Robotic dry cleaner for photovoltaic solar panels: an implemented design that evaluated in iraq's weather

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Article Info

Article history:

Received Mar 25, 2021
Revised Jun 18, 2021
Accepted Jul 5, 2021

Keywords:

Dust
Embedded system
IoT
Photovoltaic system
Portable PV cleaner
PV power mitigation

ABSTRACT

Arabian desert areas are suffered from high mitigation in the produced photovoltaic (PV) power due to high dusty weather. This article presents a robotic cleaner that will significantly reduce the impact of dust on the installed PV systems in these areas. The proposed robotic cleaner is simple, low cost, standalone, self-powered, portable, and connected to the cloud. ESP32 used as a controller that manages the cleaning process and monitors its PV power production, the battery's state of charge, time of the day, and weather conditions. Thanks to the ESP32 features and its ability to connect to the cloud, as an internet of things (IoT), via the ThingSpeak website. All the electrical, mechanical, and electronic design aspects are presented and implemented in this article. The results show the effectiveness and performance enhancement due to periodic cleaning using the proposed robotic cleaner. The results also show that the total percentage of the monthly normalized accumulated losses for the two scheduled cleaning photovoltaic strings with a performance improvement of 15.54% for the weekly cleaned string (WCS) 83.04% for the never cleaned string (NCS) through the tested month.

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1. INTRODUCTION

The photovoltaic soiling index (PVSI) is an indicator for the performance of photovoltaic (PV) panels under exposure to dust at the standard test conditions (STC) [1]. Soiling is described as the dirt accumulation on the solar panel modules. It is a critical loss factor, mainly when there are arid conditions, scarce rain, and even frequent dust or sand storms [2]. Two independent parameters, the local environment and the dust properties, which consist of shape, component, weight, and size [3], affect the characteristics of soiling accumulation on solar panels. These properties play an essential role in dust scattering and result in various problems that cause soil accumulation on solar panels. Environmental factors such as irradiation, wind movement, wind direction, dust storm, temperature, air pollution, air pressure, volcano, and snow could be environmental factors. Dust type can also classify into carbon, soil, and sand, clay, bacteria. In contrast, physical factors depend on other aspects such as the installation location (sandy area, industrial area, latitude, and longitude), glass material, orientation, height, tilt angle, and flat surface [4]. In article [5], a real-time experiment has been conducted to analyze the effect of many factors on the PV system performance included the soiling effect. Other researchers [6] proposed a strategy to reduce the consumed energy by controlling the home appliances. Moreover, in the article [7], the authors proposed a robust maximum power point tracking (MPPT) controller with an adaptive PI controller based on fuzzy logic. Such a controller can be helpful to extract the PV maximum power in dusty weather.

There are many dust-accumulation mitigations strategies discussed by researchers, such as [8]-[11], but dust-accumulation is still a significant problem facing efficiency, especially in the desert area. It significantly reduces the efficiency of a PV module. Researchers presented many strategies to reduce the accumulation of dust on the PV panel. Such as enhancing the glass transmittance and self-cleaning properties due to several coating techniques, metallic anti-corrosion, drag resistant coatings [12], and self-cleaning coating with antireflection (AR) properties [13], Dip-coating method using a sol-gel [14], and anti-adhesion coatings [15]. Moreover, as in [16], researchers offer electrostatic cleaning equipment to remove the dust removal from soiled solar panels.

In [17], the authors proposed cleaning the PV module by sodium solution reduced the generated energy loss when the module is contaminated with natural dust and particulate matter, but its effect is limited on soil and $CaCO_3$. Several studies were done to analyse the dust composition, but we will focus on this article on Iraq studies. In [18], they examined samples from different areas of Iraq. The results show; Mahmoodia, the Karbala-Najaf desert road, has a high percentage of silica which can be traced back to the fertile valley of Mesopotamia with precise proportions of clay and silt. In contrast, significant percentages of particulate matter (PM), lead, and sulfur were found in Fao, south of Iraq. The result was indicating high contamination by fossil fuel combustion emissions. A review article [19] shows the effect of dust on PV in a separate area of Iraq was dedicated to researchers, designers, and engineers dealing with PV systems in Iraq. Also, there is a dedicated book section in [20] that dedicated several publications in Iraqi university journal that described all the physical properties of the dust in Iraq and its effect on PV Systems. As in Iraq [21], there is a gap between the available power and the growing demand for power in a growing country. Researchers such as in [22]-[25], are developed many techniques to reduce that gap. However, the dust increases this gap due to the reduction in the produced power.

