechanical cleaning may void the warranty coverage if it is contradict or not approved with the manufacturer's guideline. (As example, see the manual retrieved from https://www.firstsolar.com/~/…/PD-5-804_PV-Module-Cleaning.ashx)

4.2.4. Electrodynamics screen (EDS)

As reviewed in the previous sub-sections on the experiment conducted by Moharram et al., it is known that dust particles might come in ionic positively charged or negatively charged due to the electrons imbalance or neutral if there is no such imbalance. The same concept about dust particle's charge was introduced much earlier by Masuda in 1971 before Moharram et al. conducted the experiment in 2013 [19]. The concept of dust's electrostatic property was used to develop the electrodynamics screen, currently known as EDS This method created from the foundation of the electric curtain concept that was first introduced by Masuda [20]. Based on the fundamental concept of the particles movement due to the electrostatic reaction on the dust, which might come in positively charged or negatively charged condition, the EDS will eliminate the dust whenever it settles on the panel surface from one edge to the other edge. By refering to Fig. 6, when an AC current energizes the EDS electrodes, a traveling wave known as the electric curtain will be created. The charged particles from airborne which settled on the EDS surface will be entrained to move along accordingly to the electric curtain direction until it pushed out at the end of the surface [96].

On the other side, we might be wondering about the ability of this concept in mitigating the neutral particle (without any electrostatic charge) that settles on the EDS surface. According to Masuda, the neutral dust particle will soon acquire a net of electrostatic charge, either by polarization of charge, known as dielectrophoresis process within the dielectric particle, or by induction charging on a conducting particle [20]. Those processes cause a net force on the particle, creating a motion of the particle on the surface and mitigate it out of the surface [20]. The process is illustrated in Fig. 7.

EDS system basically consists of a parallel electrodes on a transparent substrate which is energized by a three phase high voltage [98–100]. The voltage range is from 750 to 1250 V at

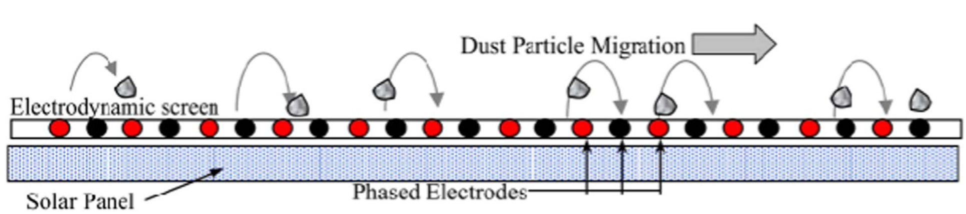

Fig. 6. The working conceptual of EDS [97].

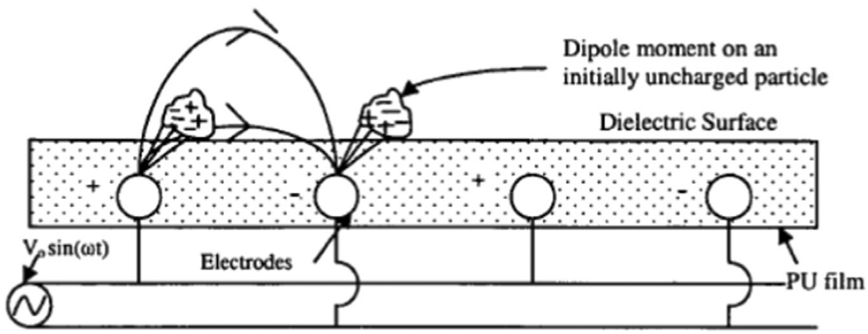

Fig. 7. The mitigation process of neutral dust particle [20].

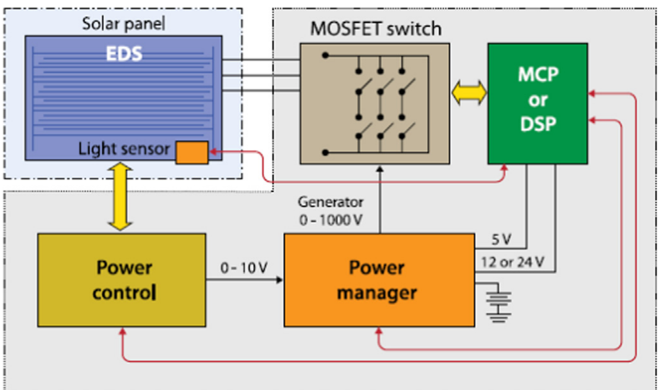

Fig. 8. EDS systems components [15].

frequency between 4 and 20 Hz [101]. Fig. 8 shows a system block diagram of one of the EDS system which has been developed.

