# Performance Evaluation of Fixed and Sun Tracking Photovoltaic Systems

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# *Performance Evaluation of Fixed and Sun Tracking Photovoltaic Systems*

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***Abstract*—Tracking photovoltaic (TPV) systems have been proposed to get the maximum production during the whole day. In fact, the TPV is more efficient by varying the modules position, the production takes its maximum value when the PV panels are perpendicular to the direct radiation. This paper investigates the performance of TPV against fixed PV systems. Mainly, we analyzed the performance of two identical PV panels, one is fixed and another one follows the sun during the day. The fixed panel was positioned with a specific fixed angle of tilt while the second panel would track the sun's movement from sunrise to sunset with two axis tracking system. Simulations and experiments have been conducted and results showed that TPV is more efficient in terms of power production.**

***Keywords*-*Photovoltaic systems; Single and dual axis tracking; Performance evaluation.***

## I. INTRODUCTION

Solar energy is becoming a very important resource to generate clean electricity from renewable sources by converting sun light to electricity. However, its high cost and low efficiency, require effective and flexible methods in order to get its performance as maximum as possible (e.g., easy manipulation of irradiance and temperature) [1, 2]. In fact, the output energy of photovoltaic systems is affected by various factors like the production material (e.g., amorphous, mono and semi crystalline), and the weather conditions (e.g., irradiation, temperature), which have been considered among the most important indicators to determine the total energy generation from the sun [22].

Numerous ways are used to try to increase the amount of solar energy converted into electricity [23]. For instance, in order to keep the photovoltaic cells' temperature relatively low, cooling systems (air cooling or closed water loops) could be used to keep the photovoltaic cells' temperature relatively low, but this method is energy-hungry and requires constant maintenance. Other PV technologies, such as Multi-cell gallium arsenide, can achieve much higher efficiencies, but are extremely costly and are not designed yet for large scale systems. Solar tracking has been considered as an efficient way to generate more energy by making solar panels perpendicular to the incoming rays of the sun.

Different types of sun tracker systems can be used as depicted in Fig. 1. In term of functions, two types of sun tracker are generally used to track the sun mechanically, active and passive trackers. Passive trackers use two cylinders containing a compressible fluid in opposite sides of the tracker. The design and positioning of the cylinders is as such to allow the fluid to be vaporized and condensed in respect to the variation of the sun's position in the sky [25]. This change in the fluid's characteristics allows the panel to tilt in function of the sun's path during the day. Passive trackers are deployed without motors, and therefore, there is no energy consumption. This technology is not very reliable as the system may get stuck in the wrong orientation or simply be affected by the wind [25].

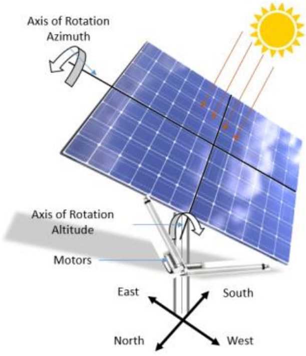



Figure 1. Dual-axis active solar tracker

Active trackers, however, use dedicated motors to change the panels' orientation. There are two main types of active trackers: *i)* Single-axis tracker, and *ii)* double axis tracker systems [24]. Moreover, single-axis trackers operate with only a single motor and one axis of movement (this movement could be horizontal or vertical). They are generally less expensive and require less maintenance as they have less moving parts. Dual-axis solar trackers are equipped with two axes of movement to have a larger range than their single-axis counterpart. They are more efficient and provide significantly more energy throughout the day. On the other hand, they become more expensive and need more frequent maintenance because of the added axis of movement.

In this work, we have designed and deployed a small double axis tracker system. In fact, we analyzed the performance of two identical PV panels, one is fixed and another one follows the sun during the day. The remainder of this paper is structured as follows. Section 2 briefly presents some related work from literature. In Section 3, an overview of PV modeling is presented. Section 4 is dedicated to the design and the prototyping of the tracking system. In Section 5, simulations and experimentation results are presented. Conclusions and perspectives are given in Section 6.