Traditional cleaning using human resources is time-consuming, costly, and preferable on the daytime, which conflicts with the system's production hour. Especially in vast solar farms, the monitoring of dusty parts of the array is difficult to find, so the researchers in [26] offered a strategy to monitor the whole array via a wireless monitoring system. In the article [3], the authors present a general recommendation of mitigation measures against the (likely) impact of dust accumulation on PV performance. They divide the world into three groups: i) Group-I: Low latitudes (wet, wet-dry, and dry tropical); ii) Group-II: Mid-latitude climate (steppe, Mediterranean, and grassland climate); and iii) Group-III: High latitude climate (taiga, and tundra climate). That concludes us that the high latitude location has less dust accumulation since the panel tilt angle is high, and that is presented in [27]. Many researchers offer solutions by presenting different designs for cleaning robots, but in general, we will evaluate these modules according to their cleaning efficiency, cleaning time, cost-efficient, reliability, simplicity, and durability. In [28], the authors present a design that needs a guidance rail to clean the PV array. While in [29], a cleaning robot is presented with adhesive feet, a rolling brush, and a dust suction model; however, cost and simplicity must be considered. A prototype is presented in [30]. However, it seems not practical since it is required a long cleaning time and not suitable for the tilted angle where most of the PV arrays are. In [31], a new type of brush uses silicone rubber foam flaps mounted onto an Aluminium core. However, this module is not self-powered and requires a guidance rail. In [32], a robotic cleaner was presented with three motors for the power generation of a coastal PV-power plant at Zahrani Lebanon. The dry cleaning was presented in [33], and the results shows highly effective and nonabrasive cleaning. Using sensor to detect dust was presented in [34], while the motor speed is proportional to the dust amount, such model is seems very good but not cost efficient. Moreover, smaller version of robotic cleaner was also presented in [35], but it need more time for cleaning process. A smart cleaning robot was presented in [36], five motors were used which increased its cost and complexity. Another small robot was presented in [37], but cleaning time in vast solar farm and inclination angle were the main weaknesses for that design.

This article presents a new design to clean the PV array efficiently, self-powered, low cost, reliable, simple, and durable. After making all the mechanical, electrical, and electronic designs, we start to build a prototype. We want to declare that most of the system components were refurbished or recycled. The rest of the paper can be concluded as follows: in section 2, the design aspect was released. While section 3 describes the implementation includes all the required calculations. Then section 4 present the results and discussion; the mitigation in power was calculated for seven scenarios. Finally, section 5 will conclude the article findings and contributions.

2. THE PROPOSED PROCEDURE

The proposed procedure include design a robotic cleaner with mechanical, electrical, and electronic design aspects.

2.1. Mechanical design

The robot striction consists of the leading steel frame with six freewheels. Four wheels are horizontal and two verticals to consider the PV panel tilt angle. It has two rolling brushes that design to rotate against the moving direction to push the dust away. The robot has a single DC motor to move the robot and rotate the brushes simultaneously via a gearbox and bullies. The gearbox is responsible for reversing the rotation direction while the bullies increase the brushes' speed. In contrast, an extra two rubber wheels are used to transfer the motor rotation smoothly for both sides. Figure 1 shows the prototype design using SketchUp software. Figure 2 shows the system's main components. It shows the main shaft that transfers the mechanical rotation force into the two rubber wheels. Two rubber belts used to rotate the front, and the back brushes cylinders via the main pulley. The pulleys, gears, controller, MPPT charger, battery are covered with a galvanized case to protect from weather conditions. The design also offers a dust fender that prevents the dust from splatting on the robot PV module while cleaning. A parking space is required for the robot while it is not cleaning to avoid its shadow on the PV string. Otherwise, it must be removed from the string after finishing the cleaning process.