It is observed that the EDS layer is placed on the PV surface and gets the supply from the PV output itself. The PV output will be regulated first to produce a constant output voltage by a power control circuit, and then it will be distributed by the power manager circuit to the battery (energy storage system), applied loads and related device to activate the EDS. In this case, a MOSFET switch bank and the controller device are used to automate the control of power manager and the switch bank. The switch bank actually is the device that converts the power it receives from the PV panel to the high voltage three phase supply for the EDS electrodes energizing. EDS is placed upon the PV panels' surface as additional layer to prevent soiling.

The effectiveness of EDS in solving the soiling issue is quite promising. Mazumder et al. have proved that, under the dry

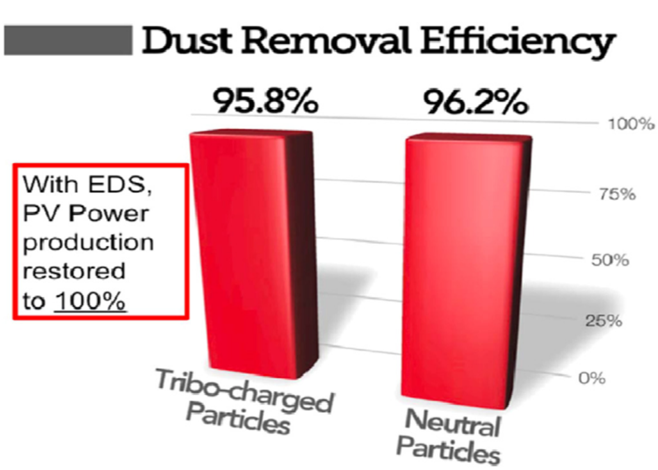

Fig. 9. Experimental result of dust removal efficiency by EDS [96].

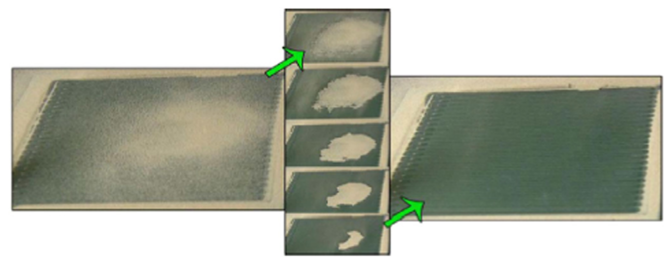

Fig. 10. Images of an EDS panel, initially covered by a dust layer (desert dust), then cleaned by EDS (Each photograph was taken at an interval of 3.3 s. The total elapsed time was 20 s) [96].

condition at relative humidity (RH) below 60%, EDS can remove dust with more than 90% efficiency [102] in less than 2 min. Experimental studies on EDS showed that the energy required for the removal of the dust layer is less than 1 Wh/m^2 per cleaning cycle, which is less than 0.1% of the energy produced by a solar panel with an area of 1 m^2 (Figs. 9 and 10).

Repetitions of experiments on EDS have been conducted by Mazumder et al. and claimed that this method is the most efficient solution to the PV soiling problems. It has been described that this method:

i. less dependent on the additional support for cleaning such as external power supply and consumable cleaning agent like chemical detergent, which is concluded as high flexibility method. EDS is originally developed for solving the soiling problems on PV panel on the probes that have been sent for the exploration in Mars and lunar where the stand alone features of those devices are highly recommended.
ii. use a considerable small amount of energy for cleaning which in this case, they used the PV outputs itself to power up the EDS.
iii. very effective at restoring the panel surface back to its original clean condition with efficiency of more than 90% [103].

