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Low-Cost Automated PV Panel Dust Cleaning System for Rural Communities

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Abstract

Dust accumulation on photovoltaic (PV) panels degrades PV panels' performance; leading to decreased power output and consequently high cost per generated kilowatt. Research addressing the severity of dust accumulation on PV panels has been ongoing since the 1940s, but proposed solutions have tended to increase the cost of PV systems either from oversizing or from cleaning the system. The objective of this work, therefore, is to design and implement a low-cost affordable automated PV panel dust cleaning system for use in rural communities of Sub-Saharan Africa (SSA); where financial resources are limited and significantly strained in meeting livelihood activities. Complete design and implementation details of a prototype system are provided for easy replication and capitalization on PV systems for sustainable energy needs. The system detects dust based on the innovative use of light-dependent resistors. Testing and observation of the system in operational mode reveal satisfactory performance; measured parameters quantify a power output increase of 33.76% as a result of cleaning dust off the PV panel used in the study.

Keywords

PV Panel, Automated Dust Cleaning, Arduino Microcontroller, Light Dependent Resistor, Dust Percentage Threshold, Low-Income Rural Communities, Sub-Sahara Africa

1. Introduction

Growing concern over climate change and environmental problems such as pollution and emission of greenhouse gas resulting from the exploitation of fossil-based fuels has led to increased emphasis on the exploitation of renewable energy sources, which are clean and sustainable [1]. Among the various renewable energy sources (hydro, wind, solar, biogas, etc.), solar energy is the most sustainable in the sense that it can be exploited indefinitely and freely on account of its being obtained from the sun; and the sun being indefinitely available. Solar energy can be harnessed through two technologies: photovoltaics (PV) and concentrated solar power (CSP). PV technology uses solar cells which exhibit the photovoltaic (PV) effect to convert sunlight into electricity in what is referred to as solar PV systems; while CSP technology converts the energy in sunlight into heat that can be used in various heat-demanding applications, in what is referred to as solar thermal systems [2].

With the rapid advancement and development of modern technology and the decline in component costs, solar energy has been embraced in all sectors of the economy. From use in industrial and agricultural operations to domestic appliances, lighting, heating, and cooling, the need for PV and CSP systems is growing daily [3]. Compared to CSP systems, PV systems have a wider range of applications since these systems produce electrical energy, which does not only have a greater demand but can easily be converted into other forms of energy. In 2018, investments in solar energy accounted for 58% of all renewable energy investments; and the exploitation of solar PV systems was noted as one of the fastest-growing industries globally, with a robust compounded annual growth rate of over 40% within the decade [4].

Generating electricity using PV systems requires various hardware, including the PV panel or module which is the key component of the system given that it contains PV cells that convert sunlight directly into electrical energy. The energy conversion processes and ultimately the performance of PV panels depend not only on the cell technology and associated losses (diode, connection, mismatch, and DC-AC wiring), material used, geographical location, and installation configuration (height and tilt-angle of panel), but also on environmental factors such as irradiance, ambient temperature, wind speed, nature of dust particles, and dust accumulation on the panels [5] [6] [7] [8].

Dust accumulation in the form of organic or non-organic particles is one of the environmental factors with the most severe impact; and which directly counters potential PV panel performance in the most advantageous places, where the highest radiation exists [9]. In other words, PV panels perform best in arid sunny areas such as deserts where irradiance is high, but it is these same areas that experience the most dust accumulation [10]. A six-year study to appreciate the contributions of potential dust source regions in the world revealed that North Africa, including the Sahara Desert area, accounts for 58% of the total global dust emission and 62% of the total global dust load in the atmosphere [11]. Another study showed that in terms of the highest dust density, the countries of Sub-Saharan Africa (SSA) ranked second (zone 3) after the Middle East and North Africa region (zone 4) [12].

In today's tough financial world economy, cheap PV systems are expected to play a great role in developing countries such as those of Sub-Saharan Africa (SSA). Large-scale adoption and deployment of PV systems will provide a huge increase in energy access for rural communities that will enable these countries to meet the United Nations (UN) Sustainable Development Goals (SDG) of universal access to affordable, reliable, sustainable, and modern energy services for all by 2030; with sub-target 7.1.1 focusing on access to electricity [13]. With such energy access, these countries can leapfrog years ahead in national sustainable development. However, the dream of reaping huge energy access from solar energy may not be a reality in SSA countries which are located in or around desert areas, where high dust concentration is a daily experience. Pollution, vehicle movement on untarred roads, winds blowing on exposed bare lands, mines, quarries, and predominant agricultural activities in SSA countries also create a substantial amount of dust on a daily basis. As a result, the exploitation of PV panels cannot be economical and sustainable as expected due to the adverse effects of dust accumulation on PV panels.

For PV systems to remain a competitive energy source among renewables, it is necessary to minimize or eliminate dust accumulation on PV panels at minimum costs. Doing so will ensure that the performance of PV panels in terms of energy conversion efficiency is maintained as high as possible thereby minimizing the cost per kilowatt [14]. In fact, research by Li *et al.* indicates that removal of particulate matter, including dust soiling on PV panels in desert regions (such as northern Africa) or heavily polluted areas (such as northern India and northern China), would more than double the efficiency of PV electricity generation [15].

Research to address the severity of dust accumulation on PV panels has been carried out since the 1940s, but proposed solutions have tended to increase the cost of PV systems either from oversizing or from cleaning the system [12]. In a recent review of the literature on PV cleaning systems, the call was made for the development and implementation of simple solutions that minimize the total costs [16]. The objective of this work, therefore, is to design and implement a low-cost automated PV panel dust cleaning system for use in rural communities of low-income countries, such as those of SSA. In these communities, financial resources are very limited and significantly strained in meeting livelihood activities. A low-cost affordable solution to address the issue of dust accumulation on PV panels in these communities is therefore in order. The design and implementation steps and procedures are presented and described in detail for easy replication. Large-scale implementation and deployment of the proposed system will go a long way to minimize cost as well as ensure sustainable exploitation of PV systems in rural communities. The rest of this paper is organized as follows. Section 2 presents related research on dust and PV panel dust cleaning processes. Section 3 details the methods and materials of the study. The prototype is presented and discussed in Section 4, and concluding remarks are presented in Section 5.

2. Related Works

2.1. Nature and Effects of Dust Accumulation on PV Panels

Dust accumulation on PV panels negatively affects their performance and efficiency. It is generally noted that the effects of dust accumulation on the performance of PV panels depend on many factors, including the size and types of dust particles, geographical location of the panels, the coating, installation height, and tilt angle of the panels; and environmental factors such as wind speed, wind direction, air temperature, and relative humidity [7] [17]. Younis *et al.* [18] have classified the factors that affect dust deposition as configurational (altitude, azimuth, tilt angle), meteorological (dust characteristics, dust storms, humidity, rainfall, and wind direction and speed), and technological (cover glass characteristics and PV technology) [18]. Dust accumulation on PV panels causes shading of PV cells; which diminishes solar radiation intensity [19], leading to decrease in, or complete loss of solar transmittance on the PV cells [20] [21] and ultimately decrease in PV power output [22]. In fact, dust accumulation on the surfaces of PV panels does not only cause a decrease in the efficiency of the solar PV panels but also an increase in temperature [23] and subsequently, a decrease in operation safety [24].

Other negative effects of dust accumulation or shading of PV cells, include a decrease in open circuit voltage, decrease in short circuit current, decrease in power output, and a decrease in or total blockage of incident irradiance [22]. Furthermore, since dust accumulation influences the characteristics of the solar irradiations reaching the PV panel [5], it creates the incidence of non-uniform solar irradiance on the panel cells, leading to the power characteristics of PV panels having more than one maximum power point (MPP). Conditions of multiple MPPs do not only make it difficult to track MPP but also decrease the efficiencies of PV systems [25].

The degree of the effect of dust accumulation depends on the particle size, duration of exposure, and geographical region. For example, Saidan *et al.* [10] investigated the impact of dust accumulation on PV panels in Baghdad, Iraq; and found that the average degradation rate of the efficiencies of the PV panels exposed to dust were 6.24%, 11.8% and 18.74% respectively for exposure periods of one day, one week, and one month [10]. Syafaruddin *et al.* [26] experimentally found out that the accumulation of dust weighing 64.11 g caused the decrease of PV panel efficiency from 17.56% to 10.06% [26]. Chen *et al.* [27] investigated the shielding, temperature, and corrosion effects of dust accumulation on PV panels in Xi'an, China and found that dust with a density of 10 g/m^2 could reduce the maximum power of PV panels by about 34%. Klugmann-Radziemska and Rudnicka [28] experimentally investigated the effect of accumulated dust on the efficiency of PV Panels in Gdańsk, Poland. The authors noted a 6% - 10% decrease in the efficiency of PV panels covered with dust (dirty panels), relative to the panels not covered with dust (clean panels) [28]. Al Qdah *et al*. [29] designed and investigated the performance of a system for cleaning dust in Medina, Saudi Arabia. Results showed efficiency reduction of 34.68% and 42.33% corresponding to solar radiation intensity of 805 W/m^2 and 460 W/m^2 respectively.

2.2. PV Panel Dust Cleaning Processes

Processes associated with the cleaning of dust on PV panels discussed in the literature have been labelled and classified in various ways by different authors. Following a review of dust and PV performance in Nigeria, Changchangi *et al*. [9] identified dust mitigation techniques including manual cleaning, natural cleaning (rainfall, wind, and gravity), automated cleaning (water and mechanized), and self-cleaning (super hydrophobic plane, super hydrophilic plane, and electrodynamic screens) [9]. He *et al*. [30] identified dust cleaning methods as manual (using water jets), natural (wind power, gravitation, rainwater), mechanical (brushing, blowing, vibrating, and ultrasonic driving), self-cleaning nano-film (using super-hydrophilic or super-hydrophobic material) and electrostatic (using electric curtain technology). Salamah *et al*. [22] maintain that dust cleaning can be done by automatic and semi-automatic processes; and while semi-automatic processes require the interventions of humans, the automated processes are mechanical-based, complex, expensive, and require the use of water. According to these authors, techniques to clean PV panels include manual (gravity, wind, and/or rainfall), electrostatics (standing and travelling electronic waves), self-cleaning (polymerization, powder coating, vapor-assisted coating, and solvent-based), and mechanical (air-blowing, water-blowing, and robotics) [22].

