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Review

Cleaning of Floating Photovoltaic Systems: A Critical Review on Approaches from Technical and Economic Perspectives

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Abstract: There are some environmental factors, such as ambient temperature, dust, etc., which cause a reduction in the efficiency of Photovoltaic (PV) systems. Installation of PV panels on the water surface, commonly known as Floating Photovoltaic (FPV) systems, is one solution to employ PV panels in a cooler environment, achieve higher efficiency, and reduce water evaporation. FPV systems open up new opportunities for scaling up solar generating capacity, especially in countries with high population density and valuable lands, as well as countries with high evaporation rates and water resources deficiency. Since the FPV system is an almost new concept, its cleaning techniques have not been comprehensively studied. While FPV systems are located on the surface of water resources and reservoirs, the water quality can limit the application of different cleaning techniques. Therefore, this paper investigates different techniques of FPV systems cleaning and categorizes them into water-based and water-free approaches. In addition, their cleaning frequencies, as well as economic aspects, are presented and discussed to determine their merits and demerits for using them in FPV systems.

Keywords: dust accumulation; Floating Photovoltaic (FPV) systems; Floating Photovoltaic (FPV) cleaning techniques; soiling; water-based cleaning approaches; water-free cleaning approaches

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Citation: Zahedi, R.; Ranjbaran, P.; Gharehpetian, G.B.; Mohammadi, F.; Ahmadiahangar, R. Cleaning of Floating Photovoltaic Systems: A Critical Review on Approaches from Technical and Economic Perspectives. *Energies* **2021**, *14*, 2018. https://doi.org/10.3390/en14072018

Academic Editor: Alberto Dolara

Received: 25 February 2021
Accepted: 26 March 2021
Published: 6 April 2021

1. Introduction

The increased energy consumption and global warming concerns have encouraged governments to promote the installation of Renewable Energy Sources (RESs) [1–3]. Due to the sustainable development goals of the 2030 agenda about increasing the share of RESs in the global energy mix, their development is imperative [4,5]. Because it is abundant and free of fuel costs, solar energy is a promising energy source that has attracted wide attention, so that a variety of its applications, including Photovoltaic (PV) panels, has been developed [6–9]. PV panels are capable of converting solar irradiation into electricity [10–12]. One of the most prominent aspects of PV systems is that they are environmentally friendly and have near zero CO_2 emissions [13–15]. In addition, the long-term perspective of PV systems due to their ongoing quality improvement and cost reduction is promising [16–19].

It is well-known that dust accumulation is one of the most important issues that have a negative impact on the performance of PV panels [20,21]. Dust accumulation and soiling reduce the transmittance of the glass cover, and accordingly, decrease the efficiency of PV panels [22,23]. By reducing the incoming solar radiation, the dust accumulation causes a decline in the power generation of panels by up to 15% per day [24]. Such a reduction in the efficiency of PV panels can reach up to 30% in dusty regions considering particle diameters and the PV panel slope [25]. The highest deposition rating occurs when the diameter of particles is about 10 µm and the lowest rating occurs when the diameter is 50 µm, approximately [26]. It has been shown in [27] that the dust accumulation rate of the upward PV panels is higher than for downward ones, and it has been observed that the peak of the accumulation rate belongs to 150 µm dust particles for all tilted PV panel angles. Dust accumulation is the most crucial subject in arid regions, which have the desired irradiation. In this regard, pervasive dust, sand storm, and insufficient rain causing deposition of dust on panel surface all affect PV panel operation [28–32]. In many cases, the dust deposition on the surface of PV panels leads to mismatch losses, which in turn creates hotspots that may damage PV panels, and therefore, reduce the lifespan of the PV system [33].

To reduce the undesirable effect of soiling, there are many water-based and water-free techniques for cleaning the surface of panels [34,35]. A water-free approach based on the electrostatic force has been proposed in [36] to remove sand from the PV panel surface. This solution is suitable for desert areas at low latitudes. Different techniques of cleaning PV panels involving the water-free approach with robotic systems have been reviewed in [30]. A water-free automated technique for cleaning PV panel surfaces has been developed in [24]. The outcome of this study indicated that the proposed technique can boost the efficiency of the system by 9.05%. A non-pressurized water system has been studied in [37] and accordingly, its cleaning impact on the performance of PV panels has been assessed. It illustrated that the efficiency of PV panels decreased by 50% after 45 days. The impacts of extreme dust and smoke accumulation on the output power of PV panels in the Western Mediterranean have been estimated in [23]. In [38], different aspects of the application of the PV cleaning techniques in arid and dusty climates, where the dust accumulation is extreme, have been empirically studied.

The efficiency of PV panels is affected by environmental factors, such as the ambient temperature, dust accumulation, partial shading, etc. [39,40]. The increase in ambient temperature causes an increment in the temperature of cells, which in turn leads to a decrease in the total efficiency. It is indicated that the efficiency of monocrystalline (c-Si) and polycrystalline (pc-Si) panels declines by around 0.45% for each degree of increase in cell temperature [41]. The Floating Photovoltaic (FPV) system is a solution to this limitation. The cooling effect caused by placing PV panels on the water surface reduces their temperature, which in turn leads to energy efficiency enhancement [42–45]. In addition to this merit, FPV systems have many other advantages, such as water evaporation reduction, land cost-saving, improving water quality, and less dust effect [34,46].

As discussed above, soiling decreases the PV panel output power and also reduces the lifespan of the panels. Therefore, investigating various aspects of soiling and cleaning of PV panels has been the topic of a variety of research studies. However, those studies have not been conducted considering the land-based PV panels' condition, and lack of a comprehensive review taking the FPV system conditions into account is felt. Floating of PV panels and the application of cleaning techniques are two possible solutions to increase the output power of PV panels. Although FPV panels have less of a soiling effect, they still need to be cleaned to be more efficient and cost-effective, especially in arid regions. Therefore, in this paper, cleaning techniques applied to FPV systems are assessed and divided into two different approaches based on the utilization of water or not in cleaning the panel surface.

The organization of this paper is as follows: In Section 2, the reasons for the development of FPV systems are explained. Then, various cleaning techniques are introduced in Section 3. In Section 4, the time interval of cleaning of PV panels is investigated considering the location of FPV systems. In Section 5, the economic aspects of cleaning PV panels are assessed. In the next section, the results of the study are presented, and in the final section, conclusions and recommendations for future work are discussed.

2. FPV System Development Purposes

Land-based PV systems require a large area of vast land (about 8 m^2 per 1 kW). This can decrease the interest in many countries because the lands needed for PV systems installation may be expensive. Furthermore, the efficiency of PV panels is characterized by a specific maximum power thermal coefficient expressed in %/°C [47]. This coefficient is negative for commercial PV panels, which means that by increasing PV cells' temperature, the efficiency of cells is reduced. Based on the aforementioned reasons, FPV systems can offer a synthetic solution for the conservation of valuable lands and increasing energy generation [48]. In the countries where FPV systems are used for energy generation, companies have developed this technology in order to gain the maximum energy based on the power generation equation of PV panels [49].

