V-TROUGH REFLECTORS USING OPEN-LOOP SINGLE AXIS SOLAR TRACKING FOR A PV MODULE

Symon Mykell P. Andres[1], John Royce D. Jamilla[1], Reden L. Loyola[1],
Neil Francine N. Molina[1,b], and Carlito M. Gutierrez[2,a]
[1]Bachelor of Science in Electrical Engineering, College of Engineering and Information Technology
[1]Faculty Member, Electrical Engineering Program, College of Engineering and Information Technology
[a]carlito.gutierrez@letran.edu.ph, [b]nfrancinem@gmail.com

ABSTRACT

Because of its geographical advantage, the Philippines is one of the countries with the highest potential in solar energy harnessing. At present, the solar industry utilizes solar trackers for large scale applications but not in small scale due to their uneconomical prices relative to the financial capability of consumers. Thus, small scale applications only make use of static solar panels. This study intends to link the gap between the presently available technology to small-scale consumers and the integration of both solar tracking and concentrating photovoltaics (CPVs) into a PV module to harness more power. V-trough solar reflectors were programmed to follow the sun based on algorithms set by NREL. A bypass mechanism was also included to protect the system from detrimental temperature levels. The device was tested based on the accuracy of the reflector inclination angles, significance of the increase in the output power and the cost-benefit analysis based on consumer perspective. The error in the inclination angles were found to be minimal, the increase in power output was significant and the device has an annual return of investment of 17.04% within a payback period of 5.83 years.

Keyword: *Energy Resources, Photovoltaic Systems, Solar Energy, Solar Panels, Solar Power Generation*

INTRODUCTION

The solar energy industry in the Philippines is emerging as photovoltaic (PV) modules become readily available in the market. PV modules are no longer just offered to institutions that operate in large scale but even in small scale such as households. Despite improved access to this technology, the low efficiency of PV modules is still a field of interest in research.

There had been studies in countries of similar climatic conditions that make use of solar tracking technologies and concentrating photovoltaics (CPVs) to improve yield. The maximum power is increased from 20% to 30%. However, other concerns such as increase in PV temperature that lead to decrease in PV life are found to be caused by unbalanced illumination.

This study introduces a technology that incorporates both the mechanism of solar tracking and CPVs to improve yield and at the same time, avoid the degradation of PV life due to high PV temperature. It intends to develop automatic v-trough reflectors using open-loop single-axis solar tracking for a single, ground-mounted, monocrystalline PV module with temperature response and bypass mechanism. This aims to test the accuracy of reflector angles to avoid unbalance illumination, determine the response of the bypass mechanism that will inhibit the module to reach critical temperature levels, know the increase in yield due to the application of reflectors and determine the financial efficiency of the device.

Literature Review

As the maximum power transfer theorem states, the peak amount of power that can be dissipated in a load is when the load resistance is equivalent to the Thevenin/ Norton resistance of the network supplying. A PV Cell is like a typical representation of a battery with a series internal resistance, $R_{INTERNAL}$. But due to variations of this internal resistance, the voltage and the current will vary for a load [1].

As electricity flows, the internal resistance of the cell opposes the flow of current and the power is dissipated as wasted heat [2]. The equation of a cell E.M.F. is written as

$$E = IR + Ir \qquad \textbf{Eqn. 1}$$

or

$$E = V + I \qquad \textbf{Eqn. 2}$$

The internal resistance can be derived as

$$r = (E - V)/R \qquad \textbf{Eqn. 3}$$

The load equivalent to internal resistance gets a voltage drop that is half of the E.M.F. Thus, maximum power, by virtue of maximum power transfer theorem, can be computed as:

$$P = (E/2)2/r. \qquad \textbf{Eqn. 4}$$

Solar tracking is an intelligent system that orients solar harvesting equipment such as reflectors, collectors and photovoltaic panels in configurations aligned with the position of the sun. Modern solar tracking methods that focus on automated systems involve two basic forms: open-loop and closed-loop solar trackings[3]. Open-loop systems are programmed while closed-loop systems make use of sensors and include mechanisms that rely on feedback [4].

The sun's direction at any point is represented by spherical system of coordinates. Spherical coordinates can be converted to Cartesian coordinates through the application of vector analysis. To convert spherical coordinates namely: ρ ,the distance from the origin to the point; θ ,the angle between the positive *x*-axis and the line above denoted by *r*; and φ , the angle between the positive *z*-axis and the line from the origin to the point [5].