However, there are small gaps in this method as noted in their publication. EDS has been tested to work best for large particles of dust which are more than 20 μm and less effective for the fine dust particles between 0 and 5 μm [104]. Besides, Mazumder et al. work on EDS are based only on dry dust [102]. The use of EDS as an additional dust mitigation layer on top of the solar panels was found to decrease the power output of solar panels by 15% [105,106] by reducing the solar irradiance intensity through its transparent screen. Not only that, one main disadvantage of EDS is that its process requires a dry ambient condition. Therefore, it is only applicable in semi-arid and desert atmospheres. It cannot work under wet conditions [96]. The efficiency of dry cleaning decreases when the relative humidity is high, as well as when the dust is allowed time to settle (1 h) before cleaning, compared to immediate cleaning (1 min after dust deposition) [96]. Thus, it

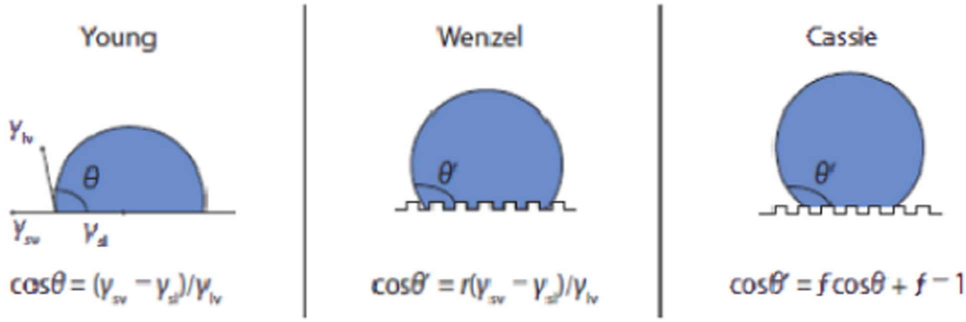

Fig. 11. Young, Wenzel and Cassie Equations [113].

seems unreliable to deploy EDS on the PV system in the condition of high humidity, which is worsening by having the possibility of the dust cementation that sticks to the screen itself. Sarver et al. mentioned about EDS regarding its cost effectiveness because PV panels will require additional processing and energy inputs despite of the loss in performance and operation that may need more than justifying the investment decision, whereas this issues need to be determined. Not only that, they also suggested that super hydrophobic coatings need to be integrated in the EDS for effective cleaning on wet soiling [15].

4.2.5. Super hydrophobic surface

A hydrophobic surface is a surface that has low wettability and prevents water droplets to stick on the surface layer. There is a study that states hydrophobicity of a surface can be determined through the ability of water droplet to bounce on a surface related to the water droplet contact angle and number of bounces, which is reliant on the surfaces microstructure [107]. Super hydrophobic surface refers to the high capability of hydrophobic characteristic. Thus, the most important parameter in developing hydrophobic surface is the contact angle, θ, as described in Fig. 11. In the case of soiling mitigation, the improved cleaning effect can be achieved by altering the surface property of the PV module to be super hydrophobic. With the super hydrophobic type of surface, soiling can be easily removed with rain falls or water cleaning system. This will increase the chance of PV module surface cleanliness recovery and also increase the sunlight absorption ability with the maximum module effective area to capture the sunlight. Besides, there are studies by [108–110] which has proven that hydrophobic surfaces accumulate less soiling in the atmospheric condition.

Historically, the hierarchy of hydrophobic equation started when Young in 1805 includes the contact angle, θ in the flat surface modelling. Below is the equation developed by Young [111]:

$$\cos\theta = \frac{Y_{sv} - Y_{sl}}{Y_{lv}} \tag{4}$$

This equation is used to determine the θ (degree) to which water droplets sticking to a surface (refer Fig. 11). The higher theθ,

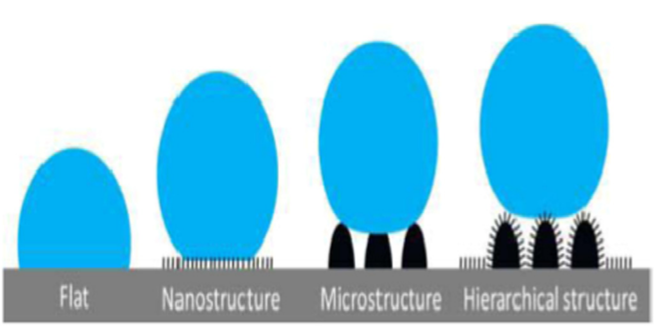

Fig. 12. Wetting of four different surfaces [114].