Under normal conditions, two factors that limit the energy generation of PV systems are: (1) the high operating temperature of PV cells and (2) any reduction in the solar irradiation incidence on the PV panel due to soiling. Therefore, PV panels should be periodically cleaned, usually by water. The use of non-fresh water can increase the soiling. Consequently, an extra water source must be provided for cleaning FPV systems, which are usually placed on the surface of non-fresh water reservoirs. Due to water scarcity in some areas, cleaning becomes difficult, challenging, and subsequently costly.

Because of the low cost of fossil fuels in oil-rich countries, using RESs is not a preferred method for energy generation. In addition, access to the vast lands for the Middle East and North Africa (MENA) countries is not a problem. For most of these countries, which are located in arid and semi-arid regions, water security is an important priority. Some of the anticipated impacts of climate changes in these countries are droughts and amplified heat waves, which accelerate the evaporation of open water resources and reservoirs [50]. Therefore, the water stored in reservoirs can be better managed if surface evaporation losses can be reduced. Covering the surface of the water with FPV systems allows these countries to tackle their water deficiency. Depending on the covered surface, FPV systems can reduce water evaporation up to 80% [50]. Furthermore, this solution can provide other advantages as follows:

- The power generated by FPV systems can be used as an income source.
- The long-time warranty of solar equipment decreases the maintenance costs and if FPV systems are installed on dam lakes, the saved water can be utilized for load peak shaving.

Companies in these countries are developing such a technology to achieve maximum water loss reduction based on the Penman equation and its derivatives [51].

3. Cleaning Techniques

Many research studies have been conducted on various techniques for cleaning PV panels using water. In addition, much effort has been made on the development of water-free approaches. Such integrated studies are becoming an important solution to yield more electricity and saved water. By reviewing different studies, cleaning approaches of FPV systems can be generally categorized as water-based and water-free.

3.1. Water-Based Approaches

The first method for cleaning a PV system on the surface of a water reservoir is the water-based approach. The slope of PV panels in FPV systems is lower than in land-based systems. Therefore, dust tends to sit on panels, and the rate of soiling is higher than for land-based PV systems. In the case of using fluids for cleaning, to prevent thermal shock, it is better to keep the temperature of the cleaning fluids close to the temperature of the PV panel surface [52]. Many FPV systems are floated on the surface of freshwater bodies. As a result, the temperatures of the PV panel surface and the reservoir water are close, particularly in the morning. This water can be simply utilized for cleaning. Also, due to the return of utilized water to the reservoir, the water loss during the cleaning process is very low, especially in the morning and night.

3.1.1. Rainfall

PV panels can naturally be cleaned by rain, but the cleaning effectiveness varies based on the amount of rain. Generally, when the rainfall is heavier and the period is longer, the cleaning effect is greater. However, no correlation between the amount of rain and efficiency variation has been observed [53]. Considering rain events, an experiment has been conducted in [54] to investigate the impacts of soiling on the generated power by the PV panel over a five-year period. It has been noticed that soiling can reduce the annual generated power by up to 3%, and rain can clean and improve the generated power by PV panels up to 1% of their full power rating. In [55], it has been shown that during dry months, PV panels' output can drop by 6% and an adequate amount of rainfall can effectively clean PV panels and restore their output power. It should be noted that due to the irregular patterns of rainfall, a definite amount of rainfall for cleaning all PV panels cannot be accurately determined [53]. In addition, it has been observed that the efficiency of PV panels can decrease after a light rainfall. The rainfall water tends to run off of upper PV cells onto the lower cells, taking some dust with it, which allows more soiling to stick in lower PV cells [56]. The slope of the PV panel affects the speed of soiling loss and the amount of rainfall cleaning. The efficiency changes of 186 PV panels have been monitored in [57] and it has been noted that the average soiling losses for the entire system with a slope that is smaller than 5° and larger than other systems. In rainfall conditions, the dust quantity on the surface of PV panels can be different due to different angle differences between the rainwater line and the PV panel surface [57].

3.1.2. Manual Cleaning

The first and most reasonable technique for removing soils is to manually clean them by washing or wiping. In many regions, natural weather assistance, such as rainfall and snow, is not so widespread, and accordingly, human labor must be employed. For this purpose, a simple cloth can be used to clean the surface of PV panels [53]. This technique needs frequent and repeated procedures and can extremely be labor-intensive. If the surfaces have to be cleaned by human labor, non-conductive materials, such as brushes, clothes, etc., should be utilized to prevent any electrical injuries and reduce the risk of electric shock. A wide range of diverse devices is available for manual cleaning assistance. The cleaning devices usually consist of telescopic rods and cleaning brushes, which are fixed to the top of the rod. The Tucker pole is a prevalent hand cleaning device for PV panels and windows, which consists of a hand nylon brush and a water flow system, as shown in Figure 1a [58]. This device allows ten teams of two people to clean 10,000 PV panels in 8 h. As illustrated in Figure 1b, PV-Spin is another cleaning device that works based on a piston motor and two durable rubber brushes rotating in opposite directions with a water pressure system [59].

Despite the enormous growth of the PV industry, the manual cleaning of PV panels has maintained a relatively large share among cleaning techniques. Small-scale PV systems are still being cleaned manually by a bucket, soap, and water at a rate of roughly 1 m^2/min [60]. For manual cleaning of larger PV systems, a fire truck has been employed in a water-intensive and non-specific cleaning process [60]. Water consumption depends on the environmental conditions. For instance, water consumption of 0.5 L/m^2 for PV panels in the Middle East area has been considered in [61].

Figure 1. Tucker pole (**a**) and PV-Spin (**b**) devices for manual cleaning [62,63] (reprinted with permission from the corresponding companies).

3.1.3. Self-Cleaning

The self-cleaning method can be used as either water-based or water-free approaches. In water-based approaches, high-pressure sprinklers can be utilized for self-cleaning of PV panels, as shown in Figure 2. The sprinkler systems are often used in an automated manner and in arid regions to keep PV panels clean [64]. In addition, the sprinklers can use a mixture of water from a filtration system and a soap dispensing system for more efficient cleaning.

Figure 2. Sprinkler cleaning system [47] (reprinted with permission from Elsevier).

The sprinklers can be employed as a multi-objective method for cleaning and cooling [65]. In this case, their cooling system can work at a pressure of 2–3 bar, but they cannot spray the whole surface of a PV panel, which means only some parts of it can be cooled [47,66].