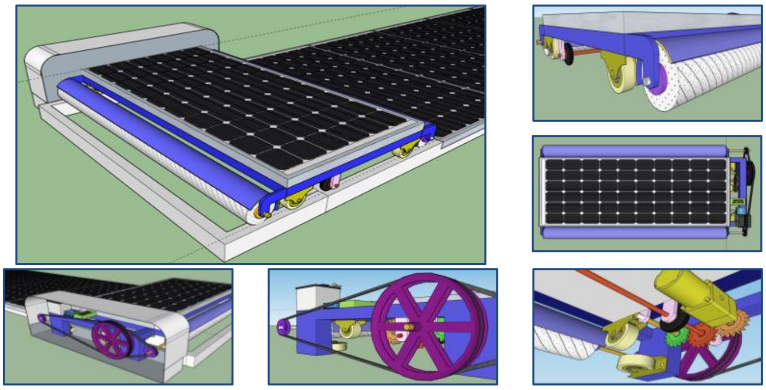


Figure 1. Mechanical design

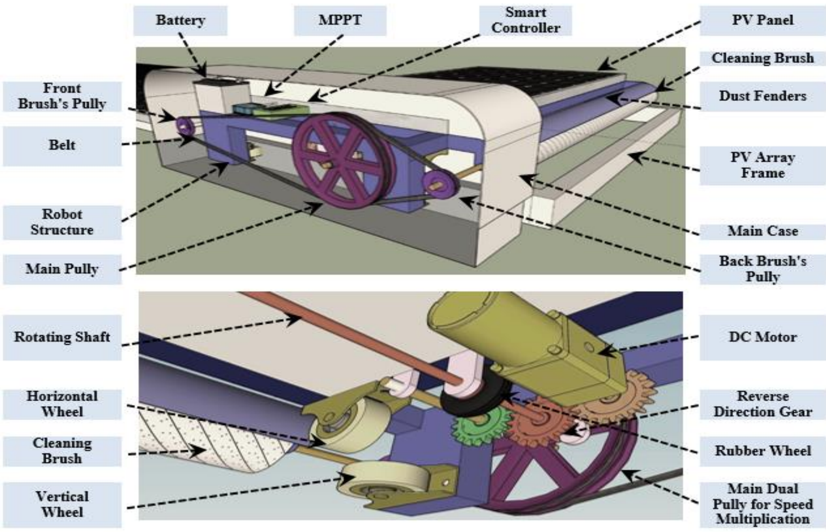


Figure 2. The main system components

2.2. Electrical and electronic design

The system is self-powered. We consider that most of the cleaning process happens before sunrise or after sunset to avoid any system interruption. A battery is charged via an MPPT charger via a single portable PV panel, as shown in Figure 3. The driver circuit consists of three relays; it is responsible for start/stop the motor and the rotation direction. The first relay is used as a switch to disconnect the power. Simultaneously, the other two are responsible for reversing the rotation direction by reversing the polarity. The driver also has a voltage shifter since 3.3 V signals from the ESP32 control it. There two limit switches on each side of the robot. These switches are used to detect the PV array's start and end by touching the pins at the PV array's ends.

The controller's main component is the ESP32, which is supplied with 5 V via a voltage regulator. All the measured data are uploaded periodically into the ThingSpeak website. It is also received the cleaning schedule, energy production data, and weather data from the website. The controller used these data to organize the working hours. Weather data is useful too, since there is no need to clean on a rainy day. The controller also measures its battery and stops cleaning under a specific state of charge SoC%. The battery's SoC data is also uploaded as a fault flag, battery low SoC could be led to a bad battery, charging problem, or the PV panel for the robot needs to be cleaned. Figure 4 shows the electronic circuit with the screenshots for the ThingSpeak site.

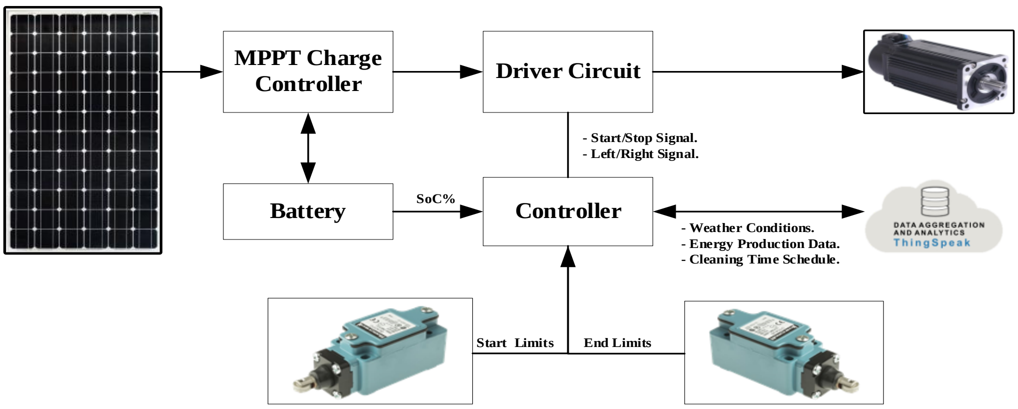


Figure 3. Electrical wiring diagram

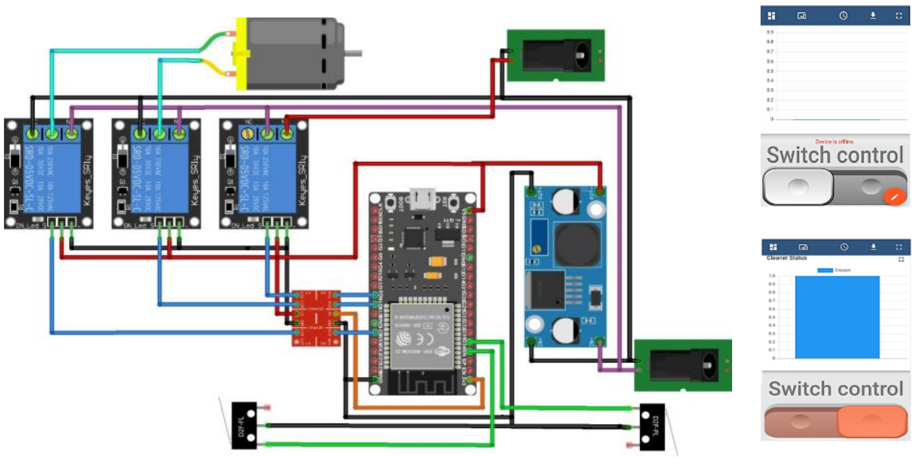


Figure 4. Electronic circuitry

3. RESULTS AND DISCUSSION

Running the cleaning robot in the daylight causes an interruption for the system generation due to the array's robot shading. We consider that the system is only cleaning once a day, before sunrise or after sunset. At the same time, from our experience, it is sometimes not recommended to clean the solar panel in the morning when it is still wet due to settled dew. The robot PV panel will be saved energy in the battery throughout the day to clean at the end of the day or the next morning. This design aspect will make our power calculations and choices are flexible. The chassis' dimensions are equal to the used PV panel dimensions plus 20 cm from the upper side. This extra space will be used for the gearbox, battery, MPPT charger, motor, and controller. We want to declare that all the materials and parts used in this project are recycled or refurbished.