## II. RELATED WORK

Recent studies present different methods in order to maximize the PV panel's production, starting by the development of production material of the PV and by the integration of some technics, which have an effect on the output panel's energy. The maximization of PV production must take into account their behavior according to the context (e.g., temperature, irradiation…) [26, 3]. For that, a model must be put in place to model a photovoltaic cell, and consequently a PV panel array. Several works study the different numerical models used to model the functionality of the PV. For example, authors in [4] present a method for modeling and simulating of photovoltaic arrays based on the parameters of the nonlinear I–V equation and by adjusting the curve at three points: open circuit, maximum power, and short circuit. The proposed circuit model in this work is useful for power electronics designers who need to be simple, fast and accurate method for using in simulations. In [5], a new method is presented for modeling and simulation study of a photovoltaic system and its experimental validation by carrying outdoor I–V characteristic measurements. The method has been applied in the simulation of a grid connected PV system and the main parameters of the PV module are evaluated in order to maximize the power generated by the PV arrays.

On another hand, several works try to maximize the efficiency of the PV by adapting the existing type of PVs according to the weather context. For example, the efficiency can be increased by designing a solar tracker system in order to change automatically the PVs position according to the sun's movement. The work presented in [6] experimentally verifies the efficiency and electrical energy output of single axis solar tracking panel with fixed mount. The system is designed to track and follow the Sun intensity in order to get maximum power from PVs. Another interesting work is [7], where authors compare between a fixed solar system and the tracking system to underline the increase in the energy produced. The tracking system reliability is tested for diverse weather conditions. Authors in [8] designed a novel passive solar tracker using aluminum/steel bimetallic strips, their prototype allowed for gains as high as 23% in production compared to fixed solar panels. In [9], authors studied a simple two-position and three-position North-South horizontal single-axis sun tracking concepts, they found an increase of 6% to 27% for a 2-position tracker and 10% to 31% increase for a 3-position tracker. The work presented in [10] designed a single vertical axis tracker, while focusing on the problem of adjacent panels casting shadows over each other. So, they proceeded to study the 'Geometry of shadowing'. They observed that the partial shadowing between two panels is more prone to occur during the early and late hours of the day (sunrise and sunset). They then proceeded to calculate the optimal orientation of panels to maximize power generation while minimizing the said shadowing effects.

In order to determine the sun's position in the sky at any given time of the day, many methods are used, such as the use of a camera behind a shaded transparent object, a pyrheliometer, GPS data, and chronological tracking (solar equations). For example, authors in [11] have developed a novel model to estimate hourly solar irradiation on short periods of time. Their model outperformed both the linear and quadratic Angstrom-Prescott models. Also, in [12] authors are proposed an open-loop system that uses GPS information and astronomical equations to drive the tracking system. The system acquires data such as time, date, longitude and latitude to generate a database of the sun's precise position represented in azimuth and elevation angles for a whole year. The mechanical part then aligns the panel in such a way that the solar rays are perpendicular to the panel's surface. The work presented in [13] carried out a simple electro-optically controlled dual axis solar tracker using a shadow casting object on top of a white translucent plate, behind which is placed a camera that captures the shading on the plate. An image was then captured from the video stream and binaries to obtain a digital shadow representation. Then, the panel's angle was calculated to determine the panel's optimal orientation in respect to sun rays, and electrical signals were sent to the motors to rotate the panel accordingly.

In this work, a double axis tracking system is developed using a simple microcontroller (Arduino) and two motors. The system is based on the measure of the sun light using the light dependent resistors (LDRs). This tracking system is tested and valeted to be used in future works.

