Mobile laboratory for FVM analysis

Laboratorio móvil para análisis de MFV

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DOI: 10.35429/P.2023.1.46.60

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Á. Marroquín, L. Castillo, J. Olivares and A. Álvarez (AA. VV.). Young Researchers. Engineering Applications -Proceedings-©ECORFAN-México, Queretaro, 2023.

Abstract

Due to its geographical location, different regions are rich in solar energy, which favors the use of solar panels, however, the installation is a process that involves taking different factors into account, and it is a recurring topic of study. In this project, a mobile unit was built for the transport of photovoltaic modules (MFV) and to study in a practical way the factors that affect their efficiency. The preliminary design of the mobile laboratory was carried out taking into account the measurements of a 410 W JaSolar module, from this consideration the pertinent calculations were made to size the laboratory, then the measurements obtained were scaled and a prototype was elaborated through a model to detail the necessary mechanisms and materials. Then proceeded with the construction of the laboratory based on the preliminary design and the prototype. Finally, the functionality of the mobile unit was verified by determining the efficiency of the 410 W JaSolar module at different inclination angles, on different floors, shading vertically and horizontally, and with ventilation cooling. It was concluded that the laboratory is practical and meets the desired characteristics.

Transport, Analysis, Photovoltaic module

5.1 Introduction

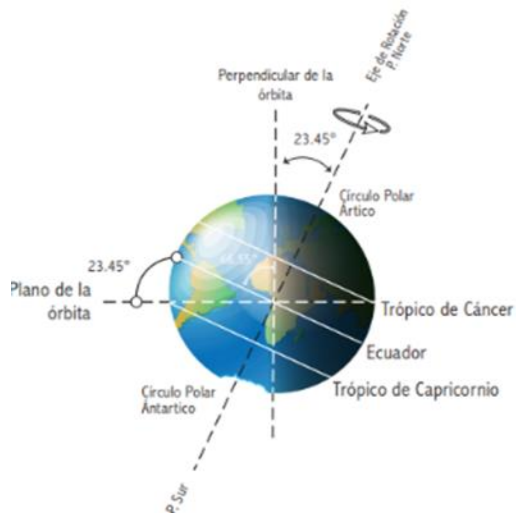
In recent years, population growth has caused energy demand to increase worldwide, the main source that satisfies this demand has been through the use of fossil fuels, which have a significant impact on the generation of greenhouse gases that damage the environment, this has led the world to set its sights on renewable energies, which is why in the last decade there has been a considerable increase in the use of these energies, as they generate less pollution and help reduce the use of fossil fuels. Urban environments, due to their high demand for energy consumption, are considered one of the most promising places for the installation of renewable technologies. Among the different types of technologies available, solar panels are the most promising in urban areas in order to meet the needs of the residential and commercial sector (Sukhatme and Nayak, 2009, p.71-108).

To understand how a photovoltaic cell works, it is essential to have a clear understanding of the concept of "radiation", defined as the energy emitted by the sun, which propagates in the form of electromagnetic waves through space in multiple directions. This energy originates from a series of nuclear fusion reactions that occur in the sun. Different types of radiation are differentiated by their wavelengths; ultraviolet rays, infrared rays, and visible rays (Duffie and Beckman, 1991, p. 747).

One of the ways to harness it is by converting solar radiation into electrical energy by means of the photoelectric effect, with the help of semiconductors. Photovoltaic devices are semiconductors that convert part of the incident solar radiation into direct current electrical energy (Goswami and Kreith, 2000, p.1-80).

The power generation of a solar cell is mainly affected by the variation in incident solar radiation and cell temperature (Tsai, Tu, and Su, 2008). This means that a PV cell works thanks to the presence of solar radiation with the minimum solar radiation they receive to start working. Figure 5.1 shows the earth's declination.

Figure 5.1 Earth's declination



Source: Goswami and Kreith, 2000

Not only radiation is fundamental, as it varies according to geographical location, but the theory of the apparent motion of the sun adds to these factors. To understand the apparent motion of the Sun, the actual motion of the Earth around the Sun and on its own axis must be taken into account. The nearly circular (it is slightly elliptical with the Sun at one of its foci) rotation of the Earth around the Sun takes place in a year in a plane called the ecliptic, and the rotation about its axis causes it to make one complete revolution every 24 hours. The Earth's axis is tilted 23.45° with respect to the ecliptic (see figure 1.1). Because of the tilt of the Earth's axis, the sun's rays strike the Earth's surface perpendicularly at a different point each day of the year. The cooper equation for declination (degrees) where "n" is the day of the year is equation 1.

