Automatic and portable cleaning photovoltaic solar panels mechanism

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Abstract: This research designed and built an automatic and portable cleaning mechanism for photovoltaic panels (PVs). The climate variation defined the amount of accumulated dust; this modified the load efficiency (η) by 11.05% on average, reaching a maximum of 39.6% in the hour of greatest solar spectrum. The highest value obtained of fill factor (FF) was 0.29 with a clean PV compared to 0.25 of a dirty PV, in all measurements the dust decreases the FF. In this study the power (W) loss should not be greater than 2.17 W, which can be because of dirty panels with dust; and the FF greater than 71%. The amount of accumulated dust decreases the FF, for this reason the cleaning mechanism must be programmable, must be portable and adjustable to different PV sizes.

Keywords: panel solar; panel cleaning; photovoltaic; dust; mechanism.

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1 Introduction

The use of PVs has increased in different parts of the world that have a high sunlight spectrum. The main reason for this increase is because it is a cheap energy alternative, easy to install and with low maintenance cost. The efficiency of PVs depends on solar irradiance, sunlight spectrum, temperature, and dust level, with these factors the cleaning process can be estimated (Khilar et al., 2022; Kumar et al., 2022; Systems et al., 2023). In the literature (Ratnaparkhi et al., 2023; Usamentiaga et al., 2020), they focus the mitigation of particulate matter on PV surfaces using a hydrophobic coating with and without dew suppression (2). Another aspect that is considered in evaluating the performance of PVs due to fouling is the relationship of mass deposition density and radiation effectiveness (Hosseini et al., 2023; Özer et al., 2019; Shaaban et al., 2020) (2). This can also be observed in numerical predictions with simulations such as Gaussian methods, neural network learning (Heinrich et al., 2020; Perez-anaya et al., 2022; Venkatesan et al., 2022) (2). Sharma and Bhattacharya (2022) define that the spectrum of sunlight varies according to geographical location, time of day, air pollution, climatic conditions, season of the year, etc. The power capacity generated by solar photovoltaic (PV) panels in the world was 618 gigawatts (GW) in 2019 according to Li et al. (2021) and Vanegas Cantarero (2020), who states that in Peru the installed capacity of PV plants is 286 megawatts (MW) and production in 2018 was 744.21 gigawatts hours (GWH). In Arequipa the solar resource is the highest in Peru, the sum of direct normal solar radiation and diffuse irradiation, reach ranges of 7.5 to 8.5 kilowatts hours per square metre (KWh/m2). The monthly irradiation profile is stable according to the results of a study carried out in three locations (Lima –12°03'16", –077°03'04", Tacna –17.711008°, –070.488738° y Arequipa –15°42'05", –072°35'30"). In Arequipa, it was verified that monthly irradiation is in the range of 150 to 200 KWh/KW for a PV networked system (Romero-Fiances et al., 2019). Air pollution, specifically, the accumulation of small dust particles affects the operation of these systems (Fan et al., 2022b), and they are the main cause of the loss of efficiency of the PV (Bosman et al., 2020), additionally there are automated modular designs that do not allow the efficiency of the PV (Almalki et al., 2022; Kennedy et al., 2021; Malik et al., 2021). It is estimated that the loss of efficiency is greater than 20% (Najeeb et al., 2018). In areas with a dry climate, the accumulation of dust increases because the particles suspended in the air have diameters between 2.5 to 10 microns (Maghami et al., 2016), this gets worse when light rains occur, because they contribute to the settlement of dust. Dust concentrations in geographic areas on Earth are measured using algorithms that work with data provided by satellites. The classical algorithms are brightness temperature difference (BTD) and normalised difference dust index (NDDI) (Yang et al., 2023). The concentration of dust on the surface of the solar panel linearly affects the decrease in the output voltage, so the amount of dust can be evaluated using a linear equation y = kx + b, where 'y' represents the dust concentration (mg/m^3), and 'b' represents the loss on output voltage (mV) (Fan et al., 2022c). The particle size of the dust is also important since, according to observations, fine particles (less than 600 microns) can reduce the zero-resistance current efficiency by up to 49.01%, while coarse particles (between 600 and 800 microns) only in 15.68% (Tripathi et al., 2022). The inclination of the PV can help dust removal (Alghamdi, 2019; Hwang et al., 2023; Menoufi, 2017), the average daily reduction of the energy generated by dust accumulation for angles of 0°, 15°, 30° and 45° was estimated at 33. 4%, 15%, 8%, 12.1% and 11.7% respectively (Khodakaram-Tafti and Yaghoubi, 2020). According to the criteria set out in the bibliography, the research work was carried out in two parts; The first consisted of directly investigate the power loss of the PV due to the effects of dust accumulation and the second was to design, build and validate a portable and automatic cleaning system that ensures maximum charging efficiency (η) during the range hours of established solar spectrum, applying degradation mechanisms and mitigating possible failures (Peinado et al., 2019; Szabó, 2022).The mechanism was designed considering its installation location, it was installed in remote mining areas, at angles less than 15° and were used for power supply in environmental and engineering measurement instruments, such as radars, battery charging system drones, computers, environmental monitoring equipment, among others (Sun et al., 2021); this mechanism can also be applied in PV for domestic use. The mechanism is based on an automatic-programmable robotic dry-cleaning system that moves over the glass of the PV surface without causing damage (Ekinci et al., 2022). Currently, information is being collected to establish the mitigation of failure risks or to establish predictive maintenance.

