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Realization of an educational tool dedicated to teaching the fundamental principles of photovoltaic energy

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***Abstract*— This article describes a low cost educational tool dedicated to teaching basic knowledge of solar energy and photovoltaic applications for first-year students at the poly disciplinary faculty of Larache. This experimental teaching method allows students to concretize all the achievements of the theory and the results obtained during the simulations of the PV systems on a simulation tool, so, it's an opportunity of sensitization and integration of the students in a world in full change towards a purely green system.**

The realized system is simple to use, solid, easy on the move, economical and not spacious. It offers students the opportunity to acquire the fundamentals of photovoltaic energy. Several models of practical work are developed to give an overview of the learning exercises that could be done by students to discover the multiple applications of photovoltaics. For example, many cases of study can be treated such as the electrical characterization of PV panels with different technologies, the effect of irradiation and temperature, the effect of shading, the effect the inclination and orientation of the panel and finally the calculation of the efficiency of the PV panel.

***Keywords*— Photovoltaic Pedagogical Tool (PPT), Simulation, Educational tool, characterization & PV practical work**

I. Introduction

The problematic of the use of renewable energies is very important and is regularly mentioned since their use is part of the environmental context of reducing the emission of greenhouse gases [1-2].

A second problematic is also raised by the networks of national energy agencies about global energy consumption. The latter could increase by more than one and a half times a year if no measures are put in place to reduce it [3]. In the case of Morocco, demand for electricity will increase by 68% in 2020 and by 295% in 2030 [4]. To address these issues, Morocco has put in place an ambitious energy strategy, this strategy defines several objectives to be achieved on 2030: reduce the emission of greenhouse gases, reach 52% of the energy mix from renewable sources on the horizon of 2030 [4].

The need to protect the environment, for example by limiting the use of fossil fuels, is particularly reflected in housing where solar energy is widely deployed, especially in countries with a legislative and fiscal framework [5]. Educational programs in schools, colleges and universities must necessarily adapt to this issue of energy management and environmental protection by integrating the environmental objectives set by international institutions [6]. New methods of teaching renewable energies and sustainable development must be put in place to sensitize and integrate students in a changing world towards a purely green system.

It's in this context that our work is entitled; it's the realization of a **Photovoltaic Pedagogical Tool** (**PPT**) dedicated to the teaching of the fundamental principles of photovoltaic energy. This system was realized within the physical department at the poly disciplinary faculty of Larache as part of the annual program of innovation of tools favoring the protection of the environment. The PPT system allows students of the first physical year at the faculty to have an experimental learning mode and fun to acquire the fundamental knowledge of solar energy and in particular, photovoltaic applications.

The realized tool is simple to use, solid, easy on the move, economical and not spacious. It's a measurement bench that allows students to characterize solar panels of low power, performing production comparison between different solar panels technologies, measure the effect of irradiation, temperature, irradiation incidence angle and shading on the performance of photovoltaic systems.

Since the simulation currently occupies an important place in the learning world, a model of the system is already realized on Matlab/Simulunk making it possible to make a simulation and to extract all the possible results. The objectif is to validate these simulation results in an experimental way by several exercises using our PPT system.

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In this article, the operation of the tool is explained. Many examples of practical work that can be implemented with this equipment are described. These learning exercises can be part of the university curriculum for students, technicians or researchers.

The use of this tool was evaluated by the first year students at the poly disciplinary faculty of Larache. A summary of the results of this evaluation is presented.

II. MATERIALS AND METHODS

The PPT system consists mainly of (Figure 1):

- A 20W photovoltaic panel, TDC-M20-36 model (see data sheet on Table N°1)
- Variable power projector from 0 to 1000 watts
- Graduated metal path from 0 to 50 cm allowing changing the distance between the PV panel and the light source
- Graduated mechanical system for rotating the PV panel.
- Ammeter.
- Voltmeter
- Temperature sensor
- 1 mega ohms rheostat
- Light Meter.

