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Towards Smart Villages: Enhancing Solar Panel Output Efficiency through Automated Dust Cleaning

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Abstract: The purpose of this research was to enhance solar output efficiency of a solar panel through an automated cleaning design, with specific focus to a rural set up. The panel's efficiency was measured first without dust particles on clear days. The results were then compared to those measured on dusty conditions. The panel's efficiencies were recorded. Air quality sensor GP2Y1014AUOF, Class A dust particles measuring device PCE-MPC10; Microcontroller, software designs and other Hardware systems were used. Results indicated a clear correlation between dust accumulation and decreased power output, underscoring the necessity of automated cleaning. Lessons learnt emphasise the importance of precise sensor calibration and the efficacy of our cleaning mechanism. The developed solution holds particular significance amid the global shift towards renewable energy, catering to both urban and rural communities. The system represents a significant step towards realising smart rural villages where solar PV arrays need to consistently operate at peak efficiency so as to contribute to long-term sustainability. This innovation aligns with the broader objectives of fostering technology-enabled research and innovation for sustainable development, particularly in ICT4D activities. Research limitations were use of some equipment that are not rugged.

Keywords: Smart Village, Renewable Energy, Sustainability, Efficiency

Introduction

Solar power stands out as the fastest-growing form of renewable energy worldwide, offering a solution to reduce carbon emissions and combat the effects of global warming [1]. Crippling power shortages in developing countries [2], have led to the widespread adoption of Solar Photovoltaics (PVs). This is the way forward for rural areas as well as towns/Cities. In developing countries like Zimbabwe, the use of Photovlotaic systems is on the rise. This is meant to reduce the energy challenges already faced by the country. There are also significant challenges in accessing reliable electricity from traditional power grids. According to the National Development Strategy 1(NDS1) [3], only about 20% of rural Zimbabwe has access to electrical power from the grid as of 2020. This highlights the urgent need for reliable alternative energy solutions.

Despite the potential, solar PVs exhibit limited efficiency, typically ranging from 11% to 15% due to semiconductor technology constraints [4], [5]. While optimal exposure, array orientation, and sun-tracking mechanisms have helped to enhance efficiency of solar PV systems. These systems are also vulnerable to soiling as depicted by the panels at the bottom of Figure 1.

Fig. 1: Clean Panel (Top) vs Soiled Panel (Bottom)

Soiling reduces the irradiance reaching the cells, leading to a significant decline in overall efficiency, with potential power losses of up to 10%-15% in PV arrays [6]. Consequently, these systems may fail to charge batteries adequately, highlighting the critical importance of maintaining clean solar panels.

This study focused on the design and prototyping of an automated solar panel cleaning system tailored for rural environments. By leveraging advances in sensor technology, microcontroller programming, and mechanical design as articulated in earlier studies [7], [8], the system aims to monitor dust accumulation on PV panels and activate a cleaning mechanism when necessary, thereby ensuring optimal power output levels. By addressing the practical challenges associated with dust accumulation on solar PV panels, our system contributes to the broader objective of enhancing energy access and sustainability in rural communities.

The overarching aim of the study was to design, build, and test a prototype automated cleaning system capable of detecting the build-up of dust on solar panels and initiating cleaning actions to restore optimal power output, particularly in rural environments. The sub-objectives of the study included: 1) designing the automated solar panel cleaning system, 2) implementing the cleaning system prototype, 3) conducting performance evaluation and testing and 4) identifying opportunities for improvement.

Following this introduction, the paper details a review of existing methods and technologies of solar panel cleaning systems. The next two sections delve into the rationale behind the design choices, detailing the hardware and software aspects of the system.

1. Literature Review

Solar panel cleaning systems have garnered increasing attention as the demand for renewable energy solutions continues to rise, particularly in regions with high solar potential such as arid and semi-arid areas. In this section, literature on various cleaning methodologies and technologies employed to maintain the efficiency of solar PV systems were looked at. Solar panel cleaning systems developed are largely depended on the climatic conditions of the region were the system is installed.