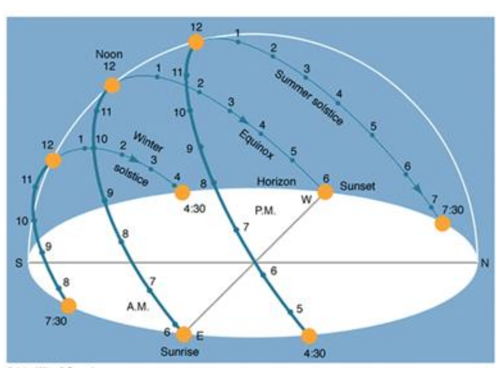
$$\delta = 23.45 * sen\ (360\frac{284+n}{365}) \quad (1)$$

In addition to the above, there are angles that affect its functionality. The solar hour angle is the angular displacement of the sun in the apparent orbit (ecliptic) east or west of the local meridian, the morning is negative and the afternoon is positive, the solar hour angle is equal to zero at solar noon and varies by 15° per hour from solar noon, for example, at 7 a.m. (solar time) the hour angle is equal to -75°. m. (solar time) the hour angle is equal to -75°. The sunset hour angle (ωs) is the solar hour angle corresponding to the time when the sun sets; it is given by the following equation:

$$Cos\ (\omega s) = -Tan\ \psi\ Tan\ \delta \quad (2)$$

Where (δ) is the declination, calculated through equation 1 and ψ is the latitude of the site, specified by the user. The orientation of the solar collector is described by its tilt angle β and the "azimuthal" azimuth (γ), both related to the horizontal and considered optimal when facing south (γ=0°) in the northern hemisphere. The optimum tilt angle depends on latitude λ, solar declination, or days of the year (J. Duffie and W. Beckman, 1991, p. 747), this is shown in Figure 5.1.

Figure 5.2 Apparent Motion of the Sun



Source of reference: Sukhatme and Nayak, 2009

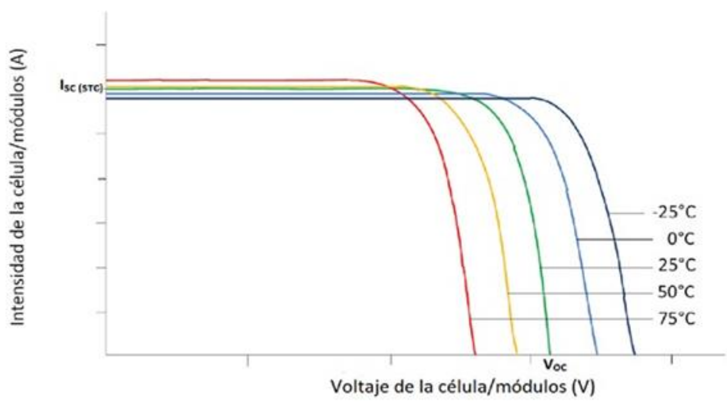
It was investigated that the daily solar energy collected was 19 % to 24 % higher with a solar PV panel, with a single-axis east-west tracking system than with a fixed system (Salmi et al, 2012). However, since solar tracking systems have high operating and maintenance costs and are not always applicable, it is often desirable to set the solar collector to a fixed value of an optimal tilt angle the standard recommended angle is ±10°.

If you live in the northern hemisphere, you would point your panels to the south. If you live in the southern hemisphere, your panels should point north. Most homeowners with solar power systems mount their panels in a fixed position, where the panels can be manually tilted as needed (Tsai, Tu, and Su, 2008).

A. Factors affecting the performance of solar panels.

In the last decade, research has been carried out to identify the factors that affect the performance of photovoltaic panels in order to mitigate their effects and achieve significant improvements in terms of efficiency for this type of system (see Fig. 5.2).

Figure 5.3 Temperature Vs open circuit voltage graph



Source: Algarín, 2011

Among the factors that interfere with the optimal performance of solar panels is temperature, which plays a key role in the energy conversion process in these systems. Both the electrical performance and the power output of the module depend linearly on the operating temperature of the panel. Solar panels absorb on average 80% of the solar irradiation received. However, a part of this irradiance is converted into electricity and the remaining is converted into heat (Cepeda, 2017). The ideal operating temperature of a solar panel is often around 25°C (Algarín, 2011).

For solar panel installation, the tilt angle of the PVM is an important consideration that will have variations between regions, as this can benefit or affect the efficiency and energy yield of the entire system. The tilt angle of the panel affects the solar radiation reaching the surface of the cells. When the panel is positioned perpendicular to the sun, it receives the maximum radiation for a time interval, which is considered the optimum tilt angle. This angle is affected by factors such as latitude, solar radiation characteristics, period of use, shading effect and the distribution of sunny days representing climatic conditions (Cepeda, 2017).