The direction of sun was expressed in terms of azimuth and altitude wherein the altitude is 90 degrees minus the zenith angle. The azimuth is the angle from north increasing clockwise respectively [6].Therefore, the following Cartesian coordinates can be expressed as:

$$x = \rho cos(Altitude) sin(Azimuth) \qquad \textbf{Eqn. 5}$$
$$y = \rho sin(Altitude) cos(Azimuth) \qquad \textbf{Eqn. 6}$$
$$z = \rho sin(Altitude) \qquad \textbf{Eqn. 7}$$

Single axis tracking is tracking the sun along its east and west components. Therefore, the PV and the reflectors will be perpendicular to x-z plane, thus x and z components will determine the inclination of the reflectors.

To write expressions in terms of collector orientation and solar angles, we transform the coordinates of the central ray unit vector **S** as shown in the figure to a new coordinate system that has the tracking axis as one of its three orthogonal axes. The other two axes are oriented such that one axis is parallel to the surface of the earth [7].The collector aperture rotates about the r axis, where N is a unit vector normal to the collector aperture. The tracking angle, with respect to zenith, is then

$$tan\ \rho = Sb/Su \qquad \textbf{Eqn. 8}$$

But with respect to horizontal, the angle of the sun (using the symbol α) at x-z plane can be derived in terms of x and z as:

$$tan\ \alpha = x/z \qquad \textbf{Eqn. 9}$$
$$\alpha = arctan\ (x/z) \qquad \textbf{Eqn. 10}$$
$$\alpha = tan^{-1}\left(\frac{tan(altitude)}{sin(azimuth)}\right) \qquad \textbf{Eqn. 11}$$

Optical devices such as reflectors or lenses deflect sunlight from a larger area and concentrate it to a smaller area of the photovoltaic collector. This technology is known as Concentrating Photovoltaics (CPV). One advantage of using CPV technology is that it makes use of cheaper material to collect more energy from the sun. For high concentration photovoltaics (HCPV), high efficiency is achieved, but it uses expensive multi-junction cells [8].

The v-trough configuration is one of the designs adaptable to low concentration. Low concentration ratio or minimal increase in concentration is easily adaptable to countries near the equator, which already have a high concentration. On the other hand, other designs require wider spaces for installation, large equipment, and greater change in PV orientation. The V-trough reflector configuration was adapted in researches that made use of conventional PV modules. The succeeding studies are some of the examples.

In a study conducted in India, the effect of reflectors and inclination of PV panel to thepower output of a PV panel has been investigated. Flat mirror reflectors were fixed to the PV panel. The panel was constructed either horizontally or at 30° inclination to horizontal. The paper evaluated the effect on I-V curve, power curve, fill factor and efficiency. It showed that the introduction of reflectors produced a significant improvement in short circuit current of 50 to 60% and in power but only a small increase in efficiency. The power-voltage graphs showed that whether there were reflectors or none, power output is maximum at noon and the introduction of reflectors almost doubled the output power [9].

Another study conducted by Jeff Freilich and J.M. Gordon involved a whole year analysis on the operation of static solar panels, solar panels using single axis tracking and solar panels using single axis tracking with v -trough reflectors. This study emphasized the need for v-trough enhanced systems to use solar tracking to minimize dissipative power losses due to non-uniform illumination of the module cells. The effectiveness of the V-trough concentrator had a monthly average of 1.34 with minimal deviation. The v-trough enhanced system had the highest yearly energy delivery in this study [10].

A study published by IIEE in 2010 dwelt in the design optimization of fixed v-trough concentrators. Their findings stated that for highly reflective materials, the opening angle should be small to reduce the incidence angle of solar beams on the PV module, while those with low reflectivity require large opening angle [11].

A study published by Energies that compared the outputs of a conventional PV module and one that makes use of stationary v-trough reflectors. It showed that even if the two systems were uncooled, the latter produces around 50 W increase in power output or 30-50% increase in yield [12].

In a study conducted in Portugal, v-trough systems were evaluated and it was shown that the utilized technology increases the yearly energy yield of conventional modules relative to a fixed flatplate system [13]. Another study utilized v-trough reflectors under various PV module inclinations and found the output of the system to be more favorable compared to the module without the reflectors [14].

