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Assessment of Various Dry Photovoltaic Cleaning Techniques and Frequencies on the Power Output of CdTe-Type Modules in Dusty Environments

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Abstract: This study presents the conditions and results of experimental investigations on various photovoltaic (PV) module cleaning methods and the effects on the performance of cadmium-telluride CdTe-type photovoltaic (PV) modules located in Doha, Qatar. The study aims to find the optimum cleaning technique and frequency based on cleaning performance and cost. PV modules are in a dusty and rocky area in the western part of Doha, Qatar within the north campus of Education City. Maximum power point tracking (MPPT) technology is employed for five different PV modules. The results show that microfiber-based wiper along with microfiber & vacuum cleaner are the most effective cleaning methods with about 6% improvement for the weekly period compared to the control panel among the considered methods. However, due to the increased cost of adding a vacuum cleaner, the microfiber-based wiper is the most efficient method when both cost and improvement rates are considered. In addition, the most efficient cleaning frequency (among daily, weekly and monthly) is found to be the weekly cleaning under the tested climate conditions.

Keywords: soiling; photovoltaic; efficiency; performance; dust

1. Introduction

Global warming is considered one of the greatest challenges that humanity has had faced on Earth. A rise in temperature of 2 °C can cause so many complex, intertwined and irreversible problems such as water scarcity and stress, increasing sea levels, leading permanent flooding of almost all coastal regions on the Earth, extinction of various animal species, increase in the heat extremes and heat waves that would lead to inhabitability in many regions such as Arabian Gulf [1,2]. A key solution for this grand challenge is reducing, if not eliminating, the harmful effects of human activities such as the burning of fossil fuels for energy needs in transportation, manufacturing, buildings, heating, and cooling. Energy has been one of the fundamental requirements of life, surpassed only by water and food. Energy obtained via burning fossil fuels releases significant amounts of CO_2, SOx, and more hazardous chemicals into our atmosphere, which is not only harmful to the living creatures exposed to them but are also the main cause for global warming. Energy generation using clean sources and improvement of energy efficiencies are considered as the key mitigation strategies to overcome the global warming challenge. Renewable energy sources, particularly, solar energy have huge potentials to be converted into a useful form of energy in a much cleaner way than fossil fuels. However, there are still a number of barriers in the wide implementation of renewable energy systems. Efficient and cost-effective harvesting from these renewable sources is harder than fossil fuels as they require special conversion technologies and systems such as photovoltaic cells and wind turbines, which are not as mature and cost effective as the fossil fuel conversion technologies. Nevertheless, with the rapid research and development efforts throughout the world; efficiency, maintenance, and cleaning costs have become considerably low to start competing with conventional fossil fuel sources and technologies. Solar power has the potential to be the main type of energy source in the world, replacing fossil fuels and ensuring a pollution free environment. Photovoltaic cells are the main energy conversion types from the sun to direct electricity.

However, in addition to inherent theoretical limitations arising from existing photovoltaic (PV) material systems and high-temperature effects, dust growth on PV panel facades distracts the transmissivity of light, hence influences the PV system's efficiency and overall performance [3]. Unfortunately, some of the highest solar power potential regions on the Earth are also found to be the highest dust accumulation zones such as the Middle East and North Africa regions [4]. For example, in Qatar, soiling can cause (on average) 15% PV energy yield decrease per month, and after 234 days without rain or cleaning as well the soiling loss, can reach up to 68% [5]. In the literature, the soiling effect was studied in Qatar by testing twelve cadmium telluride (CdTe) thin-film frameless solar panels having a maximum power rate of 90 W, tilted at 22°, and facing south [6]. The collected dust was subjected to four tests involving particle size analysis, X-ray fluorescence, X-ray diffraction, and scanning electron microscopy [6]. Each time period had different dust composition, but calcite and dolomite were found to be the highest in percentage among all due to the fact that natural local sand in Qatar mainly consists of carbonates (i.e.; limestone/calcite or dolomite) [7].

Another study was conducted to obtain data on how the dust deposition has degraded the solar system performance. One of the aims was to obtain data of ambient dust and weather conditions to identify the correlation between these factors [3]. Authors examined the temperature levels of the solar panels to identify the soiling effect and cleanness index since clean panels have a higher temperature than the dirty ones [3]. An important aspect to be investigated is the dust deposition mechanism. In order to model this phenomenon, Lu et al. [8] numerically studied the dust deposition on a solar photovoltaic system, where it was mounted on the windward roof of an isolated building. They used computational fluid dynamics modeling to find out the effects of various dust particle sizes, differing quantities of released dust particles, and the force of gravity on the rates of dust deposition upon the PV panels. In further study, Lu et al. [9] proposed an empirical model for approximating the losses from PV power output due to the dust deposition for different tilt angles.

Javed et al. [10] investigated the performance degradation of solar PVs caused by soiling and they performed the characterization of the accumulated dust. They explained that the 4 mm rain was found to be the threshold amount of rainfall to effectively clean the solar panel and anything beyond does not increase the cleaning effectiveness [10]. According to another study [11], 5 mm of rainfall is enough to clean PV surfaces and reinstate its power output. However, rainfall is scarce in dry desert climates like Qatar.

Additionally, Touati et al. [12] also studied the effect of temperature, relative humidity and dust settlement on the performance degradation of commercial monocrystalline and amorphous silicon PV technologies. Nimmo and Said [13] conducted a study on solar collector glass and PV panels for six months in Saudi Arabia and found out that the PV panels lost 40% of their efficiency. Mani and Pillai [14] showed the relationship between the tilted angle and the loss in transmittance taken from a study performed in Kuwait. The study used glass plates to show the relationship. They found the transmittance loss after thirty-eight days of exposure amounts for 64% to 17% for angles ranging from 0° to 60°. Another year-long study was conducted in the UAE to identify the seasonal effect of dust deposition on a field of evacuated tube collectors on the performance of a solar desalination plant [15]. For the daily cleaning, the loss was limited to 2%, while the energy loss for the weekly and monthly cleaning frequency varied from month to month. They concluded that identifying the optimal cleaning frequency is an important issue that needs to be studied further. A study performed in Belgium [16] analyzed the magnitude of dust accumulation on the glass cover of the PV modules issue. Solend [17] conducted an experimental study between November 2016–April 2017 in Kalkbult, South Africa in a solar plant. He investigated the amount of soiling losses in the summer period, the composition of the dust particles in the area, and frequency of cleaning solar panels taking into account the soiling losses. The marginal cost of cleaning was calculated by dividing the total cleaning cost by the number of modules to determine the price of cleaning one module. The cost of soiling for one module was found to be $0.12 [17]. A cleaning frequency optimization study was conducted in Arizona [18]. Those experiments were performed by exposing PV modules to natural soiling, then cleaned in various cleaning frequencies, and weather monitoring [18]. It was found that panels that were on the bottom experienced high soiling losses in the range of 5 to 6%. It was explained that this happened due to their closeness to the human activity in the test field, and to the sand-covered floor. In hot and desert climates, there is an abundance in irradiation but an abundance also in dust and humidity. Soiling of solar panels has a large impact on the electrical power output of the panels if left uncleaned. If they are not cleaned, the power outputs of solar modules can drop about 0.4% to 0.8% per day. This means that a PV panel can lose between 12% to 24% of the power production in case it is left uncleaned during one month [3].