The chassis was welded then the rolling brushes are attached. These rolling brushes are fabricated using a galvanized pipe that spiral with a fabric towel, as shown in Figure 5. After building and attaching the gearbox, and the motor, which is recycled from car wipers, the consumed current is measured. The total consumed current under full load was 8 A, 12 V, so the consumed power was 96 W. A 10 A MPPT charger is used to manage the battery charging at 0.5 C. The used battery is a lead-acid battery with a 20 A.h capacity. Figure 5 shows photos of various stages of implementation.

Figure 5. Robot implementation photos

Figure 6 shows the normalized power generation for the three strings with a noticeable daily power degradation (DPD) in the string production (0.3% a day). The dark blue circles mean the string was cleaned that day. The weekly cleaned string (WCS) string was cleaned every Tuesday (2^{nd}, 9^{th}, 16^{th}, 23^{rd} of Feb, and the 2nd of Mar/2021). We also referred for the daily cleaned string as (DCS), and never cleaned string for the (NCS).

A string of 6 PV panels, 100×200cm each, were used for testing and evaluation. The panels were attached vertically, so the string length was 6 meters and 2 meters in height. We calculate the time required to clean the string; the cleaning process starts by moving the robot from start to end, then reverse its movement direction to back into the start point. The cleaning time for the forward course (CTFC) was 36 sec, then another 36 sec for the backward course (CTBC). However, here we will calculate per one panel as in (1) to (3).

$$\text{Measured string cleaning time (SCT)} = \text{CTFC} + \text{CTBC} = 36 + 36 = 72 \text{ sec} \quad (1)$$

$$\text{Panel cleaning time (PCT)} = \frac{\text{SCT}}{\text{n}} = \frac{72}{5} = 14.4 \text{ sec/panel} \quad (2)$$

Where (n) is the number of panels per string.

$$\text{The consumed cleaning energy per panel} = \text{Power} \times \text{PCT} \quad (3)$$

$$= 96 \text{ W} \times 14.4 \text{ s} = 1{,}382.4 \text{ W.sec} = 0.384 \text{ W.h}$$

The used solar panel is a SunPower, Model SPR-305-WHT-D, 308 W_p, 280 W_p (50 °C), I_{MPP} 5.7 A, UMPP 48 V, thermal Loss factor 20.0 W/m²K, Wiring Ohmic Loss 142 mOhm. We used PVsyst Software to simulate our hypothesis to run the robot for one hour from 5 am to 6 am. The simulation results show in Figure 7(a) that the panel energy is enough all year. The daily power profile is presented in Figure 7(b). In this hour, the robot able to clean approximately (3600 s/14.4 s = 250 panels). Now let calculate the required battery capacity as in (4) and (5).

$$\text{Battery total storage energy (W.H)} = \frac{\text{Power} \times \text{Time}}{\text{DoD}} = \frac{96\text{W} \times 1\text{h}}{0.5} 192 \text{ W.h} \quad (4)$$

DoD is the Deep of Discharging, for the used battery which is Lead Acid Batteries is 50%.

$$\text{Battery total capacity (A.H)} = \frac{\text{Energy (W.h)}}{\text{Voltage (V)}} = \frac{192}{12} = 16 \text{ Ampere.hour} \quad (5)$$

Based on the calculated degradation ratio and the robot design calculations, we will evaluate the effectiveness and the enhancement of an array string consists of 250 solar panels as a case study.

$$\text{The string peak power } W_{pt} = \text{number of PV panels} \times \text{Wp} = 250 \times 308 = 77000\text{W} \quad (6)$$

$$\text{The daily total degradated power (DTDP)} = \text{total power } \times \text{DPD} = 77000 \times 0.3\% = 231\text{W} \quad (7)$$

$$\text{The daily total degradated energy (DTDE)} = \text{DTDP} \times \text{active hours} \quad (8)$$

$$= 231\text{W} \times 7 = \ 1{,}617\text{W.h}, \text{ Average production active hours are 7 hours in Baghdad}$$

$$\text{Accumulated power degredation (APD)} = \sum_{n=1}^{N} n \times \text{DPD} = \text{DPD}\ \frac{N(N+1)}{2} \quad (9)$$

A constant degradation rate is considered for simplicity.

$$\text{The weekly total power degradation (WTPD)} = \sum_{n=1}^{7} W_{pt}\ \times \text{APD} \quad (10)$$

$$= 77000\ \times 0.3\% \times \frac{7(8)}{2} = 6{,}468\text{W}$$

All seven days with constant dust rate.