Fig. 1 Photovoltaic Pedagogical Tool (PPT)

TABLE I

PV PANEL TECHNICAL DATA SHEET

Specification	Value
Model Type	TDC-M20-36
Cell type	Monocrystalline
Number of Cells	36
Maximum Power(W)	20 W
Optimum Power Voltage(Vmp)	18.76 V
Optimum Operating Current(Imp)	1.07 A
Open Circuit Voltage(Voc)	22.70 V
Short Circuit Current(Isc)	1.17 A
Temperature Coefficients of Pmax:	-0.435%
Temperature Coefficients of Voc:	-0.35%
Temperature Coefficients of Isc:	0.043%
Module Efficiency (%)	12.74%

The measuring bench (Photovoltaic Pedagogical Tool) is intended for laboratory operation with all the necessary utilities regardless of external weather conditions. This system makes it possible to:

- Study of the components of a solar power generation system
- Study of PV panel characteristics
- Study of the effect of radiation intensity on the PV panel production
- Study of the temperature effect
- Take the P(V) characteristic of de PV panel to determine a MPP
- Study of the effect of shading and angle of incidence on a solar installation.
- Study of the effect of the distance between the PV panel and the light source
- Energy efficiency calculation of the PV panel

Before proceeding with the practical work, it's essential to criticize the Photovoltaic Pedagogical Tool (PPT) to the students. After a presentation by the teacher, we remind them about the standard test conditions STC (1000 Wm², 25 °C, AM=1.5) [7]. In reality, the system does not provide the necessary 1000W/m², moreover, the light spectrum is not normalized and finally the temperature is not controlled. The conclusion is quickly drawn: if this tool does not allow a normative characterization, it nevertheless makes it possible to highlight electrical characteristics as well as trends of size evolution as a function of the external parameters.

The extraction of results from the system is ensured by several practical works that we have developed and tested that we can note:

A. PV panel characterization

The first exercise proposed is to extract the main electrical characteristics of the photovoltaic panel. Students should determine the I(V) and P(V) curves by applying a fixed spot light intensity of 1000 W on the surface of the PV panel and vary the load value using a rheostat (Fig.2) . From the curves obtained, it's then possible to extract the open-circuit voltage Voc, the short-circuit current Icc and also the maximum power point MPP of the PV module.

The PPT system can collect several values of current and voltage depending on the load, this exercise can be completed by analyzing the behavior of different cell technologies (amorp, monocrystalline, polycrystalline, …) for the same level of irradiation (same projector power).

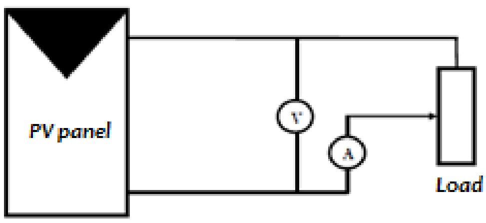

Fig. 2 Mounting to extract the PV panel characteristics

During these tests, the panel is subjected to constant amplitude illumination. However, to keep the panel at an ambient temperature, students are asked to take measurements quickly and then turn off the projector.

B. *Effect of illumination*

In this exercise, students are asked to raise the effect of the change in irradiation applied to the solar panel. To do this, two methods are possible:

Set the distance between the solar panel and the projector to 50 cm and vary the brightness intensity between 0 to 1000W.

Fix the power of the projector at 1000W and vary its distance with the solar panel between 50cm and 10cm.

In these two cases, the student is asked to draw the curve representing the evolution of the power according to the illumination power.

C. *Effect of temperature*

To observe the influence of the temperature, students leave the projector illuminating the PV panel for a long duration.

The temperature of the panel rises and then stabilizes after a few minutes. Using a temperature sensor, students detect the temperature stabilization and note its value. They then report the current-voltage and power-voltage characteristics while comparing them to the characteristics obtained before (in ambient temperature).

Finally, it's necessary to estimate the coefficient of degradation of the voltage and the power as a function of the temperature and to compare them with those given in the manufacturer's instructions (Table 1).

D. *Effect of the incidence angle of radiation*

The incidence angle is the angle formed by the ground plane and the plane of the PV panel.

For this experiment, we plan to find if the inclination of the solar panels interferes in their electricity production.

The experimental protocol requires placing the PV panel in front of a 1000 W projector and varying the angle of inclination from 0° to 90°. During this variation of the angle, the different values of the current and of the voltage produced by the PV panel are recorded and the corresponding characteristic is drawn.

E. *Shading effect*

The PV panel object of the experiment consists of 36 cells mounted in series.

To observe the influence of shading on the performance of the PV panel, students are asked to illuminate it with a fixed power of 1000W and to submit some cells to shading.

For each variation of the shading size, the students proceed to measure the output electrical quantities; current and voltage.

F. *Determination of PV panel yield*

The efficiency η of the PV module is the part of radiative energy (radiation) that it's able to transform into electrical energy.