2 Materials and methods

A monocrystalline PV of silicone with 36 cells (12 in the longitudinal axis and 3 in the transverse axis) was used, each cell measuring 156 mm × 104 mm. The PV was mounted on an aluminium base whose dimensions were 1.390 mm × 540 mm × 30 mm. The total weight was 8 kg, and it was protected by a tempered glass of 3.2 mm. The manufacturer's technical specifications are shown in Table 1.

The study was divided in two parts; the first one was to directly investigate the power loss of the PV because of dust accumulation and the second to design, build and validate a portable and automatic cleaning system that ensures maximum charging efficiency (η) during the established range of solar spectrum hours. To carry out this design, the technical specifications were considered.

Table 1 PV technical specifications

Parameters	*Value*
Maximum power (Pmax.)	100 W
Optimal operating voltage (Vmp)	17.5 V
Optimal operating current (Imp)	5.72 A
Open circuit voltage (Voc)	21.5 V
Short circuit current (Isc)	6.0 A
Module efficiency	13.3%

2.1 PV power loss calculation

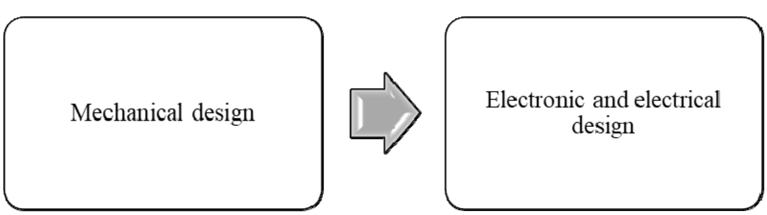
To evaluate the power loss due to dust accumulation on the PV, an ATMega2560® development board was used where power (W), amperage (A) and voltage (V) sensors were installed during the PV battery charge, the values were displayed on an LCD screen. Figure 1 shows the established module. These data were collected in Arequipa (16°23’56” S 71°32’13” W) for eight weeks, between 7 and 16 hours. The PVs were kept dirty for the first four weeks and then manually cleaned an hour before the reading.

Figure 1 Power (W), amperage (A) and voltage (V) evaluation module (see online version for colours)

2.2 Design and construction of the automatic cleaning device

A simple, portable, and low-cost device was designed. The design sequence is shown in the block diagram in Figure 2.

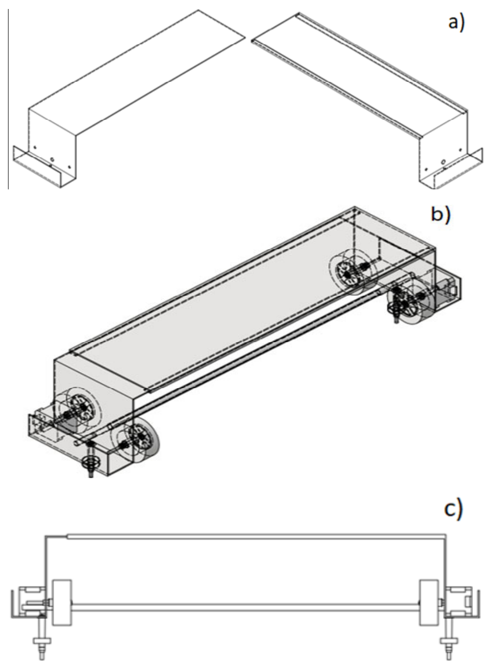
Figure 2 Design sequence



2.2.1 Mechanical design

A 1.8 mm thick, 670 mm long and 161.3 mm wide iron plate chassis was designed and built, where four 68 mm diameter rubber wheels were mounted, two of these are traction connected to stepper motors with bipolar NEMA standard (National Electric Manufacturers Association), with an intensity of 1.7 amps (A), resistance (Rs) of 2.1 ohm (Ω) and 0.42 Newton metre (N.m), of maximum torque per motor [see Figure 3(a) and Figure 3(b)]. The lateral guide system consists of two pivots with bearings that fit into the side of the aluminium base of the PV, it has a cleaning system consisting of a longitudinal crosspiece with a microfibre cloth [see Figure 3(c)].