One problem arising in the use of CPVs is the presence of non-uniform illumination on the surface of the PV created by the optical device. The flux profile projected by the reflector causes hotspots. It reduces output and efficiency of the system [15].

A 1-Year, Side-by-Side Comparison of Static, 1-Axis Tracking and V-Trough Mirror-Assisted Grid-connected PV Modules in a Desert Environment showed that the V -trough enhanced tracking system received 57% more irradiance compared to the static solar panels, while those applying single-axis tracking only had an increase of 27%. However, in terms of output power, it was found that the single-axis tracking produced more than the v-trough system. This was accounted to the partial shading on the PV panels on some parts of the year [16].

For solar energy systems that make use of steady reflectors, the changing direction of sun deprives the function of reflectors. It causes unbalanced lighting and shadows on the surface of the module. Solar tracking was used in this study so that reflectors will continuously track the sun to treat non-uniform illumination.

In a study conducted in Egypt, the addition of a mirror reflector on a PV panel showed a significant increase in output power and PV efficiency. However, the increase in PV panel temperature led to a decrease in open circuit voltage, short circuit current and maximum power [17].

As the PV cell temperature rises, voltage dramatically drops and module efficiency suffers. Also, the module performance is also affected by the sun irradiance. When the sun is full, i.e. at a solar density of 1000W/m2, current is at its peak, and when there is a low level of sunlight, current and conversion efficiency decreases. The sunlight intensity and module or cell temperature vary throughout the day and the year. It results to Maximum Power Point (current and voltage) that also varies accordingly [18].

A study evaluated the effect of cell temperature to the photovoltaic parameters of monocrystalline silicon solar cells. The results showed that the increase in PV cell temperature reduces the open circuit voltage, short circuit current, fill factor and maximum output power by -0.0022/°C to -0.0025/°C, 0.002/°C, -0.0013/°C and -0.002/°C respectively[19].

The inclination angles of the reflectors to be used in this study will be dependent on the component of the sun's direction that is coplanar to the collector aperture normal which is given by the variable α. For east and west reflectors, each having equal width as the PV module, reflection law and angle properties are applied to determine their angle of inclination.

The law of reflection states that when a ray of light reflects off a surface, the angle of incidence is equal to the angle of reflection [20].The sum of the measures of the interior angles of a triangle is 180 [21]. The measure of an exterior angle of a triangle is equal to the sum of the measures of the two remote interior angles [21].

Arduino is a hardware and software microcontroller that allows circuit and objects to interact with its environment. Arduino boards are in the readily assembled structure. This microcontroller is an open-source hardware. Arduino codes, on the other hand, may be constructed using any programming language with the aid of a compiler. On the internet, Arduino community provides different applications including temperature sensors and DC motor control using Arduino [22].

The Arduino Sun Position Program is a program that takes in latitude, longitude, date and time as input and gives the position of the sun in terms of altitude and azimuth angles [23]. It makes use of an algorithm that is used by the National Renewable Energy Laboratory (NREL) in locating the position of the sun. This algorithm calculates the solar zenith and azimuth angles in the period, from the year 2000 to 6000, with uncertainties of +/- 0.0003 degrees based on the date, time, and location on Earth [24].

METHOD

Research Design

The study on v-trough reflectors using open-loop single axis tracking for a PV module employed the quantitative and experimental methods of research. It is a quantitative research since measurements were acquired from the operation of a prototype. Mathematical and computational techniques were also conducted to come up with required equations for the algorithms of the microcontroller program. Being an experimental research, the study had a control setup, or the conventional PV module; and an experimental setup, or the proposed solar harnessing equipment. The two setups were compared based on the tests that were conducted on both systems. Conclusions were drawn from observations in the actual experiments.

Research Procedure

The researchers designed both the software and hardware element of the prototype. The software is composed of the program for the automatic movement of the reflectors. The prototype hardware was constructed. It will be tested based on power output, percent increase in maximum power, program accuracy, and cost.