## III. PV CELL AND IRRADIATION MODELING

### A. PV cell modeling

In order to predict a photovoltaic panel's electrical behavior under different climatic conditions (temperature, irradiation…) and electrical operating points (no load, heavy load, open circuit…) a model must be put in place. To model a photovoltaic cell (consequently a whole PV panel or array), many numerical models exist [14]. The most used (mainly because of its high accuracy and simplicity) is the model presented in Fig. 2.

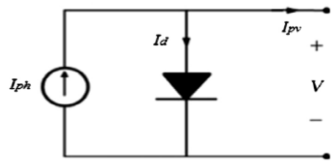



Figure 2. Equivalent circuit of a Shockley diode equation

This model uses the Shockley diode equation [20] to determine the electrical characteristics of a photovoltaic cell. From the electrical circuit above (Fig. 2), it is clear that:

$$I_{pv} = I_{ph} - I_d \quad (1)$$

where the diode current is defined by the following equation:

$$I_d = I_0 \left[ exp\left(\frac{q.V}{N_s.a.k.T}\right) - 1 \right] \quad (2)$$

$I_d$ being the diode current, $I_o$ the diode reverse bias saturation current, $q$ the charge of an electron ($1.602\times10^{-19}$ C), $k$ the Boltzmann constant ($1.38\times10^{-23}$ J. K$^{-1}$), $a$ the ideality factor of the diode, $T$ the operating temperature in kelvin, Ns the number of cells in series and $V$ the voltage of the photovoltaic panel. The photocurrent $I_{ph}$ can be computed as follows:

$$I_{ph} = [I_{sc} + K_i\ (T_{op} - T_{ref}\ )].\ \frac{G}{G_{ref}} \quad (3)$$

where $K_i$ is the short circuit temperature coefficient at $I_{scr}$ (25 C° and $G_{ref}$=1000 W/$cm^2$) and $G$ is the PV module illumination. The saturation current of the diode is computed by:

$$I_o = I_{rs}.(\frac{T_{op}}{T_{ref}})^3\ .exp[N_s(\frac{1}{T_{ref}} - \frac{1}{T_{op}}).\frac{E_g.q}{K.n}] \quad (4)$$

where $$I_{rs} = I_{sc}\ [exp(\frac{V_{OC}.q}{K.n.T_{ref}.N_s}) - 1]$$

It's worth noting that $I_{rs}$ is the reversed saturation current at $T_{op}$, where $T_{op}$ and $T_{ref}$ are the operating and the reference temperature respectively, $E_g$ is the band gap energy of the semiconductor, $V_{oc}$ is the open circuit voltage and $I_{sc}$ is the short circuit current.. The resistance at $V_{oc}$ is best proportional to the series resistance but it is larger than the parallel resistance. $R_p$ is represented by the slope at $I_{sc}$. Typically, the resistances at $I_{sc}$ and at $V_{oc}$ will be measured and noted by the manufacturer.

Finally, $I_{pv}$ can be defined by the equation:

$$I_{pv} = [I_{sc} + K_i\ (T_{op} - T_{ref}\ )].\ \frac{G}{G_{ref}} - I_o\left[exp(\frac{q.V}{N_s.a.\ k.T}) - 1\right] \quad (5)$$

If we want to incorporate the losses due to the flow of the current through the semiconductor, we can simply add two resistances and the circuit becomes:

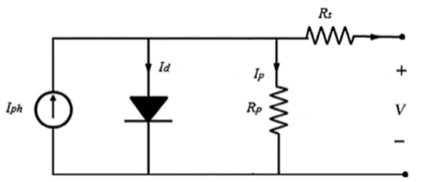



Figure 3. Equivalent circuit of a Shockley diode equation with semiconductor flow losses [20]

The output current of the PV cell becomes [15, 16]:

$$I_{pv} = [I_{sc} + K_i\ (T_{op} - T_{ref}\ )].\ \frac{G}{G_{ref}} - I_o\ [exp(\frac{q(V+I.R_s)}{N_s.a.k.T})-1 \quad (6)$$

### *B. Solar angles and the position of the sun in the sky*

The position of the sun in respect to any position on earth is given by the zenith angle (the elevation) γs and the azimuth αs. The zenith angle is the angle between the local vertical line and the line that connects the observer to the sun. The sun's azimuth is the deviation of the position of the sun from the south. The azimuth of the PV module with respect to the South is noted α, and the inclination with respect to the horizontal is noted β. Zenith and elevation depend on the local time of day t, the day of the year d and the latitude of the observer λ. The hour angle in degrees is: $h = \frac{360(t-12)}{24}$.