Figure 3 (a) Adjustable chassis bodies according to the length of the PV (b) Isomeric of PV cleaning mechanism (c) Side guide system

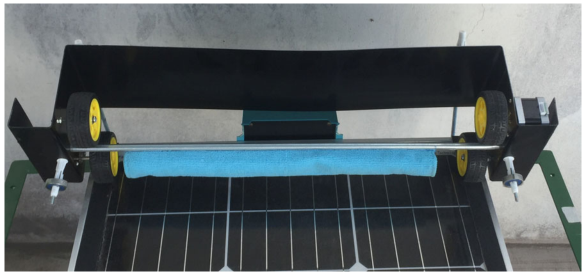


The diagonal configuration of the drive wheels (to the left side at the front and to the right side at the rear) ensures that the lead remains parallel with the longitudinal axis of the panel. At the end of the route, the mechanism stops when it collides with a perpendicular bar installed at the four corners and to improve the traction of the wheels on the glass, non-slip tape was placed on the PV edges.

The design is simple, portable, and low cost to meet the stated objective. The design sequence begins with mechanical design and then with the electronic and electrical design (see Figure 4).

The configuration of the tracing wheels is diagonal (on the left side at the front and on the right side at the rear), this ensures that the advance maintains parallelism with the longitudinal axis of the panel. At the end of the route, the mechanism stops when it collides with a perpendicular bar installed in the four vertices and to improve the traction of the wheels on the glass, non-slip tape was placed on the PV edges.

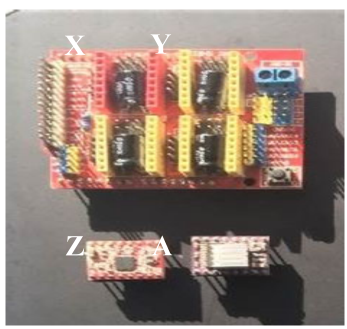
Figure 4 Cleaning mechanism (see online version for colours)



2.2.2 Electronic – electrical design

The control of the NEMA 17 motors is done by programming an ATMega 2560® development board where the driver control board (CNC Shield) was installed, which allows to independently handle three stepper motors in each of the Cartesian axes and duplicate the operation of one. The drivers (drivers A4988) are used for programming the micro steps, the direction of rotation and the motor operating time of the engine. These can be installed in four 'bays' marked with X, Y, Z and A on the control board. The driver was configured so that the main engine runs with full step in X and the configuration of the second motor was duplicated in A (see Figure 5).

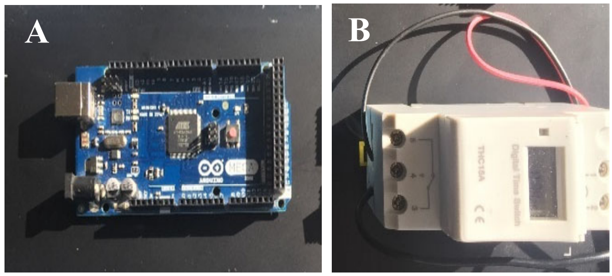
Figure 5 Driver control board (CNC Shield) (bays X, Y, Z and A), and drivers A4988 (see online version for colours)



The electrical power supply necessary for the operation of the system comes from two sources; the ATMega2560® development board was powered directly from a solar charger with a lithium polymer battery whose capacity is 20,000 microamps per hour (mAh), the output voltage is 5 V, and the current is 2.1 A. To power the drivers and the board control, it can be used between 12 V and 36 V, the required current varies depending on the number of motors used.

For each motor, the current must be greater than 2 A, the drivers support voltages between 8.2V and 42V and the electric current per motor must be 2.5 A when a heat dissipator is used, see Figure 6. The power supply to the drivers control board is made with a connection to the 12V battery from the solar panel or other source. It was installed a programmable digital timer (THC15A) that regulates the on/off time of the motors based on the hourly cleaning requirement (see Figure 6).

