A Short Review On Automated and Semi-Automated Cleaning Systems for Photovoltaic Panels to Enhance Power Efficiency

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Abstract. The efficiency of solar panels depends on both photovoltaic technology and operating conditions, including cell structure, material properties, and system design. Monocrystalline PV modules are currently the most widely used due to technological advances and their high photoelectric conversion efficiency. However, environmental soiling from dust and debris degrades performance by increasing surface contamination and inducing localized hotspots, while even limited partial shading can cause significant energy losses due to electrical mismatch within the module. Consequently, current research and industrial efforts focus on reducing soiling-related losses, improving long-term system reliability, and advancing photovoltaic technologies. Promising solutions include anti-soiling surface coatings and automated cleaning systems based on robotic and electrostatic methods, particularly suited to arid and dusty environments. In parallel, emerging technologies such as bifacial and perovskite PV modules offer opportunities for higher energy yield and enhanced scalability of solar power systems.

Keywords: Anti-soiling coatings, Autonomous Cleaning system, Dust Accumulation, Photovoltaic efficiency, Solar Panel.

1 Introduction

Solar panel efficiency can be affected by technology, as well as the environment it is operating in. Many things affect solar panel efficiency such as solar cell type, intensity of sunlight, temperature, dust build-up on the solar panel. The issue of dust build-up on solar panels is of major importance in arid and semi-arid areas where cleaning frequency can have a direct impact on energy yield. Previous work has shown dust can reduce

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transmittance by 30% or more per month and reduce output power by approximately 20% in dry conditions [1]. Therefore, efficient cleaning methods and anti-soiling technologies will be important for stable PV performance. This review will summarise the different types of automated and semi-automated cleaning methods currently available that can be used to reduce the build-up of dust on solar panels, thereby reducing maintenance efforts and improving power efficiency. We will look at all three forms of cleaning methods (manual, semi-automated and fully automated), the benefits and disadvantages to each type of method, and analyse this information in relation to the recent literature written on this topic.

2 Photovoltaic Panel Cleaning Techniques

Automation is changing the way cleaning occurs on photovoltaic products. Future advancement with cleaning methods will be through robotic cleaners, water-based or electrostatically operated cleaning devices, and automatic sprinkling systems that will keep the surfaces clean and reduce soiling costs [2]. Therefore, the development of solar photovoltaic systems to enhance the efficiency of operation will require more integration of automated cleaning systems [3] and Anti-Soiling [4] to ensure that the surface is kept clean from dust and debris and that the performance of the panels will not degrade over time. In addition to using conventional methods of automation, the prevention of dirt accumulation is still an important objective, and the application of new advanced protective coatings, electrostatic scrubbers, robot cleaning systems, vibration-based systems, and air-blown systems have been developed to prevent soiling from accumulating. All of these approaches to prevent soiling will ultimately limit the amount of solar energy absorbed by the photovoltaic panel and therefore result in a decrease in energy production by the photovoltaic panel [5].

In contrast with increasing deployment of automated technology to support solar panel systems, the manual method for cleaning solar panels provides support for maintenance where there are no existing advances or impractical applications. These types of systems generally use a mixture of soft bristle brushes, microfiber cloths, rubber blades squeegees, and high-pressure water pumps, all depending upon the size of the facility and the environment that it is installed in. In addition, operators of solar panels often use telescopic poles, and water-fed brush systems, as well as the appropriate personal protective equipment (PPE) used when cleaning roofs to ensure both the operator's safety and the ability to access difficult locations. As a result, the manual cleaning method for maintaining PV panels is an effective option in remote or hard to reach areas while also preventing mechanical damage [6]

Meanwhile, recent investigations found that certain automated solutions still performed well when subjected to very harsh dust conditions. In particular, Biaxially Oriented Polyamide (BOPA) coatings were identified as a viable, low-cost option to help reduce the efficiency losses associated with soiling [7]. Likewise, a recent advancement in the use of electrostatic cleaning as a new, efficient non-contact method was identified, as it has shown to be highly effective at removing debris without damaging the panels [8]. Additionally, the development of self-cleaning systems based on nano-coatings is currently underway, with the long-term goal of decreasing both manual and automated cleaning frequency through improved dust accumulation prevention techniques.