The soiling effects are critical not only for the Middle East but also for many other regions of the World. In a study performed in Norway by Pedersen et al. [19], the losses due to soiling of PV modules in an inland climate were identified. They also assessed the cleaning effect of rain in this environment. They showed that the effect of soiling can be accurately determined by a combination of optical measurements and high precision balance measurements, where the accumulated dust density was evaluated by measuring the weight-changes of cloths used to clean glass samples. You et al. [20] performed comprehensive modeling of PV soiling in seven different cities around the world. They accounted for relative net-present value change to define the optimal cleaning intervals. One of the selected cities was Doha, for which they obtained an efficiency loss over 80% for a 140-day of soiling. They also found out that among the selected cities, Doha has the shortest optimal cleaning intervals with 23 days for manual cleaning, where it corresponds to the relative net-present value change of 21%.

Erdenedavaa et al. [21] investigated the dust deposition for particularly solar thermal collectors by a focus on in cold climate zones, such as Ulaanbaatar (Mongolia). This shows that the dust concern can also be available other climatic conditions as well. They used a simulation model for the assessment of deposition behavior for finding the best cleaning time for the collectors. In addition to dust, there can be other issues such as natural pollens affecting the performance of the PVs. Conceição et al. [22] studied the soiling ratio index in a rural environment of Southern Europe by calculating the maximum power output and short circuit current of two photovoltaic (PV) panels. Their results show a soiling rate of 4.1%/month in April, 1.9%/month in July and 1.6%/month in September.

Kalogirou et al. [23] showed that especially the artificial soiling on the wet PV surface presented a serious degradation of the PV performance. The effect of natural dust deposition on the PV panel surface for a year period was investigated. They found that in winter, the occasional rain is satisfactory to keep the PV surfaces clean while when a dust event occurs, the panels should be cleaned manually. However, this was not the case for the summer time. They recommended to perform the cleaning immediately after a dust event and every 2–3 weeks in summer time according to the associated cleaning cost. Tanesab et al. [24] investigated the seasonal effects of dust on the degradation of PV modules positioned in two different climate areas, Perth, Western Australia, a temperate climate region and Nusa Tenggara Timur, Indonesia, a tropical climate region. It was found that the degradation of all modules is more affected by dust compared to non-dust related factors for a short-term period of study. In addition to conventional silicon based-PV modules, there are recent advancements in perovskite materials to be used in photovoltaic as well as photocatalysis applications [25]. Lay-Ekuakille et al. [26] attempted to prepare a model for simulation of dust and pollutants deposition. They compared a CdTe-type clean PV module under MPPT variations with the dusty module. They resulted that after many years of operation, the dust deposition becomes very hard to remove because of crystallization. Mani et al. [27] studied the relationship between power output, incident irradiance and soil particle size composition of soiled photovoltaic panels. The soil present on the panel is rich in the particles with a diameter (75 µm and below), the deviation from the tilt angle of a clean panel is 4°, however, if the soil contains higher composition of both 150 µm and 300 µm particle sizes the deviation is 8°.

Al Shehri et al. [28] studied the cleaning performances of some equipment as well. An enhancement in the maximum power output of solar panels cleaned with silicone rubber was about 1% from the un-brushed initial power output, which could be attributed to the created surface geometry. The silicon rubber foam provided a simple brush design, which could reduce the cost of the brush used in robotic cleaning systems. It also provided highly effective, nonabrasive cleaning a result of the brush-based dry cleaning with the other materials. The influence of dry cleaning for the elimination of dust particles settled down on the glass and the effect of brushing on the transmission of the glass were also studied by Al Shehri et al. [29]. It was revealed that dry cleaning using Nylon brushes did not have a significant, permanent effect on the optical characteristics of the glass surface, even when the brush was employed to clean a dusty surface. However, the cleaning efficiency of the nylon brushes was not as high as cleaning using water and delicate wipers.

Jiang et al. [30] proposed a model to estimate the cleaning frequency of PVs in desert climates. They found out that the cleaning criterion was a 5% reduction in power with the accumulated dust density of 2 g/m^2. As well, they concluded that the cleaning time for PV modules in desert regions is about 20 days. Jing et al. [31] investigated the impact of winds on the dust removal from PV surfaces, which was not much effective.

Cleaning plan is also a significant decision parameter. Fathi et al. [32] evaluated a PV power plant cleaning plan from a technical and economic point of view in Algeria. They wrote that PV panel technologies were affecting the soiling threshold level. They made a case study for power capacities of 1 and 5 MW and two types of PV panels' technologies: cadmium telluride (CdTe) thin films and monocrystalline silicon.

Based on the presented literature, this study experimentally investigates the influences of several cleaning methods on the operation performance of thin film PV modules in hot arid circumstances. In this study, we present the waterless PV cleaning techniques to overcome the challenge of installing PV panels in desert climates and of dust accumulation on the PV surfaces. Since it is also difficult, quite costly and environmentally impactful to access water in these climates, waterless cleaning methods are more preferable. This research attempts to answer whether the performance improvement is noteworthy when water is eliminated during PV cleaning. In addition, the cleaning techniques applied here are unique and commercially existing low-cost arrangements. One of the main differences of this study is to assess the cleaning techniques in case there is no water usage. This study also compares the obtained improvement results and approximate cost values with the literature.

This paper firstly introduces the literature review and possible PV cleaning applications. Section 2 focuses on the experimental methodology, where all selected cleaning methods are clearly explained. In Section 3, the results and discussion are presented including the PV performance, cost analysis, and overall comparison results. Section 4 summarizes the main findings and conclusions of the study as well as recommendations.

Numerous types of cleaning methods are available. Each of them has certain disadvantages and advantages. This section provides a brief explanation of possible cleaning alternatives. In addition, since this study reports the improvement rates of solar PV power outputs achieved through dry cleaning methods, the efficiency improvements, as well as power losses obtained in the literature studies, are also elaborated in this section. Further discussion on the comparison of the results is written in the results and discussion section.