3.1.4. Robotic

Utilizing autonomous robots is one of the promising ways to efficiently clean PV panels. Robots are widely employed for cleaning tasks. One of the most famous ones is RobuGLASS that works based on a water-based approach and has been designed to clean the glass pyramid entrance of the Louvre in Paris, France [67]. For cleaning PV panels, cleaning robots should be operated on the surface of PV panels. On the other hand, PV panels are sloped with an angle for better absorption of solar irradiation. Therefore, the robots must provide an adherence mechanism for walking on the PV panel surface. The attachment mechanisms which are developed for robots to walk on sloped surfaces are classified into two main types [68]. Suction adhesion is the most prevalent type, where the robot creates a vacuum inside cups, which are pressed against the surface [69,70]. Magnetic adhesion is another prevalent type of adhesion mechanism [71]. For magnetic adhesion, the surface must be ferromagnetic, which is not feasible for PV panels. The robots utilized for cleaning are usually symmetrical, and their weight is uniformly distributed, which increases the stability of the robot on the PV panel [72]. The heavyweight of some existing autonomous robots in the global market makes them inefficient for cleaning PV panels. Utilizing robots without human intervention can decrease water wastage for cleaning [73]. Moreover, the water sprayed during cleaning can further increase the efficiency of PV panels by up to 15% due to its cooling effect [74].

The soiled layer on the PV panel surface can be composed of sand, construction, rock, bird droppings, and traffic emissions with the function of moisture, oil, fog, and mist. Depending on the installed configurations, the thickness of the layer can vary. Therefore, the soiling pattern recognition abilities and understanding the level of soiling should be taken into consideration [75]. An optimized dust absorbing structure for better performance of the PV panel cleaning robots based on the mechanical behavior of the dust particles and the relationship between the dust particle velocity and the pressure distribution has been designed in [37]. It must be noted that the more robots become autonomous and precise, the more their initial cost increases.

The power consumption of cleaning robots is varied due to the slop of the PV panel, wind speed, and thickness of the soiled layer. In [76], a portable robot with soft microfiber and controlled airflow has been designed and implemented, and it has been shown that the robot power consumption increases as the wind speeds up.

3.2. *Water-Free Approaches*

After soiling, strong chemicals or mechanical bonds can develop on the surface of PV panels. For more effective cleaning, different chemical solutions and various water quality can be utilized. Using chemical solutions for FPV systems cleaning can pollute the reservoir. Therefore, it is not desirable in all cases. In [77], different chemical solutions and water qualities/sources have been evaluated, and it has been shown that the use of demineralized water gave the best result, which can minimize the deposition of other extrinsic materials carried by the proposed solution. As mentioned before, some FPV systems are floated on non-fresh water reservoirs. Due to water scarcity in some areas, providing demineralized water for cleaning becomes a severe problem.

Water-free techniques can impressively reduce water consumption for the cleaning of the system, but they cannot completely eliminate water usage in the cleaning process. However, it becomes very helpful under conditions when the application of the water-based cleaning approaches is not feasible.

3.2.1. Airflow

Wind can naturally remove PV panel soiling, and consequently, keep the solar irradiation absorption high. As a result, estimating the wind effect on cleaning the accumulated dust of the PV panel surfaces is a precious study topic. The wind cleaning process has been investigated in [78], and a model for particles attached to a flat surface including particle adhesion and hydrodynamic forces, and torque, has been developed to investigate the impact of wind speed on the resuspension of dust particles from the PV panel surface. The bonding mechanism between soiling and the PV panel surfaces depends on the environmental conditions, dust characteristics, contact surface area, and surface treatment [79]. In arid regions, the Van der Waals forces between PV panel surfaces and dust particles are dominant, while the adhesion mechanism dominates under high relative humidity, accounting for up to 98% of the total forces [80].

Removing the soiling without making any physical contact with the surface is one of the favored options for cleaning surfaces. In addition, imparting high-velocity turbulent airflows onto the soiling as a non-contact approach can clean the fine particles from a surface [81]. Different studies have been conducted to produce turbulent airflows via different devices, such as butterfly valves, roller rotating disks, and wheel-blade assemblies.

A rectangular nozzle for the resuspension of spherical particles on flat surfaces by pulse air jets has been investigated in [82] and successfully cleaned fine particles. To gain better performance in comparison with the air knife in dry conditions, a multi-stage expansion nozzle has been developed in [83], and its performance has been evaluated by the Monte Carlo model. The results have shown a 7.86–17.70% increase in the dust removal rate. The dust removal ability of a polycarbonate disk surface has been studied in [84] and it has been noted that the rotational speed and dust particle size significantly influence the rate of dust removal from the panel surface.

Although the airflow can be utilized for dust cleaning, it also increases the rate of dust accumulation for the clean PV panels. In this regard, the numerical analysis of the airflow, particle concentration, and dust accumulation effect on a rooftop PV system efficiency has been conducted in [20]. The results have shown that PV efficiency reduction for a windward roof is higher than for a leeward roof. Additionally, by increasing the wind speed, the differential pressure on PV panels increases, which can create cracks on the PV panel surface. Installing windbreaks with different porosity can drop the pressure on PV panels by up to 50–68% (as shown in Figure 3) [85].

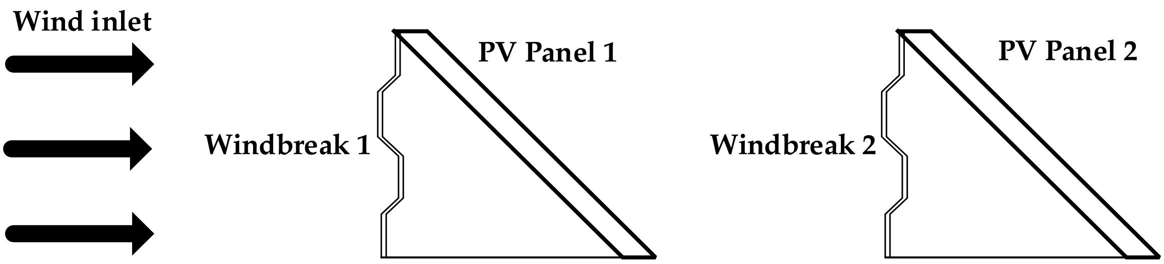


Figure 3. Physical model of a windbreak for PV panels.

3.2.2. Coating

Coating techniques are utilized to shield surfaces from the undesirable effects that can change the surface features of substrates, such as corrosion resistance, adhesion, wettability, and wear resistance [15].

The surface wettability on a flat surface is derived by calculating the Contact Angle (CA), θ, of a water droplet using the following equation [86].

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}, \quad (1)$$

where γ_{SV}, γ_{SL}, and γ_{LV} are the interfacial tensions of solid-vapor, solid-liquid, and liquid-vapor, respectively.

In general, if $CA < 90$, the solid surface is termed as a hydrophilic surface, and when $CA > 90$, the surface is defined as a hydrophobic surface. Coating techniques are classified into two main types: (1) superhydrophobic, which has a water contact angle of more than 150°, and (2) superhydrophilic, which has a water contact angle of less than 10° [35].

For hydrophobic surfaces, low surface energy materials, such as silicones, silanes, nanoparticles, and polymers, are utilized because of their water-repelling features. Superhydrophobic surfaces are cleaned based on the "Lotus-effect". In the "Lotus-effect", water spilled on a superhydrophobic surface simply rolls off. As a result, the surface does not become wet. Additionally, while water is moving across a superhydrophobic surface, it picks up the dust.