Finally, while each of these emerging and established technologies provides a measurable benefit over previous techniques, challenges remain relative to their respective costs, scalability, and complexity of implementation. Therefore, continued investigation will be

needed to develop the best combination of efficiency, durability, and sustainability when considering photovoltaic cleaning solutions.

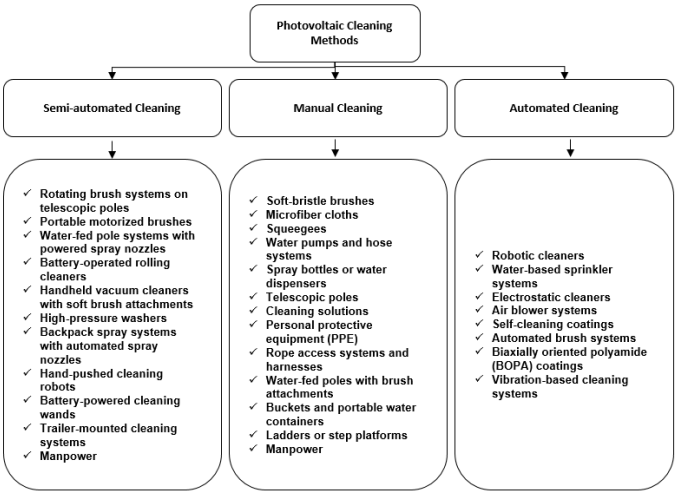

Figure 1. Photovoltaic Panel Cleaning Techniques.

3 Semi-automated and automated photovoltaic cleaning

Rotating brush systems on telescopic structures are commonly used as an effective method for keeping photovoltaic (PV) modules clean [9]. Testing has shown that using this method will result in an average of 86.8% more dust removed from repeated cleaning than if no cleaning takes place at all, which equates to a dramatic reduction in the amount of lost energy due to soiled solar panels. In extreme dry areas, these cylindrical brush designs have been proven to be highly effective at maintaining their efficiency when dirty, with reported efficiency losses of as low as 30-40% due to dust build-up on them [10]. Additionally, to the mechanical design of the unit, how those brushes are operated will also affect overall performance [11]. For example, when the brushes are activated based on a time-based control mechanism, they have been shown to vastly increase the ability for energy recovery, with averages reaching as high as 26% more than previous methods of energy recovery when utilizing a high-efficiency cleaning operation rate of >70% [11]. By integrating an additional portable, automated robotic cleaning unit capable of adjusting brush size, weight, and contact pressure, surface coverage is enhanced while the risk of panel damage due to excessive mechanical force is reduced [12]. Continual use of such an automated robotic cleaner for brush cleaning has been proven to see significant gains in electrical outputs and accompanying increased total energy production [13].

Besides dry mechanical cleaning, another primary type of maintenance solution of photovoltaic systems are the water-assisted maintenance techniques. The use of water-fed pole systems and powered spray nozzles helps to restore performance to those systems as substantiated through testing in the field, where it was found that systems cleaned with low-pressure and high-volume water jets gained over 27% additional power when compared to uncleaned systems [14]. Cleaning systems that utilize only water are considered non-abrasive, meaning that they do not damage the optical transmittance of the surface of the module, allowing for extended periods of operation. However, as a result of the amount of water that such systems employ, they cannot be utilized within arid regions due to their high-water use [15][16].

Methods of maintenance have evolved to eliminate the aforementioned drawbacks through alternative to traditional cleaning methods of solar panels. Examples of these alternative methods include low-cost (spray-type method), especially backpack-mounted powered-spray systems. The basic principle of spray-type systems is simplicity, while their use can provide moderate and measurable benefits (e.g., a voltage increase of 2.1V for the removal of dust and an increase of 30% in power output) [17][18]. A more recent example of how the use of technology will continue to reduce the amount of time and risk associated with the maintenance of panels is through the introduction of autonomous robotic cleaning technologies; today, robotic cleaning is being performed in an average of 13 minutes per cleaning cycle [19]. Newer developments, responding to ongoing issues with water scarcity, are focusing on the creation of water-free and hybrid cleaning strategies. The electrostatic cleaning process has developed as an attractive alternative, particularly for those living in desert or semi-arid environments. In particular, the combination of rolling-brush robotic systems with vacuum or pressure systems has produced dust-removal efficiency rates that exceed 92%. In addition to their dust-removal characteristics, these systems have been reported to produce increases in the efficiency of energy generation of between 11% and nearly 50% [8][20]. Therefore, these systems are particularly well suited for large-scale solar photovoltaics (PV) installations located in extreme soiling conditions and with limited availability of water.