Figure 6 (a) ATMega2560® (b) Programable Digital Timer THC15A (see online version for colours)

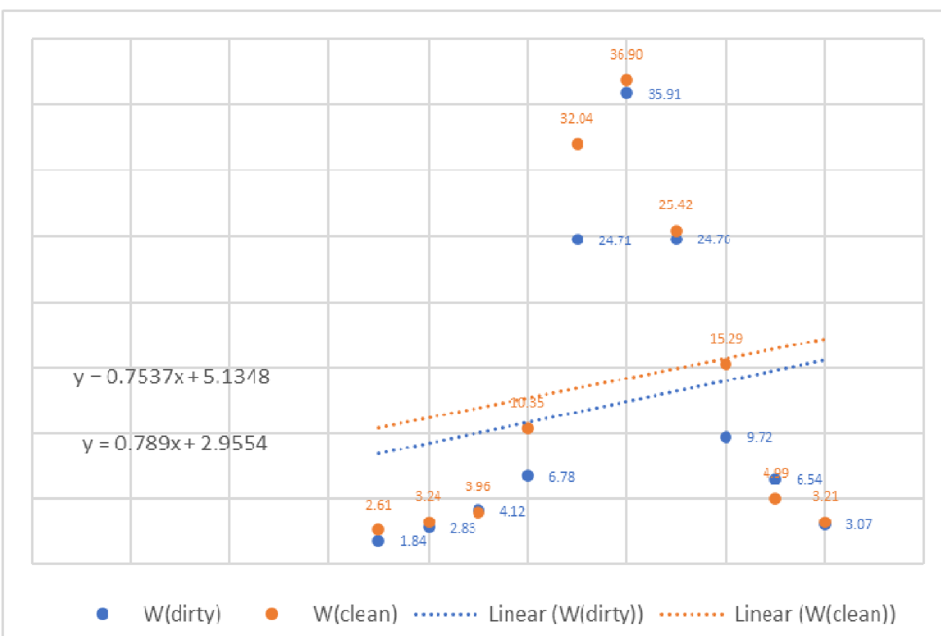


3 Results and discussion

3.1 Evaluation of charging efficiency due to dust accumulation effects

To calculate the gain power (W) with the clean PV, the linear equation was determined based on the data recorded in the Table 2 and Figure 7. The power gain was 2.17 watts during all testing hours.

Figure 7 Determination of the linear equation of data collection with dirty panel and clean panel (see online version for colours)



The power drop of the PV, due to dust accumulation, was evaluated through the reduction of the load power (W). To measure the percentage load efficiency (η), the measured power (Pmed.) is divided by the maximum power (Pmax.) (Fouad et al., 2017; Khodakaram-Tafti and Yaghoubi, 2020) with the following equation (1):

$$\eta = \frac{Pmed}{P\max} * 100 \tag{1}$$

Table 2 Power gained between dirty panel (input) and clean panel (output)

Hours	*W (input)*	*W(output)*	*W(gain)*
7	8.49	10.66	2.17
8	9.28	11.45	2.17
9	10.05	12.24	2.19
10	10.86	13.02	2.16
11	11.65	13.81	2.16
12	12.44	14.6	2.16
13	13.23	15.4	2.17
14	14.01	16.18	2.17
15	14.81	16.97	2.16
16	15.59	17.76	2.17

Figure 8 Power (W), amperage (A) and voltage (V) values in dirty PV (see online version for colours)