1.1. Mechanical

Mechanical cleaning is the most common type, which includes robots, manpower, brushes, etc. It typically necessitates an operator [33]. There are other smaller more generic robots that are usually employed for smaller facilities. Those smaller robots include brush type, which do not need a lot of water. The autonomous machines are robust; however, they need customization and a lot of construction (especially where rails are needed). The other type is sprinkler-based robots, which use more water to clean the panels. The key drawback is vast quantities of water need. Manual labor is generally used for cleaning domestic solar panels or small facilities [33,34]. Water inaccessibility and manual labor cost changes, as well as extreme hot weather conditions, can be considered as the main disadvantages of this method. However, the automated versions of mechanical cleaning methods can bring flexible cleaning.

Patil and Mallaradhya [35] studied an automatic wiper dust cleaning mechanism for solar panel in which they obtained about 1.6% to 2.2% increase in power output via regular cleaning. Bunyan et al. [36] investigated the impacts of dust density on annual PV panel power output in Kuwait. They found out that there is a need for often weekly water washing to maintain the power efficiency loss of about 15% in the month of April and 8.7% in the month of November. Abdallah et al. [37] studied the performance of silicon heterojunction photovoltaic modules in which they utilized regular water cleaning and they observed a decrease of about 15% in energy yield and performance ratio due to dust accumulation over a month period. Al-Shehri et al. [28] observed a difference of about 1% on average in the maximum power production of solar modules cleaned with a silicone rubber brush and unbrushed initial power output.

1.2. Electrical

The most popular electrical dust removal method is based on the "electric curtain concept" developed by F.B. Tatom and collaborators at NASA in 1967 [38] and further developed by Masuda at the University of Tokyo in the 1970s [39]. The basic concept of this solution is applying an electrical wave forming a moving wave that would block particles settling on the PV module [39]. Also, the surface of the panel will be charged at all time, which would not be safe during rainy days.

1.3. Chemical Self-Cleaning

Self-cleaning nanofilms can be in the form of super-hydrophilicity and super-hydrophobic films [40]. They have recently been summarized by Yilbas [41] to emphasize the importance of self-cleaning surfaces as a solution for cleaning of the solid surfaces. Syafiq et al. [42] reviewed the progress in various self-cleaning methods for PV panels in which they mainly focused on super hydrophobic coating based methods for self-cleaning. Since the durability and stability of these type of coating materials are important parameters for long-term operations, they have presented various test results of selected superhydrophobic glasses.

The popular type of coating film, TiO_2 [43], cleans the solar panels as follows: First, the photocatalytic process would take place, where the film reacts under the ultraviolet light and split the organics dirt. After that, the rainwater will remove all the dust off. However, this solution requires rain to rinse the dust off the solar panels, which means that it needs water in dry regions. Furthermore, the second type would help enhance the contact angle (CA) to higher than 150°, so that water droplets hitting on the surface would quickly roll off, carrying dust and other particles. This solution also requires water, which is not well suited for desert climates [44]. Piliougine et al. [45] studied the modules with coating films, which have an average daily energy soiling losses of 2.5% whereas for the uncoated modules this loss was about 3.3%. They also checked the degradation level of the PV modules after one year and found that there was no degradation of the modules or the coating film after one year of outdoor exposure. They have also emphasized that the cost of cleaning and economic losses due to soiling should be carefully studied before anti-soling surface applications. The transmission losses caused by the coatings are also being investigated for minimization such that the path length and quantity of incident light reaching the solar cell module could be increased by incorporating anti-reflection and light-scattering patterns [46].

In addition, Pedersen et al. [19] reported a loss in efficiency of about 0.2–0.3% over the two-month period. They estimated this number based on an estimation of 1–2% transmission losses. Oh et al. [47] utilized silica-based anti-soiling and antireflection coatings for which about 2.56% improvement was obtained on average because of the anti-reflection coating. On the other hand, higher improvement values were also reported in the literature. Arabatzis et al. [48] observed that the coated PV modules established an average improvement of 5 to 6% for the observed duration of (less than 3 months) in which they utilized a self-cleaning, photocatalytic coating. It is important to note that the measurement period and calculation methods of performance improvement can affect the reported values.

2. Description of Experimental Methodology and Conditions

In the first part of the experiments, the most suitable cleaning apparatus will need to be selected based on the effectiveness of cleaning, consumption of energy, and duration of cleaning for different types of soiling (e.g., dust or mud). Especially in Qatar, high humidity with dust help create a very thick muddy layer that is hard to clean. Furthermore, the proper cleaning frequency will need to be established for different apparatuses.

This study will mainly use mechanical cleaning methods, which do not include any water during cleaning. The main cleaning tools and techniques that are compared in this study are brushes, wipers, and vacuum cleaners. Some of the cleaning techniques are simultaneously used to increase cleaning efficiency. The mechanical methods and the relevant experimental setup are given in Table 1.

Table 1. Selected cleaning methods and associated photovoltaic (PV) modules.

Solar Module Number	Cleaning Method
1	Mechanical brush
2	Microfiber-based cloth wiper
3	Mechanical brush & vacuum cleaner
4	Microfiber-based cloth wiper & vacuum cleaner
5	Control panel (no cleaning)

The type of cleaning techniques was based on their energy requirements, weight, size and effectiveness for dust removal.

For the experiments, five solar panels are installed on a platform tilted 20 degrees to the south. Their characteristics as well as power ratings are listed in Table 2. The nominal power output of the selected PV panels under standard test conditions (STC) is 85 W (+/−5%) as given by the manufacturer. One panel is cleaned with a brush (PV28), one with a microfiber-based cloth wiper (PV27), one with a brush and a vacuum cleaner (PV26), one with a wiper and a vacuum cleaner (PV25), and one is not cleaned (PV30). The location of experiments is the Solar Test Facility (STF), HBKU, Doha, Qatar. The selected test panels located in solar test facility (STF) are shown in Figure 1.

Figure 1. Five PV panels being tested in solar testing facility and a dusty PV panel surface before cleaning.

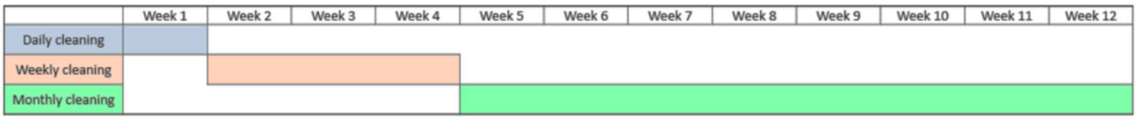
Three frequencies were selected namely; daily, weekly, monthly as the cleaning schedule is given in Table 3. The measurements are taken from January to April in 2018. This period in Qatar can be mainly characterized as mild temperatures, windy and low humidity compared to summer conditions.