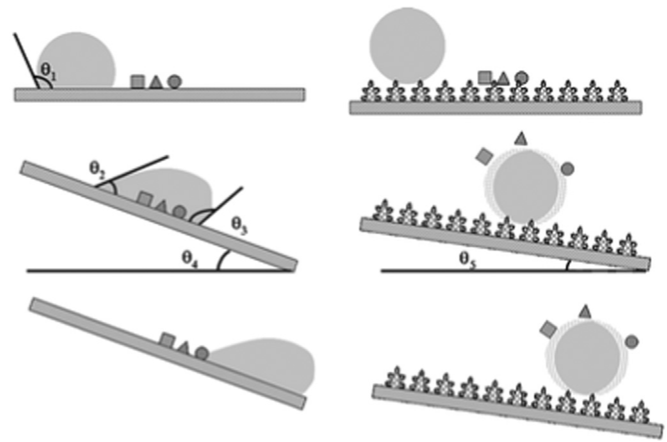

Fig. 13. Self-cleaning property of the flat surface and the hydrophobic surface [116].

the hydrophobic effect of a surface will be increase further. Wenzel (1936) and Cassie (1944) then improved Young's equation by introducing rough surface instead of flat surface. It is seen that the relation between θ and the stickiness of the water droplet on the surface is observed clearly when comparing to Young's equation. According to Wenzel and Cassie's equation, the study on super hydrophobic surface has been expanded by others into the development of the formation of microstructures, nanostructures of the flat surface or even hierarchical structures [112] which is the combination of microstructures and nanostructures to increase θ as well as the hydrophobic effect. The rough structure of the surface in smaller scale such as micro and nano will decrease the water droplet stickiness and may enhance the hydrophobic feature of it. This is as shown in Fig. 12.

The nanostructures of this surface can enhance θ to higher than 150°, so the water droplets that hit the surface would quickly roll off, carrying dust and other particles with them [115]. Fig. 13 shows the comparison of the dust cleaning feature of the flat surface versus the microstructures hydrophobic surface. Note that the surface must be placed in a tilt position to allow the rolling movement of the water droplet.

Conventionally, super hydrophobicity means not only a high contact angle, but also a low hysteresis (difference between advancing and receding angles) of the contact angle in which a water droplet can easily roll off the surface and remove dust from the surface [116]. A study by [117] stated that the super hydrophobicity of a surface can be achieved when θ is higher than 150° and hysteresis lower than 5°. Worth mentioning that, a remarkable development in this field is the work by Yong et al. This group has developed a perfectly ordered microshell array, which was fabricated on a transparent and flexible polydimethylsiloxane (PDMS) elastomeric surface to create a super hydrophobic and water-repellent surface for solar cell applications. They have successfully

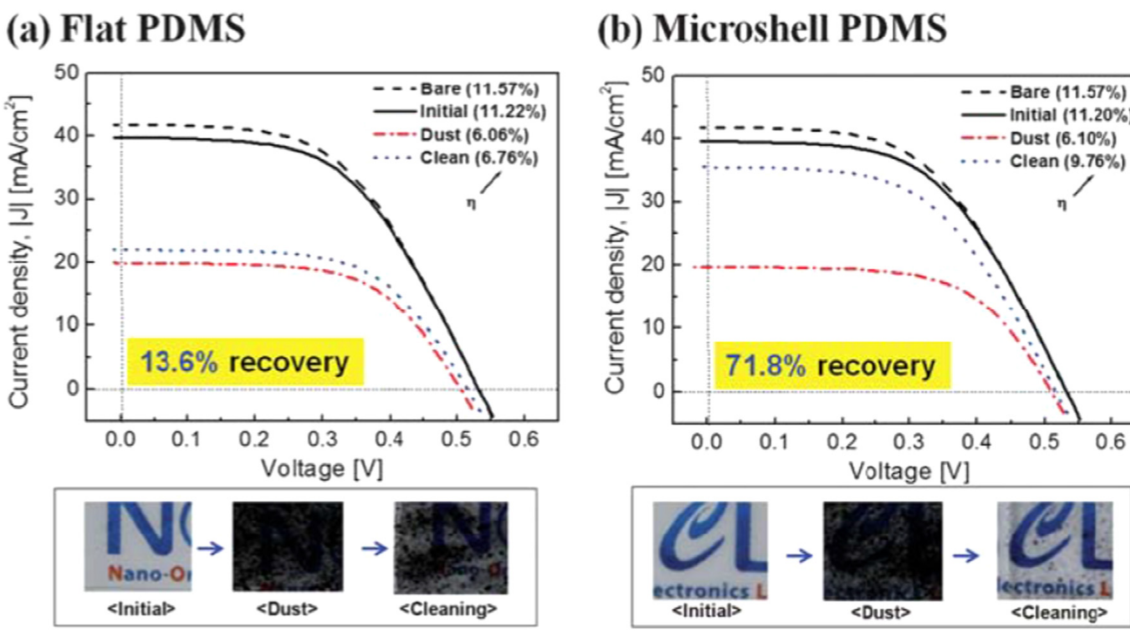

Fig. 14. Experiment result of the microshell PDMS in restoring PV panel efficiency by water cleaning [28].

