Multi-Criteria Approach to Solar Cell Cleaning Methods Selection

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Abstract**—**Solar photovoltaic (PV) is a promising renewable energy source that converts solar energy into electricity in an environmentally friendly manner. However, it can be easily affected by the weather and surrounding environment, which could decrease its efficiency. In Oman, dust accumulation is one of the main challenges facing solar systems. To overcome these drawbacks, solar panels need to be cleaned consistently. This paper will analyze the performance and cost of a dry robotic system and a dry Manual Cleaning system to determine the region's most effective cleaning method. In addition to the performance and cost Analysis, a frequency analysis is performed to find the optimal cleaning frequency based on cleaning performance and cost. The PV modules are located at Shams Solar Site in Halban, within the German University of Technology (GUech) campus. Results show that Manual dry cleaning outperformed robotic cleaning by 6.07%, though technical issues hindered the robot's effectiveness. Daily cleaning yielded the highest average power output, but weekly cleaning was deemed cost-effective, balancing cost and performance.

Index Terms**—** Photovoltaic Panel, Solar System, Manual, Cost, Efficiency, Power Output, Contaminants and Cleaning

I. Introduction

Photovoltaic (PV) systems are integral to renewable energy strategies, converting solar energy into electrical power [1]. However, their efficiency is influenced by environmental and design-related factors [2]. This detailed analysis explores shading, soiling, temperature, solar radiation variability, and humidity as environmental factors affecting PV performance [3]. It examines material degradation and tilt angle as crucial design factors and reviews existing cleaning methods to enhance PV system efficiency [3]. Shading poses a significant challenge for photovoltaic (PV) systems. Even partial shading of a single cell can significantly decrease overall power output, especially in large solar facilities connected in series. Common shading sources include trees, buildings, and clouds, which can disrupt current flow and power output [6]. Soiling, caused by dirt and pollutants accumulating on PV panels, also reduces light absorption and can lead to efficiency reductions of up to 20%, necessitating regular cleaning to mitigate losses [7]. Additionally, high temperatures, such as those experienced in hot climates like Oman, can decrease PV panel efficiency by approximately 0.5% per degree Celsius due to semiconductor bandgap reduction, resulting in power loss as temperatures rise [10]. Solar radiation variability, influenced by atmospheric conditions and seasonal changes, impacts panel performance, with higher irradiance boosting output up to a certain maximum power before efficiency decreases [7]. Moreover, high humidity, particularly in coastal areas like Oman, can exacerbate soiling issues by promoting dust adhesion and dew formation, further impairing panel performance [11]. Material degradation over time is a significant concern for PV panels, with temperature changes and thermal cycling leading to reduced power output, typically at about 0.5% annually, with faster degradation in the initial years [12]. Crystalline silicon modules generally outperform thin-film modules under harsh conditions [13]. Additionally, the tilt angle of PV modules plays a crucial role in maximizing power generation, with proper tilt angles optimizing sun exposure throughout the year and ensuring sufficient power generation even in low sunlight conditions [14].

Cleaning PV panels manually involves using non-conductive materials like brushes and cloths to remove dirt, with costs varying depending on the method used, such as brushes or microfiber cloth wipers. However, it is labor-intensive and not recommended for high-humidity regions where dust firmly adheres to panels [15][16]. Robotic cleaning systems automate the process, utilizing either dry cleaning with microfiber, nylon, or silicon brushes for water-scarce regions or wet cleaning with water for areas with abundant water resources, albeit with high initial and maintenance costs [18][19][20]. Semi-automated cleaning combines manual and robotic methods, with robots cleaning panels and requiring manual relocation between rows, or with vehicle-driven cleaning where cleaning brushes are attached to vehicles moving along panel rows, suitable for large installations but requiring careful handling to avoid panel damage [21].

A. Case Studies

The following table (Table 1) compares three case studies focusing on different aspects of photovoltaic (PV) panel cleaning methods. The objective is to evaluate, and compare the total cost of ownership, efficiency, and optimal cleaning techniques across diverse environmental and operational contexts.