The change in performance (i.e.; electricity output) is recorded 24/7 h, using a data logger. In this way, the optimum cleaning technique and frequency can be determined.

Table 2. Main characteristics and ratings of thin-film solar panels used in this study.

Parameter	Description
Length	1200 mm
Width	600 mm
Weight	12 kg
Thickness	6.8 mm
Area	0.72 m^2
Lead wire	4.0 mm^2, 610 mm
Cell type	CdS/CdTe semiconductor, 154 active cells
Cover type	3.2 mm heat strengthened front glass laminated to 3.2 mm tempered back glass
Encapsulation	Laminate material with edge seal
Nominal power (+/−5%)	85 W
Voltage at P_{max}	48.5 V
Current at P_{max}	1.76 A
Open circuit voltage	61 V
Short circuit current	1.98 A
Temperature coefficient of P_{mpp}	−0.25%/°C

Table 3. Cleaning schedule of daily, weekly, and monthly cycles (every day in the first week).



The experimental block diagram of this study is shown in Figure 2 in a simplified manner. The five modules utilized in this study are thin-film type. During the experiments, the five PV modules were connected to the SOL.Connect® measurement system, which integrates the ISET®-mpp meter measuring board as well. The PV modules are operated in MPP and are measured simultaneously under identical conditions. The measurement data are collected by the SOL.Connect® data logger. Therefore, each PV module is monitored separately.

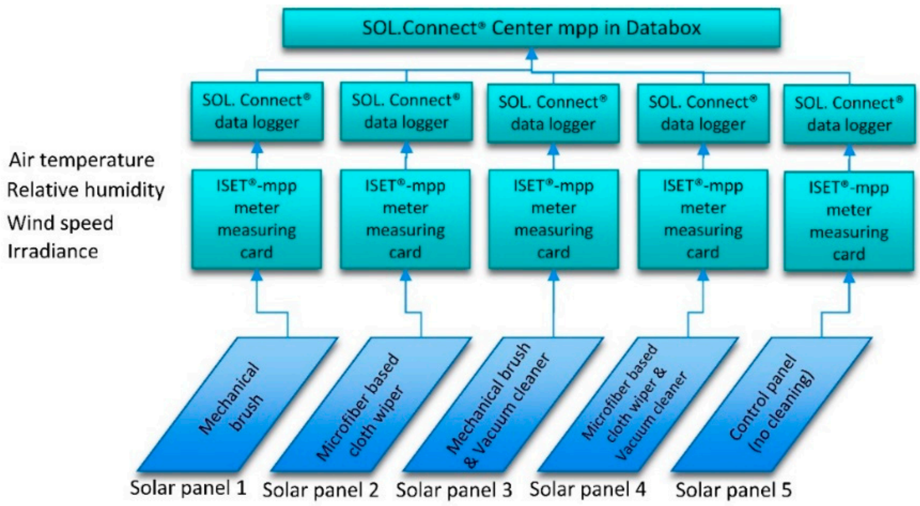


Figure 2. Simplified experimental block diagram of this study.

3. Results and Discussion

The results and discussion section presents the main findings from the thin-film PV module cleaning experiments in the field. The results are separately presented for the daily, weekly and monthly cleaning periods. Most of the literature studies reported the change in power output or energy yield with respect to an uncleaned PV panel as well as status before and after the cleaning. Similarly, this method is employed in this study having a control panel, which is kept uncleaned during the considered cleaning frequency. For example, after daily cleaning experiments are finalized, the PV panels are completely cleaned with water in order to make sure there is a just comparison for the weekly cleaning schedule. In addition, here, the power outputs just after the cleaning are reported, which are then compared with the power output before the cleaning under the same irradiance levels. Therefore, it is a common and reliable approach for comparison purposes.

Figure 3 illustrates the output from the PV module for the daily cleaning schedule. It is shown that a complete improvement in all PV modules is available with respect to the control panel. Changes in days from 28 January to 1 February are because of the clouds on the sky.

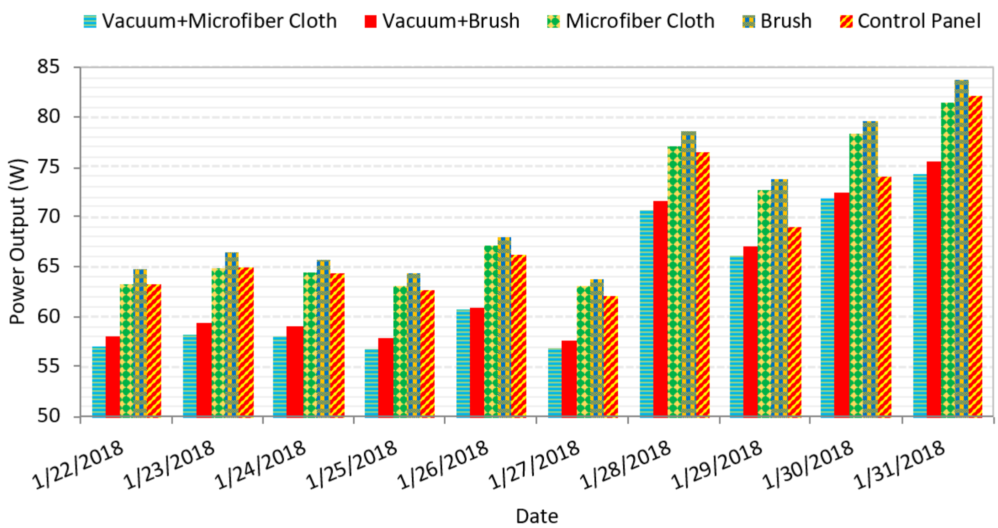


Figure 3. Comparison of daily power outputs of CdTe thin-film PV panels cleaned by various PV cleaning techniques as well as control panel.

The measured total irradiance values at the time of the cleaning for each day (of daily cleaning) are given in Table 4.

Table 4. Total plane of array irradiance values at the time of cleaning during the daily cleaning phase.

Date	22 January 2018	23 January 2018	24 January 2018	25 January 2018	26 January 2018	27 January 2018	28 January 2018	29 January 2018	30 January 2018	31 January 2018
Total irradiance (POA) (W/m^2)	895	920	917	904	952	917	805	1018	1021	1069

Figure 4 shows the changes in outputs of power with respect to the control panel. Here, the negative changes imply the power output difference between the control panel and measured panel. More important to note the difference between the days, because the dust accumulation on the control panel increases every day. On contrary, the cleaned panel power outputs become better compared to the control panel. Hence, the figure clearly shows the improvements in the power outputs as the days pass. The use of cleaning techniques improved the power outputs every day compared to the control panel. This is due to the accumulation of dust on the control panel, but in terms of other PV modules, the dust is removed every day. On February 1, there was a significant reduction in improvement, which was caused by rain. This eliminated the dust on the surfaces and led to less improvement.