$$\text{The weekly total degradated energy (WTDE)} = \text{WTDP} \times \text{Active Hours} \quad (11)$$

$$= 6{,}468\text{W} \times 7 = 45.3\ \text{kW.h}$$

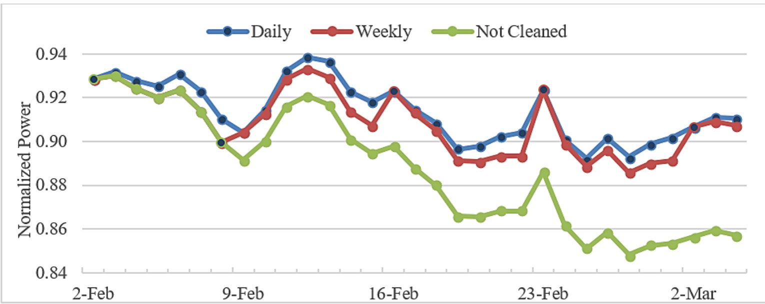
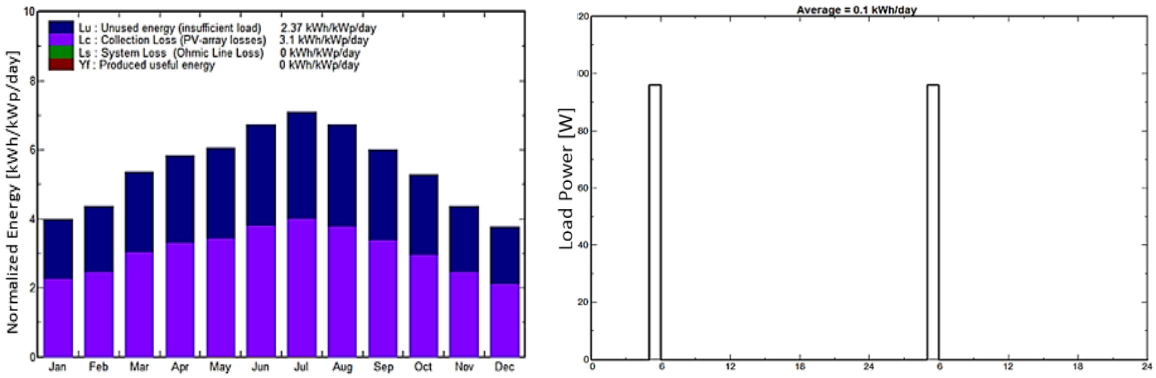


Figure 6. Normalized power generation of the three strings under varying treatment



(a) (b)

Figure 7. PVsyst simulation results: (a) Normalized productions (per installed kWp), nominal power 308 Wp and (b) User's needs: the daily profile, constant over the year

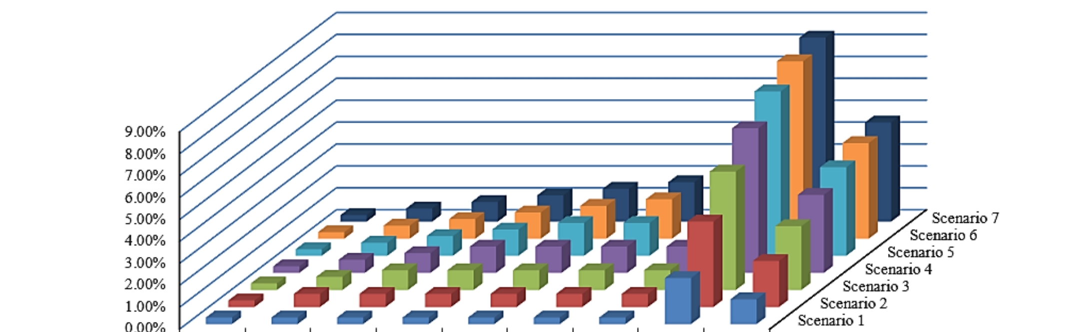
A study with seven days' window is adopted with seven scenarios to understand the dust effectiveness. The first scenario: if only the Sunday were dusty and $DPD_{Sunday} = 0.3\%$, while the other days of the week were not dusty, but the PV string will be left uncleaned, so the DPD for the rest of the week will stay 0.3%. This scenario would result $APD_w = 2.1\%$ in that week. The second scenario is that Sunday and Monday are dusty with the same DPD = 0.3% so that Monday will have twice the amount of the dust on the PV string, $DPD_{Monday} = 0.6\%$. For this scenario, the $APD_w = 3.9\%$. The same principle is applied for the other five scenarios, and the results were shown in Figure 8. The results show the high impact of the accumulated dust on the PV panels string, and the worst case when the whole week is dusty shows an $APD_w = 8.4\%$.