Case Study 1 analyses the long-term costs and effectiveness of manual wet cleaning versus autonomous robotic cleaning in a large-scale solar power plant. Case Study 2 employs a multi-criteria decision-making approach to determine Dubai's most appropriate cleaning method, considering sustainability factors. Case Study 3 evaluates different dry-cleaning techniques and frequencies in Qatar to identify the most cost-effective and

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efficient cleaning strategy for PV panels in dusty environments [22]

The three cases highlight optimal solar panel cleaning methods and frequencies in different contexts in the Middle East. In the first case, a Middle East-based solar EPC company found that robotic cleaning was more cost-effective, significantly reducing total cost of ownership (TCO) and 70% higher efficiency than manual wet cleaning.

The robotic cleaners are solar-powered, eliminating the need for external power, while manual cleaning requires 4 liters of fresh water per module and must be done 600 times over 25 years. In the second case, the most suitable method for Dubai is water-based robotic cleaning, followed by manual cleaning, dry-based robotic cleaning, and nano-coating cleaning techniques. The third case in Qatar reveals that using a microfibre mop or a combination of microfibre and vacuum cleaner shows an efficiency improvement of approximately 6% on the control panel, with microfibre mopping being the most cost-effective. Weekly cleaning was found to be the most efficient. Additional insights indicate that cleaning frequency and methods are influenced by climate, dust type, and cost considerations [23].

II. Material and Methods

This study aims to compare the cost-effectiveness and performance of manual and robotic dry-cleaning methods for solar panels to identify the most economical option for the region. Additionally, it will determine the optimal cleaning frequency. The quantitative methodology uses performance data from the S-miles website and Meteo Virtual Control Room (VCR) and cost data from local cleaning company quotations. This chapter covers the research site description, solar site specifications, research approach, data collection and analysis procedures, and challenges encountered.

The study is being conducted at the Shams Solar Facility at the German University of Technology in Oman (GUtech), developed by Shams Global Solutions and BP Oman and inaugurated on November 18, 2019.

The facility includes four training zones and three PV module installations: a flat roof system, a pitched roof, and a ground-mounted system. The study focuses on two ground-mounted PV modules, one cleaned by a robot and the other manually.

Additionally, two manually cleaned panels (D1 and D2) will be cleaned at different intervals to determine the optimal cleaning frequency. The four training zones collectively have a combined capacity of 18 kWp. The modules used in this case study are part of the ground-mounted area. The panels are tilted at an angle of approximately 17 degrees with a 180-degree south orientation. They are manufactured by Trina Solar with the TSM-33mmPD14 designation.

The ground-mounted solar panels in a solar facility are equipped with silicon irradiance sensors and PT1000 temperature sensors, as these factors significantly influence photovoltaic system performance. The silicon irradiance sensor, made of monocrystalline silicon, has dimensions of 50 x 33 mm and weighs between 0.35 to 0.47 kg, effectively measuring solar irradiance and temperature from -35°C to 80°C. This cost-efficient sensor is mounted directly on the solar panel, ensuring accurate irradiance measurements. The PT1000 temperature sensor, encased in an aluminium cuboid, measures the surface temperature of the solar panel and is directly attached to its rear wall. It can connect to any Meteocontrol data logger's analog input, making it versatile for data collection in monitoring PV system performance.

Hoymiles HM-250 inverters are used for ground-mounted systems. The Hoymiles inverter boasts compact dimensions of 153×178×28 mm and a lightweight design at 1.98 kg. It operates efficiently within a wide temperature range from -40°C to +65°C, utilizing natural convection cooling without a fan. With a maximum efficiency of 96.70%, it supports DC input from modules with a power of up to 440W. The inverter's peak power MPPT voltage range spans from 33V to 48V, with a start-up voltage of 22V and an operating voltage range of 16V to 60V. It can handle a maximum input voltage of 60V and a maximum input current of 11.5A.

The Shams solar facility uses a locally designed and manufactured dry-cleaning robot by Dymuma Advanced Projects (DAP) LLC. This self-powered robot, equipped with an onboard mini solar panel, operates based on the four-meter length of the PV string, cleaning the panels in two modes: forward (dock station to return station) and backward (return station to dock station). The robot consists of three main parts: an aluminum frame (1.996 m x 0.04 m), the robot body, and a two-meter spiral brush. It moves horizontally across the array on eight wheels, with four rail wheels and four driving wheels connected by a shaft. The driving wheels, powered by a rotating motor, turn the cleaning brush to ensure the PV cells are cleaned without scratches.