Each day is defined by an inclination angle, which represents the latitude of the sun. The solar declination angle in degrees is:

$$\delta = 23.44 \times sin[\,360.\,(\frac{d-80}{365.25})] \quad (7)$$

The elevation and azimuth angles are then obtained thanks to the following equations:

$$cos\gamma_s = sin\delta.sin\lambda + cos\lambda.cos\delta.\cosh \quad (8)$$

$$tan\alpha_s = \frac{sinh}{cosh.sin\lambda - cos\lambda.tan\delta} \quad (9)$$

To determine the daily solar radiation reaching a south facing surface with a tilt angle of $\beta$, authors in [17] have introduced an analytical equation that gives the total daily extra-terrestrial radiation in function of the solar declination angle $\delta$ and the sunrise-hour angle $h_{ss}$, where L being the latitude.

$$I_{daily} = \frac{24}{\pi} \times I_0\left[1 + 0.034 \times cos\left(\frac{2\pi N}{365}\right)\right] \times [cos(L-\beta) \times cos(\delta) \times sin(h_{ss}) + h_{ss} \times sin(L-\beta) \times sin(\delta)] \quad (10)$$

They also determined analytically the optimum surface tilt using the equation [17]:

$$\beta_{optimum} = L - tan^{-1}\left[\frac{h_{ss}}{sin\,h_{ss}} - tan\,\delta\right] \quad (11)$$

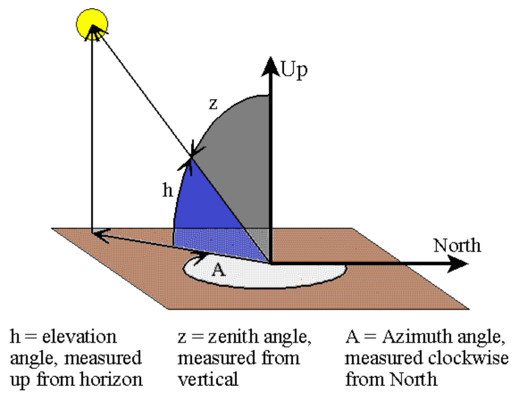



Figure 4. Diagram illustrating the different solar angles [21]

## IV. Design and Implementation of TPV

This section presents the design and the prototyping of the TPV system. It also introduces the Hw/Sw components we have developed and tested. Another component was designed and focused on the stability aspect.

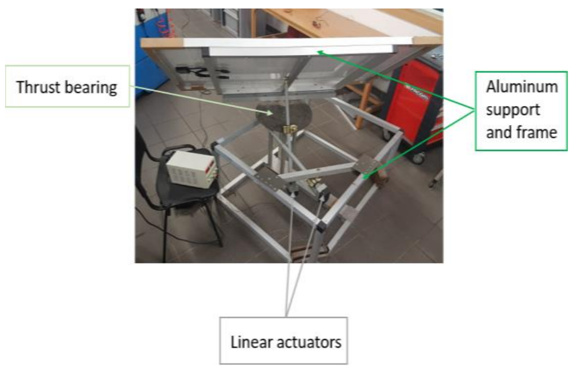



Figure 5. Mechanical prototype of the dual axis solar tracker

### *A. Design and prototyping of the tracking system*

The tracking system is made from 3 blocks: Sensors (LDRs), Command (Arduino) and Execution (Motors). The sensors are connected to the Arduino which allows to transmit the data to our IoT and big data platform [27]. To track the sun's position in the sky, we use four light dependent resistors (LDRs). These resistors are similar to normal resistors, but the difference between the two is that their resistance varies with how much photon (light) reaches them. We link each signal provided by the four LDRs to an analogic input to Arduino, and we wrote a code that always tries to keep a minimal difference between the values by changing the panel's position (by sending electrical impulse signals to the linear actuators).