If we consider that:

E: illuminance, measured in lux. (It will be admitted that for the projector used, an illumination of 100 lux corresponds to approximately 1 W.m ^{2})

Pm: maximum power delivered by the cell.

S: area of the photovoltaic cell (in m^2)

So, the yield of the PV panel is: η = Pm / (E x S)

In this exercise, the objective is to determine experimentally the performance of the PV panel used and to compare it to the theoretical performance given by the PV panel manufacturer's sheet.

G. *Simulation of the PV panel on Matlab/Simulink*

We modeled on Matlab/Simulink the same solar panel used in the PPT system. The objective is to prepare a simple, configurable model that allows students to carry out simulations of the PV panel in order to master on the one hand the simulation world of solar systems on Matlab/Simulink and on the other hand to make a comparison with the results obtained during the practical work done on the pedagogic tool.

The PV generator consists of several PV cells. Each solar cell is basically a p-n junction fabricated in a thin wafer of semiconductor. With exposure to sunlight, some photons having energy greater than the band gap energy of the semiconductor create electron–hole pairs [8]

The characteristic of a solar panel is given by equation (1) and (Fig. 3) [9].

$$\left[I = I_{sc} - I_0\left\{exp\left[\frac{q(V+R_S I)}{nkT_K}\right]-1\right\} - \frac{V+R_S I}{R_{sh}}\right] \qquad (1)$$

- I represents the output current of the solar panel
- V is the voltage of the solar panel.
- Rsh is the shunt resistance of the cell.
- Rs is the series resistance of the cell.
- q represents the electron charge (1.60217 x 10-19 C).
- Isc is the current generated by light;
- Io is the reverse saturation current;
- N represents a dimensionless factor;
- K represents the Boltzman constant, and Tk is the temperature in °K.

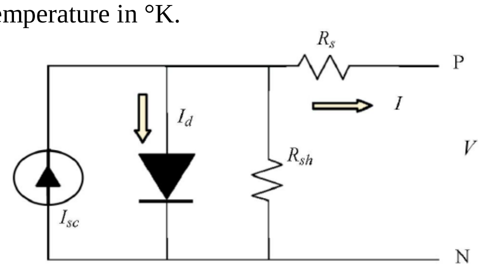

Fig. 3 Equivalent circuit of PV array

As shown in Fig 4, equation (1) has been used to extract the output characteristics of the solar cell.

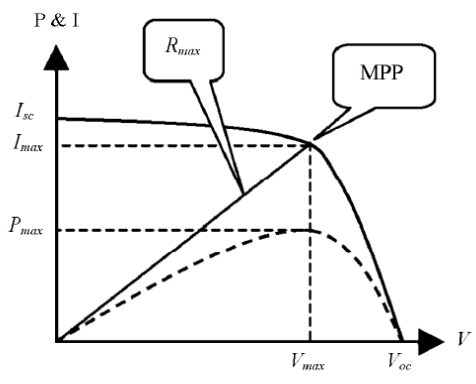

Fig. 4 Output characteristics of a solar cell

This curve clearly shows that the characteristic operating point of the said generator is strongly linked to the temperature variations, the solar irradiation and the load. Each feature has a point with maximum power and the PV generator works perfectly.

Thanks to the mathematical model of the solar cell, we have developed a simple model of the PV panel with two variables which are the irradiation intensity and the temperature and two outputs which are the current and the voltage of the PV module (Fig. 5). Students are asked to do the various tests that are possible, varying the irradiation and the temperature in order to extract the characteristics of the PV panel.