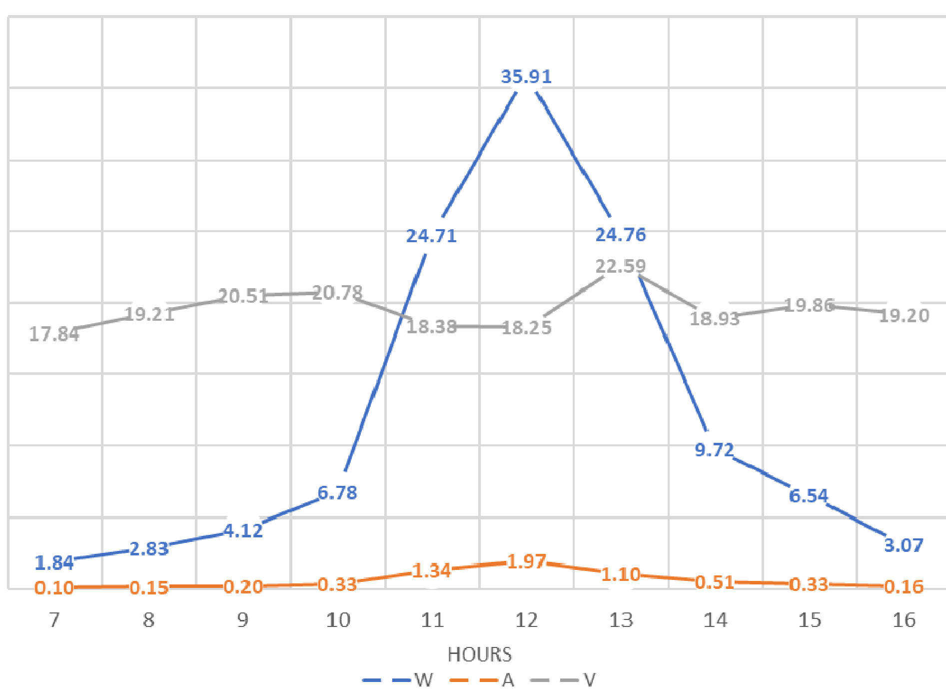


Figure 9 Power (W), amperage (A) and voltage (V) values in clean PV (see online version for colours)

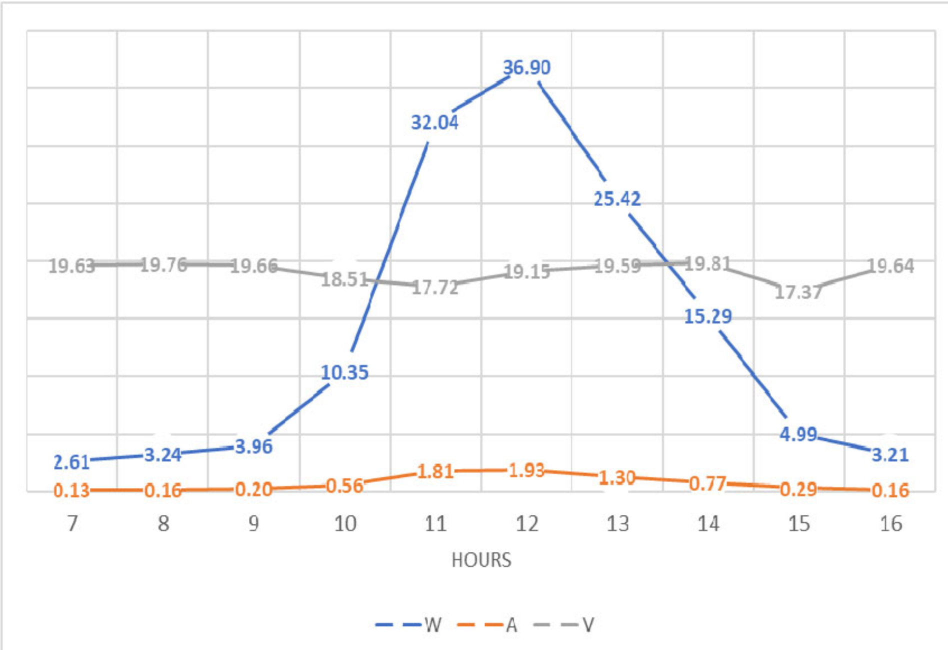


Figure 10 Hourly variation of power (W) of dirty PV and clean (see online version for colours)

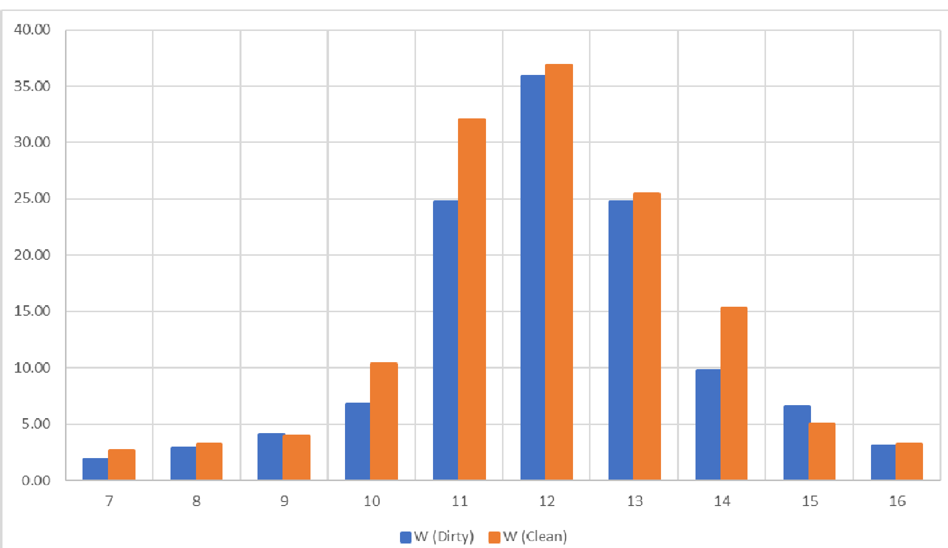


Figure 8 shows the average of power (W), amperage (A) and voltage (V) of four weeks of data reading for dirty PV and Figure 9 shows the average W, V and A for clean PV. The maximum η was 36.9%, reached at 12 noon, which coincides with the W maximum recorded in clean PV because this was 100 W, the voltage (V) remained stable in a range of 17.4 to 19.6 and the maximum amperage (A) was 1.93 at the same time. The highest efficiency of PV occurred between 10 and 16 hours due to the time of greatest solar spectrum, temperature, and irradiance (Fan et al., 2022a).