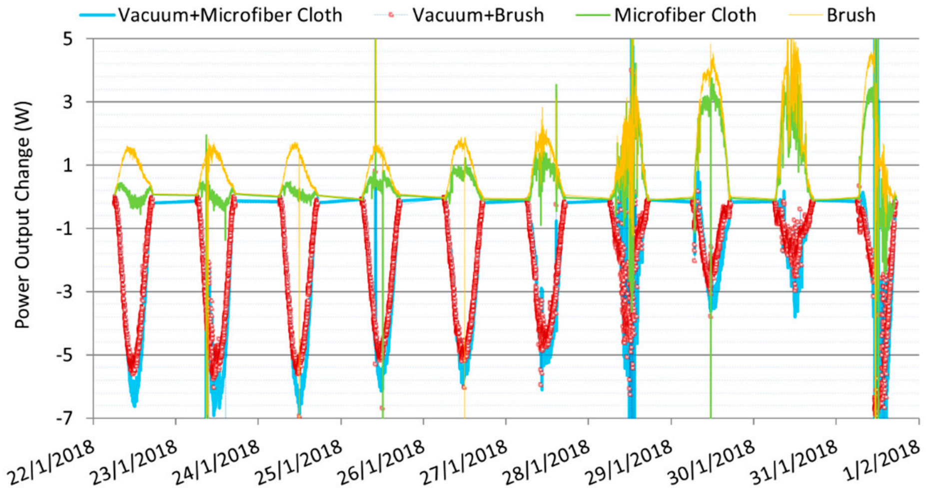


Figure 4. Comparison of normalized daily power outputs from CdTe thin-film PV panels cleaned by various PV cleaning techniques.

If the average of all cleaning techniques is considered, the improvement is about 0.5 W/day compared to the control panel. But this number is the average of all cleaning techniques and does not reflect the individual performances. When it comes to weekly cleaning, the performance improvements are more visible. Figure 5 shows the power outputs of the PV modules for the weekly cleaning cycle.

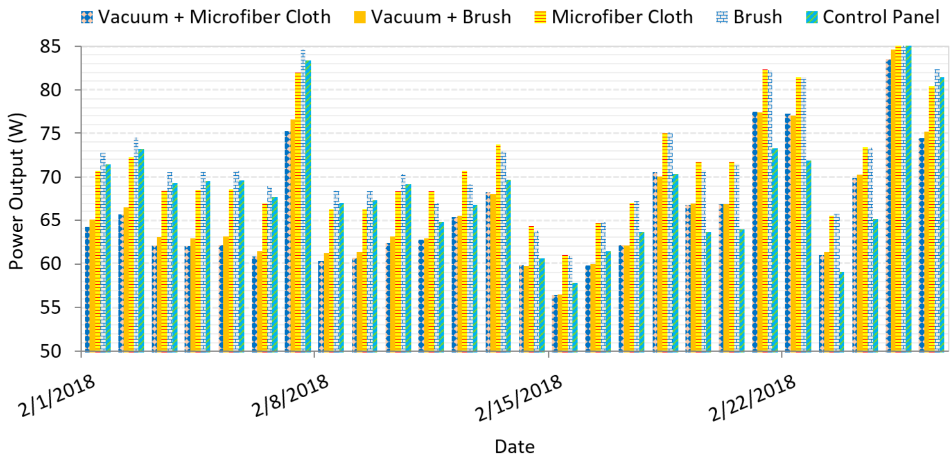


Figure 5. Comparison of weekly power outputs of CdTe thin-film PV panels cleaned by various PV cleaning techniques as well as control panel.

The measured total irradiance values at the time of the cleaning for each day (of weekly cleaning) are given in Table 5.

Table 5. Total plane of array irradiance values at the time of cleaning during the weekly cleaning phase.

Date	31 January 2018	7 February 2018	14 February 2018	21 February 2018
Total irradiance (POA) (W/m^2)	932	879	808	870

For weekly cleaning, Figure 6 depicts the changes in panel outputs, which are standardized. There are three improvements peaks occurring on the cleaning day of the week. In Figure 6, the red line (representing brush cleaning) jumped from ~1.47 W to ~2.5 W after the cleaning on 2 November 2018. This corresponds to an improvement of about 1 W per week. Similarly, it jumped from ~4.55 W to ~8.2 W on 19 February 2018. This corresponds to an improvement of about 3.65 W in two weeks. This increase is the result of cleaning the panel on that day. As the daily frequency, weekly cleaning can also achieve close to 0.5 W/day improvement (average of all cleaning methods) with respect to the control panel. This number can be higher when the cleaning methods are considered individually.

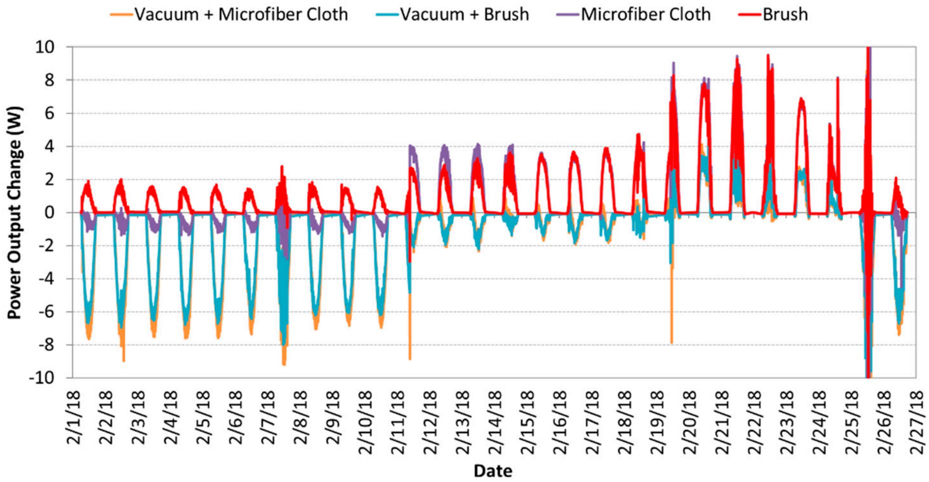


Figure 6. Comparison of normalized weekly power outputs from CdTe thin-film PV panels cleaned by various PV cleaning techniques.

Figure 7 depicts the performance of the PV modules during the last three days of the monthly cleaning frequency. There are only three days shown due to reflecting the improvements in a better way. As shown in the figure, the cleaning process was performed on April 2. It implies the power output change with respect to the control panel. As noted in Table 6, this period for the monthly cleaning had some rainfalls. Hence, the improvement was only 2 W (average of all cleaning methods) after the cleaning compared to the control panel. This is primarily due to the natural cleaning of all PV surfaces. It is expected to be higher under no rain conditions.