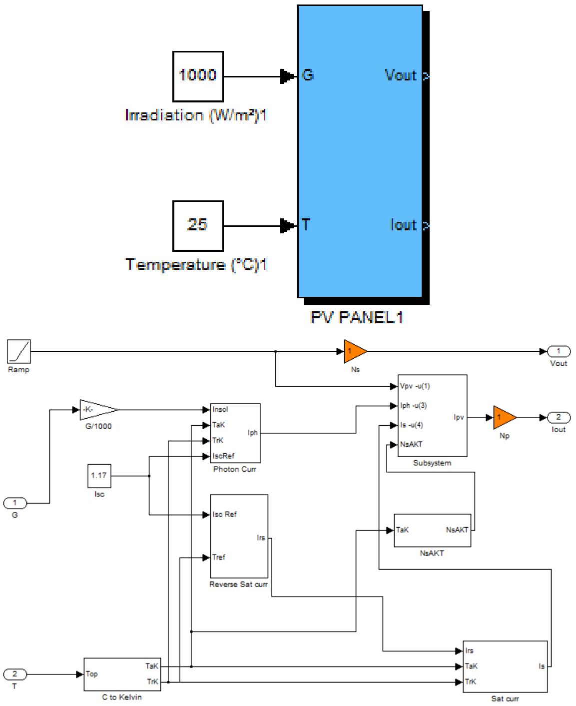

Fig. 5 Simulink Model of PV generator

III. RESULTS AND DISCUSSION

The different results are classified in two categories, firstly the simulation of the block developed and secondly the results obtained following the various practical work.

A. Simulation of the PV panel on Matlab/Simulink

At constant temperature and illumination, and particularly at Standard Test Conditions (E=1000 W/m², T = 25 °C). The characteristics of the PV panel are given in Figure 6.

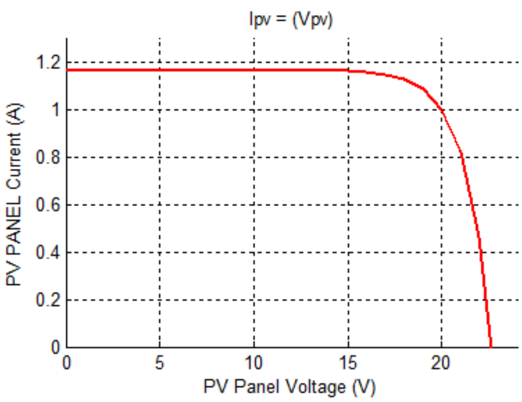

Fig. 6-a I(V) characteristic PV Panel

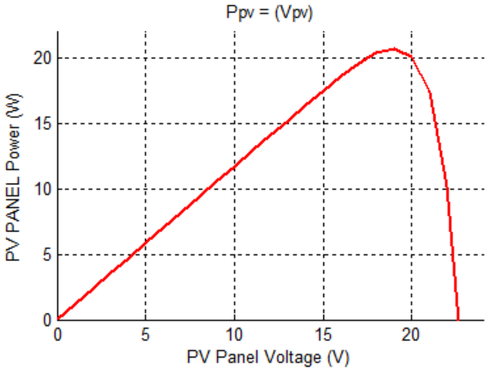

Fig. 6-b P(V) characteristic PV Panel

The characteristics of the PV panel obtained show clearly a strong correlation between the simulation results on Matlab and the technical data sheet of the manufacturer of the TDC-M20-36 PV panel (Table 1).

Fixed temperature at 25 °C and varying the irradiation between 200 W/m² and 1000 W/m², the characteristics I=f(V) and P=f(V) are given respectively by the figures 7 and 8.

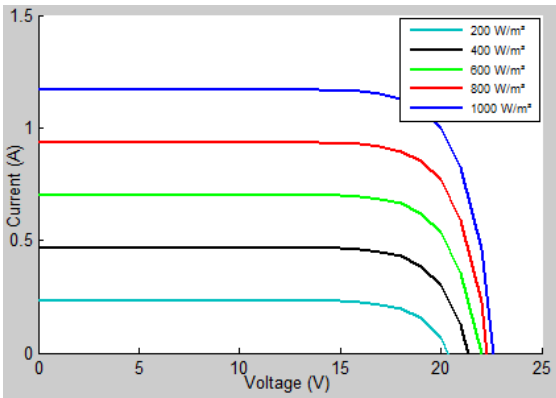

Fig. 7 Influence of irradiation on the I(V) characteristic at 25°C

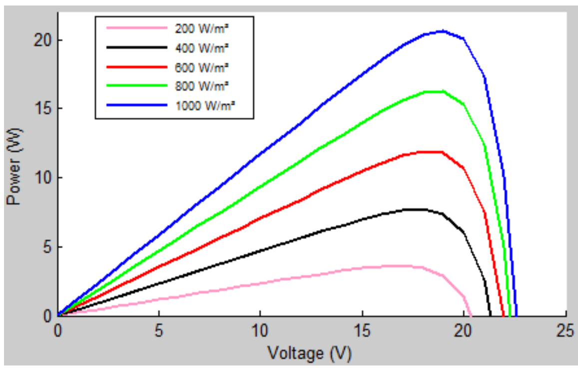

Fig. 8 Influence of irradiation on the P(V) characteristic at 25°C

According to the simulation results of the PV panel (figure 7 and 8), we note that:

- The value of the short-circuit current is directly proportional to the radiation intensity. By against, the open circuit voltage does not vary in the same proportion, it remains almost identical even at low illumination.
- The PV Generator is heavily influenced by the variation of irradiation, the power varies in proportion to radiation and maximum power point is moving according to the sunshine intensity.

fixing irradiation at 1000W/m² and varying the temperature between 16°C and 28°C, the characteristics I=f(V) and P=f(V) are given respectively by the figures 9 and 10.