1.1 Contact Cleaning

Several methods have been looked as shown below:

1.1.1 Manual Methods

Manual methods remain prevalent for cleaning solar PV panels, ranging from simple rinsing, brushing, and mopping for domestic applications [9], [10] to more sophisticated brush and water outlet configurations for industrial cleaning [11].

1.1.2 Mobile Cleaning Vehicles

Mobile cleaning vehicles equipped with extending arms, brushes, and water jets offer a semi-automated solution, albeit requiring human operators [12]. Notable examples include the MEGAWASH by Coldwell Solar shown in Figure 2a, capable of cleaning large-scale solar installations efficiently [13]. With the MEGAWASH system, a single operator can clean a 1-megawatt solar installation in approximately four hours. This system utilizes filtered and deionized water, requiring around 3000 litres of water for a single wash [14]

1.1.3 Autonomous Cleaning Robots: Waterless

A recent innovation in solar panel cleaning is the development of autonomous robots that eliminate the need for water-based cleaning systems. Robots such as the RAYBOT from Ecovacs Robotics shown in Figure 2b utilise vacuum cleaning technology, microfiber, and air blower mechanisms to remove dust and dirt without water [15]. Automated systems have shown promise in enhancing energy capture compared to dirty panels in local installations [16]. Raybot can clean roughly five solar panels an hour [17]. This waterless approach offers advantages in regions where water scarcity or poor water quality may pose challenges to traditional cleaning methods.

Fig. 2: a) MEGAWASH by Coldwell Solar b) EcovasRaybot c) Lectro Blaster Solar Cleaner

1.2 Contactless Cleaning: With Water

1.2.1 Heliotex Technology

Heliotex technology represents a water-based contactless cleaning solution for solar PV panels, employing spray nozzles and purified water to wash and rinse panels [18]. Its main operation is based on water supply, water pressure and water quality. The Heliotex has spray nozzles fitted to each panel with 24v AC electro-valves and wiring is connected to the controller, to channel water to the nozzles. The water rinses and washes the panels using purified water and detergent. The detergent reservoir and filters need occasional replacement for proper functionality.

1.2.2 LectroBlast Solar Blaster

Similarly, the LectroBlast Solar Blaster utilizes high-velocity water sprays to shear off dust and debris from panel surfaces [19]. A 2000 litre tank distributes water along with a powerful 400km/h cleaning fan that sprays water onto the panels [20]. The high velocity of the water shears off dust and debris that has accumulated onto the Solar Panels. It is also compatible with panels that actively track the sun by adjusting the angle and direction of cleaning. Figure 2c, shows the LectroBlaster Solar Cleaner. While effective, these systems rely on water resources and may not be suitable for regions with water scarcity or quality issues.

1.3 Contactless Cleaning: Without Water

1.3.1 Nano-Films

Nano-films incorporate pellucid materials with self-cleaning properties, leveraging photocatalytic and hydrophilic or hydrophobic effects to remove dust and debris [21]. Use of nano-films is still largely experimental and the process is still in the developmental stage. The films are implemented using two different strategies. Super-Hydrophilic material TiO2 has an initial photocatalytic process where it reacts under UV light incident on it, splitting the organic matter in the dust. The hydrophilic activity in the film then diffuses the rainwater on the surface of the panel to rinse the dust off the solar PV panel [22]. Super-Hydrophobic materials form nano-structures [23] that create a contact angle of about 150o causing water droplets to run off the surfaces of the panels [24]. As the water runs off, it carries the organic and inorganic particles off the panel.

1.3.2 Electrostatic Cleaning

Electrostatic cleaning employs dielectrophoretic forces to lift and transport particles from panel surfaces, eliminating the need for water [25], [26]. The Electric Curtain Concept employs a series of parallel conducting electrodes (depicted in Figure 3) embedded deep within a dielectric surface. Oscillations in the electrode potentials traverse across these electrodes [24].