created a super hydrophobic surface with a contact angle, θ, higher than 150° and a hysteresis of lower than 20°[28].

To prove this achievement, their super hydrophobic microshell PDMS surface was tested by placing it on the PV panel at the inclination of 45°. The cleaning action was developed by using carbon powder as the dust sample and water. Meanwhile, the performance of the PV panel was measured with regard to module's efficiency depending on the I-V curve. The result of this test is as shown in Fig. 14. Microshell PDMS surface was found able to recover 71.8% of module's efficiency relatively in restoring the surface to its clean initial condition. In this experiment, they also stated that the super hydrophobic layers, either microshell PDMS or flat PDMS on the solar cell module, has no significant distraction to η due to those layers' transparency, which have no adverse effect on the PV panel. They also claimed that their transparent, flexible and super hydrophobic microshell PDMS surface provides feasibility for a practical application of super hydrophobic surfaces in solar cells [28].

Apart from that, super hydrophobic effect not only gained using fabricated layer but also by applying a certain chemical coating on the PV surface [118–120]. Nevertheless, the capability of super hydrophobic surface in solving the problem of soiling efficiently is still ambiguous. As mentioned in the finding by Yong et al., only 71.8% of the PV panels' efficiency able to recover from degradation due to soiling. In this case, considering it as passive methods, without considering the exposure duration, the recovery rate may reduce from time to time. Mitdal and Jelle found that the cleaning effect using the super hydrophobic surface is not durable which can last for about 3-4 years [121]. Besides, this layer is made from polymer [112,122–125] and according to Sarver et al., even though some of these layers exhibit high initial transmittance, they actually tend to accumulate more dirt (due to high surface energies of the polymer surfaces), suffer abrasion damage, and degrade (often due to the high UV exposure) much quicker than glass [15,126]. Additionally, this surface also can get corroded in a short period with a frequent exposure to certain aqueous chemicals which possibly come from the acid rain or salty air [127].

4.2.6. Super hydrophilic surface

Hydrophilicity can be defined as the opposite characteristic of hydrophobicity, and this term is used to express the complete dispersal of water or liquid on a substrate. It was introduced a few years after the hydrophobicity [128]. A hydrophilic surface has a strong attraction to water but a hydrophobic surface resists water [129]. Super hydrophilicity refers to the high level of the hydrophilic characteristic and effect. The hydrophilic condition of a surface can be achieved, demonstrated by the Wenzel model (liquid-solid contact) through the enhancement of the surface roughness and surface energy. According to the literature source published in the last 10 years, super hydrophilic surface can be achieved whenever the contact angle, θ, is near to 0° [128]. This can be obtained by using Titanium Oxide nano-film, chemical coating and the glass surface fabrication by nano-patterning. Similar to super hydrophobic surface, the cleaning effect of the super hydrophilic is obtained by washing with water. Fig. 15 shows the difference feature between hydrophilic surface and hydrophobic surface. It can be seen that the water droplets on hydrophilic surface is flattened and widely spread onto the surface. Meanwhile, the water droplets on the hydrophobic surface are mostly sphere shaped and do not spread on the surface.

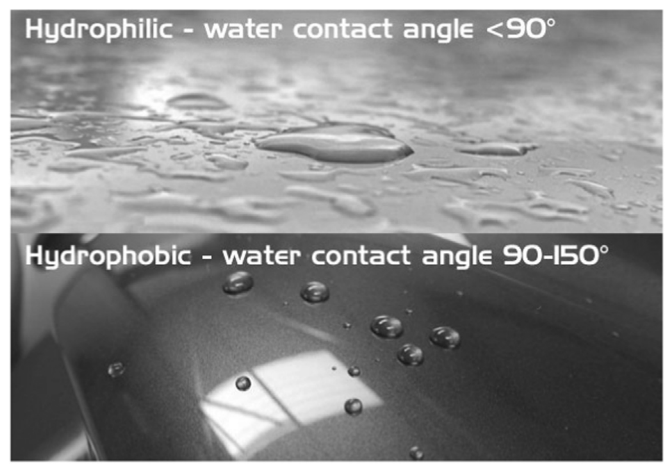

Fig. 15. Water droplet of the hydrophilic surface versus hydrophobic surface (Image retrieved from http://www.theultimatefinish.co.uk/).