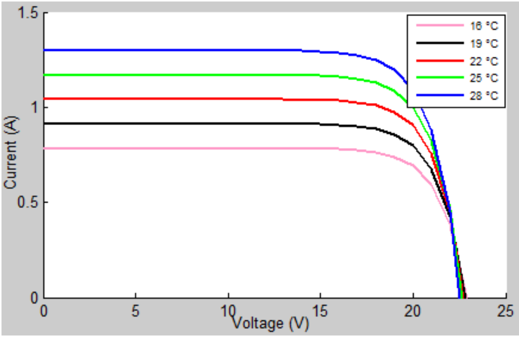

Fig. 9 Influence of temperature on the I(V) characteristic at 1000W/m²

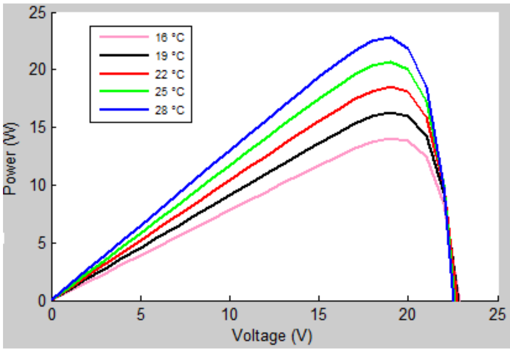

Fig. 10 Influence of temperature on the P(V) characteristic at 1000W/m²

Temperature also affects the characteristic of the PV panel; we note that at given irradiation:

- The open circuit voltage decreases with temperature; more high temperatures, plus the voltage is low.
- The short-circuit current Icc increases with temperature, this increase is significantly less than the voltage drop. The influence of temperature on Icc is very often neglected.
- The power of the Generator increases slightly with decreasing temperature.

B. PV panel characterization:

In order to characterize our PV panel constituting the PPT system, we have taken the corresponding current and voltage values for each load value (Table 2). Then, we plotted the necessary characteristics namely I(V) and P(V) (Figures 11 and 12).

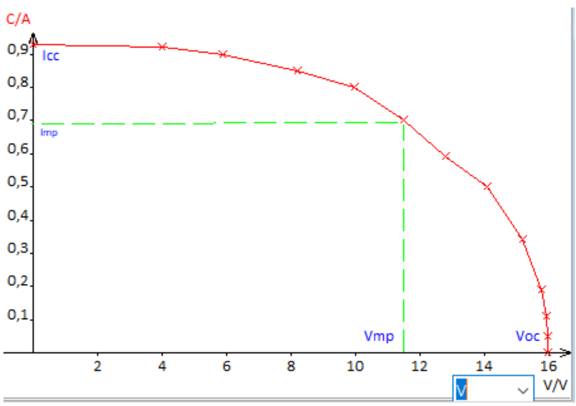

Fig. 11 I=f(V) PV Panel characteristics

TABLE II

ELECTRICAL VALUES FOR EACH LOAD VALUE

Current (A)	**Voltage (V)**	**Power (W)**
0	15,96	0
0,05	15,96	0,798
0,11	15,94	1,753
0,19	15,78	2,998
0,34	15,18	5,161
0,5	14,1	7,05
0,59	12,8	7,552
0,7	11,5	8,05
0,8	9,98	7,984
0,85	8,2	6,97
0,9	5,9	5,31
0,92	4	3,68
0,93	0	0
0,93	2	1,86