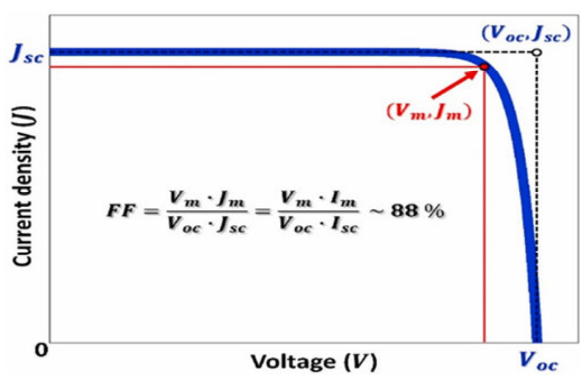
The W variations between dirty PV and clean PV are shown in Figure 10. The variation is 29.6%, 34.6%, 22.9% and 36.4%, at 7, 10, 11 and 14 hours respectively. The other variations are small.

Table 3 shows that, during the hours of data collection, the power has a nonlinear percentage variation, this is due to the climatic conditions, especially for the temperature, wind, and solar irradiance, which are not stable during the day. By taking a simple average of these variations, it can be deduced that the decrease in power, in the hours of greatest solar spectrum in our geographical position, is 11.08%.

Table 3 Percentage variation of power in measurement hours

Hour	*W (dirty)*	*W (clean)*	*% change*
7	1.84	2.61	29.57
8	2.83	3.24	12.71
9	4.12	3.96	-4.08
10	6.78	10.35	34.56
11	24.71	32.04	22.86
12	35.91	36.90	2.68
13	24.76	25.42	2.59
14	9.72	15.29	36.42
15	6.54	4.99	-31.01
16	3.07	3.21	4.47

Figure 11 Scheme of the typical J-V behaviour observed for a high-PCE and high FF solar cells (see online version for colours)



Source: Tan et al. (2022)

For the mathematical determination of the performance of photovoltaic cells, many formulas have been used based on equations that describe the current-voltage characteristics of each device, although these do not exactly adjust to the behaviour of photovoltaic panels, they describe acceptably the performance of solar cells, especially when there is medium and high concentration of sunlight (Ardoz and Madrid, 1987; Wang et al., 2022).

The critical parameters for the evaluation of the efficiency of a solar panel are power conversion efficiencies (PCEs) and the fill factor (FF), commercially these characteristics define low-cost solar panels. PV made from silicon (Si) meet this condition. The most widely accepted mathematical model to evaluate a high PCE and high FF, is shown in Figure 11. The FF is defined as the maximum voltage (Vm) multiplied by the maximum current density (Jm) divided by the open circuit voltage (Voc) multiplied by the open circuit current (Joc). The equation can also be expressed in terms of the maximum photo-generated current (Im) and short circuit current (Isc) in the solar cells. The approximate value of being 88%, in the cells manufactured based on Si this value is greater than 70% (Mrázková et al., 2016; Mulazzani et al., 2022; Paiano, 2015).

Temperature is an especially crucial factor in the evaluation of the efficiency of Si cells in solar panels, in ranges from 10 to 50 °C it has been verified that at higher temperatures the FF decreases, this is due to its relationship with the Voc. The Voc shows a high decrease with the increase of the temperature due to the dependency with the Isc (Jasim, 2022; Limmanee et al., 2017).

The evaluation of PV cell performance can be carried out by using the load factor or 'fill factor' (FF). This relates the maximum power (Pmax) reached from the PV between the product of the open circuit voltage (Voc) and the value of the short-circuit current (Isc) (Chen et al., 2019; Maghami et al., 2016) [see equation (2)].

$$FF = \frac{P\max}{(Voc * ISc)} \tag{2}$$

The FF measures the photoelectric conversion efficiency of the PV cells. Therefore, the higher the value, the higher the photoelectric conversion efficiency.