III. Results and Discussion

If you are using *Word*, use either the Microsoft Equation Editor or the *MathType* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* MathType Equation). “Float over text” should *not* be selected.

A. Performance Analysis

This section analyzes the performance of two solar panel cleaning methods—Manual Dry Cleaning and Robotic Dry Cleaning—over two months period.

Performance metrics include each method's irradiance, DC Current, DC power, and DC voltage. Note that data from April 21 to April 27 were lost, except for irradiance data.

Figure 1 shows the relationship between irradiance and DC current for automated panels. Both metrics show a direct proportional relationship: higher irradiance results in higher currents. The average irradiance recorded was 498.89 Wh/m², resulting in an average current of 4.26 A. Following a wet cleaning, the highest current (5.44 A) was recorded on April 12. The lowest current (3.049 A) was recorded on June 6 due to low irradiance.

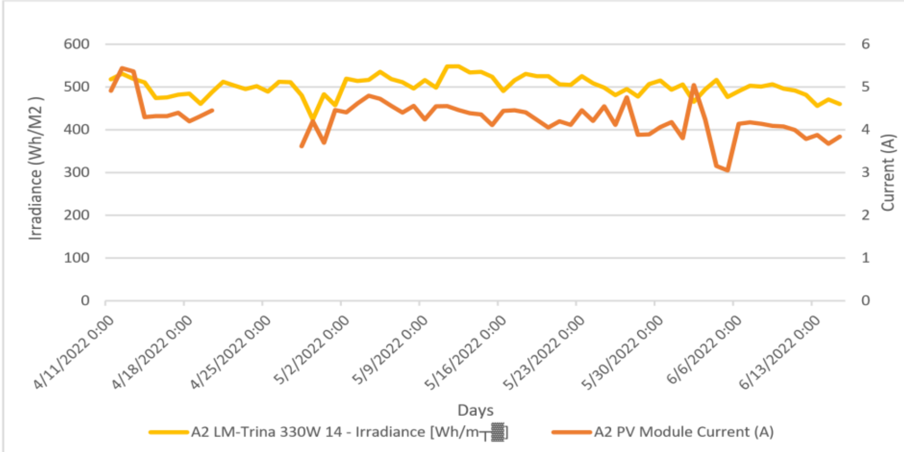

Fig. 1 Experimental data of Robotic cleaned panel between irradiance and DC Current.

Figure 2 shows irradiance and DC current for manually cleaned panels. The average irradiance was 498.89 Wh/m², and the average current was 4.55 A. The highest current (5.64 A) was on April 21, and the lowest (3.84 A) was on June 25, corresponding with the lowest irradiance of 424 Wh/m² during cloudy weather.

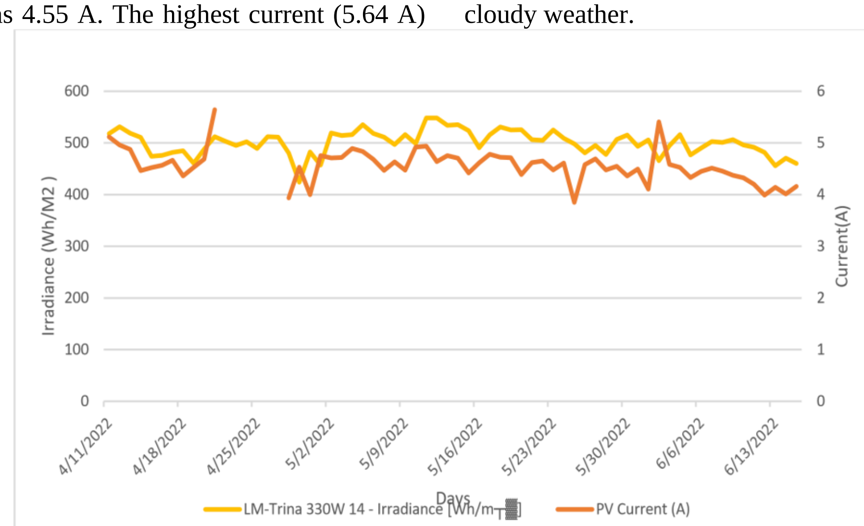

Fig. 2 Experimental data of Manual cleaned panel's system between irradiance and DC Current.