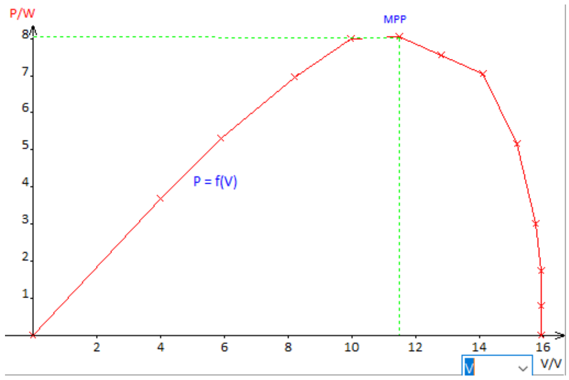

Fig. 12 P=f(V) PV Panel characteristics

We can draw three physical quantities of the two curves

- The open circuit voltage Voc: 15.96 V
- Short circuit current Icc: 0.93 A
- The maximum power point MPP: 8.05 W
- The current whose power is maximum Imp: 0.7A
- The voltage whose power and maximum Vmp: 11.5 V

After comparing the characteristic obtained experimentally with the manufacturer's data sheet, we notice that there is a strong correlation between the two, so, we notice that the lighting power of the projector does not allow to reach the nominal power of the PV panel. On the other hand, the values obtained are small compared to the manufacturer's values, these results are very normal, as we did our test in a laboratory whose conditions are different from the Standard Test Conditions to testing PV panels.

C. Effect of illumination

In order to determine the effect of the intensity of irradiation on the PV panel we used two different avlues of projector powers, 1000W and 700W. The results obtained are given in the graph at figure 13.

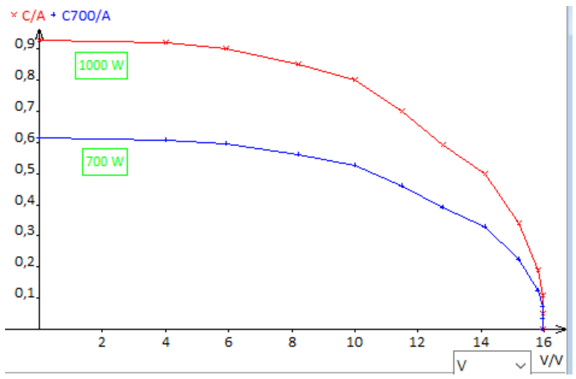

Fig. 13 effect of irradiation on the I(V) characteristic

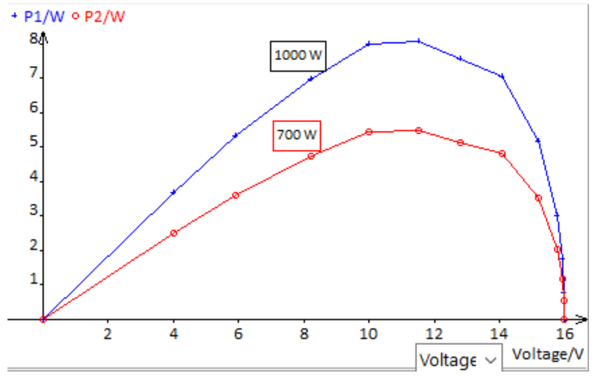

Fig. 14 effect of irradiation on the P(V) characteristic

Figures 13 and 14 shows the superposition of current-voltage and power-voltage characteristics as a function of illumination. The power reduction and the shift of the maximum power point according to the illumination are observed.

D. *Effect of temperature*

Table 3 presents the values of current, voltage and power at three different temperatures and fixed irradiation at 1000W. We very easily notice the decrease in energy production when the temperature increases.

TABLE III

TEMPERATURE EFFECT ON THE PV PANEL

Temperature °C	Current (A)	Voltage (V)	Power (W)
23	0.65	11.57	7.52
25	0,7	11,5	8,05
27	0.78	11,44	8.92

The experiment results are in agreement with the theoretical study and the simulation results. When the PV panel temperature increases, the open circuit voltage decreases substantially while the short circuit current increases slightly.

So, in reality we can notice that PV cells have better performance in a cold environment with clear sky, unlike a warm environment.

E. *Effect of the incidence angle of radiation*

The experimental results of current and voltage obtained during the variation of the PV panel incidence angle of irradiation are grouped together in Table 4.

Note: This test is performed under optimal value of load that gives the maximum power.

Using these results, we have been able to trace the characteristic that models the variation of the power produced according to the variation of the inclination of the PV panel (figure 15).