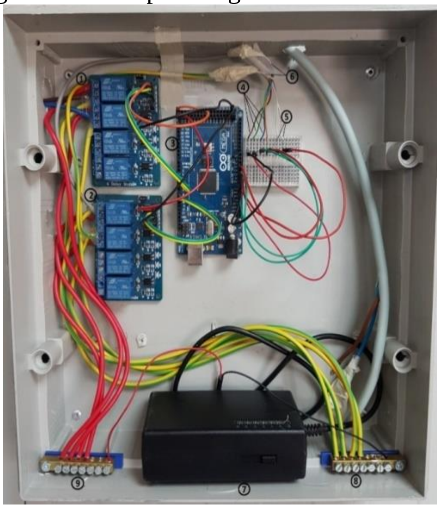


Figure 6. Wiring of the command part of the system

In order to support the panel's weight, we made a support out of aluminum tubing. We chose aluminum because of its low cost and light weight. The motors were then attached to the frame and to the panel. To assure smooth movement between the panel and the support without much friction, we mount the metal plate supporting the panel on top of a thrust bearing as depicted in Fig. 5. For the motors, two linear actuators were used to move the panel around. These motors are driven by 12V DC and their stroke length is 36 inches (91 cm).

Fig. 6 shows the Hw/Sw part we have developed and deployed to ensure the right movement of the system. Number 1 corresponds to the first relay array controlling the azimuth motor, 2 is the second relay array controlling the elevation motor,3 is an Arduino Mega, number 4 are the four analogic signals coming from the LDRs, 5 is the first motor's power supply, while 6 is the second motor's power supply,7 is a 12V-24V variable power supply, 8 is the negative terminal and 9 is the positive terminal. Both the panels' outputs are then linked to two MPPT (Maximum Power Point Tracking) controllers 75/15 (12/24V-15A). The MPPT algorithm aims to find the single point where the power is at its peak *Pmax* [19], which is no easy task, as the output voltage and current vary with external conditions like insolation and temperature variation.

### *B. Implementation of wind security mechanism*

This section focuses on implementing a security feature to make our system resistant to strong wind, to maintain stability and good operation. In order to achieve that, real-time wind speed data was fed to our command block. The wind speed threshold was set to 16 m/s [18], which means that every time the wind speed exceeds that value for a given time, the panel should go to a horizontal position right away, to decrease the contact area between the panel and the wind. We can view this from the linear actuators perspective, especially the one controlling the elevation: when the stroke's length is equal to 90 cm (maximum value), the panel is perpendicular to the ground, and when it's equal to 0 cm (minimum value) the panel is horizontal to the ground. More precisely, we distinguish two operating modes: Normal and windy. For the normal scenario, the system follows the sun by keeping the sun rays perpendicular to the panel's surface. In the windy scenario, the system still tries to maintain the sun rays perpendicular to the panel's surface, but it prioritizes switching to the position of security when there are strong winds, i.e., the wind speed exceeds the set threshold.

## V. SIMULATION AND EXPERIMENT RESULTS

This section is dedicated to simulations and experimentations we have conducted in order to compare both systems. A MATLAB program was written to simulate the behavior of the solar panel used in the experiment as well as mechanical equations for our solar tracker. This program was validated for an earlier experiment with a percent error of only 7%. The MATLAB code simulates the solar irradiance on a surface with and without a solar tracking system in function of the day of the year, location and the slope of the studied surface. It also simulates the behavior of the photovoltaic cells based on Shockley's diode equations. The diode model used is the Gow and Manning model. It takes as inputs: i) cell temperature in Celsius using the average value of the measured temperatures during the production phase, ii) the panel's slope in degrees, iii) the absence or presence of the solar tracking device, iv) the number of cells in the module, and v) the day and the month.