The use of water in a PV cleaning technique means measures must be in place for the collection, storage, and possible recycling of water. PV panel cleaning processes requiring the use of water (wet-cleaning) are not mendable in water-scarce areas such as deserts. Al-Housani *et al*. [31] identified four waterless (dry-cleaning) dust cleaning techniques based on the use of a mechanical brush, a microfiber-based cloth wiper, a combination of a brush and a vacuum cleaner, and combination of a microfiber-based cloth wiper and a vacuum cleaner). An experimental investigation on the effectiveness of these waterless dust cleaning techniques on PV panel performance in Doha, Qatar found that the microfiber-based cloth wiper, and the combination of microfiber-based cloth wiper and vacuum cleaner combination, were the most effective cleaning methods, yielding about 6% performance improvement (compared to control panel) over a weekly period [31].

Derakhsandeh *et al*. [16] categorized automated PV dust cleaning systems as either active or passive. Active systems require the use of electrical power in their operations, while passive systems do not. The authors identified the predominant automated PV dust cleaning systems used globally within the last two decades: Brush Cleaning System (BCS), Electrostatic Cleaning System (ECS), Heliotex

Cleaning System (HCS), Robotic Cleaning System (RCS), and Coating Cleaning System (CCS) [16]. A comparative analysis of these systems using the criteria proposed by the authors (cost, efficiency, human involvement, cleaning time, and volume of water used) reveals BCS systems are the best, with only one high requirement (cleaning time) (**Table 1**).

Table 1. Comparative analysis of predominant automated cleaning systems.

S/N	Criteria	BCS	ECS	HCS	RCS	CCS
1	Cost	L	H	M	H	H*
2	Efficiency	L*	H	L	M	H*
3	Human Involvement	M	L	H	M	L*
4	Cleaning Time (Hour)	H	M	L*	H*	L
5	Water Usage (m^3/s)	L	L	H	L	L*

Legend: L = Low, M = Medium, H = High; L* = Lowest L, H* = Highest H.

2.3. PV Panel Dust Cleaning Processes

It is recognized that cleaning accumulated dust from PV panels helps ensure the performance of the panels at maximum efficiency and hence maximum power output. But the question arises as to the frequency of cleaning. Establishing a rationalized dust cleaning frequency for PV panels is important not only because it keeps down costs [18] but also because unnecessary frequent cleaning causes destruction and affects PV panel lifespan [8]. The literature has different frequency schemes not only because researchers have different perspectives but also because cleaning frequency depends on climatic conditions and local conditions such as buildings, construction, and vegetation [31].

From an operational and maintenance perspective, the cleaning of PV panels should either be based on a specific time interval or on certain conditions [32]. With the view of desert regions with little or no rain, Jiang *et al.* [33] proposed a formula for the calculation of optimal cleaning interval (T), as depicted in Equation (1). Using this formula, the authors determined the optimal frequency of cleaning PV panels in desert areas to be 21 days. In other words, cleaning is done once every three weeks.

$$T = \frac{M_d}{C_d V_d} \tag{1}$$

where T is the cleaning time or frequency (in days), M_d is the dust accumulation density, C_d is the dust mass concentration in air, and V_d is the dust particle velocity, defined by Equation (5) in [33]. The perspective of Abu-Naser [34] calls for a balance between cost of cleaning the PV panels and the degree of efficiency losses that can be tolerated [34]. With this perspective, Abu-Naser proposed a mathematical formula for the determination of optimal number of days, N, between cleanings that maximizes profit and minimizes efficiency losses as depicted in Equation (2).

$$N = \sqrt{\frac{2P}{\alpha s i \beta}} \tag{2}$$

where N is the optimal number of days between cleaning cycles, P is the cost of cleaning the solar array, α is the average daily losses in solar conversion efficiency due to accumulation of dust, s is average sun hours per day, i is the capacity of the installed PV system, and β is the price per kWh. Al-Otaibi *et al.* [5] developed a system with cleaning based on a specified time interval and duration: every Saturday morning at 2 am for 3 min. The weekly cleaning was done using water only and complemented with a once-a-month cleaning using water and soap [5]. Ghazi *et al.* [12] recommend that the frequency of cleaning PV panels should be based on climatic conditions: in humid cold climatic conditions, PV panels should be cleaned every six months; in humid temperate conditions, every three months; in humid equatorial conditions, every month; and in dry climatic conditions, every week. In terms of cleaning methods, wet cleaning, involving the use of soap and warm water is proposed for PV panel cleaning in humid cold and temperate environments; nano-surface coating and automatic cleaning with wipers in equatorial humid conditions; and dry cleaning, including the use of automated robotic devices, self-cleaning technology, rotary brush, and air hose/compressor systems be used in dry arid climatic conditions [12]. Maghami *et al.* [6] proposed weekly cleaning of PV panels during dry periods and daily cleaning in cases of heavy dust accumulation. Following an investigation of the global impact of particulate matter on the PV electricity generation, using world data for a 12-year period, Li *et al.* [15] investigated the effects of cleaning in improving PV generation relative to precipitation-only removal. The authors proposed cleaning be based on monthly or quarterly basis, in addition to precipitation-only removal, depending on the locality of the PV system.

2.4. Controllers in Automated PV Panel Dust Cleaning Systems

At the heart of all automated PV dust cleaning systems is the controller, which monitors process parameters and controls the system. The controller receives input from sensors on the PV system as well as other components of the system, processes the inputs according to specified algorithms, and sends out corresponding control signals for the appropriate actions by other components the system such as DC motors, for movement of an element in a specified direction or simply display of parameters on LCDs. Automated PV dust cleaning systems have used micro-controllers, and while many studies generally indicate the use of micro-controllers, only few studies have been specific on the type of micro-controller used.

The specified micro-controllers used are based on the Arduino family such as Arduino Uno or Nano [26] [35] [36] [37]. Hadipour *et al.* [35] developed an Arudino-based system for cleaning of street lights in Kermansha, Iran. The system was controlled by using either a manual push button, a timer, a remote control unit, or through an Ethernet network. Malik *et al.* [37] designed an Arduino-based system for real-time monitoring and reporting on the status of accumulated dust on PV panels; enabling the user to proceed with cleaning as per status of the PV panel. Syafaruddin *et al.* [26] designed an automatic dust cleaning system based on the ATmega micro-controller with a wiper control mechanism and water spray; and subsequently used it to experimentally demonstrate the decrease of PV panel efficiency resulting from dust accumulation [26].

3. Methods and Materials

The major consideration in the design and realization of this system is to make the system simple, cheap, efficient, and easy to use. The prototype system is realized on the basis of the automated wiper cleaning method, with use of an Arduino Nano microcontroller interfaced with various input and output devices. A modular design approach was adopted; and the block diagram of the system is shown in **Figure 1**; noting that two links: PV panel to power supply unit and power supply unit to cleaning unit are not shown.

The implementation of the system has been done using both hardware (electrical and mechanical) and software. The major blocks in **Figure 1** are presented and described in detail, with all technical specifications for ease of replication.

3.1. Control Unit

This unit monitors and controls the operation of the entire system. The unit obtains input signals from the dust sensing and measurement units; and after processing, sends output signals to the display and cleaning units of the system. The control operations are effected through the execution of programs in the Arduino microcontroller. Arduino Nano, which is a small and complete breadboard friendly microcontroller was selected not only because of its prevalent use in previous research [26] [35] [36] [37], but more importantly because it is very suitable as a low cost, easily programmable microcontroller. The circuit diagram of the control unit is shown in **Figure 2**.

The control unit includes two limit switches and three push buttons. The limit switches are used to detect the presence of the wiper at the two ends of the PV panel, while the push buttons are used to perform settings in the system.

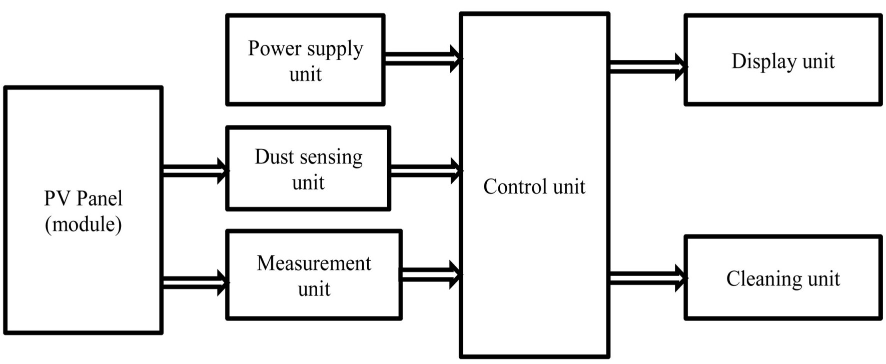

Figure 1. System block diagram.