Many studies have been carried out to prove the soil-preventing features of superhydrophobic surfaces. A high optical transparent and flexible superhydrophobic film with a contact angle of 154.6° has been fabricated in [87]. The PV panels' efficiency remains at 95.8% of its initial value after covering them with the superhydrophobic film, which is about 1.7 times higher than the same PV panels covered with dust in practical conditions. A micro-shell array in a perfectly ordered manner on a Polydimethylsiloxane (PDMS) substrate for PV panels has been fabricated in [88], and the cleaning behavior of the PDMS with micro-shell compared with a flat PDMS substrate without micro-shell has been evaluated. The efficiency of the micro-shell PDMS displays a 71.8% recovery rate and the flat PDMS shows a 13.6% recovery rate after cleaning the carbon powder through sloping at an angle of 45°. A superhydrophobic coating for the PV panel cover glasses based on aluminum oxide coatings with a static water contact angle that exceeded 160° has been produced in [89]. The superhydrophobic coating has recovered the efficiency of the soiling contaminated PV panel by more than 90% after being cleaned by water.

Due to the excellent wettability features of high surface energy materials, they must be considered for synthesizing superhydrophilic surfaces. There have been many attempts to obtain superhydrophilic surfaces by utilizing the photocatalytic feature of titanium ethoxide composite layers [90–92]. A superhydrophilic coating obtained from KH550 and titanium ethoxide has been developed in [93], and it has been noticed that the water contact angle, provided by the glass sheet coated with these two layers, was lower than 5°. The PV panels' efficiency has increased by a maximum of 4.3% in the first month using the developed superhydrophilic coating. In [94], silica nanoparticles have been coated over the PV panel glass to prevent soiling on it. The increase in porosity and roughness of the thin film surface made the glass substrate optically well-transparent and superhydrophilic, and it enables the PV cell to receive 7% more irradiation. In [95], the development of a glass surface via a simple bottom-up nanopatterning technique and consequent surface energy efficiency drop has been presented. The results have shown only a 1.39% drop in the PV panel efficiency during an outdoor test for 12 weeks, while the PV panel with bare glass packaging has shown a 7.79% efficiency drop.

3.2.3. Self-Cleaning

The technique of forced airflow of air-conditioner return air uses the pre-cooled returned air of air-conditioners for cleaning and removing the heat from PV panels. This water-free approach uses a convection mechanism for cooling, which is applicable for arid regions, such as the United Arab Emirates (UAE) [96]. The performance procedure of this technique is shown in Figure 4.

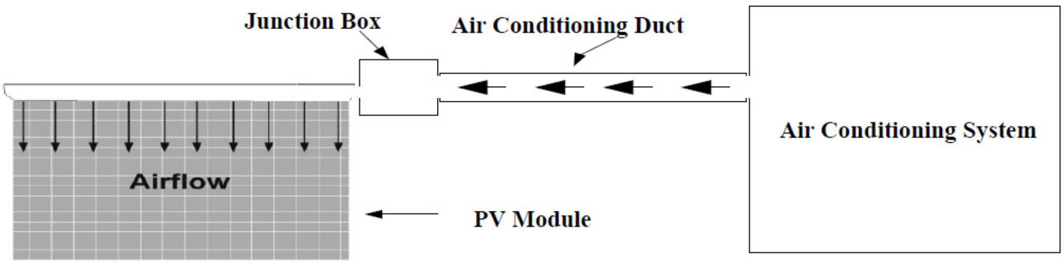


Figure 4. Performance procedure of forced airflow of air-conditioner return air technique [24] (reprinted with permission from Elsevier).

3.2.4. Electrodynamic Screen

An Electrodynamic Screen (EDS) utilizes the electrodynamic force generated by parallel electrodes to clean the soiling on the PV panel surface. A single-phase or multi-phase voltage is applied to the electrodes to generate a traveling or standing wave. Such waves can generate an electric field, and the vertical component of this field can lift off the charged particles and sweep them to the edge of the screen. Utilizing electrostatic force for transporting particles has been developed in [97]. In [98], it has been shown that electrode widths, spacing, applied voltages and frequencies, and angle of the surface affect the achievement in the efficiency of soiling removal. For a flat surface, EDS can remove more than 90% of deposited soiling during two minutes of operation [99]. Based on simulation and experimental evaluations, it has been noticed that the power consumption of the EDS is much lower than the generated power of PV panels (<0.1%) [100]. A typical schematic of the EDS is shown in Figure 5.

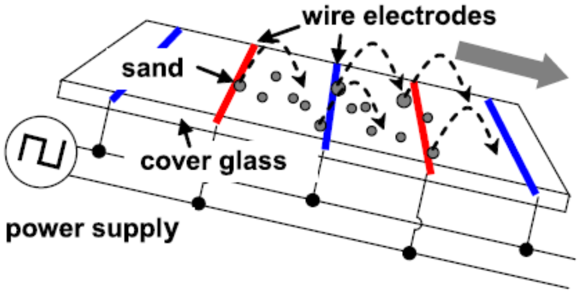


Figure 5. Schematic diagram of the EDS cleaning system for soiling removal of a PV panel [36] (reprinted with permission from Elsevier).

Different concepts for the control of the soiling removal process have been investigated based on single-phase rectangular high voltage applied to parallel-plate insulated electrodes printed on a substrate [36,101]. A single-phase voltage cannot generate a traveling wave, and it can only levitate particles on the curtain, but not cause net transport. When the electrodes are connected to a multi-phase AC voltage, a traveling wave is created, which makes the dust particle move along the surface following the electric field. In this way, particles cannot deposit on the surface. The traveling waveform of the EDS has been developed for space applications [102]. In this case, expensive electrode materials, such as dielectric polymer film and indium tin oxide, have been utilized and make this method sophisticated and costly for large-scale PV systems.

In [103], a four-phase rectangular voltage has been applied to a transparent conveyor through transparent indium tin oxide electrodes printed on a glass substrate. However the soiling removal efficiency of 98% has been achieved, the proposed solution can be costly and complicated for large-scale commercial PV systems. In [104], it has been demonstrated that more than 94% of the soiling on a PV panel can be removed by a 1.2-kVp-p 3-phase 5-Hz pulsed voltage EDS system.

3.2.5. Surface Vibrations

The inertia of particles at a specific acceleration causes re-entrainment from a vertical-sinusoidal vibrating surface [105]. This phenomenon is the basis of the vibration technique. Due to vibration alternating detachment and contact pressure forces, the dynamic stresses act on particles during frequently used operations, which in turn result in soiling cleaning. To achieve a proper cleaning process, the effect of the diameter of a particle on its motion, trajectories, and velocities of different-sized particles must be examined [106].