An experiment was carried out on May the 15th 2018 in Sala El Jadida, Morocco on a sunny day. Our aim was to collect voltage and current data multiple times each minute for the entire day for a fixed panel (31 degrees oriented south) and a panel mounted on a tracking system. Both panels are of the same kind. This allowed us to have the same irradiation profile on both panels which assured exactitude in our acquired data. Both PV panels were connected to the same load (400 W), and we let the experiment run for the day (see Fig. 7).

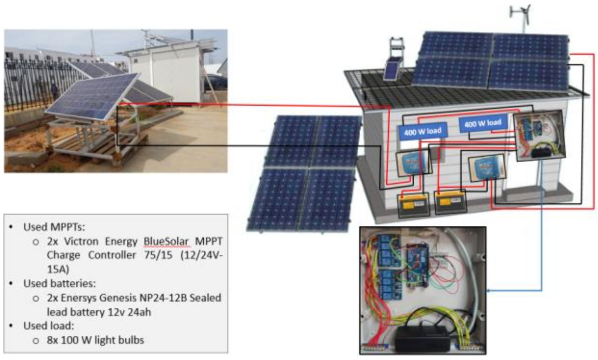
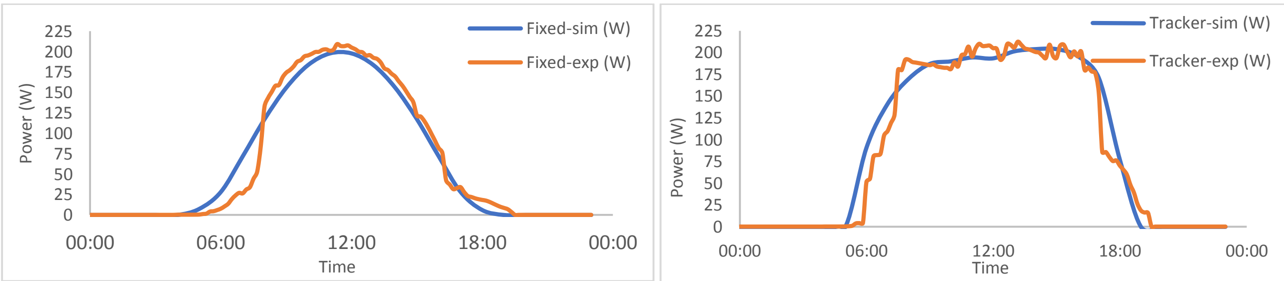



Figure 7. Overview of the experimental protocol




(a) (b)