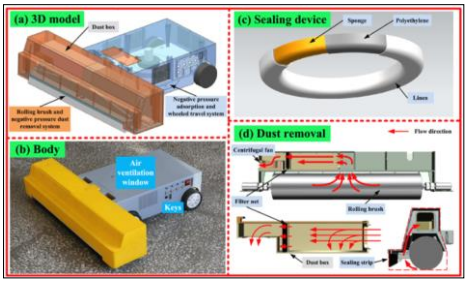

Figure 2. Water-free Cleaning Robot [20].

To alleviate the detrimental effect of dust on PV system performance caused by dust adhesion, cleaning technologies and surface treatments are vital. Self-cleaning coatings, including Biaxially Oriented Polyamide (BOPA), known for treating unsealed surfaces, are one such technology. Unfortunately, under significant soiling conditions, passive methods alone cannot provide enough cleaning action to justify the use of BOPA [7].

To overcome this limitation, active automated cleaning technologies have recently experienced an increase in adoption because they include mechanical cleaning devices (automated brush systems) that offer adjustable geometries, allowing for improved surface coverage, greater cleaning consistency, and thus, increased performance recovery. In contrast, the non-contact method of vibration cleaning provides selectivity for removing dust without mechanically abrading the surface;

however, the variability of its cleaning capabilities and high operation and implementation costs may prevent the widespread use of these systems [12].

The advancement of technology has led to the use of semi-autonomous robots to clean utility scale installations. Semi-autonomous robots can clean utility scale solar installations at 96%, while using fewer workers and using less water than current methods. Recommended energy output increases for semi-autonomous robotic cleaners are up to 7% on large solar fields [21].

In addition to cleaning solar panels, thin film coatings and metal oxides or polymers can also be used to improve the efficiency of solar panels in the marketplace. When deposited using controlled methods (such as PVD or magnetron sputtering), both thin films and coatings made from either metal oxides or polymers increase the optical transmittance and thermal management of PV modules. This has led to significant increases in the conversion efficiency of PV modules (14%-20%) due to the application of these structural coatings [22].

Technique	Dust Removal Efficiency	Advantages	Challenges	Citations
Rotating Brush System	Up to 86.8% dust removal over 4 cycles; 72% in other setups	Flexible design, suitable for large-scale installations	Persistent residues require optimization	[24] [25]
Portable Motorized Brushes	72% dust removal; 26% energy yield improvement	Adjustable height and angle, lightweight, reduces labor costs	Sticky layers of dust in specific environments remain a challenge	[26] [27]
Water-Fed Pole Systems	27% increase in power output (Saudi Arabia)	Minimal surface damage, versatile for manual/automated setups	High water usage; not sustainable in arid regions	[28] [29]
Backpack Spray Systems	33.76% power output increase	Low-cost, mobile, reduces manual labor hazards	Initial setup costs, maintenance requirements	[30] [31]
Water-Free Cleaning Robots	92.46% cleaning efficiency; 11.06%-49.53% efficiency improvement	Avoids water wastage, suitable for arid regions	High initial investment; not suitable for all panel angles	[20]
Self-Cleaning Coatings	Maintains 12.19% efficiency under high dust levels	Prevents dust accumulation, reduces maintenance costs	Effectiveness varies by environmental conditions	[20] [30]
Electrostatic	Highly	Preserves surface	Limited scalability	[21]

Cleaners	effective, non-abrasive	integrity		
Autonomous Robotic Systems	>96% cleaning efficiency; 7% energy output increase	Reduces manual labor, eco-friendly	Operational costs	[21] [23]
Hydrophobic Coatings	Up to 30.7% efficiency increase	Self-cleaning properties, durable, reduces frequency of cleaning	Higher upfront costs for application	[30] [32]
Hydrophilic Coatings	8.1% dust deposition reduction	Improves light transmission, self-cleaning	May require combination with other coatings	[33] [34]
Thin Film Coatings	Up to 66% efficiency in solar collectors	Enhances thermal insulation and light absorption	Requires specialized application techniques	[35]