Piezoelectric vibrator features, such as high torque to volume ratio (5–10 times higher than electromagnetic actuators), silent operation, no electromagnetic interference, high positioning position, and flexible structure design, have successfully been utilized in a variety of applications, including cleaning of PV panels [107]. As shown in Figure 6, a linear piezoelectric with two elliptical motions of driving feet for driving the vibrator and the wiper have been employed in [108]. At the right pressure force between the PV panel and wiper, the wiper can effectively clean a soiling layer from the PV panel [108]. The ultrasonic vibrator can clean the smallest crevices and penetrate areas that are hard to access for other cleaning techniques [109]. As illustrated in Figure 7, an ultrasonic piezoelectric vibrator has been used in [109] for cleaning the surface of a PV panel. It is worth mentioning that the vibration system has consumed 32 W power during 15 s of operation.

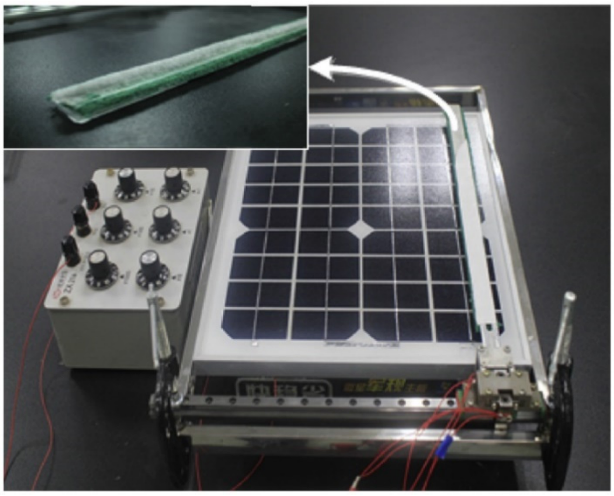


Figure 6. Cleaning using a linear piezoelectric vibrator [108] (reprinted with permission from Elsevier).

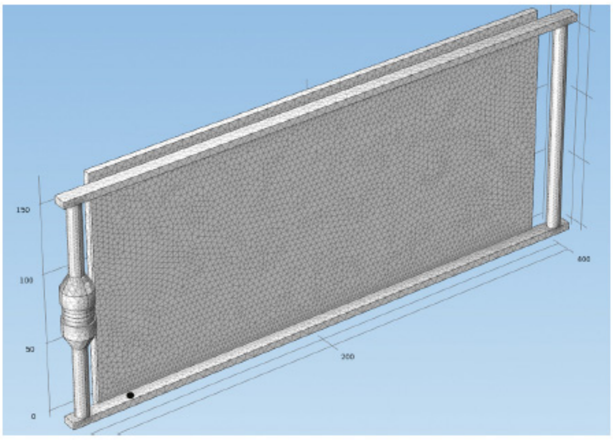


Figure 7. An ultrasonic cleaning system [109] (reprinted with permission from Elsevier).

3.2.6. Robotic

As a counterpart to water-based robots, there are wiper robots that can wipe off soiling without any need for water but they are limited to low mass particles [73]. For the excess dirt solution, some of these robots use a scraper to wipe off the soiled layer from the PV panel surface, which puts the panel at the risk of being scratched [60,110]. The utilized brush for dry cleaning can affect the transmission of the PV panel glass [30]. It has been noticed in [111] that using the silicone rubber foam brush effectively minimizes the impact of soiling on the PV panel power generation for robotic applications. A review of some existing soiling cleaning robots with different approaches, as well as their features and capabilities, is listed in Table 1.

Table 1. Existing soiling remover robots (reprinted with permission from the corresponding companies and Elsevier).

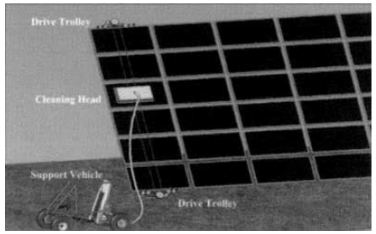
Name of Research Study/Robot	Type	Features	Visual at Workplace
Robotic Device for Cleaning PV Panel Arrays [74]	Water-Based	• Using natural brushes and water for the cleaning process. • The cleaning head connected to an adjacent support vehicle via umbilical. • Assembling/disassembling ability. • Moving vertically and horizontally.	
GEKKO Solar Company: Serbot AG [112]	Water-Based	• Using rotating brushes, airflow, and water for the cleaning process. • The robot is 4 times faster than manual cleaning. • The robot can clean 400 m^2/h. • The robot water consumption is 0.5–3.0 L/min. • Capability to operate up to 45° sloped PV panel.	
Solar Cleano Company: Solar Cleano [113]	Water-Based and/or Water-Free	• Utilizing brushes and water for the cleaning process. • One operator is needed for each robot. • The system provides brushes for dry and wet cleaning depending on the soiling grade. • Capability to operate up to 25° sloped PV panel. • Moving vertically and horizontally.	
Tafresh University [114]	Water-Free	• Utilizing rotating microfiber brushes for the cleaning process. • The robot can clean 100 m of PV arrays in each hour. • Electricity consumption is 6–7 Ah. • The robot can be operated in fully-automated or semi-automated mode.	

Table 1. *Cont.*

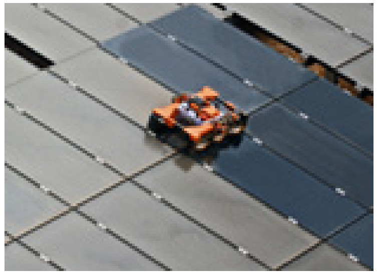
Name of Research Study/Robot	Type	Features	Visual at Workplace
Ecoppia's T4 Company: Ecoppia [115]	Water-Free	• Utilizing microfiber elements and airflow for the cleaning process. • The robot can clean 4 m^2/min. • The locking mechanism will withstand winds of up to 160 km/h. • Low-cost deployment with no need for construction retrofitting nor additional railing. • Capability to operate up to 5° sloped PV panel.	
Ecoppia's E4 Company: Ecoppia [115]	Water-Free	• Utilizing microfiber elements and airflow for the cleaning process. • The robot can clean 99% of the PV panel soiling. • The robot can clean up to 1200 panels in a single nightly operation. • The locking mechanism will withstand winds of up to 170 km/h. • Capability to operate up to 35° sloped PV panel.	
PV-Rob Company: 01mechatronics [116]	Water-Free	• Utilizing suction-cups for the cleaning process. • Low cost and man-portable robot. • Ability to be attached on a PV panel and hover all-around a complete panel. • Fully capable to maneuver and perform any cleaning routine. • Capability to operate up to 65° sloped PV panel. • Moving vertically and horizontally.	
SMR-640AD Company: Miraikikai [75]	Water-Free	• Utilizing a dry cleaning process. • The robot can operate fully-automated. • These systems reduce cleaning costs by 80 percent compared with manual cleaning. • Crossing gaps between PV panels by a specialized mechanism. • Moving vertically and horizontally.	

Table 1. *Cont.*

Name of Research Study/Robot	Type	Features	Visual at Workplace
NOMADD Company: NOMADD Desert Solar Solutions [117]	Water-Free	• Utilizing a dry cleaning process. • The robot can be operated in fully-automated or semi-automated mode. • The robot can handle large panel overhangs.	