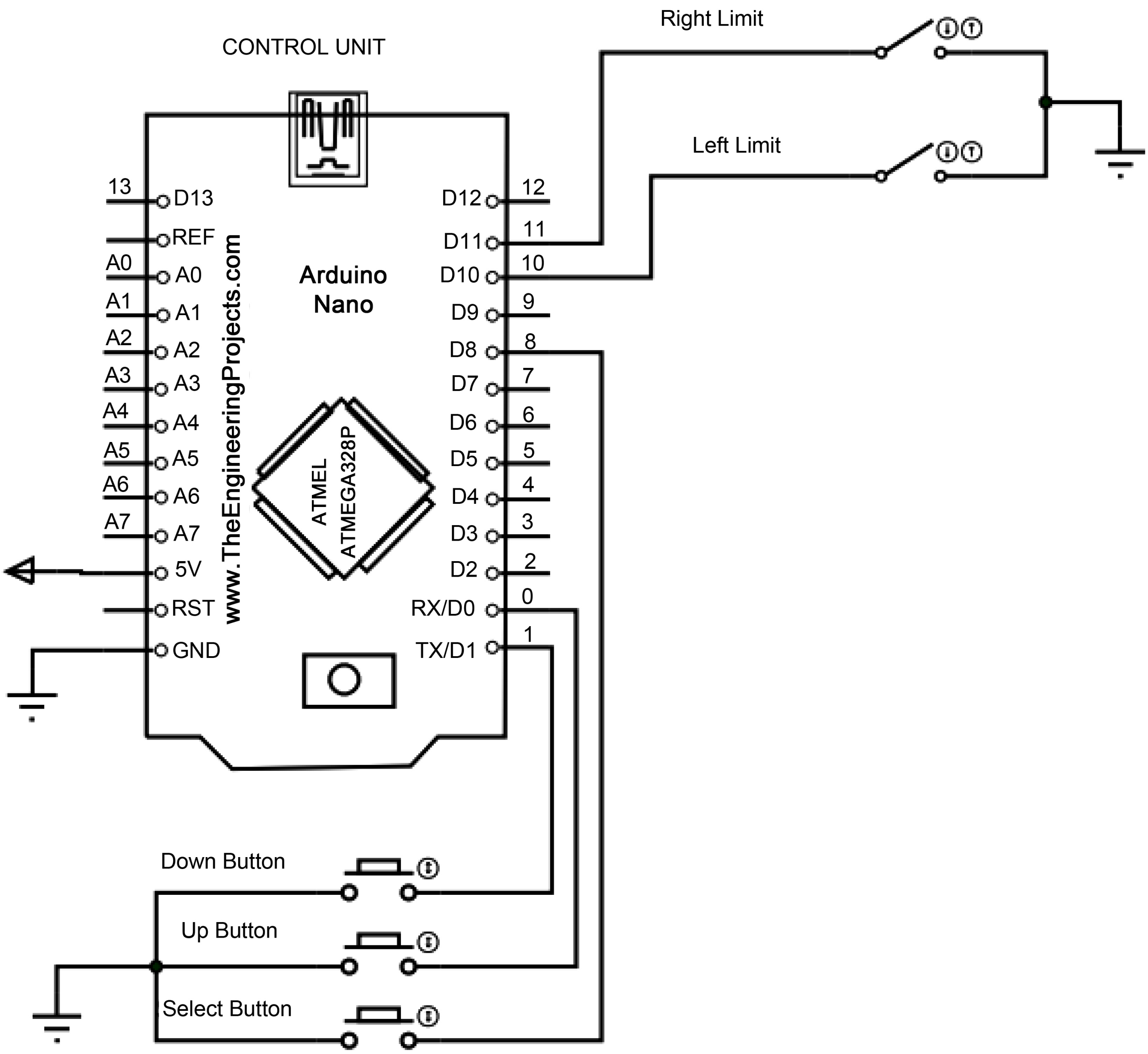

Figure 2. Electronic diagram of the control unit (with push buttons and limit switches).

3.2. PV Panel

PV panels are basically the combination of multiple solar cells used to convert energy from the sun (solar radiation) into electrical energy. The PV panel used in this project is of the polycrystalline type. This selection was guided not only by cost and size considerations but also by consideration of its wide availability and use in the locality. The specifications of the PV panel are presented in Table 2.

3.3. Power Supply Unit

The power supply unit provides electrical power required for the operation of the entire cleaning system. The unit comprises the solar panel itself, a battery, a DC-DC converter, and a charge controller. The solar panel converts energy from

Table 2. Specifications of PV panel model ZB70202010 20 W.

Peak power	20 W
Maximum power voltage	17.5 V
Maximum power current	1.14 A
Open circuit voltage	21 V
Short circuit current	1.28 A
Maximum system operating voltage	1000 V
Standard test condition	1000 W/m^2, AM = 1.5˚C, 25˚C
Weight	1.8 kg
Size: Length × Width × Depth (L × W × D)	0.54 m × 0.36 m × 0.02 m
Surface Area, S_{pv}	0.19 m^2

the sun into electrical energy, and this energy is stored in the battery through a charging process. A deep cycle rechargeable lead acid battery was selected for this project based on low cost and widespread use in the locality. Given that the deep cycle rechargeable battery is rated as 12 V, it cannot be used to directly power the microcontroller of the control unit. A DC-DC converter is used to convert 12 V (from battery) to 5 V (for use in the microcontroller). The DC-DC converter (buck converter) used in this project is preferred over traditional voltage regulators, because of its relatively high efficiency.

The last element of the power unit, the charge controller, regulates the rate of charging and discharging of the battery. A PWM charge controller as opposed to an MPPT charge controller was chosen for this project on account of it lower cost and wide use in off-grid solar application. The electronic diagram of the power unit is presented in Figure 3.

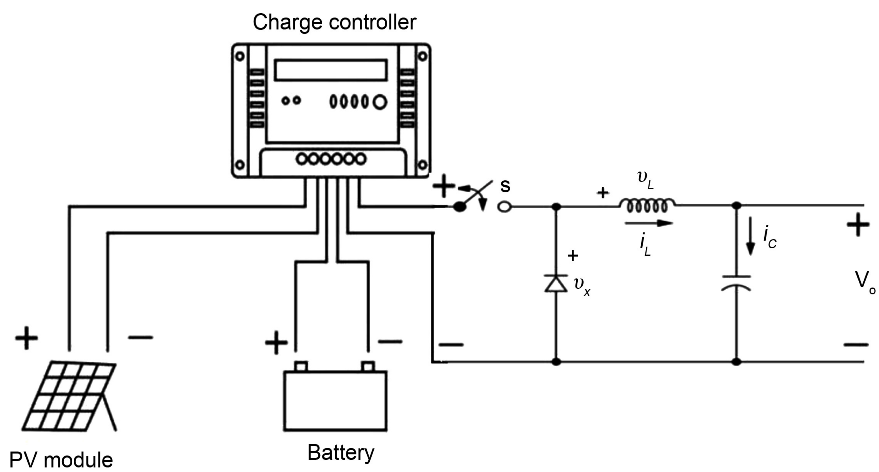

Figure 3. Power unit.

3.4. Dust Sensing Unit

The dust sensing unit is responsible for detecting the presence of dust on the surface of the PV panel. This unit measures the amount of dust accumulated on the surface of the PV panel as input to the control unit. Within the control unit, if the quantity of dust is above a specified threshold value, the cleaning unit is triggered for cleaning of the PV panel when other conditions discussed below are fulfilled. To measure the quantity of dust, an innovative use of two light dependent resistors (LDRs) is applied in the dust sensing unit: LDR1, to sense parameters on a dusty PV panel and LDR2 to do same for a clean PV panel. The design with the use of LDRs to sense and measure the accumulated dust on the panel is a cheap and cost-effective option compared to using specialized equipment such dust photometer, employed by Saidan *et al.* [10]; solar analyzer, used by Abderrezek and Fathi [38]; or optical dust sensors used by Seetaamma *et al.* [39].

In measuring dust accumulation, the assumption made here is that dust is uniformly and linearly deposited on the PV panel at all times, and hence also uniformly and linearly deposited on the two LDRs which are placed on the panel. The assumption of linear dust deposition has been used in the derivation of a mathematical formula for the determination of optimal number of days between two cleaning sessions of PV panels [34] and is a valid consideration for this study.

In its operation, an LDR produces a voltage as output, which varies as a function of the light intensity on the LDR: the greater the light intensity on the LDR, the lower its resistance and hence the greater its output voltage. In this design, LDR1, exposed to the accumulation of dust serves to reflect the state of a dusty PV panel; while LDR2, which is periodically cleaned of dust based on a programmed algorithm of the control unit, serves to reflect the state of a clean PV panel. The dust sensing and threshold detection paradigm employed in the system design is grounded on the fact that accumulated dust particles scatter or reflect incoming solar radiation resulting in decreased light intensity reaching the PV cells on the panel [8] [10] [40]. Hence the difference in the output of the two LDRs is considered to be due to accumulated dust; and is used to compare with the set dust threshold. The relationships between the state of the PV panel (dusty vs. clean), dust accumulation (high vs. low), light intensity on PV cells (low vs. high), and output voltage of LDR (low vs. high) are shown in **Table 3**.

The detection of accumulated dust is performed by comparing the outputs of LDR1 and LDR2 by the control unit. The quantity of accumulated dust at which to consider triggering the cleaning is established by a metric, DP, the accumulated dust percentage, which is computed by Equation (3).

$$\mathrm{DP} = \left(1 - \frac{\mathrm{VLDR1}}{\mathrm{VLDR2}}\right) \times 100 \tag{3}$$

where DP is the accumulated dust percentage, VLDR1 is the output voltage of LDR1 (dusty PV panel), and VLDR2 is output voltage of LDR2 (clean PV panel).

At the start of operation of the system, the PV panel is dust-free (clean). This means VLDR1 = VLDR2 and the fraction in Equation (3) equals to the number 1;

Table 3. Relationship between accumulated dust, light intensity, and output voltage of LDR.

PV Panel			Light Dependent Resistor (LDR)	
State	Dust Density	Light Intensity	Resistance	Output Voltage
Dirty	High	Low	High	Low
Clean	Low	High	Low	High

resulting in DP = 0% (which is less than the threshold value set in the system); meaning the control unit cannot consider triggering the cleaning process.