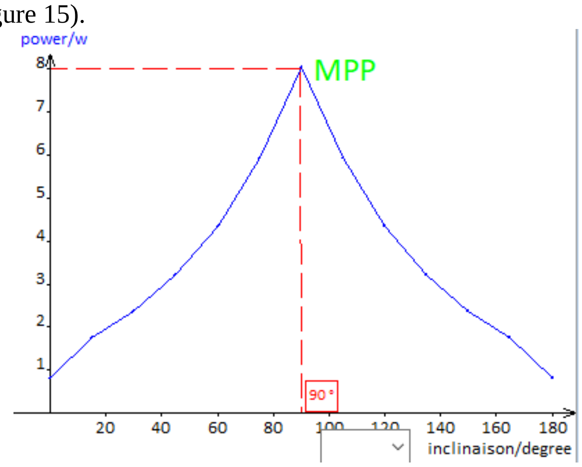

Fig. 15 effet de l'inclinaison du panneau PV sur sa production énergétique

Thanks to our experience, we have shown that the photovoltaic cells efficiency is optimal when the plane of the cells is perpendicular to the rays of the light source (The sun). Therefore, when we want to size and install a system a PV system, it's necessary to take into account the season and location of the installation.

The inclination of the solar panels therefore seems to be an essential factor in the performance of a system based on PV modules.

F. *Shading effect*

We subjected the PV panel to several masks of different sizes, after that, we collected the electrical quantities mentioned in Table 5, finally we plotted the corresponding curve (figure 16).

TABLE V:

SHADING EFFECT ON THE PV PANEL

Number of shaded cells	Voltage (V)	Current (A)	Power (W)
0	11,50	0,70	8,05
6	9,58	0,58	5,59
12	7,67	0,47	3,58
18	5,75	0,35	2,01
24	3,83	0,23	0,89
36	0,00	0,00	0,00

TABLEAU IV

EFFECT OF THE INCIDENCE ANGLE OF RADIATION

Angle °	**180**	**165**	**150**	**135**	**120**	**105**	**90**	**75**	**60**	**45**	**30**	**15**	**0**
Voltage (V)	5,12	6,79	7,55	8,38	9,32	10,35	11,50	10,35	9,32	8,38	7,55	6,79	5,12
Current (A)	0,16	0,26	0,31	0,38	0,47	0,57	0,70	0,57	0,47	0,38	0,31	0,26	0,16
Power (W)	0,82	1,74	2,37	3,21	4,36	5,93	8,05	5,93	4,36	3,21	2,37	1,74	0,82

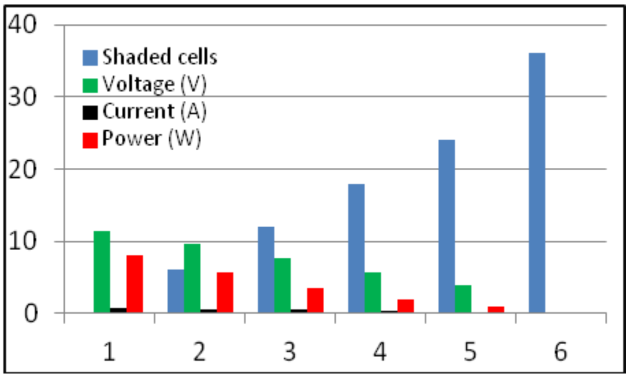

Fig. 16 Shading effect on the PV panel

It is very remarkable that shading on photovoltaic cells causes a loss of production. This loss of production varies with the size and density of the obstacle.

The interest of this exercise is not only to understand the influence of partial shading on the production of solar system, but also to be able to optimize the positioning of the photovoltaic system in order to overcome this problem.

G. Determination of PV panel yield

For the projector power of 1000W that we used (which has no relation with 1000 w/m²) The maximum power of the TDC-20 panel at Pmax=8.05W was determined experimentally during the characterization exercise.

The calculated yield of the PV panel under test is 6.54%. This yield is low and lower than 12.74%, yield announced by the manufacturer of TDC-20 Panel (Table 1).

This result is justified by the fact that the ideal yield is obtained under standard test conditions, in the laboratory of the faculty it's impossible to ensure these conditions, thus, 1000W of the projector used does not correspond at 1000W/m², however, the principle is the same and the results show that the trend of variation of the output quantities of the PV panel following external parameters is verified.

IV. RETURN OF EXPERIENCE

First-year students at the poly disciplinary faculty of Larache (40 students) interviewed following the practical work sessions realized with the Photovoltaic Pedagogical Tool (PPT), dedicated to teaching of basic knowledge of solar energy and performing the exercises described in this article.