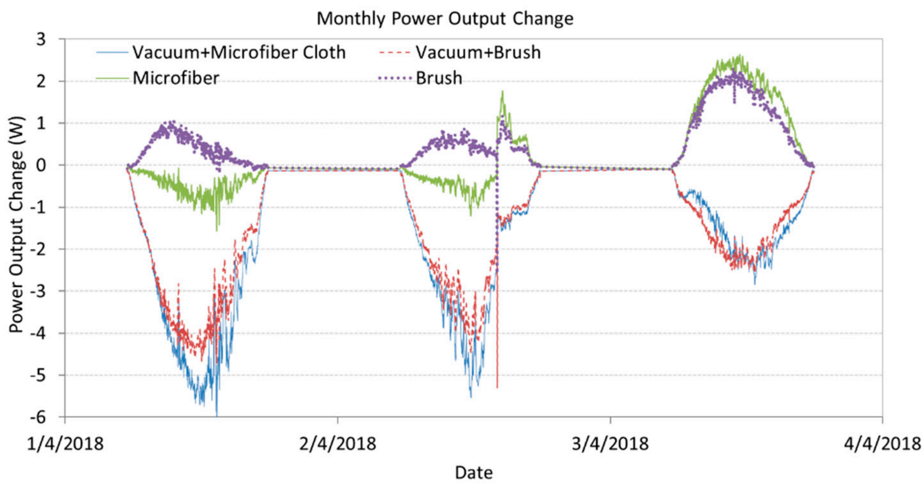


Figure 7. Comparison of normalized monthly power outputs from CdTe thin-film PV panels cleaned by various PV cleaning techniques.

Table 6. Percentage improvements (average of all) in power outputs after different cleaning frequencies.

Cleaning Frequency	Time	Improvement in Power Output (Compared to the Control Panel)	Details
Daily	(30 January 2018) First week	4.80% ± 0.95%	No rain
Weekly	(11 February 2018) Second week	5.10% ± 0.95%	No rain
Weekly	(19 February 2018) Third week	7% ± 0.95%	No rain
Weekly	(26 February 2018) Fourth week	11% ± 0.95%	Rain on 25/2/2018
Monthly cleaning	(2 April 2018) Eighth week	4.20% ± 0.95%	During a rainy period

It can be noted that 8th week of cleaning was in a rainy period, in which rain acts as a natural cleaner for all PV modules including the control panel. In this case, the relative difference between the cleaned PV modules and the control panel are not clear. Hence, the improvement was not as high as expected.

While daily cleaning provides excellent performance, it is by far the most expensive and energy consuming option compared to weekly and monthly cleaning. In comparison, cleaning on a weekly basis can deliver similar results to cleaning on a daily basis. In weekly cleaning, the cost and energy consumption are significantly reduced. The summary of percentage improvements for different frequencies is given in Table 6. The improvement rates given in Table 6 are calculated using normalization. The normalization for improvement rates is performed for each module based on the power output after cleaning and power output before cleaning at the same irradiance levels.

The improvement rates reported in this study are in the range of literature studies using mechanical cleaning techniques. For instance, Patil and Mallaradhya [35] reported 1.6% to 2.2% increase in power output, Bunyan et al. [36] reported power loss of 8.7% in the month of November and Abdallah et al. [37] reported about 15% decrease in energy yield after one-month dust accumulation. Similar to those studies, a power output of about 11% is observed in this study after 3 weeks of the uncleaned period on the thin-film modules. The weekly power loss was about 5.1% with respect to the control panel (uncleaned). Here, it is noted that the improvement potentials may vary based on the cleaning technique selected. Self-cleaning surface methods commonly yielded lower improvements in the literature compared to mechanical methods. This study shows that if the dry cleaning is properly applied, water usage can be eliminated for regular conditions. However, a thin layer of dust can remain on the PV surface unless the water is thoroughly used. This does not necessarily mean a significant loss in the energy yield. In addition, water can be used after a significant accumulation of dust in extreme conditions rather than regular utilization.

Most of the literature studies reported the change in power output or energy yield difference with respect to an uncleaned PV panel as well as status before and after cleaning. Similarly, we have selected this method and had a so-called control panel, which is kept uncleaned during the experiment period. In addition, we report the power outputs just after the cleaning and calculate the improvement by comparing the power output change before and after the cleaning under the same irradiance level. The reference point is the same for all modules. This was the main reason for employing a control panel. In this way, we eliminate the difference between each module. And the improvements due to cleaning are identified for each module. Therefore, it is a common and reliable approach for comparison purposes.

The improvement rates given in Table 6 are calculated using normalization. The normalization for improvement rates is performed for each module as follows:

$$\frac{Power\ output\ after\ cleaning - Power\ output\ before\ cleaning}{Power\ output\ before\ cleaning} \quad (1)$$

These normalized values are compared with the control panel.

The cost of cleaning is another significant parameter. Using operational costs, capitals costs, and equipment lifetime, the total cost is calculated for each cleaning method as listed in Table 7. Since the optimum cleaning frequency was one week, the table is prepared for weekly cleaning only. Obviously, for daily cleaning, the cost value would increase significantly. The capital cost and lifetime of cleaning apparatuses are determined based on the market price. Then, the cleaning period is fixed as one week. The number of cleaning apparatus usage is determined based on the lifetime and weekly cleaning period. The manual labor cost is taken as the average of Qatar conditions. For the electricity consuming methods, the grid electricity price is selected and the energy consumption is calculated using the power rating and duration of the cleaning process. The total cost is calculated based on the capital, operation and replacement costs. Then, the costs are normalized for the unit area and extended to the yearly cost of cleaning. As listed in Table 7, the maximum cleaning cost is estimated for the combination of vacuum cleaner and brush because of a longer period of cleaning and electricity consumption. The lowest cost per unit PV area is found to be about 21.1 USD/m^2/year. On the other hand, the highest yearly cost of cleaning is calculated for vacuum cleaner & brush combination corresponding to about 60 US $/m^2/year. This shows that with a combination of some techniques, it might be more complicated and high cost. In addition, for the combined methods, there is more time spent on cleaning, which increases the manpower cost.

Table 7. Estimated costs of selected PV cleaning methods for the weekly cleaning schedule.