As dust begins to accumulate, VLDR1 begins to decrease resulting in a corresponding decrease from 1, of the fraction in Equation (3). Consequently, DP begins to increase from 0% up to 100% (when the output of LDR1 equals to zero, *i.e.* VLDR1 = 0 because of a high amount of accumulated dust that completely blocks solar radiations from reaching the PV cells).

The introduction of a set dust threshold value is the first design consideration which ensures the system does not wait until a high amount of dust is accumulated (DP = 100%) before considering to trigger the cleaning; equally the system will not consider cleaning when there is absence of dust on the PV panel or the amount of dust on the panel is low. A second dependent design consideration is that the PV panel power output be above a specified threshold value. Once the dust percentage threshold criterion is satisfied, the system will initiate cleaning only when this second criterion is satisfied along with a third consideration. The introduction of a power threshold below which cleaning cannot be triggered even if the dust percentage is above its specified threshold is a design decision to ensure that cleaning of the PV panel cannot be initiated at night, when the PV panel output is zero. A third design consideration is to ensure that when the accumulated dust is above the specified threshold, the value must be persistent for a specified time. This consideration avoids false triggering of cleaning when low light intensity on the PV panel may be the result of something other than dust accumulation that may temporarily be shading the PV cells. Based on practical experimentation and trials in the course of realizing the prototype system, the threshold value was set at DP = 60% for the locality. For the two identical LDRs used in the project, this occurs when dust has accumulated to the level that the output of the LDR1 decreases to 40% of the output of LDR2. To summarize, the cleaning process effectively starts when all three considerations (conditions) are met. The connection of the dust sensing unit and the control unit is shown in Figure 4.

3.5. Measurement Unit

The measurement unit is responsible for measuring the voltage, current, and the power generated by the PV panel. Sophisticated equipment such as Solar Power Meters [29] and Solar Analyzers [38] have served as the measurement units in PV cleaning systems. In order to ensure a low-cost system, cheap current and

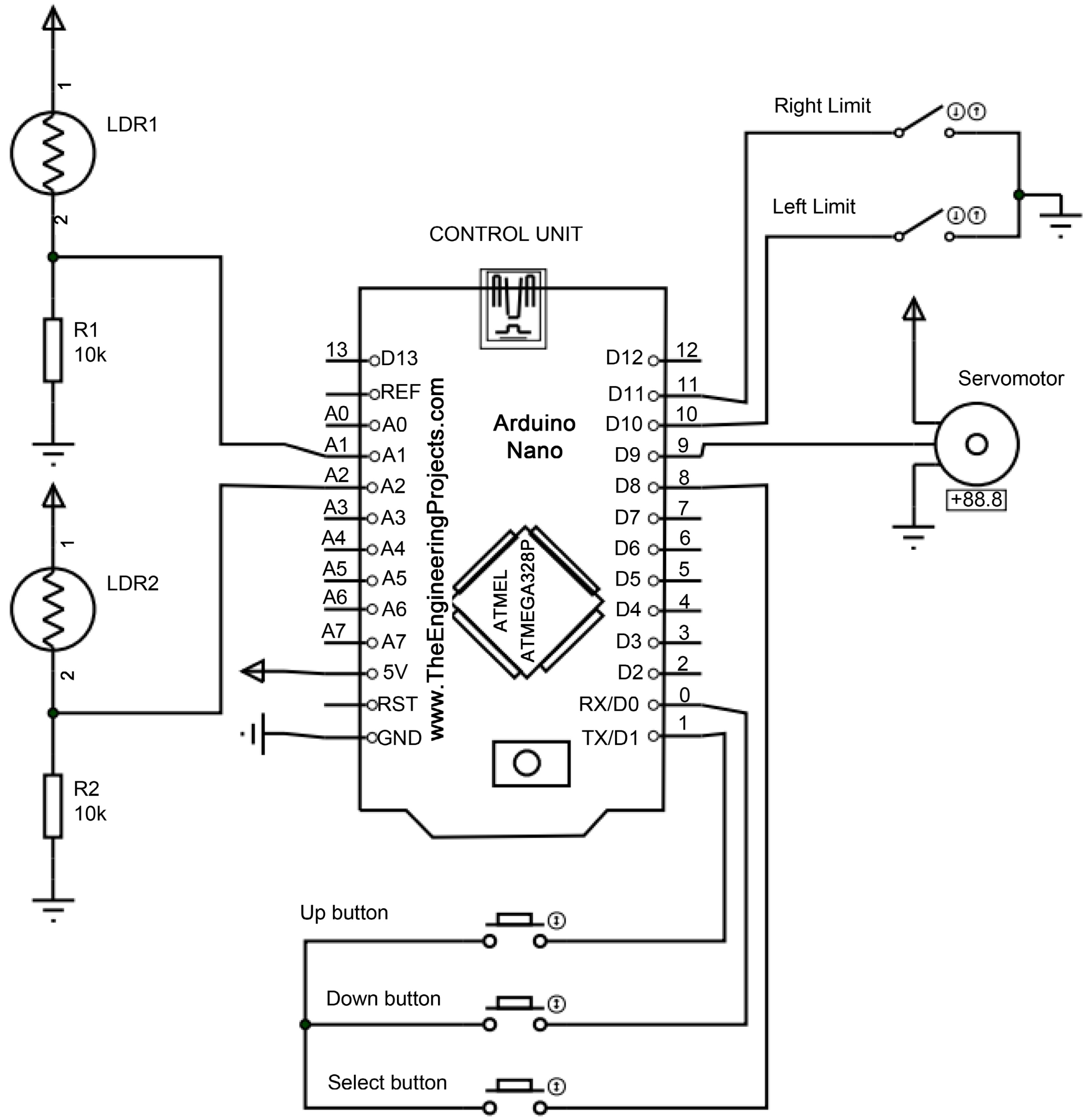

Figure 4. Connection of the dust sensing unit to the control unit.

voltage sensors were used; respectively to measure the current (I) and voltage (V) of the PV panel. The measured values are fed to the control unit which then calculates the corresponding power (P) of the PV module by Equation (4):

$$P = IV \tag{4}$$

3.6. Display Unit

A 16 × 2 LCD is used to display information about the state of various parameters of the automated cleaning system. This unit displays the output voltages of the LDRs, and the current, voltage, and power of the PV panel measured by the measurement unit. It also displays information on the state of the PV panel (clean, when the dust accumulation threshold has not been reached or dirty, in the contrary situation).

3.7. Cleaning Unit

This unit is responsible for cleaning dust from the surface of the PV Panel. Actual start of the cleaning process occurs when all three considerations (conditions) discussed above are fulfilled. Fulfilling these conditions is necessary in order to avoid unnecessary frequent cleaning which is detrimental to the health of the PV system as indicated in the literature review. Several cleaning methods were reviewed and the use of water and wiper was chosen as the most appropriate for this project in terms of cost. The cleaning unit is composed of DC motor, lead screw, wiper, wiper frame, water pump and pump jet. The steps and procedures for the specification and selection of these components, as well as their descriptions, and technical parameters are presented in the following sections.

3.8. Water Pump and Water Jet

The water pump sucks water from a storage container and delivers it onto the surface of the PV panel through the water jet. Selecting the water pump was based on a few fundamental parameters: flow rate, pressure, head, power, and efficiency [41]. From **Table 2**, the surface area of the PV panel, $S_{pv} = 0.54 \times 0.36$ m^2 = 0.1944 m^2 = ~0.20 m^2. For this relatively small area to clean, it is necessary to avoid waste of water. Therefore, a constantlow water flow rate ($\dot{Q}$) is assumed as indicated in Equation (5).

$$\dot{Q} = 0.25\ \text{L/min} = 0.000004\ \text{m}^3/\text{s} = 4.0 \times 10^{-6}\ \text{m}^3/\text{s} \tag{5}$$

Furthermore, assuming a water pressure (P) of 0.5 bar = 0.5×10^5 Pa, the power (P_{wp}) required to pump the water is calculated by Equation (6):

$$P_{wp} = \dot{Q} \times P \tag{6}$$

Numerically, $P_{wp} = 4.0 \times 10^{-6} \times 0.5 \times 10^5 = 0.2$ watts. With this low power, a submersible micro DC water pump is to be selected. Submersible water pumps are noted to have high efficiencies ranging from 76% to 84% [42]. So, assuming the efficiency of the submersible water pump, η_{wp} to be 80%, the power of the motor required for the water pump (P_{mp}) is obtained from Equation (7):

$$P_{mp} = \frac{P_{wp}}{\eta_{wp}} \tag{7}$$

Numerically, $P_{mp} = \frac{P_{wp}}{\eta_{wp}} = \frac{0.2}{0.8} = 0.25$ Watts.

The water jet is propelled through a plastic tube. The relationship between the speed of water (v) and the size of the plastic tube used to provide the water jet is depicted in Equation (8).

$$\dot{Q} = Av \tag{8}$$

where $\dot{Q}$ is the flow rate [m^3/s], A is the cross-sectional area of the of the tube [m^2] and v the speed of water through the tube [m/s].

Substituting for area, $A = \pi\left(\frac{d}{2}\right)^2$, where d [m] is the diameter of the tube in Equation (8), and transforming, the expression for the speed of water from the water jet is obtained by Equation (9):

$$v = \frac{4\dot{Q}}{\pi d^2} \tag{9}$$

Based on the calculations above, the battery-power micro submersible DC water pump was selected with its specification in **Table 4**.

Table 4. Specification of DC water pump: model see sensor.