Construction of Prototype

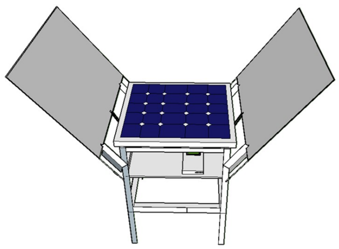

Figure 1. Conceptualized design of Prototype

Aluminium reflectors are hanged on the two sides of the PV module, West and East. The width (from the fulcrum to opposite edge) of the reflectors are determined by the desired concentration ratio (low to medium) that, in the actual case, is 0.66 m., which is equal to the width of the PV (0.54 m) plus the 0.06 m space on both sides. The reflectors' fulcrums are placed away from the PV by 0.06 m. It allows minimal errors for reflected light and also allows time intervals between reflectors' movement. The length of the reflectors (from north to south) are longer than the PV module. Offsets in length allow extra length of flux profiles during considerable north and south components of the sun. Weights on the opposite sides of the reflectors were placed in order to neutralize the weight and reduce necessary torque.

Principle of Operation

General System Operation

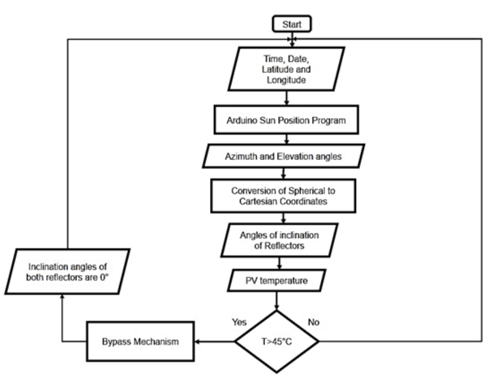

Figure 2. Reflector System General Operation

The program first determines whether the PV temperature is greater than customer-preferred temperature. If this condition is satisfied, the program will result to zero inclination angle for both reflectors. If this is not satisfied, the program will read the time and date from the DS1307 real time clock. The initial setting of time and date depends on when the equipment will be first installed or powered for operation. It also includes the longitude and latitude values of the location of Intramuros, Manila. The Gizduino microcontroller, with respect to the location indicated, will then locate the exact position of the sun using the Arduino Sun Position Program (ASPP) at a certain date and time of the day. The output of the ASPP is converted to the east and the west components for the single axis operation. The final output will be the angles of inclination of the two reflectors.

Inclination Angles of Reflectors

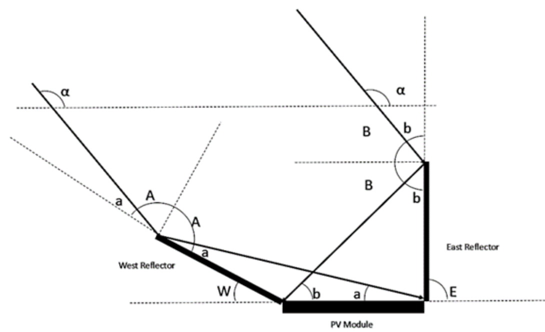

Figure 3 Diagram illustrating the angles of inclination of v-trough reflectors

The illustration in Figure 0.3 shows the inclination of the two reflectors with respect to the sun's direction α, i.e Equation (11).Angle α, as discussed in the Literature Review, is the projection of the sun angle coplanar to the aperture normal and is computed as function of the azimuth and the altitude that are given by the Arduino sun path program. By virtue of the reflection law, angle of incidence is equal to angle of reflection, which are labelled A and B for east and west respectively.

By virtue of exterior angle theorem, since reflectors width are equal to PV width, west reflector angle W and east reflector angle E can be written as

$$W = 2a \qquad \textbf{Eqn. 12}$$
$$a = W/2 \qquad \textbf{Eqn. 13}$$
$$E = 2b \qquad \textbf{Eqn. 14}$$
$$b = E/2 \qquad \textbf{Eqn. 15}$$

By inspection,

$$\alpha = E + b \qquad \textbf{Eqn. 16}$$
$$\alpha = 180 - (E + b). \qquad \textbf{Eqn. 17}$$

Substituting the previous equations west and east reflector angles are derived as:

$$E = \frac{2\alpha}{3} \qquad \textbf{Eqn. 18}$$

$$W = \frac{2(180-\alpha)}{3} \qquad \textbf{Eqn. 19}$$

High-Temperature Shutdown Mechanism

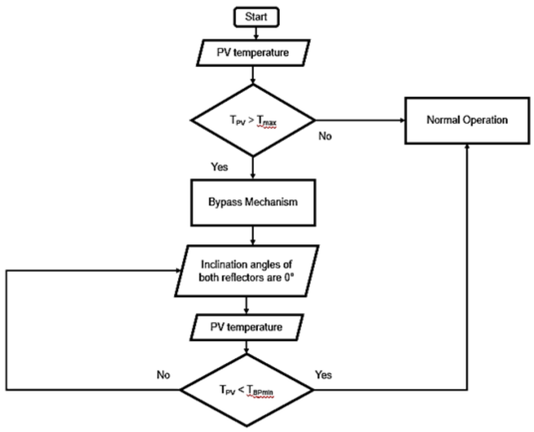

Figure 4 High-temperature Shutdown Mechanism

The figure shows how the sun path program is bypassed when the PV Module temperature is above the pre-set maximum allowable PV temperature. Using LM35 as the PV module temperature sensor, the signal after exceeding the maximum operating temperature will direct the microcontroller to turn the servo motors to zero angles, thus eliminating the extra heat transferred by the reflectors. When the system cools down, reaching the minimum operating temperature after being idle, the system will read and execute the output of the sun path program.

Testing of Prototype

Accuracy of the Angle

Reflectors were subjected to a set of random time inputs that are of the same date. The procedure was done three times [25] using the same set of time inputs. A protractor was used to measure the accuracy of the angles. The data shown by the LCD screen was compared to the actual angle of the reflectors. The absolute error for each angle was computed and the average absolute error of the angle shift of the east and west reflectors were calculated.

$$Absolute\ Error = |Actual\ Value - Expected\ Value| \qquad \textbf{Eqn. 20}$$

Power Output

A single load was used for the control and experimental setup. The maximum current, maximum voltage, and maximum power shall be observed every hour. This is based on a study that observed the output power of the PV modules per hour [26]. The data were recorded within the daily time frame. The average measured maximum power within the time frame was computed and was averaged again for five testing days. The output of the two setups shall be compared.

$$Internal\ Resistance = \left(\frac{open\ circuit\ voltage}{load\ voltage} - 1\right)(load\ resistance) \qquad \textbf{Eqn. 21}$$

$$P_{max} = \frac{\left(\frac{open\ circuit\ voltage}{2}\right)^2}{Internal\ Resistance} \qquad \textbf{Eqn. 22}$$

Paired t-test was used to determine whether the application of the automated v-trough reflectors on the PV module led to a significant increase in output power.

Functionality Test of the Temperature Sensor

The LM35 transistor was used as the temperature sensor. The program was designed to allow the user to set a maximum allowable temperature and a minimum bypass temperature. The typical operating temperature of a PV module is 45 degrees but for ease of testing, the minimum bypass and the maximum operating temperatures were set to 28°C and 30°C respectively. To test the functionality of the transistor, program was tested five times and was recorded whether the response of the bypass mechanism was a success or failure.

Cost-Benefit Analysis (Consumer Perspective)

The quantitative analysis was conducted assuming that the residential kWh rate of electric power is constant throughout the life of the equipment. The rate used was based on the latest Meralco residential rate of Php 9.2491 per kWh as of September 7, 2017. For this specific study, the time value of money was not recognized. The cost of the system implementation was calculated as follows:

$$Total\ Cost = Capital\ Cost + Operation\ Cost + Maintenance\ Cost \qquad \textbf{Eqn. 23}$$

Capital cost refers to the total cost of equipment materials. The operating cost refers to the energy consumption incurred by the electrical devices namely the Gizduino and servo motors. Maintenance cost refers to the cost of materials for cleaning the equipment.

Payback period (also known as payoff and payout period), measures the length of time required to recover the amount of initial investment. It is the time interval between time of the initial outlay and the full recovery of the investment. Since the periodic cash flows were assumed to be uniform, payback period was computed as:

$$PB\ period = \frac{Net\ Investment}{Annual\ Cash\ Returns} \qquad \textbf{Eqn. 24}$$

Accounting rate of return or simply rate of return, also known as book value rate of return, measures profitability from the conventional accounting standpoint by relating the required investment to the future annual net income. It is computed as follows:[27]

$$AAR = \frac{Average\ Annual\ Net\ Income}{Investment} \quad \textbf{Eqn. 25}$$

RESULTS AND DISCUSSION

To measure the accuracy of the device, specifically the deviation of the actuators from the program, angular measurements of reflectors were taken. This is necessary in ensuring that there is no shadowing in the PV module. As mentioned in the related literature, this phenomenon increases PV temperature and reduces the efficiency of yield. The testing of the accuracy of the inclination angles of the East and West reflectors used a fixed date as basis of the expected values of angle. The 11th of September was the date used. The time inputs were from 7:00 to 17:00, in military time. This length of time is based on the time where sunlight is significantly present during the day. Three trials were conducted to avoid biases in measurement. The average absolute error of the East reflector is 2.81829°, while the West reflector 5.41948°.