The self-cleaning mechanism is shown in Fig. 16. Different from the super hydrophobic surface, the water droplet on this surface

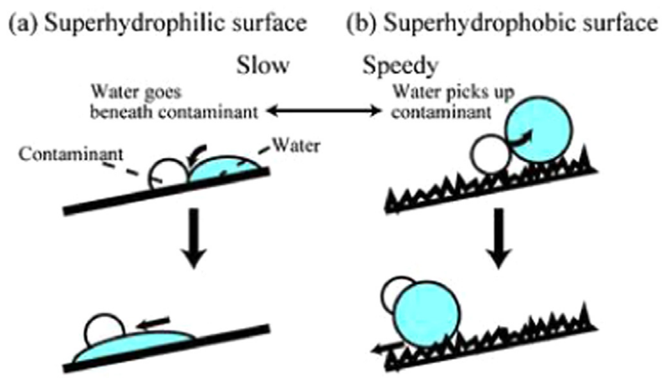

Fig. 16. Self-cleaning of super hydrophilic surface versus super hydrophobic surface [130].

may spread, go beneath the dirt particle and carries it away, compared to the super hydrophobic surface that remove the dirt by picking up using the rolling water droplet [130]. The surface characteristic will naturally dehydrated quickly, avoiding from fogging up when in contact with vapour or condensation [131]. Not only that, based on the high energy surface characteristic and the usage of Titanium dioxide (TiO_2) nano-film rather than the usage of chemical coating, this type of surface can encounter soiling problems by chemically breaking down the organic dirt through the reaction to the UV light [115,132]. Consequently, the organic elements contained in dirt settling on the surface will be converted into carbon dioxide, water, nitrate ion or other simple basic products, leaving the inorganic element [133]. This is also known as photocatalytic effect [134,135]. Not only that, experimental studied by [136] showed that the hydrophilic surface is capable of splitting down the water droplet, although in normal cases hydrophilic surface only able to flatten the water droplet.

He et al. found that the super hydrophilic surface is inapplicable for solar cell array in the dry region [115]. Similar to super hydrophobic surface, this surface also requires rainfall to obtain its cleaning effect. However, the judgement cannot be made only based on this condition. This kind of cleaning method can be used in the moderate and high annual precipitation region where PV system is required based on situation demand such as the rural and isolated area. Not necessarily with the aid of water, the help of wind can also blow away the dust on this kind of surface, whereby most are organic dirt particles that have been decomposed through the photocatalytic effect. Besides, the usage of TiO_2 photocatalytic film has been described as chemically stable, has long durability [137], non-toxicity, low cost, and transparent to visible light [138].

Even though many studies suggested the self-cleaning feature application of this surface in mitigating the dust problems, most of them did not provide the quantitative result on the PV systems efficiency restoration or retention. Son et al. showed that the nano-patterned super hydrophilic glass without surface chemical treatment resulted to maintain the PV system performance with only 1.39% of efficiency drop, which was 1.23% better than super hydrophobic surface during the 12 weeks outdoor observation and also much more durable [29]. In the same year with Son et al., Verma et al. through their study were able to increase 0.2% efficiency of a solar cell by applying a nano-structured super hydrophilic glass layer upon the cell surface. They found that within the thickness of 50–200 nm, this super hydrophilic glass managed to reduce the reflection from the solar radiation at the air-glass interface [139]. Graziani et al., showed that the photocatalytic action of the TiO_2 was able to inhibit the adhesion of the moss on the nano-coated surface under the optimal UV exposure but this study still needs to be improved from time to time as the adhesion is not able to prevent the moss vegetation [140]. Regarding the super hydrophobic surface, its durability against time has been disputed, but only for the super hydrophilic surface which is not the polymer based material [141], as this surface may endure in much longer period [133,142]. Therefore, due to robustness and photocatalytic feature of the super hydrophilic surface, this method can be considered better than the super hydrophobic surface.