Input DC	5 V
Current	1.8 A
Power	0.36 W
Flow	2 - 3 L/Min
Size	43.4 × 24.4 mm
Material	Plastic
Noise	40 db max

3.9. Wiper and Lead Screw Drive Systems

The wiper system is made of the wiper (**Figure 5**) [43], and a metallic frame designed to hold the wiper on the PV panel. The wiper system which weighs 0.54 kg is attached to the lead screw, and becomes the mass, M [kg] of the lead screw drive system. This is the total mass driven by the DC motor across the surface of the PV panel during the cleaning process.

The lead screw selected, with schematic in **Figure 6** has major diameter, d = 10 mm and is characterized by Equation (10) [44].

Figure 5. Wiper [43].

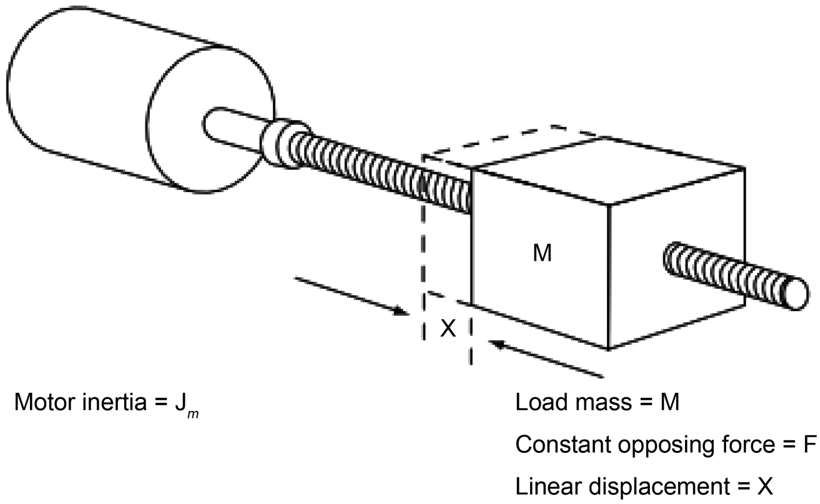

Figure 6. Lead screw drive system [44], with M representing the wiper system.

$$\omega = \left(\frac{2\pi}{L}\right)v \tag{10}$$

where ω is the angular velocity of the screw [rad/s]; v, the linear velocity of the mass [m/s^2]; and L is the lead, *i.e.* length by which the lead screw is advanced by a single rotation.

L is dependent on other parameters of the lead screw. The ISO metrics specifications for the Acme coarse pitch lead screw selected for this project are presented in **Table 5** [45].

Table 5. Acme coarse pitch leads screw specifications [45].

Major diameter, d	10.00 mm
Minor diameter, d_r	8.16 mm
Mean diameter, $d_m = (d + d_r)/2$	9.08 mm
Pitch diameter, $d_p = d_m$	9.08 mm
Pitch, p	1.5 mm
Lead, $L = L_m = 2\pi r_m$	28.29 mm
Minor diameter area, A_r	52.3 mm^2
*Coefficient of friction, f	0.10 - 0.15

*Note: Low value (f = 0.10) for very efficient system and high value (f = 0.15) for worst case.

3.10. DC Motor Selection

The selection of a DC motor can be based on peak torque, speed/torque curves, or winding specifications depending on available manufacturer's information [46] but for a non-heavy duty project such as the one presented in this research, speed, peak torque, and voltage constitute the minimum specifications to be known in order to select an appropriate DC motor. The DC voltage is determined by the available electrical power source; which in this project is a 12-volt battery (power supply unit). Therefore, only the torque and speed are to be determined for use in selecting the DC motor.

The PV panel used in the system is inclined at an angle of $\alpha = 6^\circ$. To move the wiper system in the cleaning process, a frictional force (F_f) and the force due to the weight of the wipersystem (F_x) have to be overcome by the DC motor. These forces are defined by Equation (11) and Equation (12).

$$F_f = \mu Mg\cos(\alpha) \tag{11}$$

$$F_x = Mg\sin(\alpha) \tag{12}$$

where $M = 0.54$ kg is the mass of the wiper system, $g = 9.81$ m/s^2 is the acceleration due to gravity, μ is the friction coefficient between the wiper and PV panel surface, and α is the angle of inclination of PV panel. The wiper is made out of a sponge-like material; with a friction coefficient $\mu = 0.3$ between the wiper and PV panel surface [29], but because the frame arrangement exerts some weight on the wiper, the friction coefficient is considered higher, $\mu = 0.4$. Given the angle of inclination $\alpha = 6^\circ$ and using foregoing equations, numerically, $F_f = 0.4 \times 0.54 \times 9.81 \times 0.99 = 2.1$ N; and $F_x = 0.54 \times 9.81 \times 0.1 = 0.53$ N. The force that the DC motor must exert in the worst case scenario occurs when the wipe system is moving up the inclined PV panel. This force, (F), is greater than or equal to the two forces acting on the wiper system as indicated by Equation (13).

$$F \ge F_f + F_x \tag{13}$$

Numerically, $F \ge 2.1 + 0.53$ N ≥ 2.63 N $= 2.7$ N, leading to Equation (14):

$$F = 2.7\ \text{N} \tag{14}$$

Given the parameters of the lead screw in **Table 5**, the torque required to move the wipe system load which is exerting a force, $F = 2.7$ N (from Equation (14)) is obtained by Equation (15) [45]:

$$T = \frac{Fd_p}{2}\left(\frac{L_m + \pi f d_p}{\pi d_p - fL_m}\right) \tag{15}$$

where $F = 2.7$ N and the other parameters as defined in **Table 5**.

Numerically, $T = \frac{2.7\times 9.01}{2}\left(\frac{28.29 + 3.14\times 0.15\times 9.01}{3.14\times 9.01 - 0.15\times 9.01}\right)\times 10^{-3}\ \text{N}\cdot\text{m}$

$$T = 12.16\left(\frac{28.29+4.24}{28.29-4.24}\right)\times 10^{-3} = 12.16\left(\frac{32.53}{24.05}\right)\times 10^{-3}$$

$$= 12.16\times 1.35\times 10^{-3} = 16.44\times 10^{-3}\ \text{N}\cdot\text{m} = 0.01644\ \text{N}\cdot\text{m}$$

$$T = 0.01644\ \text{N} = 0.02\ \text{N}\cdot\text{m}\left(204\ \text{g}\cdot\text{cm}\right) \tag{16}$$

It is recommended to select DC motor with the peak torque requirement of an additional 15% to ensure a safety margin [46]. Such a safety margin ensures the power requirement for moving the wiper system across the PV panel at a specified speed. Based on the safe margin consideration, the torque for DC motor selection, Tdc, is obtained by Equation (17):

$$T_{dc} = 1.15T = 1.15 \times 0.02 = 0.023\ \text{N} \cdot \text{m}\left(235\ \text{g} \cdot \text{cm}\right) \tag{17}$$

The mechanical power output of the motor is the product of shaft torque multiplied by its rotational speed, and is determined by Equation (18):

$$P_{mech} = T_{dc} \times \omega \tag{18}$$

where T_{dc} is the shaft torque and ω is the shaft rotational speed in radians per second as defined by the relationship $\omega = \left(\frac{2\pi}{L}\right)v$ (Equation (10)). With $L = L_m =$ 28.51 mm, Equation (10) can be re-written as:

$$\omega = \left(\frac{2\pi}{L_m}\right)v = \left(\frac{2\pi}{0.02851}\right)v\ \text{rad/s} = 220.39v\ \text{rad/s} \tag{19}$$

In order to determine ω, it is noted that the wiper system can travel the distance $x = 0.54$ m (length of PV panel used) at various speeds, v, depending on the time required (Table 6).

Table 6. Linear and rotational speeds for wiper system and DC motor with corresponding mechanical power ($x = 0.54$ m, $T_{dc} = 0.023$ Nm).

Time, t [s]	Speed, $v = x/t$ [m/s]	$\omega = 220.39v$ [rad/s]	$N = \omega(60/2\pi)$ [rpm]	$P_{mech} = T_{dc} \times \omega$ [w]
0.1	5.40	1190	11,370	27.37
0.15	3.60	793	7577	18.24
0.2	2.70	595	5685	13.69
0.25	2.16	476	4548	10.95
0.3	1.80	397	3793	9.13
0.35	1.54	340	3249	7.82
0.4	1.35	298	2848	6.85
0.45	1.20	265	2532	6.10
0.5	1.08	238	2274	5.47
0.55	0.98	217	2074	4.99
0.6	0.90	199	1902	4.58
0.65	0.83	183	1749	4.21
0.7	0.77	170	1625	3.91
0.75	0.72	159	1520	3.66
0.8	0.68	149	1424	3.43
0.85	0.64	140	1338	3.22
0.9	0.60	133	1271	3.06
0.95	0.57	126	1204	2.90
1	**0.54**	**119**	**1137**	**2.74**
1.5	0.36	80	765	1.84

For the selection of the DC motor, assume the cleaning time is 1 second, and the velocity, $v = (0.54/1)$ m/s = 0.54 m/s. From **Table 6**, a DC motor with required power, $P_{mech} = 2.74$ watts. It is also recommended that the motor's rated power be at least twice the required (calculated) power in order to ensure sufficient power for operation without overworking the motor, as specified by Equation (20) [47]:

$$P_{dc} = 2P_{mech} = 2 \times 2.74 = 5.48 \text{ watts} \tag{20}$$

For $P_{dc} = 5.48$ watts, $T_{dc} = 0.023$ Nm = 235 gcm, and $\omega = 119$ rad/s ($N = 1137$ rpm). The specifications of the DC motor selected are presented in **Table 7**.

Table 7. Specification of DC motor: SGMADA RS-775-12-2500.