The slight variability in the measured angles may be accounted to deviations caused by the chain factor and measurement errors that are further divided into random and systematic errors. Random errors are caused by factors that randomly affect measurement of the variable across the sample such as the mood of the observer while measuring. Systematic errors, on the other hand, are caused by factors that systematically affect measurement of the variable across the sample such as instrumental errors and environmental errors[28][29].

To see the significance of adding reflectors to the yield of the PV module, the maximum power capacity was measured. From the data gathered in the testing of power output**,** open circuit voltages showed little differences between plain PV module values and those of PV with reflectors. However, the differences between the load voltages have shown significant difference highlighting the larger current capacity of the PV module with reflectors, thus higher power capacity. The values of maximum power of the experimental and control setup were plotted. The use of reflectors consistently raised the output throughout the day. The yield usually doubled and increased up to 500% during low levels of light when sun was low.

The use of reflectors has given an average maximum power of 29W which is almost twice of the plain PV module which is 15W. The plotted average percent increase at different times of the day shows high values during morning and late afternoon. The visible trend is due to small area of PV projected perpendicular to the sun's direction during low altitudes. At this time of the day, the reflector has larger area projected, which is opposite when the sun is high at noon. At noon or at high altitude of the sun, the area of PV projected perpendicular to the direction is much bigger while the area projected by the reflectors is smaller, causing smaller percent increase in yield.

A paired t-test was performed to determine if the application of v-trough reflectors using open-loop single axis solar tracking was effective in increasing the output power of a PV module. The mean increase in output ($M=13.10$, $SD=8.85$, $N=44$) was significantly greater than zero, $t=9.82$, two-tail $p=1.51E-12$, providing evidence that the reflectors are effective in increasing output. A 95% confidence level about mean increase in power is (10.41, 15.79).

Functionality of the Temperature Sensor

To test the reliability of the temperature response, a functionality test for the temperature sensing device was simulated. The test on functionality of high temperature bypass mechanism resulted to 100% functionality.

Cost-Benefit Analysis

In evaluating the marketability of the proposed design, a cost-benefit analysis was conducted. The summary of the cost of materials needed to build the prototype of this study assumed that the configuration of time, date, latitude and longitude were already set upon buying the kit. The total cost of the prototype is Php 2663.50. Since two rechargeable batteries were used to power the servomotors and microcontroller, the annual operational cost will only be equal to the yearly consumption of the electrical devices when charging. Maintenance cost is composed of all the costs of the cleaning materials needed to maintain the equipment. The benefits of the equipment were quantified in terms of the energy consumption saved by a consumer per year. The calculations show that it will take 5.83 years to retrieve all of the monetary investments on the equipment. The calculations show that 17.04% of the total investment is returned per year during the payback period of the equipment.

CONCLUSION

The reflector inclination angle has absolute errors of 2.81829° and 5.41948° for the East and West reflectors respectively. This minimal error values can be accounted to chain factor, measurement error and systematic error. Despite the minimal deviation in the angles, the v-trough reflector system yielded to a significantly high output power. The use of V-trough reflectors can significantly increase the maximum power output capacity of a PV module. The average yield of the v-trough enhanced system is twice the yield of a conventional PV module. The mechanism of the reflectors maintains large area for light reception which makes it relatively greater than that of a PV module as the altitude of the sun increases. The high temperature bypass mechanism was evaluated to be 100% functioning. The investments on the v-trough system has a payback period of 5.83 years. The return of the investment is 17.04% per year.

To achieve more accurate angles, the use of sprockets with larger diameter and more teeth is recommended. More solid rods compared to hollow rods must be used for the reflector frames. A rain sensor that will orient the reflectors in a safe condition may also be added. The behavior of the design for longer period of time may be a good subject of study. One may also identify and compare good materials for construction of the equipment, study the effects of the reflectors on the lifespan and conversion efficiency of PV modules, test the durability of design, and test the marketability of the device. The researchers also suggest to conduct a study that will enable the system to use the energy it harnesses to charge the rechargeable batteries used by the microcontroller and the motors.

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