In Iraq, these scenarios are highly possible for two reasons, the first reason is the dusty weather in the summertime, and the second is because of the high ash particles from the oil refineries and the local private generators that distributed everywhere due to the uncertainty in the power availability from the grid. The results also show in scenario seven that weekly mitigation in energy for the PV solar string equals 45.3 kW.h/week. Even after the sky is clear after the seven dusty days in scenario 7, the system degradation will continue. For example, in the rest three weeks of the months, the energy mitigation will be equal to 52.50% of the nominal power (0.525×77 kW×7 h= 282 kW.h/month).

In Figure 9, the collected energies from the three strings are presented in watt-hour per day. In the first, all the strings are cleaned so, the produced energies from all the strings are the same. While the dust is accumulated the degradation the in produced energy will increased. Also, we can find that the WCS string production is equal to the DCS on the day# 1, 8, 15, 22, and 29. The maximum energy imitation of day 31, for the NCS was 150 w-h/last tested day. The monthly accumulated losses for the tested strings were 15.54% for the WCS, while it was more worse for the NCS, 83.04%. these percentage were calculated according to the total percentage of the normalized accumulated losses (TPNAL), as in 12:

$$\mathbf{TPNAL} = \frac{\sum_{n=1}^{n=N}(W_{DCS}(n) - W(n))}{N \times W_P} \times \mathbf{100\%} \quad (12)$$

Where N is representing the total number of samples, here we take one sample every day for 31 days.



	Sun	Mon	Tue	Wed	Thu	Fri	Sat	ADP	WTDE (MW.h)
Scenario 1	0.30%	0.30%	0.30%	0.30%	0.30%	0.30%	0.30%	2.10%	0.011319
Scenario 2	0.30%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	3.90%	0.021021
Scenario 3	0.30%	0.60%	0.90%	0.90%	0.90%	0.90%	0.90%	5.40%	0.029106
Scenario 4	0.30%	0.60%	0.90%	1.20%	1.20%	1.20%	1.20%	6.60%	0.035574
Scenario 5	0.30%	0.60%	0.90%	1.20%	1.50%	1.50%	1.50%	7.50%	0.040425
Scenario 6	0.30%	0.60%	0.90%	1.20%	1.50%	1.80%	1.80%	8.10%	0.043659
Scenario 7	0.30%	0.60%	0.90%	1.20%	1.50%	1.80%	2.10%	8.40%	0.045276

Figure 8. A case study for the dust effectiveness on a PV string for seven days with seven different scenarios. WTDE was calculated based on the hypothetical PV solar string, which consists of (250×308 Wp=77 kWp)

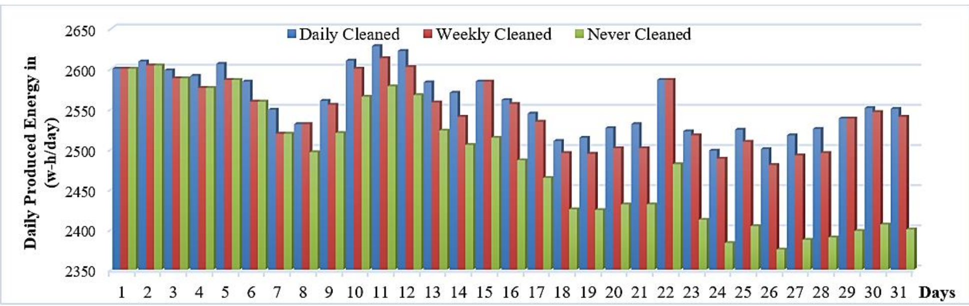


Figure 9. Daily produced energy in watt-hour/day

4. CONCLUSION

In this article, a design and implementation of a robotic cleaner were presented. The offered system shows a key advantage of being low cost, lightweight, self-powered, simple, and remotely controlled via IoT. All the mechanical, electrical and electronic design aspects are discussed in details. The article presents a study for the dust effectiveness on the solar power performance in Baghdad, Iraq. The implemented system showed a promised design with high efficiency in Iraq weather. We also conclude that cleaning the PV panel strings after the sunset is more efficient than cleaning before the sunrise due to the dew drops on the panel on humid days. From our observation of the robot cleaner working for more than a month, we noticed that the birds were not standing on the panels anymore, which reduced bird droppings. Finally, the system shows a significant enhancement in power production due to its daily cleaning for the PV strings. In contrast, the PV system efficiency enhancements were 15.54% for the weekly cleaned strings and 83.04% for the monthly cleaned string through the tested month.

REFERENCES

[1] K. Menoufi, "Dust accumulation on the surface of photovoltaic panels: introducing the photovoltaic soiling index (PVSI)," Sustainability, vol. 9, no. 6, p. 963, 2017, doi: 10.3390/su9060963.

[2] A. J. Abid, A. A. Obed, and F. M. M. Al-Naima, "Detection and control of power loss due to soiling and faults in photovoltaic solar farms via wireless sensor network," *International Journal of Engineering Technology*, vol. 7, no. 2, pp. 718-724, 2018, doi: 10.14419/ijet.v7i2.10987.

[3] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable sustainable energy reviews*, vol. 14, no. 9, pp. 3124-3131, 2010, doi: 10.1016/j.rser.2010.07.065.