Rated Voltage	12 V
No Load Current	≤200 mA
No Load Speed	2500 rpm
Torque at Maximum Efficiency	300 gcm (0.03 Nm)
Speed at Maximum Efficiency	1850 rpm
Powerat Maximum Efficiency	5.6 watts
Current at Maximum Efficiency	≤0.9 mA
Stall Torque	1200 gcm (0.12 Nm)
Stall Current	3.3 mA

3.11. Physical System

The 3D design of the PV panel dust cleaning system produced using Solid Works software is shown in **Figure 7**.

3.12. System Design and Simulation

The design and simulation of the circuit diagram for the entire system, the creation of schematic capture, and PCB design was done using Proteus version 8.0 [48]. The circuit diagram with all the component of the PV panel cleaning system is presented in **Figure 8**.

3.13. Programming the System

The programming of the automated cleaning system was performed using the Arduino Integrated Development Environment (IDE Arduino IDE 1.8.18; offered by Arduino.cc, for writing, compiling and uploading codes (sketches) to Arduino boards [49].

3.14. Operation of the System

When the system is switched on, the control unit takes over control of the operation of the system, starting with initialization and setting of the required

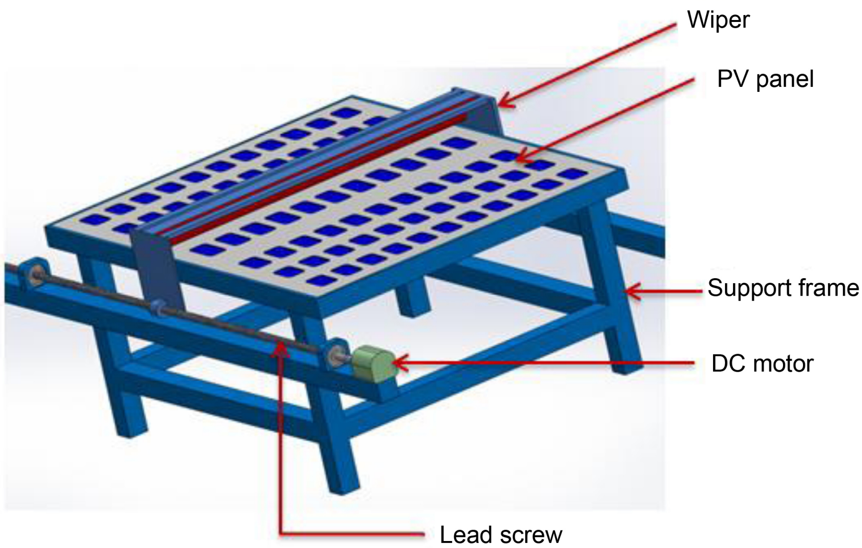

Figure 7. Solid Works 3D design of the PV panel dust cleaning system.

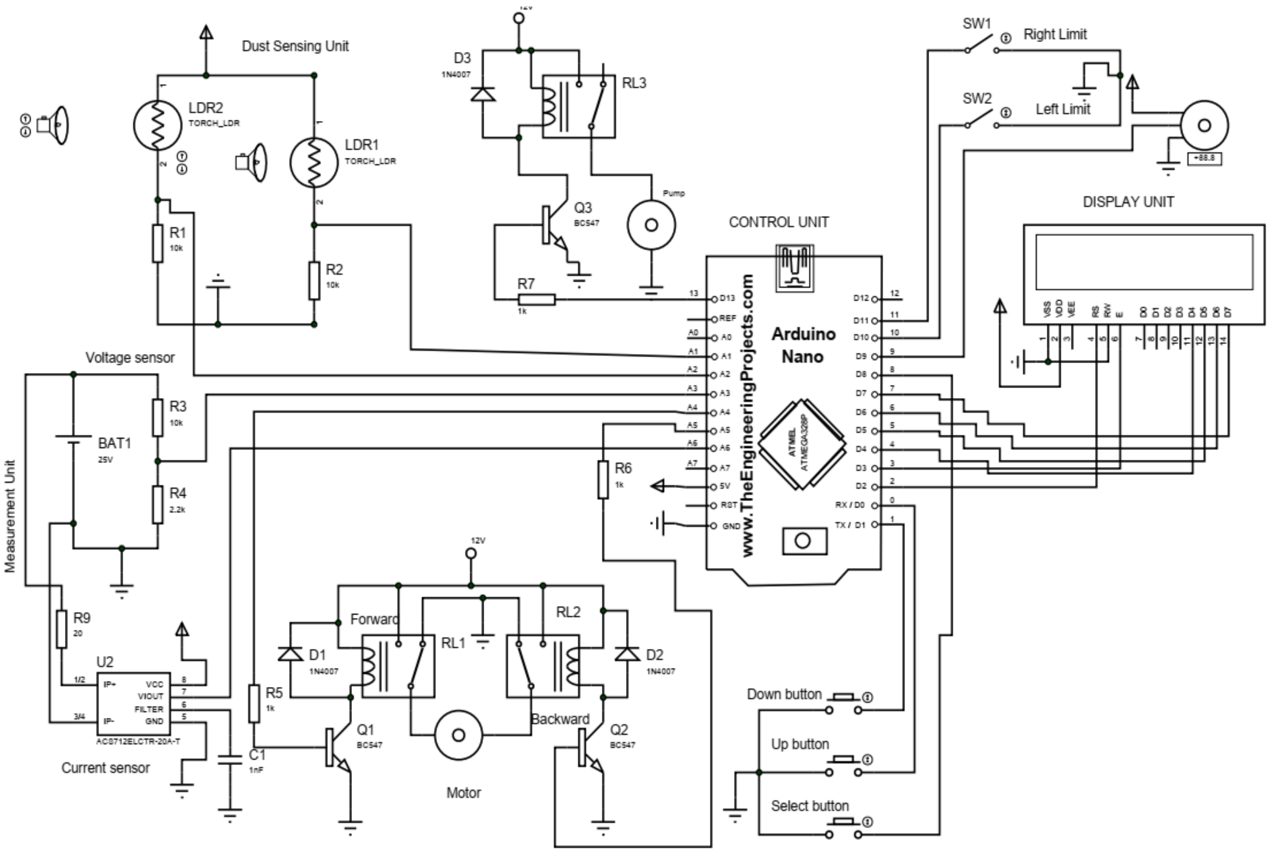

Figure 8. Circuit diagram of the complete PV panel dust cleaning system.

threshold values for specified parameters. Data is obtained from the dust sensing unit and the measurement unit on the level of dust accumulation on the surface of the solar panel and the amount of power produced by the PV panel. With input from the two LDRs, the control unit calculates the dust percentage (DP) deposited on the PV panel, the power output and the persistence of the dust percentage value. If all three criteria are met, the water pump starts and water is delivered onto the surface of the solar panel. Subsequently, the DC motor starts and moves the wiper system across the surface of the PV panel in the forward direction until the wiper system activates the limit switch at the end of the PV panel, at which point the water pump and the DC motor are stopped. After a short pause, the water pump and DC motor start again; however, with the DC motor operating in reverse mode, and the same sequence described above is repeated. When the wiper system activates the limit switch at the initial end of the PV panel, the water pump and DC motor stop. The summary of the operation of the automated PV panel dust cleaning system is presented in the flowchart shown in **Figure 9**.

4. Results and Discussions

The prototype automated PV dust cleaning system is shown in **Figure 10**, with a white bucket serving as a water reservoir.

In order to test and assess the performance of the prototype system, current and voltage measurements were carried out when the PV panel was dusty and when it was clean. Results of the measurements and calculated power output are shown in **Table 8**; while the corresponding I-V curves are shown in **Figure 11**. The current, voltage, and power values at the maximum power point are highlighted in bold (**Table 8**).

From the results, it can be observed that more power is obtained from the PV panel when it is clean compared to when it is dusty. PV panels are normally clean (dust-free) when they are acquired and installed, and maintaining them clean ensures maximum output.

Consistent with other studies, the above results indicate that there is degradation in PV panel performance when exposed to dust accumulation. To quantify the negative effects of dust accumulation, we compare the performance of the PV panel operating at maximum power point (MPP), when it is clean and when it is dusty.

From **Table 8** and by Equation (4), the power output of the dusty panel at MPP is $P_{\text{mppD}} = 5.75$ W while that of the clean system at MPP, $P_{\text{mppC}} = 8.68$ W. The relative percentage increase in performance as a result of using the system to clean dust on the PV panel, $P_{\text{dustclean}}$, is calculated by Equation (21):

$$P_{\text{dustclean}} = \frac{P_{\text{mppC}} - P_{\text{mppD}}}{P_{\text{mppC}}} \times 100\% \tag{21}$$

Numerically, $P_{\text{dustclean}} = \frac{8.68 - 5.75}{8.68} \times 100 = \frac{2.93}{8.68} \times 100 = 33.76\%$.