Table 4 Percentage variation of power in measurement hours

Hours	*PV dirty*	*PV clean*
7	0.014	0.020
8	0.022	0.025
9	0.032	0.031
10	0.053	0.080
11	0.192	0.248
12	0.278	0.286
13	0.192	0.197
14	0.075	0.119
15	0.051	0.039
16	0.024	0.025

The FF was determined for each hour and in each measurement, for this the Isc has been considered with a value of 6 A (according to the PV specifications in Table 1) and the average of the measurements of W and Voc during four weeks for both the Dirty PV and the Clean PV, the data is seen in the Table 4, it is observed that in all cases the accumulated dust affects the FF of the PV. The maximum loss of the FF observed in the study PV was 0.286 (28.6%), which indicates that the panel works with an FF greater than 71.4%. With respect to temperature, it is observed that the difference in FF is less in the hours of higher temperature.

In Figure 12, the values of FF at 6, 7, 8 and 16 hours have a difference of –0.006, –0.003 and –0.001 and –0.001 respectively. This would be because the temperatures are lower than between 9 to 14 hours.

Figure 12 PV Fill Factor values (see online version for colours)

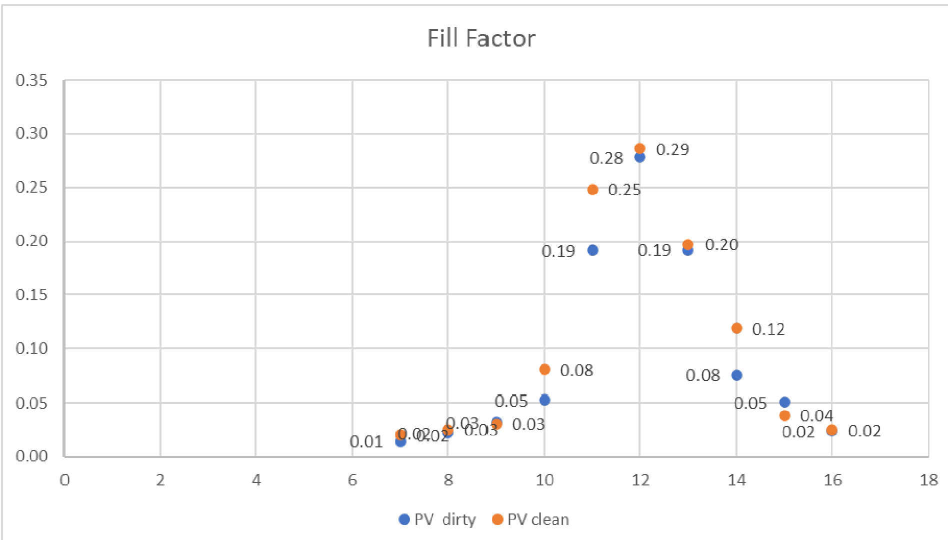


Table 5 Number of cycles and duration of PV cleaning

Hour	*Number of cycles*	*Duration(min)*
7	1	2
8	1	1
9	1	1
10	2	2
11	2	2
12	2	2
13	2	2
14	2	2
15	1	1
16	1	1

To determine the loss of η and FF due to dust accumulation, the cleaning frequency was calculated to maintain constant energy efficiency during all hours of effective sun exposure. The frequency is determined based on the cleaning cycles and the duration necessary for the mechanism to ensure the objective of the maximum maintain of η and FF. These are shown in Table 5.

The frequency and duration of cleaning varies in the different geographical locations or conditions of use of PV, for this reason it was decided to use a programmable digital timer that facilitates the change of values at the site of use of the PV.

3.2 Engine calibration and mechanism programming

A robotically designed mechanism was used because it can be moved independently, with no parts attached to the PV frame, and over the cleaning area without damaging the glass. Power supply is simple using an independent 5V/2.1A rechargeable battery mounted in the same mechanism and a quick connection to the panel battery or other 12V-36V source. The use of stepper motors with NEMA standard is because it is an electromagnetic actuator that converts the digital pulses of the conductors (drivers) into precise and low torque turns on the shaft. Calibration of drivers (drivers) is necessary to use the stepper motor. To obtain the highest torque we will use the double phase sequence making the motor advance one step at a time, the calibration is done by calculating the transconductance. The maximum current (Itrip.max) that the conductor (drivers) sends to the motor must be determined. The calculation is made with equation (3) provided by the manufacturers.