4 Conclusion

The use of both automated and semi-automated cleaning methods reduces dirt build up on solar panel systems that occurs mostly in dry and dusty areas, allowing for continued optimal efficiency. The comparative analysis performed identifies that the greatest sustainable options for cleaning systems are waterless robotic systems and self-cleaning, hydrophobic coatings. Non-abrasive electrostatic cleaning technologies are an option for removing dirt but are limited due to the constraints of scaling. Future research should focus on improving the cost and durability of existing coatings, as well as developing low-maintenance, renewable-powered robotic cleaning systems and integrating IoT-based predictive monitoring to provide real-time data about the cleaning status of PV systems. The best total solution for utilizing the combined benefits of using both a cleaning system through the use of coatings and either a robotic or electrostatic cleaning method may yield greater efficiency while reducing the use of water and labour. Conducting parallel economic evaluation studies on these technologies will be important to encourage their adoption by users operating PV systems in both utility-scale and decentralized installations.

References

1. Al Shehri, A., Parrott, B., Carrasco, P., Al Saiari, H., & Taie, I. (2016). Impact of dust deposition and brush-based dry cleaning on glass transmittance for PV modules applications. Solar Energy, 135, 317-324.Jordan, D. C., & Kurtz, S. R. (2013). Photovoltaic degradation rates—an analytical review. Progress in Photovoltaics: Research and Applications, 21(1), 12-29. https://doi.org/10.1016/j.solener.2016.06.005

2. Oubari, A., Nouneh, K., Hamzaoui, E., Amayoud, H., Fathi, K. (2025). Enhancing photovoltaic power efficiency: a comparative analysis of unprotected, anti-dust coated, and IoT-enabled automatic cleaning systems in solar energy conversion. International Journal of Power and Energy Conversion. 16. 160-175. https://doi.org/10.1504/IJPEC.2025.10069407
3. Dorge, P. D., Sayankar, B. B., Umate, R., Damahe, L. B., Masram, B., Titarmare, A., & Nagmote, S. (2024). Design of Automatic Solar Panel Cleaning Robot System for Industrial Applications. SSRG International Journal of Electronics and Communication Engineering, 11(11), 110–117. https://doi.org/10.14445/23488549/ijece-v11i11p110
4. Najmi, N., & Rachid, A. (2023). A Review on Solar Panel Cleaning Systems and Techniques. Energies, 16(24), 7960. https://doi.org/10.3390/en16247960.
5. Luting Xu, Pei Ding, Yan Zhang, Yijing Huang, Jimei Li, Ruihua Ma, Sensitivity analysis of the shading effects from obstructions at different positions on solar photovoltaic panels,Energy,Volume 290,2024,130229,ISSN 0360-5442, https://doi.org/10.1016/j.energy.2023.130229.
6. Aljaghoub, H., Abumadi, F., AlMallahi, M. N., Obaideen, K., & Al Alami, A. H. (2022). Solar PV Cleaning Techniques Contribute to Sustainable Development Goals (SDGs) Using Multi-Criteria Decision-Making (MCDM): Assessment and Review. SSRN, https://doi.org/10.1016/j.ijft.2022.100233.
7. Safa Faisal Saleh, Mahdi Hatf Kadhum Aboaltabooq, Hasan H. Khwayyir; Improvement of PV cell performance by using different cleaning methods: Review. *AIP Conf. Proc.* 12 April 2023; 2776 (1): 050015. https://doi.org/10.1063/5.0136522
8. Ning, Zang., Yong, Tao., Zuyi, Yuan., Yuan, Chen., Bian-shun, Jing., Renfeng, Liu. (2024). 1. Rasterized Data Image Processing (RDIP) Techniques for Photovoltaic (PV) Data Cleaning and Application in Power Prediction. Energies, https://doi.org/10.3390/en17123000
9. Escobedo-Márquez, D. (2023). Dry cleaning analysis for photovoltaic modules. Journal of Technology and Innovation, https://doi.org/10.35429/joti.2023.20.7.1.8.
10. Islam, S., Athira, Z. A., Noor, M. M., Kamarudin, M. S., & Uddin, J. (2022). Time-based dry cleaning brush controller for PV energy yield enhancement. International Conference on Power Engineering, https:// doi.org/10.1049/icp.2022.1685.
11. Dahlioui, D., El Ayane, S., Medaghri Alaoui, S., Barhdadi, A., Dambrine, G., Menard, E., & Boardman, J. (2018). Innovative Cleaning Technique for PV Modules on Helioslite Biaxial Solar Trackers. International Renewable Energy Congress, https://doi.org/10.1109/IRSEC.2018.8702864.
12. Jboor, M., Younes, M., Zayed, N., Zainab, O. A., Diab, S. A., Al-Qadi, B., Alsadi, S., Foqha, T., Maghrabi, L. A., & Kanan, M. (2023). Automated Solar Panel Cleaning System. International Conference on Electrical and Electronics Engineering, https://doi.org/10.1109/eiceeai60672.2023.10590137.
13. Alghamdi, S. A., Bahaj, A. S., Blunden, L. S., & Wu, Y. (2019). Dust Removal from Solar PV Modules by Automated Cleaning Systems. Energies, https://doi.org/10.3390/en12152923.