Cleaning Equipment	Unit	Brush	Microfiber Cloth Wiper	Vacuum Cleaner & Brush	Vacuum Cleaner & Microfiber Cloth Wiper
Normalized Capital Cost	US $/cleaning	0.12	0.11	0.33	0.32
Duration of Cleaning Per Panel	minutes/panel	1	0.75	2	1.75
Electricity Cost of Cleaning Per Panel	US $/panel	0	0	0.000021	0.000021
Manpower Cost	US $/panel	0.25	0.19	0.5	0.44
Cost of One Cleaning Per Panel	US $/panel	0.37	0.29	0.83	0.76
Total Cost of One Cleaning Per Unit PV Area	US $/m^2	0.51	0.41	1.15	1.05
Energy Cost Lost Due to One Week Soiling on Per Unit PV Area	US $/m^2/year	0.0905	0.1423	0.1062	0.1224
Total Yearly Cost of Cleaning Per Unit PV Area	US $/m^2/year	26.42	21.07	59.76	54.45

Although there are various review studies on the PV cleaning techniques, the cost evaluations were not much performed. Hence, it is not easy to have an obvious cost comparison of the cleaning techniques. Some researchers used the cost of soiling rather than the cost of cleaning. For example, Solend [17] reported the cost of soiling corresponding to a value of about 0.12 US$ per panel. The cost input parameters were quite different in that study compared to this study. In addition, Electric Power Research Institute (EPRI) reported a PV cleaning cost range of 0.2 US$ to 0.325 US$ per panel [49]. Here, in this study, it is calculated a cost of 0.29 US$ for cleaning per panel when microfiber cloth wiper is used on a weekly basis. The frequency of cleaning as well as the surface area of the PV panel has a definitive role in the total cost of PV cleaning. For thin-film PV modules, a larger area is often required due to lower energy conversion efficiencies (compared to silicon types).

Since the temperature of the PV panels are quite significant for the performance, the cell temperatures T_c are calculated based on the following correlation [50]:

$$T_c = T_o + I_{rPOA}\, e^{(-3.473-0.0594\times v)} \tag{2}$$

where v is wind speed, T_o is ambient temperature and I_{rPOA} is the irradiance on plane of array.

All of these parameters are already measured during the experiments. The wind speed measurements for daily and weekly cleaning phases are illustrated in Figure 8. The average wind speed was 2.556 m/s during the daily cleaning cycle, whereas the maximum wind speed was measured as 7.5 m/s as shown in Figure 8a. On the other hand, the average wind speed during weekly cleaning was 2.268 m/s, although the maximum wind speed reached to 7.4 m/s as shown in Figure 8b. Although there is wind speed data at 5-m height, in order to reflect the PV panel level, 2-m height is used.

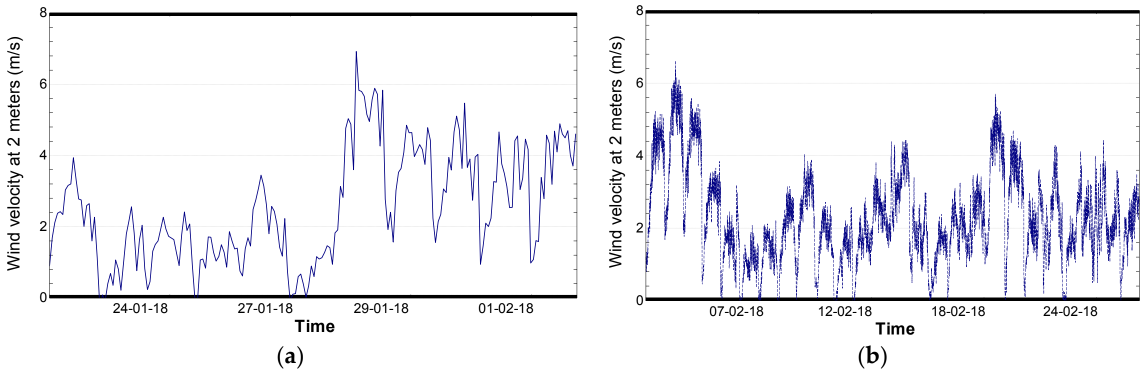


Figure 8. Variations in the wind velocity during (**a**) daily cleaning and (**b**) weekly cleaning phases.

Using the correlation for the PV panel temperature, the daily and weekly temperature variations are calculated as illustrated in Figures 9 and 10, respectively. The average cell temperature during daily cleaning was 34.75 °C, whereas the maximum was 56.94 °C. The average ambient temperature was 20.63 °C as shown in Figure 9.

In February, when weekly cleanings were performed, the average ambient temperature was 23.23 °C. However, the PV cell temperatures reached up to 60 °C as shown in Figure 10. Soiling decreases light transmission over the PV glass, which reduces the cell temperature slightly. Therefore, just after the cleaning, higher cell temperatures were observed in general.

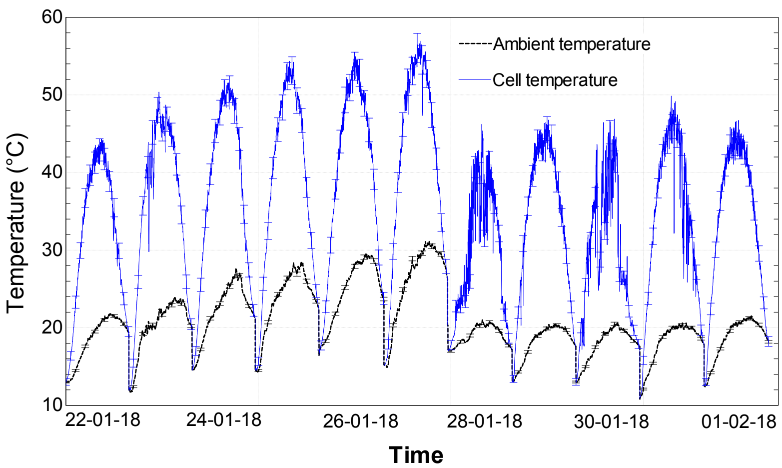


Figure 9. Variations of ambient and cell temperature during the daily cleaning phase.