Figure 8. Experiment and simulation data comparison for: a) fixed and b) tracked

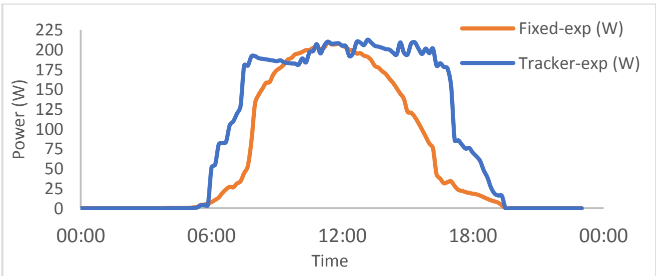



Figure 9. Experimental results for fixed and tracked systems

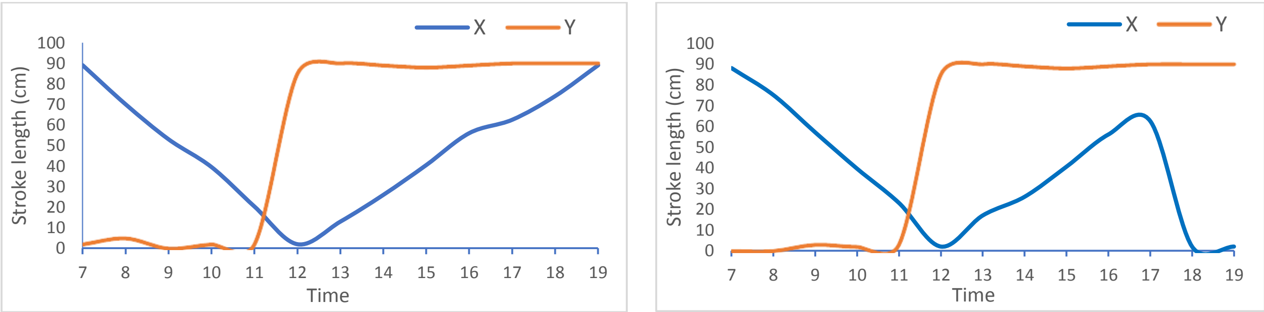
From the results depicted in Fig. 8 and Table I, we can see that the simulation shows a good approximation of the real-world scenario, with a minimal error. This is stated clearly in Fig. 9, as we can see the orange curve corresponding to the fixed panel, has a single peak around noon. Right after noon, the electricity produced starts to decline and then reaches values higher than 75 Watts at just 16h20. The blue curve corresponds to the tracked panel and shows that the production reaches values above 175 watts around 7h40 in the morning (9h20 for the fixed panel) and keeps the production around 200 watts right until 17h, while providing more than 75 watts until 18h. Table 1 shows a 31.49 % gain in the simulation scenario and 28.02 % gain in the real-world scenario.

Table I. Daily electrical power for both fixed and tracked

| | Simulation | Experiment | Error |
|---|---|---|---|
| Electric power produced -Fixed | 1521.55 W | 1545.76 W | 1.57 % |
| Electric power produced -Tracker | 2220.81 W | 2147.62 W | 3.30 % |
| Power gain (%) | 31.49 % | 28.02 % | - |

### *A. Experimental results for the Wind security mechanism*

In order to show the usefulness of the proposed Wind security mechanism, we have conducted several experiments. The main aim is to see how the actuator's stroke length varies during a normal day (wind speed < threshold). Fig. 10-a shows the elevation (blue) values decreasing from their maximum value (90 cm) at sunrise to 0 cm at noon, while the azimuth is at around 0 cm this entire time, at noon it goes quickly to 90 cm as the elevation starts increasing to reach 90 cm again at sunset. These synchronized movements allow us to track the sun's position at every instant. Fig. 10-b shows normal behavior up until 17h when winds exceeded the threshold, so the elevation values dropped to 0 cm meaning the panel went flat. From these results, we conclude that the proposed security feature works as expected. It could be further improved by increasing the data's feed intervals and by using more responsive motors to allow a faster switching to the flat position in case of stronger wind that could damage the system in little time.



(a) b)

Figure 10. Variation of the stroke's length throughout the day: a) normal day, b) windy day

## VII. CONCLUSIONS AND FUTURE WORK

This paper introduces a performance evaluation using simulations and experimentation of tracking system. Obtained results showed around 31% gain in the simulation and 28% gain in the real-world prototype. This means that by using the tracking system instead of a fixed one for 3 days, we earn about another day of power production while having the same surface occupied by the panels. It also means that we can get the same amount of power produced by 4 fixed panels by only using 3 tracked panels. This both reduces cost, losses due to heat and reflection and most importantly occupied surface. We can conclude that the developed model is reliable and could be used in our future work as a base to test the variation of other parameters for future experiments (cells temperature, fixed panel tilt and/or orientation, the tracking system precision and time of responsiveness…).

## ACKNOWLEDGMENT

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