14. Rodrigues, J. A. P., Diniz, A. S. A. C., & Kazmerski, L. L. (2021). Evaluation of the Impacts of Various Cleaning Techniques on Photovoltaic Module Glass. Photovoltaic Specialists Conference, https:// doi.org/10.1109/PVSC43889.2021.9518864.
15. Falah, M. M. A., Kumara, I. N. S., & Ariastina, W. G. (2022). Perkembangan riset dan produk komersial sistem pembersih panel surya. Jurnal Spektrum, https:// doi.org/10.24843/spektrum.2021.v08.i04.p4.
16. Kumar, L. A., Indragandhi, V., Teekaraman, Y., Kuppusamy, R., & Radhakrishnan, A. (2022). Design and Implementation of Automatic Water Spraying System for Solar Photovoltaic Module. Mathematical Problems in Engineering, https:// doi.org/10.1155/2022/7129610.
17. Asoh, D. A., & Awangum, N. N. (2022). Low-Cost Automated PV Panel Dust Cleaning System for Rural Communities. Smart Grid and Renewable Energy, https:// doi.org/10.4236/sgre.2022.138011.
18. Prisma, Megantoro., Abdul, Abror., Muhammad, Akbar, Syahbani., Antik, Widi, Anugrah., Sigit, Dani, Perkasa., Herlambang, Setiadi., Lilik, Jamilatul, Awalin., Pandi, Vigneshwaran. (2023). 2. Autonomous and smart cleaning mobile robot system to improve the maintenance efficiency of solar photovoltaic array. Buletin Teknik Elektro dan Informatika, https:// doi.org/10.11591/eei.v12i6.5950.
19. Fan, S., Liang, W., Wang, G., Zhang, Y., & Cao, S. (2022). A novel water-free cleaning robot for dust removal from distributed photovoltaic (PV) in water-scarce areas. Solar Energy, https://10.1016/j.solener.2022.05.053.
20. Munasinghe, I. U., Vijenayake, V., Viduranga, S., Lokugama, Y., & Jayasekara, P. (2024). Design and Implementation of a Semi-Autonomous Robotic System for Systematic Solar Panel Cleaning. International Conference on Control, Robotics and Engineering, https://doi.org/10.1109/iccre61448.2024.10589856.
21. Bhandari, S. R., Chhetri, A., Rai, A., Rawal, M., & Deub, R. (2024). Performance Analysis of Semi-Automatic Solar Panel Cleaning System. Journal of Clean Energy and Sustainable Technology, https://doi.org/10.3126/ocemjmtss.v3i1.62230.
22. Aditharajan, A., Radhika, N., & Saleh, B. (2022). Recent advances and challenges associated with thin film coatings of cutting tools: a critical review. Transactions of The Institute of Metal Finishing, https://doi.org/10.1080/00202967.2022.2082154.
23. Michael, F., Durstock., Robert, J., Spry., Jeffery, W., Baur., Barney, E., Taylor., Long, Y., Chiang. (2003). 4. Investigation of electrostatic self-assembly as a means to fabricate and interfacially modify polymer-based photovoltaic devices. Journal of Applied Physics, https://doi.org/10.1063/1.1601315
24. Kim, Junghwan & Lee, Sunmin & Hwang, Yun-Hwa & Lee, Seongyu & Park, Byoungwook & Jang, Jae-Hyung & Lee, Kwanghee. (2016). Highly efficient self-power pack system integrating supercapacitor and photovoltaics with area-saving monolithic architecture. J. Mater. Chem. A. 5. https://doi.org/10.1039/C6TA09117B.
25. Amna, Al, Baloushi., Maryam, Saeed., Shaza, Marwan., Shiaikha, AlGghafri., Yacouba, Moumouni. (2018). 3. Portable robot for cleaning photovoltaic system: Ensuring consistent