5. Comparison of the PV module cleaning methods

Table 3 summarizes the comparison on the soiling mitigation techniques. This comparison is useful in determining which preliminarily alternative technique should be considered for the PV systems soiling mitigation in the aspects of the initial cost, installation purpose, the site condition and the environmental factors (location, climate, weather, etc.) which might interfere with the new PV system installation or the productivity of the current PV system. It also gives the overall view on each technique requirement, advantages, disadvantages and the efficiency of cleaning based from the literature review resources. The information gathered is simplified from the overall theory and concept of each technique in real application. Apart from the above mention criteria, a new column on the proposed improvement to the existing methods has been added.

Table 4 specifically shows the limitation area in the available application techniques mentioned in the sub-Section 3 according to their requirement and working principle. It is observed that the labour cleaning technique can be applied in any region at any weather condition, climate or environment but it is limited to the PV system facility that within reachable state; for example, the high place of mounted panel which is difficult to be cleaned manually since it is not reachable. Therefore, the mechanical cleaning system has been developed not only to replace the labour but also to support the cleaning jobs in the dangerous area or hardly reached by man. On the other hand, the current EDS technique can only cater during dry dust condition, thus currently it is only applicable for the dry climate, even if the locations that have high air pollution index, it might cause serious soiling on the panel's surface and hence this technique is really effective in order to recover the panel cleanliness. Alternatively, the water cleaning technique can be applied in any regions, by using water tank for storage system. However, it is best applied in the regions where water resource is easy to obtain or excess. Water can easily evaporate due to the hot sun and can get contaminated through the closed loop cleaning cycle; not to mention its price per gallon. Besides, for super hydrophobic surface and super hydrophilic surface techniques, they are dependent of rainfall to activate natural cleaning, areas with high or moderate annual precipitation. Still, wise decision needs to be made since high precipitation throughout the year will reduce the amount of sunlight, which is crucial for PV system's energy harvesting.

6. Conclusion

To date, several soiling mitigation techniques have been developed. Nevertheless, most of them still require further research to make them more reliable and low cost. The reviewed methods have their own strengths and weaknesses, and can only methodically rated. Most of the soiling mitigation methods currently are focusing on the PV module surface cleanliness restoration in order to gain and maintain as maximum possible output power from solar irradiation [15]. Therefore, the focus has been given more on the development of mechanical cleaning system and water cleaning system for the large scale PV system and the usage of

Table 3
General comparison of each soiling mitigation technique.