Figure 3 displays DC power, voltage, and current for robotic cleaned panels. The average current was 4.26 A, generating an average power of 134.729 watts at 32.2 volts. The highest current (5.44 A) and power were recorded on April 12. A decline on May 5 was due to the robot being out of service from May 4 to May 8. Data loss occurred from April 21 to April 27.

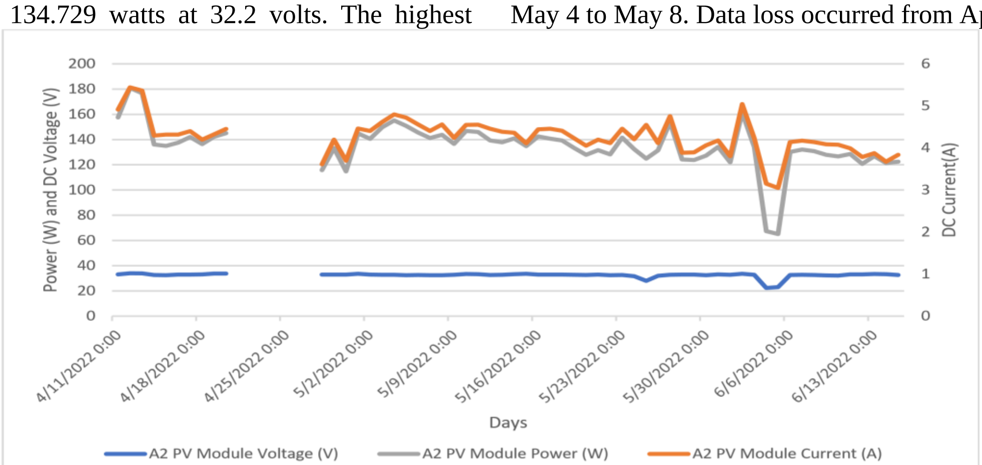

Fig. 3 Experimental data of Robotic cleaned panel between Power, voltage, and current.

Figure 4 presents DC power, voltage, and current for manually cleaned panels. The average current was 4.49 A, producing an average power of 141.63 watts at 32 volts. The highest power (181.34 watts) was on April 21, and the lowest (121.2 watts) on June 25, corresponding with the lowest irradiance.

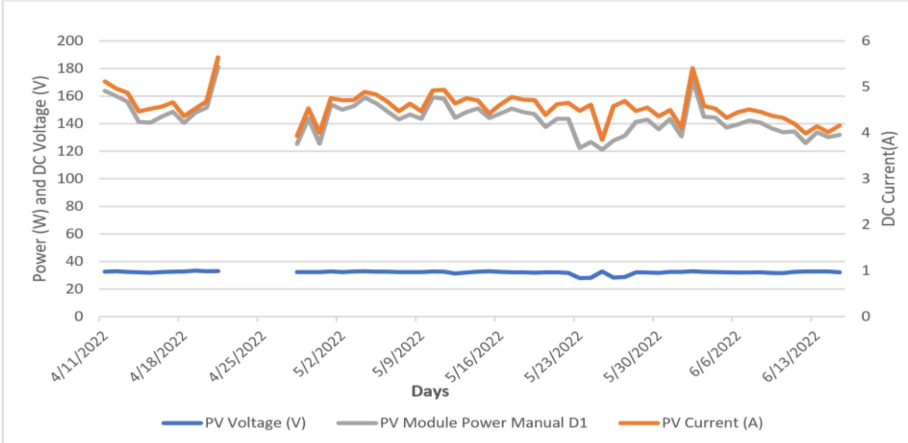

Fig. 4 Experimental data of Manual cleaned panel between Power, voltage, and current.