and optimal year-round photovoltaic panel performance. https://doi.org/10.1109/ICASET.2018.8376781.

26. S, Santosh, Kumar., Shiva, Shankar., Keshava, Murthy. (2020). 2. Solar Powered PV Panel Cleaning Robot. https://doi.org/10.1109/RTEICT49044.2020.9315548.
27. Zheng, Y., Zheng, K., Ma, L., & Liu, Z. (2021). Robots are taking up the challenges in photovoltaics R&D. Materials Today, https://doi.org/10.1016/j.matt.2021.06.012.
28. Zulkefli, M. Z., Rusli, N. D., Hashim, N. A., Jamian, J. J., & Abdullah, M. N. (2017). Investigation of solar photovoltaic performance via cooling-light concentrating and cleaning system using robotic arduino approach. International Conference on Electrical Engineering and Informatics, https://doi.org/10.1109/ICEEI.2017.8312395.
29. Papadopoulos, N. D., Vourna, P., Milidonis, K. F., Eliades, A., & Falaras, P. (2024). Fostering wider application of anti-soiling strategies in existing solar power plants: A comparative study of novel quaternarized silica hybrids with commercial self-cleaning coatings. Materials Chemistry and Physics, https://doi.org/10.1016/j.matchemphys.2024.129046.
30. Tayel, S. A., Abu El-Maaty, A. E., Mostafa, E. M., & Elsaadawi, Y. F. (2022). Enhance the performance of photovoltaic solar panels by a self-cleaning and hydrophobic nanocoating. Scientific Reports, https://doi.org/10.1038/s41598-022-25667-4.
31. Elsaadawi, Y. F., Tayel, S. A., Abu El-Maaty, A. E., & Mostafa, E. M. (2022). Hydrophobic nanocoating impacts on the PV panels' current-voltage and power-voltage curves. Al-Azhar Journal of Agricultural Engineering, https://doi.org/10.21608/azeng.2022.278933.
32. Boutamart, M., Rafqah, S., Hadri, A., Nouneh, K., Zaidi, S., Bichara, H., & Briche, S. (2024). Design of fluorine-free superhydrophobic coating for fibred architectonic concrete. Construction and Building Materials, https://doi.org/10.1016/j.conbuildmat.2024.136086.
33. K. Alam, S. Saher, S. Ali, A. Mujtaba and A. Qamar, "Super hydrophilic nano particulate coating for solar PV module," 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST), Islamabad, Pakistan, 2019, pp. 14-19, https://doi.org/10.1109/IBCAST.2019.8667141. 44
34. Cao, S., Wang, Y., Wang, Z., & Yang, J. W. (2022). Research on the Application of Super-hydrophilic Self-cleaning Coating in Photovoltaic Power Plant. International Conference on Power and Renewable Energy, https://doi.org/10.1109/ICPRE55555.2022.9960454.
35. Naser, A. K., Hachim, D. M., & Abed, Q. A. (2021). Improving the efficiency of crystalline silicon solar cell through regulating their temperature using thin films of polyvinyl alcohol. In E3S Web of Conferences (Vol. 286, p. 02012). EDP Sciences. https://doi.org/10.1051/e3sconf/202128602012