The shading effect is caused when the light hitting the panel surface is obstructed causing voltage and current mismatches in the system. This is mainly due to shadow formations produced by elements close to the panels such as trees, structures or external agents that prevent sunlight from reaching evenly over the panel surface. A solar panel that is under the effects of shading collects energy unevenly, which leads to fluctuations in the delivered power causing damage to the PV system components such as the inverter or batteries (Cepeda, 2017). Figure 5.3 shows the shading effect caused by tree branches.

Figure 5.4 Shading effect

Source of reference: Sukhatme and Nayak, 2009

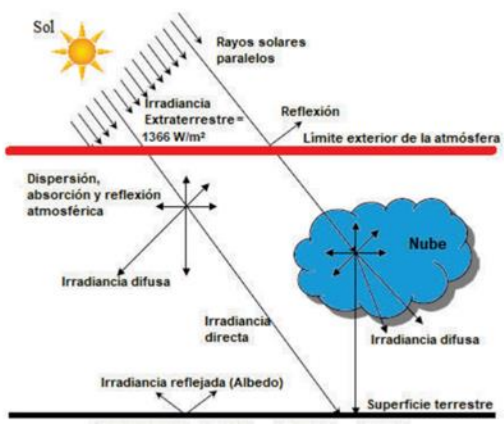
Solar irradiance is an important monitoring parameter, used to evaluate the efficiency and performance of photovoltaic systems mainly, just as the operating temperature affects the performance of a panel, the irradiance to which the solar cells of a panel are exposed affects the efficiency of the system. Among the types of irradiance are (Cushicóndor, 2019):

- Direct irradiance: direct irradiance is the component of global irradiance, which is incident on a surface and comes directly from the sun, with no change in direction (Cushicóndor, 2019).

- Diffuse irradiance: It is the one that impacts on the earth's surface indirectly, since it goes through the atmosphere and clouds, which causes it to disperse, diffuse irradiance represents 15% of the global irradiance on sunny days and on cloudy days this percentage increases considerably (Cushicóndor, 2019).

- Reflected irradiance: This is the irradiance reflected by the earth's surface, and depends on the reflection coefficient of each surface or ground where the panels are installed. It is also known as albedo [10] (see figure 5.4 types of solar irradiance).

Figure 5.5 Types of solar irradiance



Source: Cushicóndor, 2019

The inclination and orientation will be factors that will directly influence the way in which the panel receives light and consequently its optimal performance. Table 1.1 shows the standard values for the recommended tilt for module installation. This will depend on the translational movement of the planet, since it will not always be the same orientation throughout the year due to seasonal changes, this is done in order to maintain a good energy production. In the specific case, Mexico is located in the northern hemisphere, therefore, the solar panels should be oriented towards the south (Tarifasdeluz, 2022).

- Solar panels in winter: At this time of the year, the sun is lower and its radiation has a more horizontal incidence. To make the most of this solar orientation, the angle of inclination of the solar panels is raised between 10° and 15° with respect to that calculated with the latitude, so that the solar panels are in a position close to total verticality (Tarifasdeluz, 2022).

- Solar panels in summer: In this season of the year, the sun is high and the radiation is vertical most of the day. To capture the most energy in this solar orientation, the tilt angle is reduced by 10° to 15° degrees to obtain a tilt close to total horizontality (Tarifasdeluz, 2022).

Table 5.1 Standard for angles

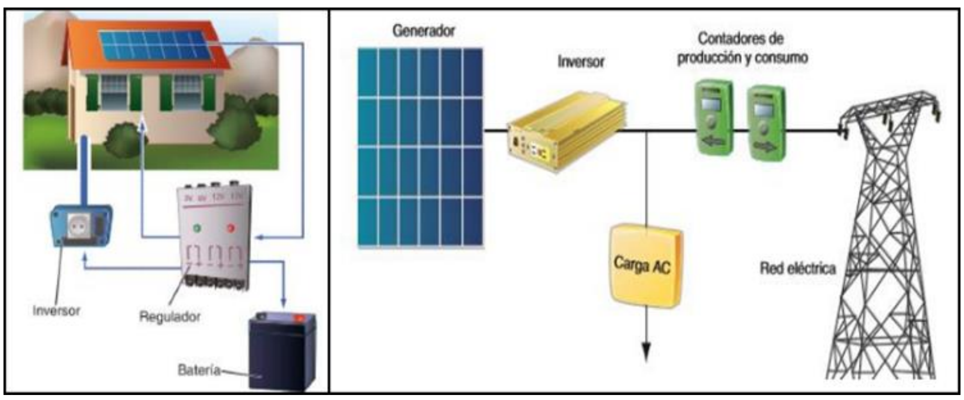
Latitude of location	Fixed angle of inclination
0° to 15°	15°
15° to 25°	Same latitude
25° to 30°	Latitude + 5°
30° to 35°	Latitude + 10°
25° to 40°	Latitude +15°
40° or more	Latitude +20°