Techniques	Requirement	Advantage	Disadvantage	Method's efficiency	Proposed improvement
Labour cleaning	• Workforces • Water • Detergent/Chemical • Equipment (Brush/Cloth)	• Really efficient in restoring the PV panel to clean condition	• High cleaning cost [48,49] • Contact with PV panels surface (abrasive)	Effective in any condition	• Resource of cheap labour to reduce the cleaning cost • Usage of smooth or soft cleaning apparatus (brush, wiper, etc.) and gentle cleaning to reduce risk of surface abrasive damage
Natural cleaning	• Tilt mounted PV panel [44,50,51] • Rain	• Free of charge	• Dependent on site condition • Dependent on weather • only caters large dust particles, more than 10 μm rather than smaller ones (2–10 μm) [41]	Unpredictable and can be less effective [9,43,57]	Surface property alteration to become super hydrophilic or super hydrophobic to enhance cleaning effect from rainfall
Water Cleaning	• Pressurized water [19] • Catalyzing chemical (ionic surfactants) [19,61]	• Cooling down of system temperature [42,67–71] • Reduces the dependency on natural cleaning	Continuous supply system [71]: • Water loss due to splashing and evaporation [19] • Unreliable for application in dry region Water tank system [19]: • Concentration of chemicals [19] • Contaminated water • Clogging of filter • Refilling of the tank [19] • Requires power for pumping (reduce system output) [19] • Water consumption cost • Labour cost for manual system • Easy to accumulates dirt whenever the panel is wet • Risk of thermal shock [66]	Moderately effective	• Cleaning schedule to be arranged either in the early morning or in the evening to avoid thermal shock on the module's surface • Usage of high efficiency water pump to save the energy required during cleaning
Mechanical Cleaning	• Brush/Wiper [78–82,84–86] • Mechanical prime mover components (motor, gears, chains, etc) [78–82,84–86] • Robotic (optional) [87–92]	• Cooling down of system temperature with the usage of water • Automatic activation of cleaning with the usage of sensors and controller (PLC, μC, etc.) [83,86] • Additional features (MPP Tracking [84,85], Bird scaring [86]) • Reduces labour cost and increases system independency especially whenever highly unmanned control is required [94]	• Contact with PV panels surface (abrasive) • Accumulates dirt on the cleaning apparatus (brush, wiper and etc.) • Cleaning system maintenance • Power consumption • High initial cost	Effective in uncertain duration	• Cleaning schedule to be arranged either in the early morning or in the evening for any methods involving water to avoid thermal shock on the module's surface • Usage of smooth or soft cleaning apparatus (brush, wiper, etc.) that will be in contact with the modules' surface to avoid abrasive damage • Usage of high efficiency motorized part to save the energy required during cleaning • Well maintained on the mechanical parts and cleaning apparatus (brush, wiper, etc.)
EDS	• Transparent screen [98–100] • High voltage supply[98–101]	• Very fast cleaning action [96] • Low consumption of power [101] • Automatic activation of cleaning with the usage of sensors and controller (PLC, μC, etc.) [15,101]	• Uncertain durability consideration on UV causes degradation on the plastic screen [15] • Decreases the power output of solar panels by 15% [105,106] • Unreliable due to wet or cemented dust [15,96,102] • Less effective for the fine dust particles between 0–5 μm [104] • High initial cost	Highly effective in dry condition [96,103]. Exceptional for high relative humidity and wet condition [96]	• Usage of high weather proofed polymer or glass to enhance the durability of EDS layer • Usage of high efficiency electrical and electronics component to at least reduce the power consumption of EDS layer • Combination of EDS and super hydrophobic or super hydrophilic as an integrated layer might possible this method to be applied in the high relative humidity regions.
Super hydrophobic Surface	• Fabricated hydrophobic surface [139]/additional screen layer/chemical	• Passive and does not require external power source	• Uncertain durability consideration on UV causes degradation on the plastic screen [15,121,126] or acid rain and salty air that might cause layer degradation	Moderately effective [28] in the presence of rain	• Usage of high weather proofed polymer, glass or coating in fabricating the hydrophobic surface to enhance its

	coating [118–120] • Water		[127] • Tends to accumulate more dirt in longer period according to site condition [28] • Tends to accumulate more dirt whenever the coating is deteriorating [15,126] • Dependent on rainfall • High initial cost whenever applied to large scale PV system		durability again weather. • Despite the cleaning effect from only rain, the surface need to be washed with water when necessary to avoid the prolong accumulation of soiling in the long dry season
Super hydrophilic Surface	• Fabricated hydrophilic surface/additional screen layer (nano TiO_2 film [138]/chemical coating • Water	• Passive and does not require external power source • Photocatalytic effect (decompose the organic dust) [115,132,134,135] • Less adhesive to dirt particle [140] • Recently reported better than super hydrophobic surface [29]	• Longer durability [137,138] (not polymer based material) • Tends to accumulate more dirt whenever the coating is deteriorating (but deterioration time is much slower than super hydrophobic surface) • Relying on rainfall • High initial cost whenever applied to large scale PV system	Moderately effective in the presence of rain (recently reported better than super hydrophobic surface [29])	• The surface also need to be washed with water when necessary to avoid the prolong accumulation of soiling in the long dry season

Table 4
Limitations for soiling mitigation methods.

Methods	Limitation Area
Labour cleaning	Only reachable area
Mechanical cleaning	None
EDS	Dry Climate [96,103]
Water Cleaning	None but areas with water resource are preferable [19]
Natural Cleaning Super hydrophobic surface Super hydrophilic surface	Moderate to high annual precipitation area [28,29]

labour for the small or medium scale of PV system. Minimal consideration has been given to the surface alteration type of soiling mitigation method such as EDS, super hydrophobic surface and super hydrophilic surface. Meanwhile, the application of natural cleaning can only been done to the PV system in the less soiling problems. The decision in selecting the best appropriate method depends on several factors; site conditions, resource availability, PV system capacity, expectation and economics. The decision to select the most appropriate technique is difficult, and further research is still needed. With the presence of various mitigation technique available currently, it can be suggested that in the future, a technique that combine all of those features can be developed as an auxiliary structure to the PV system. In doing so, the next generation of the PV system can adapt most of the geographical condition pertaining to soiling issue.

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