B. Cost Analysis Results

This section of the research is devoted to setting out the results of the Cost analysis for the two solar panel cleaning methods, Manual Dry Cleaning and Robotic Dry Cleaning for each cleaning method, considering various cost parameters, including investment costs, yearly savings, yearly cash, and return on investment percentages for each cleaning method. Note that we have two different quotations for manual dry cleaning from two other companies, with company A charging 500 OMR per hour for daily cleaning for two months. And Company B charges 90 OMR per hour. Companies A and B represent the range of cleaning costs in the market, with company B representing the lowest cost and company A representing the highest. An annual system cost breakdown was conducted for the first ten years of cleaning to determine the return on investment when implementing robotic cleaning.

The graph in Figure 5 shows the annual savings by implementing robotic cleaning systems in a site cleaned by Company A and Company B over 10 years. During the first year, replacing a cleaner from Company B with a robot saves 500 OMR, while replacing a cleaner from Company A saves 3000 OMR. With Company B, savings are almost consistent during the first ten years, whereas savings with Company A experience a gradual rise.

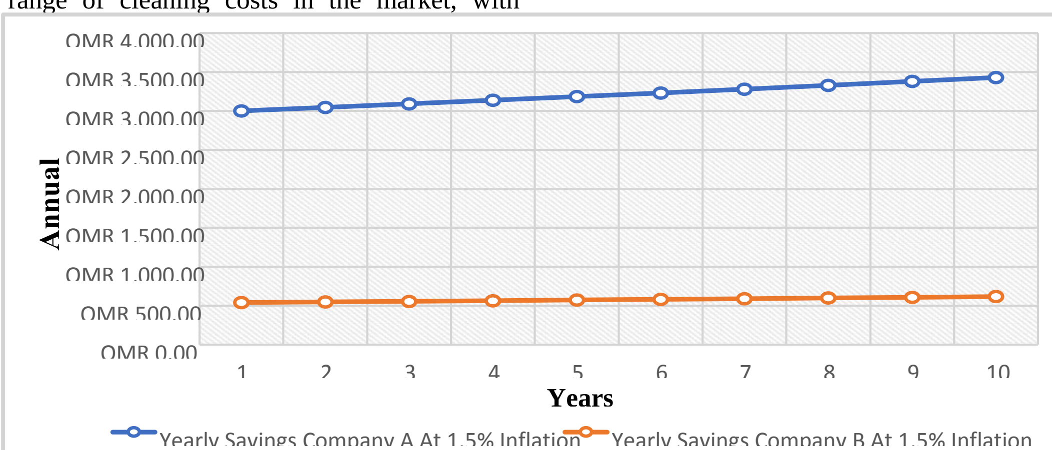

Fig. 5 Annual Savings for cleaning company A and B

Figure 6 illustrates the accumulated savings when implementing a robot instead of workers from Company A and Company B for the 10-year interval. As shown in the graph, company B has no accumulated savings for the first four years since the robot's return on investment was only seen after the fourth year when it reached 172.22 OMR. Despite this, savings are growing steadily, albeit slowly. However, when the robot replaces company A cleaning services, the savings begin to show in the first year when the panels are cleaned daily for the first 9 months, this is when it reaches 690.00 OMR. Overall, the robot’s accumulated savings are higher in case of Company A than in Company B