Applying a single-phase AC voltage across the electrodes generates a standing-wave field. Recent studies indicate that this standing wave not only suspends particles on the curtain but also facilitates their net transport [27]. When a multi-phase AC voltage is applied, a traveling-wave electric curtain is formed [25]. This causes charged particles to move along and off the solar panel surface [28], driven by the electromagnetic effect induced by the multiphase voltage. See Fig 3 below

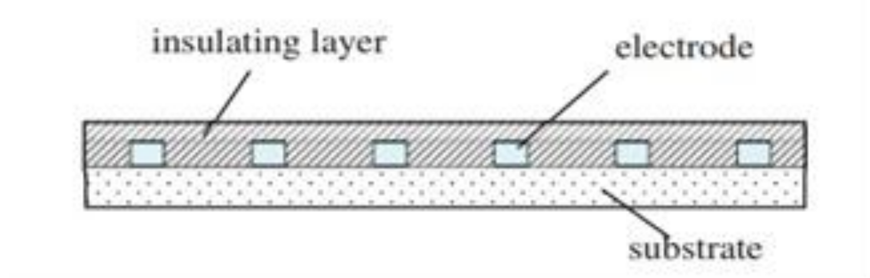

Fig 3: Basic Structure of Electric Curtain

Originally this was developed for lunar missions to prevent module shutdown due to dust accumulation on solar panels, the Electric Curtain Concept offers the advantage of operating without water. However, it relies on multiphase voltage for effective particle transport, presenting a trade-off [28].

1.4 Summary

Other studies have shown that the impact of soiling on PV systems can vary widely, with efficiency reductions ranging from 4.7% to 50% [29]. This renders regular cleaning a necessity.

2. Methodology

A conceptual design for the Automatic Solar Panel Cleaning system was formulated by defining specific system requirements, including sensor specifications, cleaning mechanism design, control system architecture, and considerations related to power supply. Figure 4 shows the block diagram of the design.

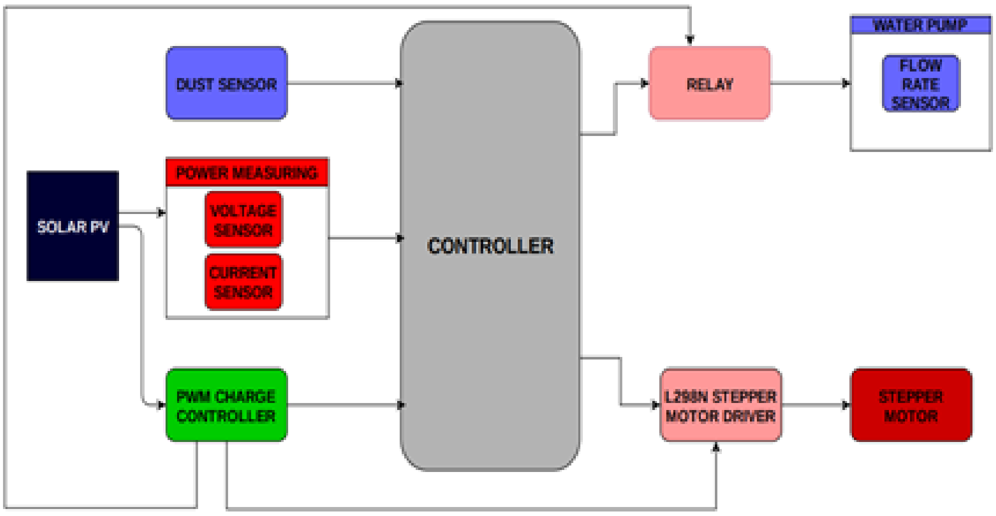

Fig. 4: Automatic Solar Panel Cleaning System Block Diagram

The block diagram outlines the key components of the design and their interconnections. Thedesign process of the Automatic Solar Panel Cleaning system involved the integration of hardware, software designs, and their seamless operation. The microcontroller serves as the central processing unit, making decisions based on input data from various sensors and controlling output devices accordingly. Additionally, the system incorporates power circuitry, dust monitoring, and cleaning mechanisms to ensure efficient operation.

2.1 Software Development

The embedded code that coordinated the process flow of the project was based on the flow chart shown in Figure 5.