4. Frequency of Cleaning

As mentioned before, dust and soils have negative impacts on the efficiency of PV panels. Therefore, the importance of cleaning PV panels is considerable from both economic and performance points of view [118]. A key factor to maximizing the economic advantage is the determination of cleaning times. There is no specified cleaning cycle for PV panels, and the soiling rate of the region mostly determines the cleaning frequency [119]. The optimal cleaning frequency mainly depends on the environmental conditions of the installation place, such as precipitation and humidity, wind velocity, particle type, source of particles, and soiling rate [119,120]. In this regard, it has been suggested in [121] that PV panels should be cleaned weekly in moderately dusty places. Furthermore, it has strongly been recommended that all equipment should immediately be cleaned after a dust storm to maintain nominal operating efficiency. The soiling rate for 20° sloped PV systems installed in Mesa (near Phoenix, AZ, USA) has been determined in [122]. It has been demonstrated that the daily soiling rate (average loss of full power energy in each day because of soiling) of this site is −0.061% during the highest soiling period. In [21], using a novel model, the cleaning frequency of PV panels in desert regions has been determined to be 20 days, considering the output power reduction and particle concentration equal to 5% and 100 $\mu g/m^3$, respectively. A method to calculate the dynamic cleaning frequency of grid-connected PV systems by achieving a coefficient of cleaning tolerance has been presented in [123]. In [61], the cleaning interval of two different manual cleaning techniques, handwashing using water and application of washing tractor, have been determined in central Saudi Arabia. The results have demonstrated that the optimal average cleaning frequency of manual cleaning has been about 20 days, whereas this period is approximately 9 days for a washing tractor. The daily soiling rate in bifacial PV systems has been calculated in Santiago (Chile) and it has been compared with the conventional mono facial minimodules [124]. It has been illustrated that the soiling rate in the mono facial minimodule is 0.301% per day, whereas a rate of 0.236% per day has been measured for the bifacial system. Moreover, the soiling rate for the rear side of bifacial PV panels has been determined as 0.0394% per day. The dust accumulation effect on PV panels in the MENA region has been assessed in [118], and it has been noted that the cleaning interval can be 12–15 days. Using an endogenous method, the soiling rate in three utility-scale PV systems located in the Middle East has been calculated to be about 0.1% per day [125]. In [38], the optimal cleaning frequency of PV panels in a hot desert climate has been recommended to be weekly, especially during summers. Different aspects of dust deposition on the PV system installed in the Hashemite University (Jordan) have been assessed in [126]. Considering the environmental conditions, it has been suggested that PV panels should be cleaned every two weeks.

The assessment of the research studies has demonstrated that the cleaning interval of PV panels depends on the environmental conditions including the soiling rate. Note that the amount of soil that is cleaned in each cleaning time can be another factor that affects the cleaning frequency. In Table 2, a summary of the reviewed research studies has been presented.

Table 2. Classified summary of papers on cleaning frequency.

Reference	Location	Cleaning Frequency
[121]	Minia region, middle of Egypt (moderately dusty places)	Weekly cleaning recommended.
[122]	Mesa (near Phoenix), AZ, USA	The daily soiling rate is determined to be −0.061%.
[21]	Desert areas	The frequency of cleaning is specified to be 20 days.
[61]	Central Saudi Arabia	The optimal cleaning interval for handwashing was 20 days and for tractor, washing was 9 days.
[124]	Santiago, Chile	The soiling rate in the mono facial minimodule is 0.301% per day, and in the bifacial module is 0.236% per day.
[118]	The MENA region	The cleaning interval is calculated to be 12–15 days.
[125]	The Middle East	It is demonstrated that the average soiling rate is 0.1% per day.
[38]	Desert areas	The panels should be cleaned weekly, especially in summers.
[126]	Jordan	The cleaning interval is better to be 14 days.

5. Economic Evaluation

Another determinative issue for optimized operation and maintenance of PV systems is the cleaning cost [127]. Soiling is one of the influential parameters, which is effective in operation and maintenance costs. Hence, it should carefully be taken into account, especially in desert regions [128]. The cleaning cost of PV systems is mainly dependent on the cleaning frequency during a specific period (by year or month). In 2006, the results of a study have indicated that the increase of the total revenue of a 100 kWp PV system, installed in Los Angeles (CA, USA) should be $1500 under the California Solar Initiative incentive program and $3000 under the lucrative European feed-in tariffs in case of cleaning twice during the dry summer period [53]. The washing cost and income of two 1 MWp PV plants in the countryside of southern Italy have been analyzed and compared in [129]. The total washing cost of both PV systems has been determined equally as $4.58. The economic aspects of the cleaning of soiling and snow in PV systems in three different regions of Europe have been investigated in [130]. The outcome of this research study has demonstrated that there is no economic benefit of cleaning in Helsinki (Finland) while there is an economic benefit in sites like Murcia (Spain) and Munich (Germany). In another evaluation, it has been shown that cleaning the soiling and snow from PV panels has not been economic in Stockholm (Sweden) [131]. The annual cleaning cost of PV panels using manual cleaning techniques assisted by washing tractor in central Saudi Arabia has been evaluated in [61], and it has been illustrated that the average of this amount is about $3.68/kW/year for manual cleaning and $1.5/kW/year for manual cleaning by washing tractor. The application of nano-coating on PV panels in the hot climate of MENA regions has been investigated in [127]. It has been revealed that the utilization of the proposed nano-coating has had an economic benefit of $20.94/MW/year. In two locations of the Sahara desert of Algeria, it has been illustrated that cleaning can be profitable under circumstances that PV panels have been cleaned twice a year for an estimated cost of $15843/MW, and soiling is superior to 7% [128].

The outcome of an evaluation accomplished in Jordan has indicated that the mediocre daily cleaning cost of PV panels can be about $0.212/kWp [118]. The applications of some waterless PV cleaning techniques and apparatuses in desert climates have been investigated in [38], and it has been noted that the most cost-effective cleaning technique had a total cost of $21.07/m^2/year. The results and summaries of the reviewed papers are presented in Table 3.

Table 3. Classified summary of papers on economic evaluation.