Each student completed a questionnaire at the end of the learning exercises. The purpose of this questionnaire is to give a score of overall satisfaction of the Photovoltaic Pedagogical Tool and its usefulness in training. Four questions were asked and scored on a scale of "1" to "4". The marks "1" and "4" respectively represent the minimum and maximum marks obtained for each question. Table 6 summarizes the results. The PPT won an overall satisfaction percentage of **83.59%.**

V. CONCLUSION

This article describes the Photovoltaic Pedagogical Tool (PPT) made at a lower cost within on the poly disciplinary faculty of Larache and dedicated to the teaching of basic knowledge of solar energy and photovoltaic applications for students in the first year of physics.

This tool has many applications. Several examples of practical work are described: the characterization of photovoltaic panels, effect of the variation of solar irradiation and the temperature on the characteristic of the PV generator, effects of environmental constraints on the energy production of the PV panel (the shading for example), the effect of the incidence angle of the light and also the simulation of the PV panel used in the PPT system using the Matlab/Simulink environment.

Educational models dedicated to teaching the basics of solar energy are marketed, the Physics department at the poly disciplinary faculty of Larache has designed their own model but at a lower cost. Using this tool, students participate in a method of interactive and didactic learning.

Overall, the students expressed a great satisfaction during the practical work sessions realized with this tool. They particularly appreciate the concrete observation of theoretical notions seen in class and the overall interest of the system.

Subsequently, it's planned to develop the PPT system so that it can be able to perform other functions namely: MPPT, AC conversion, interconnection to the power grid.

TABLE VI

RETURN OF EXPERIENCE OF THE PPT SYSTEM

Question	1 « Not at all»	2 « good »	3 « very good »	4 « excellent »	Average	Results
Is the PPT useful in teaching the fundamentals of photovoltaic applications?	5,00%	7,50%	37,50%	50,00%	3,33	83,13%
Do you feel that you have gained more knowledge of solar applications?	2,50%	12,50%	32,50%	52,50%	3,35	83,75%
Evaluate the usability of the PPT	0,00%	10,00%	37,50%	50,00%	3,33	83,13%
Evaluate the interest of the PPT	5,00%	7,50%	32,50%	55,00%	3,38	84,38%
Overall satisfaction					**3,34375**	**83,59%**

REFERENCES

[1] M. A. Saidel, T. M. Reis, Jr F. A. A. Prado, "Carbon Credits and Energy Efficiency", International Journal of Green Energy, Vol. 6, Issue 3 (2009), pp. 312-322.

[2] G. D. Bolt, M. Kleingeld, J. F. van Rensburg, "Carbon tax: Future models and impact", Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy, 2011, pp. 152-158 .

[3] D. Singh, N. K. Sharma, Y. R. Sood, R. K. Jarial, "Global status of renewable energy and market: Future prospectus and target", Proceedings of International Conference on Sustainable Energy and Intelligent Systems, 2011, pp. 171-176 .

[4] Masen : Mroccan Agency for solar energy, 9th edition of the National Science Week « Renewable Energies & Sustainable Development » - 2011

[5] H. M. Hwang, J. B. Park, J. H. Rho, J. H. So, H. E. Song, G. J. Yu, "Comparative analysis of system economics for the Korean and German photovoltaic support program", Proceedings of IEEE Photovoltaic Specialists Conference, 2011, pp. 3254-3259.

[6] A. Filipkowski, "Introducing future engineers to sus-tainable ecology problems: a case study", European Journal of Engineering Education, Vol. 36, Issue 6 (2011), pp. 537-546.

[7] Standard Test Conditions [total irradiance = 1000 Wm-2, device temperature = 25 °C, reference spectral irradiance for air mass = 1.5 as defi ned by IEC 60904-3

[8] Ting-Chung Yu, Yi-Ting Shen, “Analysis and Simulation of Maximum power point tracking for photovoltaic systems,” Proceedings of the 30th ROC Symposium on Electrical Power Engineering, Taoyuan, Taiwan, pp. 92-96, Nov. 28 29, 2009.

[9] Anurag, A., Bal, S. & Sourav, S. (2014). A Comparative Study of Mathematical Modeling of Photovoltaic Array. International Journal of Emerging Electric Power Systems, 15(4), pp. 313-326. Retrieved 29 Aug. 2017, from doi:10.1515/ijeeps-2013-0115