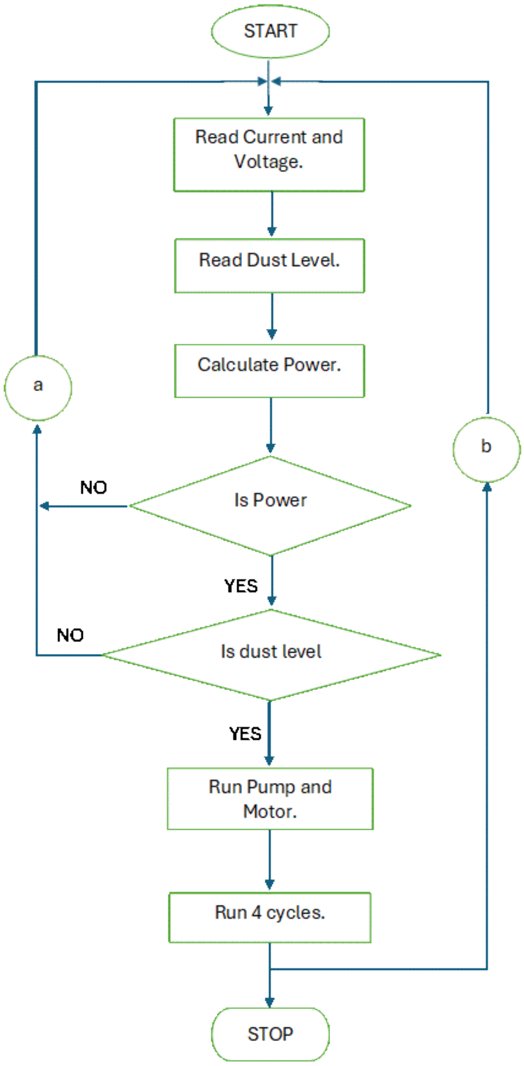

Fig. 5: Flowchart of the embedded code

The Arduino's versatile programming environment was utilised to offer flexibility in implementing complex control algorithms and integration with various sensors and actuators. The modular nature of the code facilitates future enhancements and optimisations to meet evolving system requirements.

2.2Hardware Development

The hardware development for the panel cleaning system involved the use of the Arduino Mega 2560 R3 microcontroller to orchestrate and implement the system's intelligence.

Robust sensing mechanisms were incorporated into the system, notably the Sharp GP2Y1014AUOF Air Quality sensor, enabling accurate detection of dust accumulation on solar panels. Additionally, voltage and current sensors were used to monitor the solar panel performance. This in turn facilitated timely cleaning interventions to maintain optimal efficiency. Efforts were made to benchmark and calibrate air quality sensors using a commercially available Class A sensor, namely the Dust Particle Measuring Device PCE-MPC10. The sensor's operation is based on the light scattering principle, with a photo-detector and an LED emitter positioned at an angle within the sensor. As air-filled dust passes through the sensor's holes, light scattering towards the photo-detector occurs, enabling measurement of total density, including particulate matter ranging from PM2.5 to PM10. The dust sensor outputs a voltage value that varies with the intensity of the scattered light which in turn corresponds to the level of dust in the air. The actual dust density can then be calculated from the output voltage value using a linear relation.

To measure power output, a circuit incorporating a voltage sensor and a current sensor was developed. The voltage sensor, based on a resistive voltage divider, was integrated to measure the solar panel's output voltage. Conversely, the ACS712-05BT Current sensor, utilising Hall-effect technology, facilitated precise measurement of current. With both sensors in place, power measurement was achieved. This was crucial for determining cleaning system activation. To measure the solar panel's output voltage, the solar panel is connected as Vin and Vout measured by the Arduino.

$$V_{panel} = \frac{30k\Omega + 7.5k\Omega}{7.5k\Omega} * V_{out} \qquad (1)$$

Additionally, the hardware setup included a Pulse Width Modulation Charge Controller responsible for charging the system's battery, a sub-control unit for the cleaning unit comprised of a non-submersible pump and a NEMA-17 Stepper motor driving the water spray and brush across the panel.Alltheses embedded on the panel and making use of energy generated by the solar panel. The Flow Rate Sensor quantified water usage accurately, optimizing water usage, while the NEMA-17 Stepper motor enabled panel cleaning as required. Overally, this comprehensive hardware design facilitated the effective operation of the Automatic Solar Panel Cleaning system.