Reference	Location	Findings
[53]	Los Angeles, CA, USA	The total revenue increase will be $1500 (under the California Solar Initiative incentive program)
[129]	The countryside of southern Italy	The total washing cost of each PV plant was $4.58.
[130]	Helsinki, Murcia, Munich	The cleaning of PV plants is economical in Murcia and Munich and not in Helsinki
[131]	Stockholm	clearing the soiling and snow from PV panels is not economical
[61]	Central Saudi Arabia	The average cleaning cost is about $3.68/kW/year for manual and $1.5/kW/year for cleaning by washing tractor.
[127]	The MENA countries	The use of the proposed nano-coating has about $20.94 /MW/year economic profit.
[128]	The Sahara desert of Algeria	Cleaning would be profitable if the PV modules are cleaned totally twice a year for an estimated amount of $15,843/MW and soiling is superior to 7%
[118]	Jordan	The average daily cleaning cost of PV panels is about $0.212/kWp
[38]	Desert areas	The most cost-effective cleaning technique has a total cost of $21.07/m^2/year

6. Critical Analysis of Techniques

As shown in Figure 8, the cleaning techniques are categorized into water-based and water-free approaches throughout this paper. In addition, four and six subdomain techniques are considered for water-based and water-free approaches, respectively. Each individual technique has its own merits and demerits, which can come in handy in cleaning FPV systems, but the lack of comprehensive analysis is obvious for the selection of the best solution. Therefore, this section provides a critical analysis for applying the techniques to FPV systems. Some of the described techniques use chemical solutions to reach more effective cleaning, and accordingly, the techniques should be analyzed from an environmental point of view. The water quality of the reservoir and water shortage in the region lead to different approaches. Therefore, the availability of techniques for each site must be taken into consideration. Two main factors considered for comparison of techniques are cost and cleaning efficiency.

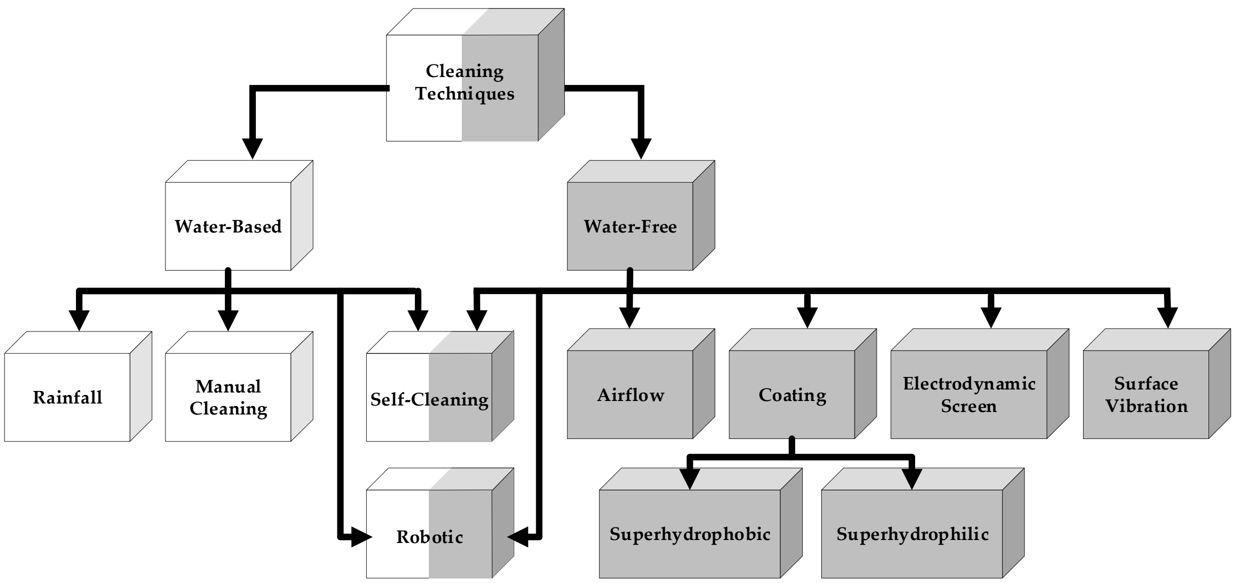


Figure 8. Overall classification of cleaning techniques.

6.1. Rainfall

Rainfall can help the cleaning process, but it is not accurately predictable and does not follow a regular pattern. Moreover, the rainfall cannot completely remove the accumulated soil, and usually, a complimentary washing step is needed. It must be noted that a cloudy and rainy environment is usually not suitable for a PV system. Furthermore, many PV and FPV systems are located in arid regions with low or inadequate rainfall. Therefore, in such regions, other cleaning techniques should be applied to provide higher output power. From an economic point of view, considering the fact that this technique does not need any apparatus for cleaning, it may seem to be cost-effective. In some countries, such as Japan, where the application of FPV systems is widespread, the precipitation is more than in arid regions and it may be enough for cleaning.

6.2. Manual Cleaning

The most crucial reason for using manual cleaning is the simplicity of its application, which is desirable for many utility operators. The human laborers employed for this job need to be professionals because of the risks and the need for selecting the right materials. Constant use of some chemicals for cleaning may decrease the performance of PV panels. Also, the leakage of such materials into the water reservoirs has a harmful impact on the environment. In addition, in this technique, the amount of wastewater is relatively high, which makes it costly for arid regions with non-fresh water reservoirs or in the case of installing FPV systems with the aim of water evaporation reduction. Nevertheless, this technique may have other limitations for FPV systems, including the difficulties in accessing panels and the need for weight-bearing floating structures.

6.3. Self-Cleaning

As mentioned before, both water and air can be used in self-cleaning techniques. Sprinklers are a water-based approach. Although this system is suitable for arid regions because of its cooling effect, it cannot spray the whole surface of PV panels. As a result, it cannot infiltrate all crevices of PV panel surfaces. It has the same cleaning effect as rainfall and can clean PV panels at a relatively low cost [59]. However, there is a significant water wastage during the operation of sprinkler cleaning systems for land-based PV panels because the nozzles spray the water a few meters outside the panel perimeter. For FPV systems located on the surface of the freshwater reservoir, most of the sprayed water returns to the reservoir and can be reused.

The method of forced airflow using air-conditioner return air has a low energy consumption, but it is only applicable in the regions, whose penetration factor of air-conditioners is high, and it is not appropriate for large-scale FPV systems. Besides, transferring the returned air to FPV systems through the water reservoir increases the initial cost.

6.4. Robotic

This technique can also be categorized as water-based or water-free. One downside of utilizing robotic techniques is their high total cost consisting of high maintenance cost for repairing, operating, and monitoring and controlling the robots. Nevertheless, considering the true cost of water, labor, and frequency of cleaning, it is found that the installation of robotic systems can be cost-effective. In addition, this system can effectively decrease the wastage of water.

Deliberation of movement of FPV systems on the surface of the water reveals a key issue for utilizing robots. These movements are unpredictable because they are highly dependent on the buoyancy force, as well as on continuous regular and irregular oncoming waves, unlike existing land-based systems. Considering the impossibility of installing fixed rails on PV panels, due to the independent movement of each floating structure, any sudden movement of the FPV system can detach the robot from the PV panel surface, and drown it into water or take it into a position, which is not planned. Hence, it reduces the reliability of the system. In addition, using robots, vehicles, or mechanically integrated mechanisms for cleaning purposes increases the possibility of damage to the PV panel surface that has been cleaned.

6.5. Airflow

Airflow improves dust removal of PV panels, mainly in the regions with water shortage. A low-speed airflow is desirable for FPV systems due to the low dust density of the air on water reservoirs. However, high-speed winds hit the surface of the PV panel with sand particles that may scratch the surface. Long-term exposure to such a wind creates problems of random scratches on the PV panel surface, which results in a reduction of irradiation transmission and reflection. Meanwhile, wind can create small cracks on PV panels via differential pressure, which in turn results in lower efficiency. This problem is intensified for FPV systems due to their offshore installation and higher repair costs.