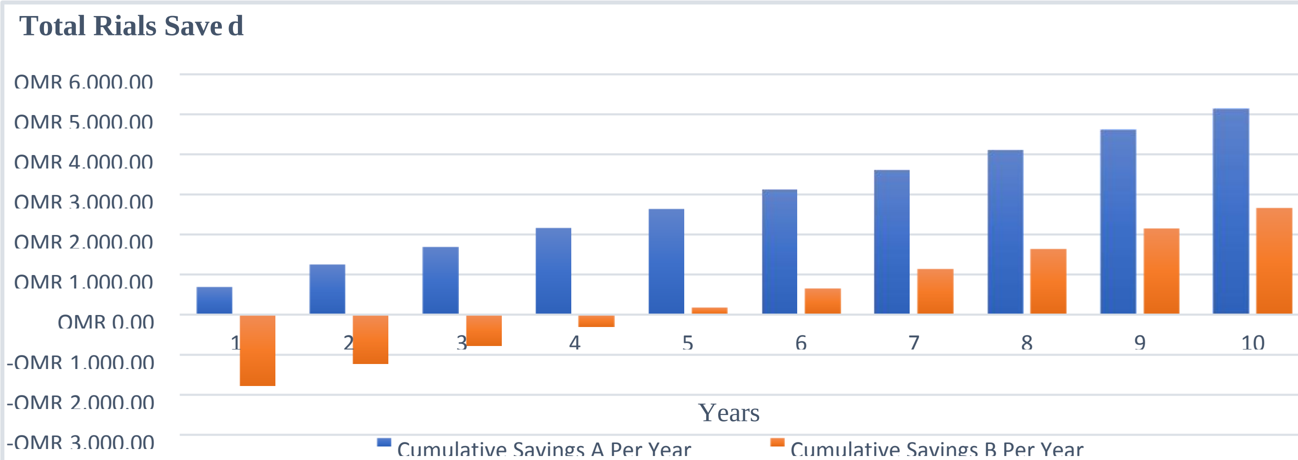

Fig. 6 Accumulated Savings for cleaning company A and B.

C. *Cleaning Frequency Analysis*

This study aimed to determine the optimal cleaning frequency for solar panels by comparing the power generation results of panels cleaned daily, weekly, and monthly over a two-month period from April 11th to June 16th. The following table shows the results.

TABLE I POWER GENERATION RESULTS OF PANELS CLEANED DAILY, WEEKLY, AND MONTHLY.

Parameter	April 11th - May 15th	May 16th - June 15th
Irradiance (Wh/m²)	Daily: 503.73	Daily: N/A
	Weekly: 502.44	Monthly: N/A
Current (A)	Daily: 4.66	Daily: Higher
	Weekly: 4.61	Monthly: Lower
Power Output (W)	Daily: 149.3	Daily: 149.32
	Weekly: 147.6	Monthly: 131.36
Voltage (V)	Both: 32 V	Both: Similar

IV. CONCLUSION

This study compared the cost-effectiveness and performance of dry robot cleaning versus dry manual cleaning of PV panels. Manual cleaning, using a microfiber cloth, outperformed robotic cleaning by 6.07% in power output, with robot performance hindered by technical issues.

Cost analysis showed that robotic cleaning was more cost-effective than manual cleaning offered by Company A, although manual services offered by Company B were cheaper.

Optimal cleaning frequency analysis indicated that weekly cleaning was the most cost-effective, providing near-daily performance (only 1.14% lower) while reducing costs.

The results highlight that local market conditions in Muscat significantly impact cost-effectiveness, with potential outcomes varying across regions.

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REFERENCES

[1] Sampaio, P. G. V., & González, M. O. A. (2017). Photovoltaic solar energy: Conceptual framework. Renewable and Sustainable Energy Reviews, 74, 590-601. https://doi.org/10.1016/j.rser.2017.02.081

[2] Khan, K. A., Paul, S., Zobayer, A., & Hossain, S. S. (2013). A study on solar photovoltaic conversion. International journal of Scientific and Engineering Research, 4.

[3] Khan, K. A., Paul, S., Zobayer, A., & Hossain, S. S. (2013). A study on solar photovoltaic conversion. International journal of Scientific and Engineering Research, 4.

[4] Arshad, R., Tariq, S., Niaz, M. U., & Jamil, M. (2014, April). Improvement in solar panel efficiency using solar concentration by simple mirrors and by cooling. In 2014 international conference on robotics and emerging allied technologies in engineering (iCREATE) (pp. 292295). IEEE. https://doi.org/10.1109/iCREATE.2014.6828382

[5] Hoffmann, S., & Koehl, M. (2014). Effect of humidity and temperature on the potentialinduced degradation. Progress in Photovoltaics: Research and Applications, 22(2), 173-179. https://doi.org/10.1002/pip.2238

[6] Salih, S. M., & Taha, M. Q. (2013). Analysis of Shading Impact Factor for Photovoltaic Modules. In proceeding at center of desert conference (Vol. 2).

[7] Vidyanandan, K. V. (2017). An overview of factors affecting the performance of solar PV systems. Energy Scan, 27(28), 216.