From the results and calculations above, it is seen that cleaning dust off the PV panel positively affects the performance of PV panels as reflected by increased power output. At the maximum power point, the relative percentage performance improvement is 33.76%. This can be interpreted to mean the

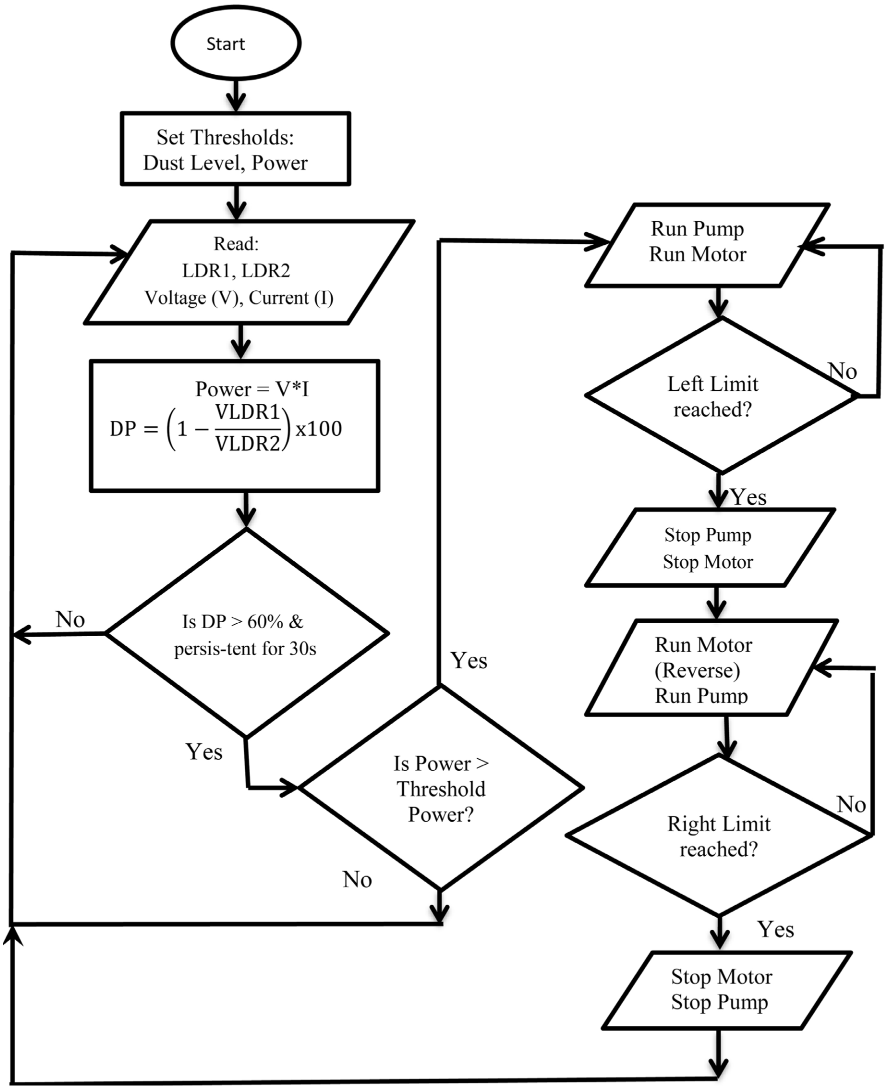

Figure 9. System flow chart.

Figure 10. Prototype of automated PV panel dust cleaning system.

Table 8. Current and voltage measurements of the PV module.

Dusty PV Panel			Clean PV Panel		
Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
0.00	0.59	0.00	0.00	0.79	0.00
4.00	0.56	2.24	5.00	0.76	3.80
10.50	0.50	5.25	8.90	0.74	6.59
11.55	0.48	5.54	12.00	0.70	8.40
12.50	**0.46**	**5.75**	**12.58**	**0.69**	**8.68**
12.80	0.44	5.63	12.60	0.68	8.57
12.90	0.43	5.55	13.40	0.64	8.58
13.16	0.40	5.26	13.55	0.62	8.40
13.20	0.39	5.15	13.82	0.60	8.29
13.30	0.38	5.05	14.00	0.58	8.12
13.50	0.36	4.86	14.20	0.56	7.95
13.60	0.35	4.76	14.50	0.52	7.54
13.70	0.32	4.38	14.60	0.48	7.01
13.80	0.30	4.14	14.70	0.46	6.76
14.00	0.20	2.80	14.80	0.44	6.51
14.10	0.10	1.41	15.20	0.25	3.80
14.20	0.00	0.00	15.40	0.00	0.00

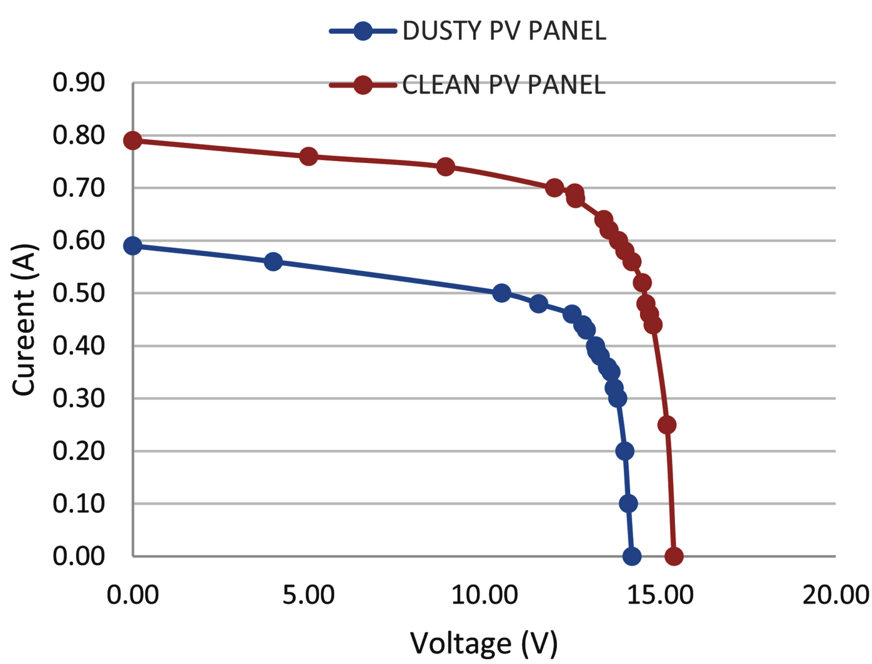

Figure 11. I-V Characteristics of dusty and clean PV panel.

percentage increase in performance efficiency as a result of cleaning dust off the PV panel in this study.

5. Conclusions

Dust accumulation on PV panels is one of the major causes of PV panel performance degradation worldwide. To restore or maintain and improve the performance of PV panels, their periodic cleaning is necessary. The problem of dust accumulation may be acute in Sub-Saharan African countries due to proximity to the Sahara Desert, vehicles moving on untarred roads, and activities that create dust in the localities. In these low-income countries, the tendency is to rely on the natural cleaning of PV panels. But this method is not effective, particularly during the dry season, when there is no rain. A low-cost prototype system for automated cleaning of dusty PV panels has been designed, implemented, and tested. The system is able to detect dust with the help of a simple and cheap dust sensing unit based on LDRs. The system is easy to use and found to be able to effectively address issues of dust accumulation on PV panels without engaging manual labour.

The performance of the system was assessed and found that there is a performance increase of 33.76% resulting from the cleaning of accumulated dust off the PV panel. These results, as in other studies contribute to highlight the imperative of PV panel dust cleaning, which should be included in all PV system installation maintenance plans. Complete details on the design and implementation process, including all circuit diagrams, and steps in sizing and appropriate selection of components are provided for easy replication. The development and wide deployment and use of the proposed system in rural communities of Sub-Saharan African (SSA) countries will be a step toward the achievement of the United Nations sustainable development goal seven; ensuring the provision of clean, modern, sustainable and reliable energy for all by the year 2030.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this work.

References

[1] Asoh, D.A., Mbinkar, E.N. and Moutlen, A.N. (2022) Load Frequency Control of Small Hydropower Plants Using One-Input Fuzzy PI Controller with Linear and Non-Linear Plant Model. *Smart Grid and Renewable Energy*, **13**, 1-16. https://doi.org/10.4236/sgre.2022.131001

[2] Desideri, U. and Campana, P.E. (2014) Analysis and Comparison between a Concentrating Solar and a Photovoltaic Power Plant. *Applied Energy*, **113**, 422-433. https://doi.org/10.1016/j.apenergy.2013.07.046

[3] Mbinkar, E.N., Asoh, D.A., Tchuidjan, R. and Baldeh, A. (2021) Design of a Photovoltaic Mini-Grid System for Rural Electrification in Sub-Saharan Africa. *Energy and Power Engineering*, **13**, 91-110. https://doi.org/10.4236/epe.2021.133007

[4] Jäger-Waldau, A. (2018) PV Status Report 2018. EUR 29463 EN, Publications Office of the European Union, Luxembourg.

[5] Al-Otaibi, A., Al-Qattan, Fairouz, A.F. and Al-Mulla, A. (2015) Performance Evaluation of Photovoltaic Systems on Kuwaiti Schools' Rooftop. *Energy Conversion and Management*, **95**, 110-119. https://doi.org/10.1016/j.enconman.2015.02.039

[6] Maghami, M.R., Hizam, H., Gomes, C., Radzi, M.A., Rezadad, M.I. and Hajighorbani, S. (2016) Power Loss Due to Soiling on Solar Panel: A Review. *Renewable and Sustainable Energy Reviews*, **59**, 1307-1316. https://doi.org/10.1016/j.rser.2016.01.044

[7] Gholami, A., Khazaee, I., Eslami, S., Zandi, M. and Akrami, E. (2018) Experimental Investigation of Dust Deposition Effects on Photo-Voltaic Output Performance. *Solar Energy*, **159**, 346-352. https://doi.org/10.1016/j.solener.2017.11.010

[8] Makkar, A., Raheja, A., Chawla, R. and Gupta, S. (2019) IoT Based Framework: Mathematical Modelling and Analysis of Dust Impact on Solar Panels. *3D Research*, **10**, Article No. 3. https://doi.org/10.1007/s13319-018-0214-7

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

[10] Saidan, M., Albaali, A.G., Alasis, E. and Kaldellis, J.K. (2016) Experimental Study on the Effect of Dust Deposition on Solar Photovoltaic Panels in Desert Environment. *Renewable Energy*, **92**, 499-505. https://doi.org/10.1016/j.renene.2016.02.031

[11] Tanaka, T.Y. and Chiba, M. (2006) A Numerical Study of the Contributions of Dust Source Regions to the Global Dust Budget. *Global and Planetary Change*, **52**, 88-104. https://doi.org/10.1016/j.gloplacha.2006.02.002