[4] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, "Power loss due to soiling on solar panel: A review," *Renewable Sustainable Energy Reviews*, vol. 59, pp. 1307-1316, 2016, doi: 10.1016/j.rser.2016.01.044.

[5] A. Pradhan and B. Panda, "Experimental analysis of factors affecting the power output of the PV module," *International Journal of Electrical Computer Engineering (IJECE)*, vol. 7, no. 6, pp. 3190-3197, 2017, doi: 10.11591/ijece.v7i6.pp3190-3197.

[6] M. A. Mohammed, A. D. Farhood, and A. J. Abid, "A smart energy consumption manager based on protues simulation," *International Journal of Power Electronics and Drive System (IJPEDS)*, vol. 11, no. 1, pp. 143-150, 2020, doi: 10.11591/ijpeds.v11.i1.pp143-150.

[7] Slamet, E. Rijanto, A. Nugroho, and R. A. Ghani, "A robust maximum power point tracking control for PV panel using adaptive PI controller based on fuzzy logic," *TELKOMNIKA Telecommunication Computing Electronics and Control*, vol. 18, no. 6, pp. 2999-3010, 2020, doi: 10.12928/telkomnika.v18i6.17271.

[8] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches," *Renewable sustainable energy Reviews*, vol. 22, pp. 698-733, 2013, doi: 10.1016/j.rser.2012.12.065.

[9] S. A. M. Said, G. Hassan, H. M. Walwil, and N. Al-Aqeeli, "The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies," *Renewable Sustainable Energy Reviews*, vol. 82, pp. 743-760, 2018, doi: 10.1016/j.rser.2017.09.042.

[10] S. Ghosh, V. K. Yadav, and V. Mukherjee, "Impact of environmental factors on photovoltaic performance and their mitigation strategies–A holistic review," *Renewable Energy Focus*, vol. 28, pp. 153-172, 2019, doi: 10.1016/j.ref.2018.12.005.

[11] A. A. du Plessis, J. M. Strauss, and A. J. Rix, "Application of dust mitigation strategies to single-axis-tracking photovoltaic modules in the semi-arid areas of South Africa," *IET Renewable Power Generation*, vol. 14, no. 15, pp. 2781-2790, 2020, doi: 10.1049/iet-rpg.2019.1424.

[12] S. S. Latthe, H. Imai, V. Ganesan, C. Kappenstein, and A. V. Rao, "Optically transparent superhydrophobic TEOS-derived silica films by surface silylation method," *Journal of Sol-Gel Science and Technology*, vol. 53, no. 2, pp. 208-215, 2010, doi: 10.1007/s10971-009-2079-y.

[13] X.-T. Zhang, O. Sato, M. Taguchi, Y. Einaga, T. Murakami, and A. Fujishima, "Self-cleaning particle coating with antireflection properties," *Chem. Mater.*, vol. 17, no. 3, pp. 696-700, 2005, doi: 10.1021/cm0484201.

[14] P. Nostell, A. Roos, and B. Karlsson, "Optical and mechanical properties of sol-gel antireflective films for solar energy applications," *Thin Solid Films*, vol. 351, no. 1-2, pp. 170-175, 1999, doi: 10.1016/S0040-6090(99)00257-6.

[15] Y. B. Park, H. Im, M. Im, and Y. K. Choi, "Self-cleaning effect of highly water-repellent microshell structures for solar cell applications," *Journal of Materials Chemistry*, vol. 21, no. 3, pp. 633-636, 2011, doi: 10.1039/C0JM02463E.

[16] H. Kawamoto, "Electrostatic cleaning equipment for dust removal from soiled solar panels," *Journal of Electrostatics*, vol. 98, pp. 11-16, 2019, doi: 10.1016/j.elstat.2019.02.002.

[17] M. T. Chaichan and H. A. Kazem, "Experimental evaluation of dust composition impact on photovoltaic performance in Iraq," *Energy Sources, Part A: Recovery, Utilization, Environmental Effects*, pp. 1-22, 2020, doi: 10.1080/15567036.2020.1746444.

[18] M. T. Chaichan, H. A. Kazem, A. H. Al-Waeli, and K. Sopian, "The effect of dust components and contaminants on the performance of photovoltaic for the four regions in Iraq: a practical study," *Renewable Energy Environmental Sustainability*, vol. 5, no. 3, 2020, doi: 10.1051/rees/2019009.