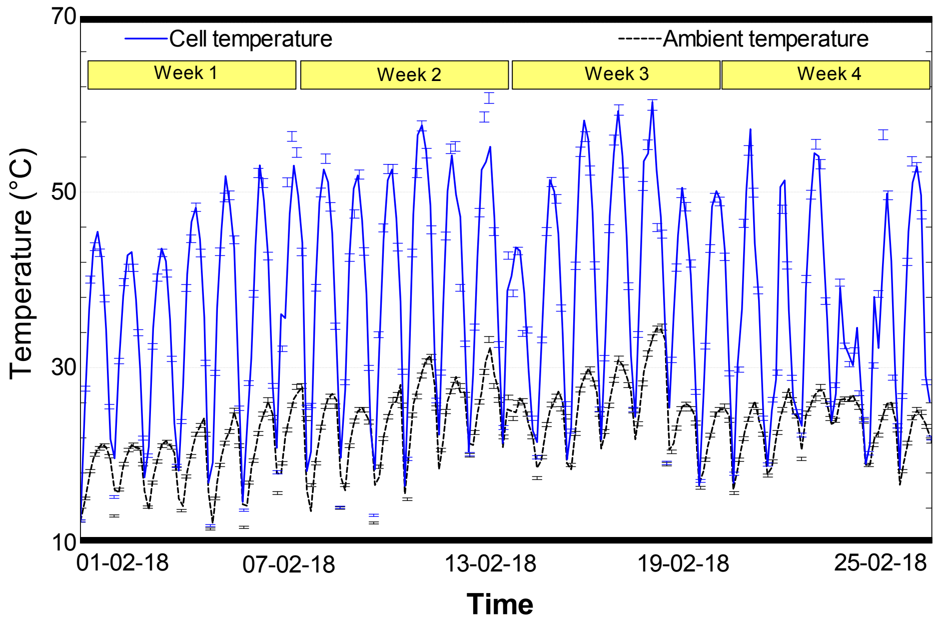


Figure 10. Variations of ambient and PV cell temperature during the weekly cleaning phase.

In this section, we rank the PV cleaning techniques employed in this study based on the cleaning efficiency, price, time and maintenance features as shown in Figure 11. The brush has the lowest cost and low maintenance of all cleaning methods. Nevertheless, the brush does not perform highly operative on the PV surface, mainly due to the brush being able to break the dust off the panel but not being able to wipe it off the panel. The dust particles can still remain on the surface unless not removed with extra force and time. It is also important to note that depending on the brush type, there can be scratches on the PV panel surface in case higher forces are applied. This can cause issues in the transmission of the light in the long-term. However, there are some detailed studies by Al Shehri et al. [28,29] in which they compared different type of brush materials including silicon rubber, nylon, and cloth. Their results implied that dry cleaning using nylon brushes did not have a significant, permanent effect on the optical characteristics of the glass surface, even when the brush was employed to clean a dusty surface.

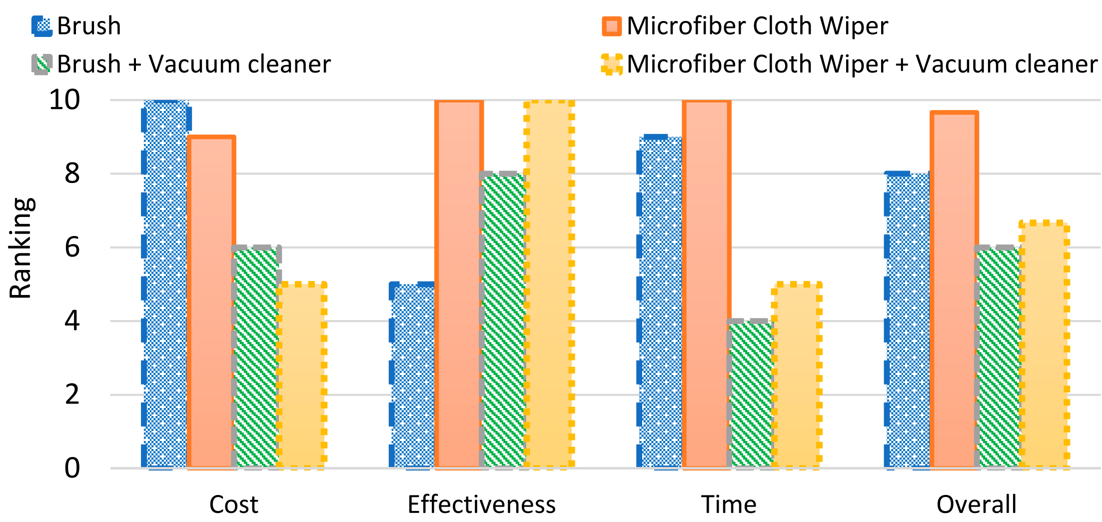


Figure 11. Assessment of various dry PV cleaning techniques from cost, effectiveness and time point of view.

4. Summary and Conclusions

In summary, five panels were tested with four different dry-cleaning methods (brush, microfiber-based cloth wiper, a combination of a brush and a vacuum cleaner) in addition to a control panel. The CdTe type PV panels were cleaned in the winter conditions of Qatar. Each cycle has been tested with three different cleaning frequencies. The first frequency is daily cleaning for a duration of a week. The second frequency is weekly cleaning for four weeks. The last frequency is monthly cleaning. The major findings of the experiment are as follows:

- A microfiber-based wiper, as well as microfiber & vacuum cleaner combination, perform the most effective corresponding to about 6% improvement (compared to control panel) for a weekly period. However, due to the increased cost of adding a vacuum cleaner, the microfiber-based wiper is the most efficient method when both cost and improvement are considered.
- Cleaning frequency selection is heavily dependent on the climate conditions of the site where PV panels are located. In addition to climate, local conditions such as buildings, construction, and vegetation also have effects on the cleaning frequency.
- A single brush does not perform well without water, which yielded about 3% improvement increase over a week due to dust particles remaining on the surface; however, when worked in tandem with a vacuum cleaner, the results show better improvements (5.4% over a week).
- In a large-scale PV power plant, the removed dust from a single PV panel can settle down on the neighboring panel if not properly taken away. Hence, vacuuming the dust can be an alternative depending on the dust settlement structure (not muddy) and reasonable (clean, low-cost, etc.) energy supply.
- After each cleaning session and in all the methods, since water is not used, there is still a thin dust layer on the PV surface. However, if the frequency is kept shorter, the impact on the power output was observed to be minor.
- The cost of cleaning per panel is calculated as 0.29 US \$ (or 0.41 US \$/m^2) when microfiber cloth wiper is used on a weekly basis.
- The frequency of cleaning as well as the surface area of the PV panel has a definitive role in the total cost of PV cleaning.
- Rain is a good natural cleaning method for solar panels.

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Nomenclature

I	Current (A)
I_r	Irradiance (W/m^2)
P	Power (W)
T	Temperature (C)
V	Voltage (V)
v	Wind velocity (m/s)
Acronyms	
CA	Contact angle
CdS	Cadmium Sulfide
CdTe	Cadmium telluride
DHI	Direct horizontal irradiance

DNI	Direct normal irradiance
MPPT	Maximum power point tracking
NASA	National Aeronautics and Space Administration
PV	Photovoltaic
QSTP	Qatar Science and Technology Park
STF	Solar Test Facility
Subscripts	
C	Cell
Max	Maximum
Mpp	Maximum power point
o	Ambient
oc	Open circuit
POA	Plane of array
sc	Short circuit

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