3. Results and Discussions

The solar panel module performed below expectations in terms of conversion efficiency, and further testing showed clearly how dust affects power output. The rest of the system performed nominally producing expected results except for glitches encountered due to the mechanical design of the chassis housing the panel and cleaning system. The panel performance was tested under normal operating conditions and under dusty conditions.

The results obtained for the Irradiance were measured using a light dependant resistor and calibrated to the values obtained using the CM6B Kipp and Zon Pyranometer and these were as shown in figure 6.

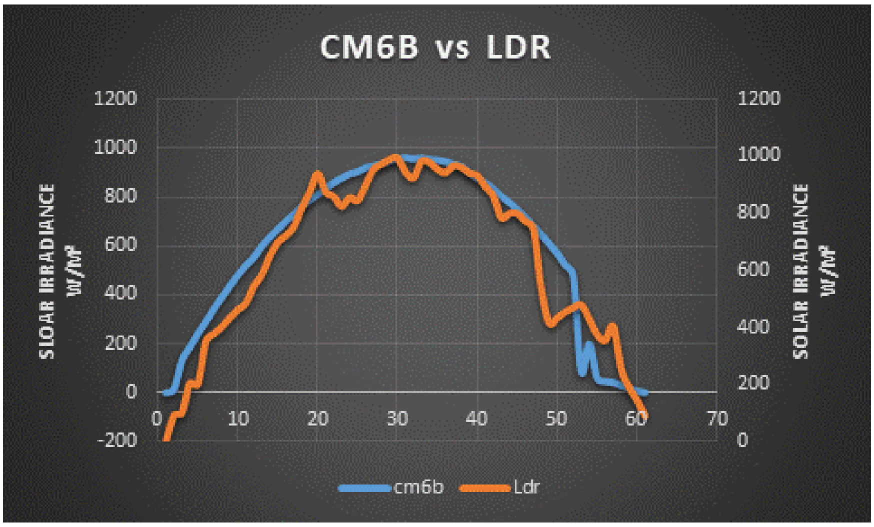

Fig. 6: Comparison of CM6B and LDR Irradiance values

The results of the panel output and irradiance measured are shown in Table I. The table shows how the power output of the panel increased as solar irradiance increased. Conversion Efficiencies of solar panel modules are usually rated between 10% and 25%. The conversion efficiency percentage of the PV solar module was determined by the following formulae:

$$\eta\% = \frac{P_{out}}{P_{in}} * 100\% = \frac{p_{out}}{G*A} \qquad (2)$$

Where:

- A= Area of solar panel = 0.525 * 0.510
  = 0.26776m^2
- *G = Solar Irradiance* = 1000W/m^2

Table I Solar Panel Performance

Time	Irradiation (W/m^2)	Voltage (V)	Current (A)	P_{max} (W)	Efficiency (η%)
07:30	202	19	0.1	1.9	0.709591
08:00	402.6	20.4	0.4	8.16	3.047505
08:30	486	20.5	0.46	9.43	3.521811
09:00	650	20.4	0.52	10.608	3.961757
09:30	753.3	20.4	0..59	12.036	4.49507
10:00	940	20.4	0.67	13.668	5.104571
10:30	825	20.2	0.68	13.736	5.129967
11:00	900	20.3	0.69	14.007	5.231177
11:30	990	20.1	0.68	13.668	5.104571
12:00	925	19.8	0.69	13.662	5.10233
12:30	955	20.1	0.77	15.477	5.780176
13:00	961.9	20.3	0.73	14.819	5.534434
13:30	894	20.6	0.67	13.802	5.154616
14:00	800	19.5	0.55	10.725	4.005453
14:30	748	19.6	0.49	9.604	3.586794
15:00	435	19.4	0.43	8.342	3.115477
15:30	480	19.3	0.33	6.369	2.378623
16:00	355	19	0.24	4.56	1.703018
16:30	190	18.2	0.14	2.548	0.951598
16:50	90	15.9	0.02	0.318	0.118763

The panel used displayed low efficiency levels than what was expected, showing an anormally with what expected. Nevertheless it was used for the experiment to prove the effect of dust removal using an automated system.