$$Itrip\max = Vref / (8 * Rs) \tag{3}$$

The voltage calibration of the conductors (drivers) is based on the required steps, this is determined by clearing the reference voltage (Vref) from equation (3). If the maximum current (I) of our motor is 1.7 Amps/phase (A/ph) and the resistance (Rs) of the conductor (driver) is 0.10 Ω then it should use 1.36 V for half steps, as it is required for full steps, 70% of the calculated value (0.952 V) is taken and calibrated in the potentiometer of the two conductors of our design. The calculation of the torque-motor or required torque (τ), is based on the force required (Fr) by the motor; the coefficient of friction (μ) between the rubber tires and the anti-slip tape estimated at 0.2; the weight (p) of the mechanism and the components that are mounted on it, 3.17 kilograms (Kg); the angle of inclination (Ø) of 0 degrees and the constant of gravity (g) of 9.81 m/s2. The calculation is made with the following equations (4) and (5) (Khadka et al., 2020).

$$Fr = \mu * p * g * \cos\varnothing \tag{4}$$

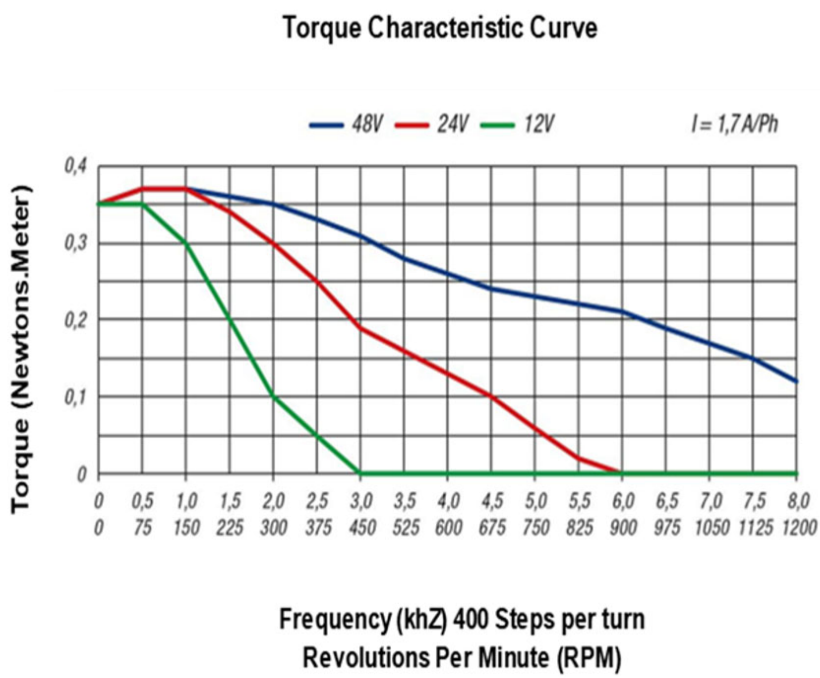
$$\tau = Fr * radius\ of\ the\ wheel \tag{5}$$

The force required at the beginning of the trajectory is 6.22 Newtons (N) and the torque is 0.21 Newtons per metre (N.m) (the radius of the wheel is 0.034 m). Figure 13 shows the manufacturer's chart to determine the required motor torque or torque based on the frequency of pulses sent by the controller (driver) that defines the revolutions per minute (RPM) on the shaft. To obtain a torque of 0.21 N.m; the frequency of the pulses should be 1.5 Kilo Hertz (KHz), this rotates the shaft at 225 RPM.

The turning time (t) of the wheels was established in 8 seconds for each direction (round trip), the speed is 0.17 m/s since the PV has a length of 1.39 m., after completing a trajectory (round trip) the mechanism waits 2 seconds to start again. These values were programmed in the Ardinuo® platform.

During the tests of the mechanism, it was verified that the established variables allow adequate cleaning of the panel surface. The mechanism works without any problems at angles less than 15°, for higher angles it is necessary to raise the RPM. The power supply of the motors can be increased up to 24V, with this the RPM will go up to 400 for the same torque (0.21 N.m) and required force (6.22 N), managing to climb slopes of up to 20°. Besides the above mentioned, this mechanism is not attached to the panel, and it makes it portable; and the use of NEMA motors maintain the required torque and force.

Figure 13 Torque-RPM for Nema® 17 engine (see online version for colours)



4 Conclusions

The use of the cleaning mechanism designed in this research ensures that the charging efficiency (η) and the FF maintain high values, as those that were obtained in the experimentation with the clean PV. In this study the power (W) loss should not be greater than 2.17 W, which can be because of dirty panels with dust; and the FF greater than 71%; this is in accordance with the construction materials (Si) of the solar cells used. These values depend on the geographic and climatic conditions of the place where the PVs are installed; the climate variation can define the amount of accumulated dust, and the dust decreases the FF; so, for this reason the cleaning mechanism must be programmable (to achieve maximum η and FF during the hours of solar irradiance), must be portable (to be use in different places with different geographical conditions), and adjustable to different PV sizes.

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