[8] El-Shobokshy, M. S., & Hussein, F. M. (1993). Effect of dust with different physical properties on the performance of photovoltaic cells. Solar energy, 51(6), 505-511. https://doi.org/10.1016/0038-092X(93)90135-B

[9] Bosman, L. B., Leon-Salas, W. D., Hutzel, W., & Soto, E. A. (2020). PV system predictive maintenance: Challenges, current approaches, and opportunities. Energies, 13(6), 1398.

[10] Ahmed, Z., Kazem, H. A., & Sopian, K. (2013). Effect of dust on photovoltaic performance: Review and research status. Latest trends in renewable energy and environmental informatics, 34(6), 193-199.

[11] Kazem, H. A., & Chaichan, M. T. (2019). The effect of dust accumulation and cleaning methods on PV panels' outcomes based on an experimental study of six locations in Northern Oman. Solar Energy, 187, 30-38. https://doi.org/10.1016/j.solener.2019.05.036

[12] AIDARA, M. C., NDIAYE, M. L., MBAYE, A., SYLLA, M., NDIAYE, P. A., & NDIAYE, A. (2018). Study of the performance of a system for dry cleaning dust deposited on the surface of solar photovoltaic panels. International Journal of Physical Sciences, 13(2), 16-23. https://doi.org/10.5897/IJPS2017.4701

[13] Derakhshandeh, J. F., AlLuqman, R., Mohammad, S., AlHussain, H., AlHendi, G., AlEid, D., & Ahmad, Z. (2021). A comprehensive review of automatic cleaning systems of solar panels. Sustainable Energy Technologies and Assessments, 47, 101518. https://doi.org/10.1016/j.seta.2021.101518

[14] Salih, S. M., & Kadim, L. A. (2014). Effect of tilt angle orientation on photovoltaic module performance. ISESCO JOURNAL of Science and Technology, 10(17), 19-25.

[15] Chanchangi, Y. N., Ghosh, A., Sundaram, S., & Mallick, T. K. (2020). Dust and PV Performance in Nigeria: A review. Renewable and Sustainable Energy Reviews, 121, 109704. https://doi.org/10.1016/j.rser.2020.109704

[16] Kazem, H. A., Chaichan, M. T., Al-Waeli, A. H., & Sopian, K. (2020). A review of dust accumulation and cleaning methods for solar photovoltaic systems. Journal of Cleaner Production, 276, 123187. https://doi.org/10.1016/j.jclepro.2020.123187

[17] Spertino, F., & Corona, F. (2013). Monitoring and checking of performance in photovoltaic plants: A tool for design, installation and maintenance of grid-connected systems. Renewable Energy, 60, 722-732. https://doi.org/10.1016/j.renene.2013.06.011

[18] Mathews, T., & Gopi, V. (2014, March). Embedded system based power management for battery operating robotic vehicle. In 2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014] (pp. 503-508). IEEE. https://doi.org/10.1109/ICCPCT.2014.7054928

[19] Mathew, D., Ram, J. P., & Kim, Y. J. (2023). Unveiling the distorted irradiation effect (Shade) in photovoltaic (PV) power conversion–A critical review on Causes, Types, and its minimization methods. Solar Energy, 266, 112141. https://doi.org/10.1016/j.solener.2023.112141

[20] 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, 241, 553-563. https://doi.org/10.1016/j.solener.2022.06.024

[21] Bagde, K. S., Choukikar, M. D., Uikey, R. A., Chahande, V. S., & Lonare, R. V. (2022). Solar Powered Smart Multifunctional Floor Cleaning Robot.

[22] AlMallahi, M. N., El Haj Assad, M., AlShihabi, S., & Alayi, R. (2022). Multi-criteria decision-making approach for the selection of cleaning method of solar PV panels in United Arab Emirates based on sustainability perspective. International Journal of Low-Carbon Technologies, 17, 380-393. https://doi.org/10.1093/ijlct/ctac010

[23] Al-Housani, M., Bicer, Y., & Koç, M. (2019). Assessment of various dry photovoltaic cleaning techniques and frequencies on the power output of CdTe-type modules in dusty environments. Sustainability, 11(10), 2850. https://doi.org/10.3390/su11102850