The panel was later on soiled and tested for its response. By blowing dust towards the sensor, a V_{oc} of 0.7V without dust was noted (0mg/m^3) and reached a maximum of 3.7V with dust at 0.724mg/m^3. The sensitivity (k) of the sensor was adjusted manually relative to the voltage output range to a value of 0.5V/0.1mg/m^3. The conversion is thus given by:

$$Dust\ Density\ (\mu g/m^3) = \left(\frac{\Delta V}{k}\right) * 1000 \qquad (3)$$

Where:

- $\Delta V = V_{out} - V_{oc}$
- V_{out} = Output at measuring dust.
- V_{oc} = Output at no dust.
- k = sensitivity.

Tests were conducted on the effect of soiling the solar panel module, and results showed decreasing power output and the overall performance of the module. Figure 7 shows the results.

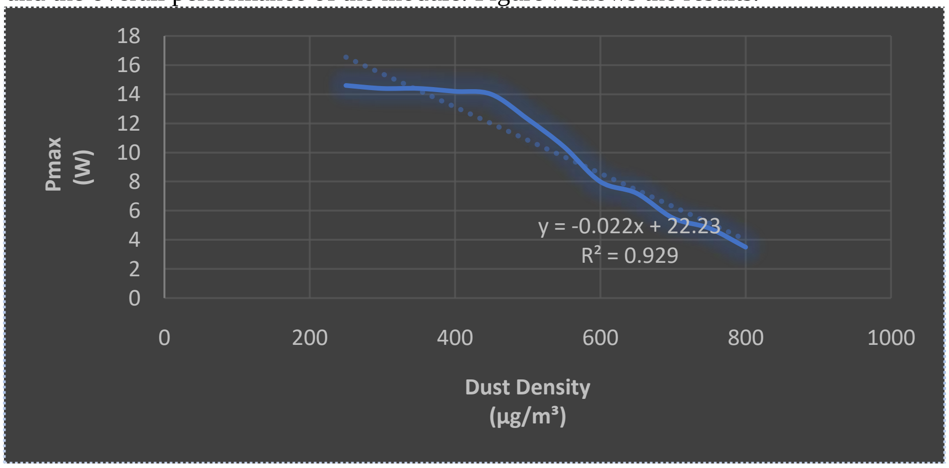

Fig 7: P_{max} against Dust Density

Power output from the panel was found to be generally constant when the dust level ranged from 250µg/m^3 to 450µg/m^3 . These levels were found to be equal to the atmospheric dust level which was read by the sensor at the time of testing. When dust levels started rising, the density level started rising from 450µg/m^3 peaking off at around 800µg/m^3 where power output would drop below 4W.

The results obtained from the experiment proved that as dust density on the panel increased, power output decreased. From these results, operating parameters for the cleaning system where determined as follows, If Dust Density was greater than 700 µg/m3 and if the Power Output was less than 5W, the cleaning system was activated.

The main and subsystems were tested and combined into one unit. The solar PV array was fixed onto the mounting chassis for full testing as shown in Figure 8. The sensing feature of the system operated as expected with a few issues encountered on the mechanical design as the cleaning arm would occasionally not reach the ends of the panel due to slight misalignment.

Fig. 8: Automatic solar panel cleaning system in operation

The prototype operated very well and could be used by organisations involved in solar energy production and maintenance. The system managed to enhance the overall efficiency and performance of a solar PV installation. Improved efficiency was found to translate to higher energy yields. Use of rugged system would lead to increased revenue generation for huge grid connected solar energy systems

Conclusion

The development and testing of the prototype cleaning system underscored its potential to address the challenges associated with dust accumulation on solar photovoltaic (PV) panels. Despite encountering challenges in the mechanical design during prototype testing, the overall performance and reliability of the system remains promising. Such systems will be of great help in smart rural villages. Such a system would offer a tangible step forward in ensuring that solar PV arrays operate optimally, leaving no room for rural communities not to be left behind.

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