[19] A. A. Kazem, M. T. Chaichan, and H. A. Kazem, "Dust effect on photovoltaic utilization in Iraq: Review article," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 734-749, 2014, doi: 10.1016/j.rser.2014.05.073.
[20] M. T. Chaichan and H. A. Kazem, *Generating electricity using photovoltaic solar plants in Iraq*. Springer, 2018, doi: 10.1007/978-3-319-75031-6.
[21] S. Al-Hamadani, "Solar energy as a potential contributor to help bridge the gap between electricity supply and growing demand in Iraq: A review," *International Journal of Advances in Applied Sciences (IJAAS)*, vol. 9, no. 4, pp. 302-312, 2020, doi: 10.11591/ijaas.v9.i4.pp302-312.
[22] F. M. Al-Naima, R. S. Ali, and A. J. Abid, "Solar Tracking System: Design based on GPS and Astronomical Equations," in *IT-DREPS Conference & Exhibition*, 2013, pp. 144-149.
[23] F. M. Al-Naima, R. S. Ali, and A. J. Abid, "Design and implementation of a smart dual axis sun tracker based on astronomical equations," *EWRES-The European Workshop on Renewable Energy Systems*, Antalya, Turkey, 10-20 Sep. 2012, pp. 1-6.
[24] A. J. Abid, R. S. Ali, F. M. Al-Naima, Z. Ghassemlooy and Zhiwei Gao, "A new power line communication modem design with applications to vast solar farm management," *2013 3rd International Conference on Electric Power and Energy Conversion Systems*, 2013, pp. 1-6, doi: 10.1109/EPECS.2013.6713015.
[25] A. J. Abid and F. M. Al-Naima, "A Photovoltaic Surveillance System for Performance Evaluation and Faults Detection at the Field," *International Journal of Automation and Smart Technology*, vol. 10, no. 1, pp. 409-420, 2020, doi: 10.5875/ausmt.v10i1.2144.
[26] A. J. Abid, A. A. Obed, and F. M. Al-Naima, "Web-Based System Design to Monitor and Control the Mismatching Effects in a Vast Solar Farm," *International Energy Journal*, vol. 18, no. 4, pp. 379-390, 2018.
[27] A. A. Hegazy, "Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors," *Renewable energy*, vol. 22, no. 4, pp. 525-540, 2001, doi: 10.1016/S0960-1481(00)00093-8.
[28] N. Hashim, M. N. Mohammed, R. AL Selvarajan, S. Al-Zubaidi and S. Mohammed, "Study on Solar Panel Cleaning Robot," *2019 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS)*, 2019, pp. 56-61, doi: 10.1109/I2CACIS.2019.8825028.
[29] S. Cai *et al.*, "Parameters optimization of the dust absorbing structure for photovoltaic panel cleaning robot based on orthogonal experiment method," *Journal of Cleaner Production*, vol. 217, no. 3, pp. 724-731, 2019, doi: 10.1016/j.jclepro.2019.01.135.
[30] I. P. G. Riawan, I. N. S. Kumara, C. G. I. Partha, I. N. Setiawan and D. A. S. Santiari, "Robot for Cleaning Solar PV Module to Support Rooftop PV Development," *2018 International Conference on Smart Green Technology in Electrical and Information Systems (ICSGTEIS)*, 2018, pp. 132-137, doi: 10.1109/ICSGTEIS.2018.8709138.
[31] B. Parrott, P. C. Zanini, A. Al Shehri, K. Kotsovos, and I. Gereige, "Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush," *Solar Energy*, vol. 171, pp. 526-533, 2018, doi: 10.1016/j.solener.2018.06.104.
[32] M. Hammoud, B. Shokr, A. Assi, J. Hallal, and P. Khoury, "Effect of dust cleaning on the enhancement of the power generation of a coastal PV-power plant at Zahrani Lebanon," *Solar Energy*, vol. 184, pp. 195-201, 2019, doi: 10.1016/j.solener.2019.04.005.
[33] A. Al Shehri, B. Parrott, P. Carrasco, H. Al Saiari, and I. Taie, "Accelerated testbed for studying the wear, optical and electrical characteristics of dry cleaned PV solar panels," *Solar Energy*, vol. 146, pp. 8-19, 2017, doi: 10.1016/j.solener.2017.02.014.
[34] A. Al Baloushi, M. Saeed, S. Marwan, S. AlGghafri and Y. Moumouni, "Portable robot for cleaning photovoltaic system: Ensuring consistent and optimal year-round photovoltaic panel performance," 2018 Advances in Science and Engineering Technology International Conferences (ASET), 2018, pp. 1-4, doi: 10.1109/ICASET.2018.8376781.
[35] M. G. Antonelli, P. Beomonte Zobel, A. De Marcellis, and E. Palange, "Autonomous robot for cleaning photovoltaic panels in desert zones," *Mechatronics*, vol. 68, 2020, doi: 10.1016/j.mechatronics.2020.102372.
[36] N. Khadka, A. Bista, B. Adhikari, A. Shrestha, and D. Bista, "Smart solar photovoltaic panel cleaning system," *IOP Conference Series: Earth and Environmental Science*, vol. 463, Bangkok, Thailand, 2020, pp. 1-8, 2020, doi: 10.1088/1755-1315/463/1/012121.
[37] T. Sorndach, N. Pudchuen and P. Srisungsitthisunti, "Rooftop Solar Panel Cleaning Robot Using Omni Wheels," *2018 2nd International Conference on Engineering Innovation (ICEI)*, 2018, pp. 7-12, doi: 10.1109/ICEI18.2018.8448530.