[12] Ghazi, S., Sayigh, A. and Ip, K. (2014) Dust Effect on Flat Surfaces—A Review Paper. *Renewable and Sustainable Energy Reviews*, **33**, 742-751. https://doi.org/10.1016/j.rser.2014.02.016

[13] United Nations (2022) The 17 Goals. https://sdgs.un.org/goals

[14] Asoh, D.A., Noumsi, B.D. and Mbinkar, E.N. (2022) Maximum Power Point Tracking Using the Incremental Conductance Algorithm for PV Systems Operating in Rapidly Changing Environmental Conditions. *Smart Grid and Renewable Energy*, **13**, 89-108. https://doi.org/10.4236/sgre.2022.135006

[15] Li, X., Mauzerall, D.L. and Bergin, M.H. (2020) Global Reduction of Solar Power Generation Efficiency Due to Aerosols and Panel Soiling. *Nature Sustainability*, **3**, 720-727. https://doi.org/10.1038/s41893-020-0553-2

[16] Derakhshandeh, J.F., Al Luqman, R., Mohammad, S., Al Hussain, H., Al Hendi, G., Al Eid, D. and Ahmad, Z. (2021) A Comprehensive Review of Automatic Cleaning Systems of Solar Panels. *Sustainable Energy Technologies and Assessments*, **47**, Article ID: 101518. https://doi.org/10.1016/j.seta.2021.101518

[17] Conceiçao, R., Gonzalez-Aguilar, J., Merrouni, A.A. and Romero, M. (2022) Soiling Effect in Solar Energy Conversion Systems: A Review. *Renewable and Sustainable Energy Reviews*, **162**, Article ID: 112434. https://doi.org/10.1016/j.rser.2022.112434

[18] Younis, A. and Onsa, M. (2022) A Brief Summary of Cleaning Operations and Their

Effect on the Photovoltaic Performance in Africa and the Middle East. *Energy Reports*, **8**, 2334-2347. https://doi.org/10.1016/j.egyr.2022.01.155

[19] El-Shobokshy, M.S. and Hussein, F.M. (1993) Degradation of Photovoltaic Cell Performance Due to Dust Deposition on to Its Surface. *Renewable Energy*, **3**, 585-590. https://doi.org/10.1016/0960-1481(93)90064-N

[20] Hegazy, A.A. (2001) Effect of Dust Accumulation on Solar Transmittance through Glass Covers of Plate-Type Collectors. *Renewable Energy*, **22**, 525-540. https://doi.org/10.1016/S0960-1481(00)00093-8

[21] Kazem, H.A. and Chaichan, M.T. (2016) Experimental analysis of the effect of dust's physical properties on photovoltaic modules in Northern Oman. *Solar Energy*, **139**, 68-80. https://doi.org/10.1016/j.solener.2016.09.019

[22] Salamah, T., Ramahi, A., Alamara, K., Juaidi, A., Abdallah, R., Abdelkareem, M.A., Amer, E.-C. and Olabi, A.G. (2022) Effect of Dust and Methods of Cleaning on the Performance of Solar PV Module for Different Climate Regions: Comprehensive Review. *Science of the Total Environment*, **827**, Article ID: 154050. https://doi.org/10.1016/j.scitotenv.2022.154050

[23] Juaidi, A., Muhammad, H.H., Abdallah, R., Abdalhaq, R., Albatayneh, A. and Kawa, F. (2022) Experimental Validation of Dust Impact On-Grid Connected PV System Performance in Palestine: An Energy Nexus Perspective. *Energy Nexus*, **6**, Article ID: 100082. https://doi.org/10.1016/j.nexus.2022.100082

[24] Fan, S., Wang, X., Cao, S., Wang, Y., Zhang, Y. and Liu, B. (2022) A Novel Model to Determine the Relationship between Dust Concentration and Energy Conversion Efficiency of Photovoltaic (PV) Panels. *Energy*, **252**, Article ID: 123927. https://doi.org/10.1016/j.energy.2022.123927

[25] Rezk, H., AL-Oran Gomaa, M.M.R., Tolba, M.A., Fathy, A., Abdelkareem, M.A., Olabi, A. and El-Sayed, A.H.M. (2019) A Novel Statistical Performance Evaluation of Most Modern Optimization-Based Global MPPT Techniques for Partially Shaded PV System. *Renewable and Sustainable Energy Reviews*, **115**, Article ID: 109372. https://doi.org/10.1016/j.rser.2019.109372

[26] Syafaruddin, Samman, F.A., Muslimin and Latief, S. (2017) Design of Automatic Control for Surface Cleaning Systems of Photovoltaic Panel. *ICIC Express Letters Part B*: *Applications*, **8**, 1457-1464.

[27] Chen, Y., Liu, Y., Tian, Z., Dong, Y., Zhou, Y. and Wang, X.W.D. (2019) Experimental Study on the Effect of Dust Deposition on Photovoltaic Panels. *Energy Procedia*, **158**, 483-489. https://doi.org/10.1016/j.egypro.2019.01.139

[28] Klugmann-Radziemska, E. and Rudnicka, M. (2020) Decrease in Photovoltaic Module Efficiency Because of the Deposition of Pollutants. *IEEE Journal of Photovoltaics*, **10**, 1772-1779. https://doi.org/10.1109/JPHOTOV.2020.3013971

[29] Al Qdah, K.S., Abdulqadir, S.A., Al Harbi, N.Y., Soqyyah, A.Z., Isa, K.J., Alharbi, M.Y. and Binsaad, N.M. (2019) Design and Performance of PV Dust Cleaning System in Medina Region. *Journal of Power and Energy Engineering*, **7**, 1-14. https://doi.org/10.4236/jpee.2019.711001

[30] He, G., Zhou, C. and Li, Z. (2011) Review of Self-Cleaning Method for Solar Cell Array. *Procedia Engineering*, **16**, 640-645. https://doi.org/10.1016/j.proeng.2011.08.1135

[31] Al-Housani, M., Bicer, Y. and Ko, M. (2019) Assessment of Various Dry Photovoltaic Cleaning Techniques and Frequencies on the Power Output of CdTe-Type Modules in Dusty Environments. *Sustainability*, **11**, Article No. 2850. https://doi.org/10.3390/su11102850

[32] National Renewable Energy Laboratory, Sandia National Laboratory (2018) SunSpec Alliance, and the SunShot National Laboratory Multiyear Partnership (SuNLaMP) PV O&M Best Practices, Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems. NREL/TP-7A40-73822. National Renewable Energy Laboratory, Golden. https://doi.org/10.1016/j.solener.2016.11.016

[33] Jiang, Y., Lu, L. and Lu, H. (2016) A Novel Model to Estimate the Cleaning Frequency for Dirty Solar Photovoltaic (PV) Modules in Desert Environment. *Solar Energy*, **140**, 236-240. https://doi.org/10.4236/ojee.2017.63006

[34] Abu-Naser, M. (2017) Solar Panels Cleaning Frequency for Maximum Financial Profit. *Open Journal of Energy Efficiency*, **6**, 80-86. https://doi.org/10.1016/j.iot.2018.08.006

[35] Hadipour, M., Derakhshandeh, J.F., Shiran, M.A. and Rezaei, R. (2018) Automatic Washing System of LED Street Lighting via Internet of Things. *Internet of Things*, **1-2**, 74-80.

[36] Naik, M.K. (2020) Economical Automatic Solar Panel Cleaning Using Arduino. *Journal of Engineering Research and Application*, **10**, 16-19.

[37] Malik, H., Alsabban, M. and Qaisar, S.M. (2021) Arduino Based Automatic Solar Panel Dust Disposition Estimation and Cloud Based Reporting. *Procedia Computer Science*, **194**, 102-113. https://doi.org/10.1016/j.procs.2021.10.063

[38] Abderrezek, M. and Fathi, M. (2017) Experimental Study of the Dust Effect on Photovoltaic Panels' Energy Yield. *Solar Energy*, **142**, 308-320. https://doi.org/10.1016/j.solener.2016.12.040

[39] Seetamma, R.P., Swati, S.P. and Veena, H.T. (2018) A Comprehensive smart monitoring system for hospitals using Internet of Things (IoT). *International Research Journal of Engineering and Technology*, **5**, 3935-3939.

[40] Jiang, Y. and Lu, L. (2015) A Study of Dust Accumulating Process on Solar Photovoltaic Modules with Different Surface Temperatures. *Energy Procedia*, **75**, 337-342. https://doi.org/10.1016/j.egypro.2015.07.378

[41] GlobalSpec (2022) Pumps. https://www.globalspec.com/pfdetail/pumps/flow

[42] Wei, Q. and Sun, X. (2017) Performance Influence in Submersible Pump with Different Diffuser Inlet Widths. Advances in Mechanical Engineering, **9**, 1-8.

[43] Luluhypermarket (2022) Vileda Floor Wiper Classic 42 Cm with Stick 1pc. https://www.luluhypermarket.com/en-sa/vileda-floor-wiper-classic-42-cm-with-stick-1pc/p/25949

[44] Tobin, S.M. and Servos, D.C. (2011) Application and Design with MATLAB. Taylor and Francis Group, LLC, Boca Raton.

[45] Budynas, R.G. and Nisbett, J.K. (2020) Shigley's Mechanical Engineering Design. 11th edition, McGraw-Hill Education, New York.

[46] Poulin, J.E. (1984) Practical Considerations in DC Motor and Amplifier Selection. *IEEEE Transactions on Industry Applications*, **IA-20**, 1130-1140. https://doi.org/10.1109/TIA.1984.4504575

[47] GlobalSpec (2022) DC Motors Information. https://www.globalspec.com/learnmore/motion_controls/motors/dc_motors

[48] Proteus (2021) PCB Design and Simulation Made Easy. https://www.labcenter.com/

[49] Arduino (2021) Arduino Integrated Development Environment (IDE) v1. https://www.arduino.cc/en/Guide/Environment