6.6. Coating

Although coating prevents soil from sticking on the PV panel surface, it requires water for soiling removal. By using this technique in arid regions, the volume of water utilized for washing is decreased, while regular washing is required. Nevertheless, because of the humidity upon the water reservoir's surface, this technique is adequately efficient. Moreover, the coating surfaces can provide other features, such as anti-icing, stability due to heavy rainfall, anti-reflecting, photocatalysis reaction (this process can chemically break down the organic dirt through the reaction to UV light), and anti-fogging [15]. It is noted that coatings accumulate more soiling when the coating deteriorates due to UV light. Considering the initial cost for the coating of all PV panels and the recoating cost after several years, it can be said that concerns should increase the cost of this technique. On the other hand, their released chemicals can be a threat to water reservoirs and damage the environment. In the end, it must be noticed that this solution has not been developed for the industrial level yet.

6.7. EDS

The EDS technique is distinctively faster than other techniques. This technique has shown proper efficiency in arid regions, but it has been shown that it is not effective for wet or cemented dust. Besides, its efficiency is low for fine particles. Due to the proximity of water with PV panels in some applications and high humidity, the ESD is not a proper option for these cases. Moreover, as illustrated before, the traveling wave method is not cost-effective for both large-scale PV and FPV systems.

6.8. Surface Vibration

The vibration method is used periodically, and accordingly, this technique consumes negligible amounts of power in comparison with other active cleaning techniques. As indicated in [107,108], the advantages of the piezoelectric actuator are its lightweight and compact structure, which makes it feasible for utilization in FPV systems. It is noteworthy that as time passes, the vibration can increase the risk of creating major cracks on the PV panel surface. These cracks may lead to the disconnection of cells and a total loss of generated power [132]. Also, employing a vibration system for each panel can affect the initial and operation and maintenance cost of FPV systems.

6.9. Analysis Remarks

The individual analysis of the above-mentioned techniques is summarized in Table 4. Considering the merits and demerits of different techniques, as well as their approaches, it can be said that manual cleaning (without using chemical materials and before sunshine) can be fine for FPV systems that are located on the surface of freshwater reservoirs as it requires no additional water source, produces no wastewater, and consumes no electrical power. The effect of coating techniques on the environment should further be studied, and it has not been developed for industrial applications yet. Considering the high stability of the coated layer, the combination of the coating technique and manual cleaning is a noteworthy solution for FPV systems located on freshwater reservoirs. Many FPV systems have been located on the surface of non-fresh water reservoirs, which their water cannot be employed for the cleaning procedure. For such an FPV system, which has been installed for water evaporation reduction, using the airflow technique as well as high stability coating layers is preferred. In the regions that do not have water scarcity problems and FPV systems have been developed for energy generation, using additional manual or self-cleaning water-based techniques leads to cooling and higher efficiency.

Table 4. Comparison of cleaning techniques.

Technique	Approach	Merits	Demerits
Rainfall	Water-Based	• No cleaning cost • Doesn't need any reformation • No electrical power consumption • Cooling effect	• Low efficiency • Not accurately predictable • No specific falling pattern • Low access in arid and desert regions
Manual Cleaning	Water-Based	• Low cleaning cost • Simplicity • No electrical power consumption • Cooling effect	• The dependency of cleaning efficiency on human labor caution • High wastage of water • Restrictions of the floating structure are weight-bearing
Self-Cleaning	Water-Based and/or Water-Free	• Fully automated • Cooling effect (water-based approach)	• Low efficiency (water-based approach) • High wastage of water (water-based approach) • High initial cost (water-free approach) • Electrical power consumption
Robotic	Water-Based and/or Water-Free	• High efficiency • Low water wastage (water-based approach)	• High total cost • Possibility of falling into water or a not programmed position • Risks of PV panel damaging
Airflow	Water-Free	• No/Low cleaning cost • No electrical power consumption	• Low efficiency • Risks of PV panel damaging
Coating	Water-Free	• High efficiency in humid regions • No electrical power consumption • Availability of providing other features such as anti-icing, more stability, anti-reflecting, photocatalysis reaction, and anti-fogging	• Recoating requirement • Treats of realized chemical materials for the environment
EDS	Water-Free	• High efficiency for desert regions • Fast technique	• Low efficiency for wet, cemented, and small-sized particles • High total cost
Surface Vibration	Water-Free	• High efficiency • Low electrical power consumption	• Risks of PV panel damaging due to the vibrations • High maintenance cost

7. Conclusions and Recommendations for Future Work

This paper has reviewed a variety of techniques for cleaning FPV systems from both technical and economic perspectives. It has been explained that considering the purpose of their development, FPV systems are classified into two groups, namely energy generation and evaporation reduction.

Plenty of techniques have been developed for cleaning PV systems. However, many of them are not applicable due to the particular characteristics of FPV systems. Furthermore, water-based techniques are typically considered the best solution for cleaning. The application of these techniques for FPV systems depends on water availability and reservoir water quality, which are always feasible. Therefore, this paper has categorized such solutions as water-based and water-free approaches and analyzed each technique individually. Furthermore, the following conclusions are drawn:

- There is no specified cleaning cycle for all FPV systems, and the environmental conditions determine the frequency of the cleaning.

For freshwater reservoirs:

- The manual cleaning (before sunshine and without using chemical materials) can be fine, as it requires no additional water or electrical source.
- Assuming high stability of the coated layer, the combination of the coating technique and manual cleaning is an ideal solution for FPV systems installed on the freshwater reservoirs.

For non-freshwater reservoirs:

- For FPV systems that are developed for water evaporation reduction, using the airflow technique in conjunction with a high stability coating layer is preferred.
- For FPV systems that are developed for energy generation, in addition to the above-mentioned solution, using manual or self-cleaning water-based techniques leads to cooling and higher efficiency.

Considering the research studies reviewed in this paper, the following topics are suggested for future work:

- Investigation of the aerodynamics of floating structures in order to minimize the water evaporation and improve the heat transfer from PV panels to the environment.
- A precise study of the endurance of coating layers on PV panels.
- Coating a layer on the surface of each PV panel imposes an additional cost, which cannot be neglected. The impact of this charge on the economic feasibility of the system is necessary to be assessed further in future researches.
- Determination of the desirable features of robots for FPV systems cleaning.
- Due to the lower amount of dust in the air upon the water reservoirs in comparison with the lands, its effects on the frequency of the cleaning should be taken into consideration.

Author Contributions: R.Z. was responsible for conceptualization, creation of methodology, conducting research and investigation process, and writing—original draft preparation; P.R. was responsible for conducting research and investigation process, and writing—original draft preparation; G.B.G. was responsible for writing—review and editing, and supervision; F.M. was responsible for writing—review and editing, and R.A. was responsible for writing—review. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflict of interest.

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