Source: Arbona, 2022

B. Principle of photovoltaic operation.

A photovoltaic system is the set of electrical and electronic equipment that produces electrical energy from solar radiation through the photoelectric effect, which is the effect of generating electric current when the semiconductor materials of a solar cell are illuminated, causing the generation of pairs of electrons. Photovoltaic systems can be stand-alone systems and grid-connected systems. Autonomous systems by means of a solar panel produce energy, to be subsequently stored in batteries to be available at any time (Cepeda, 2017). This is shown in Figure 5.6.

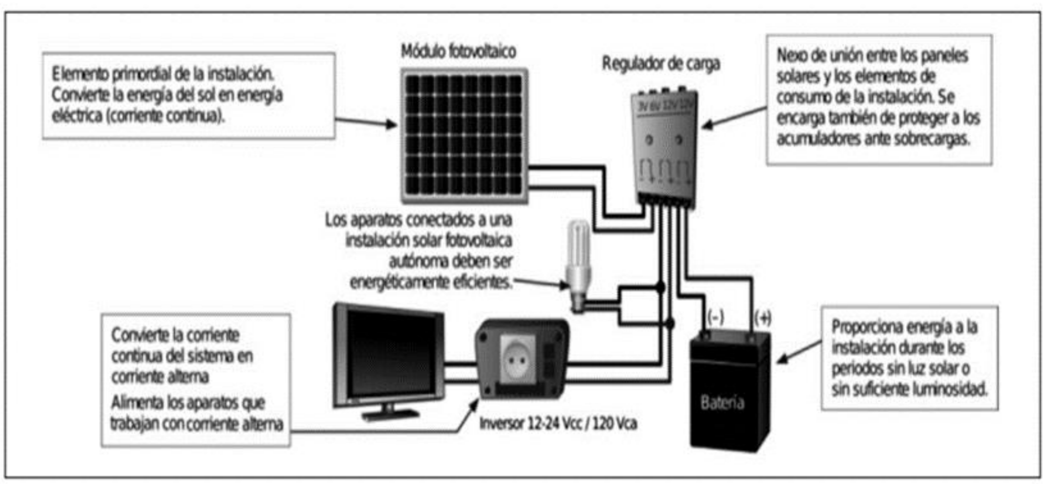
Figure 5.6 Stand-alone installation, grid-connected installation



Source: Cepeda, 2017

Solar cells or solar cells can be considered commercially as the smallest commercially available element to transform the sun's radiation into electricity. The combination of solar cells with similar characteristics allows increasing both the voltage and the current generated and make up what is known as a solar photovoltaic module or panel (Ortiz, 2013), (see Figure 5.7).

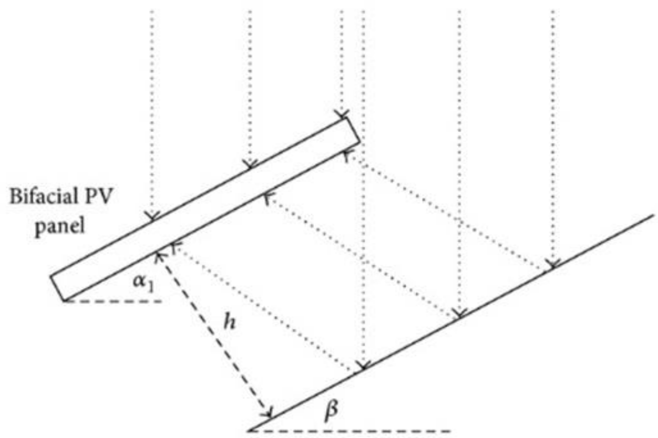
Figure 5.7 Diagram of a solar photovoltaic system



Source: Ortiz, 2013

On the other hand, bifacial modules are those with two layers of photovoltaic cells, generally with PERC technology. The cell located on the upper or front face has the objective of capturing direct solar irradiation, while the cell located on the lower or rear face takes advantage of the diffuse radiation reflected on the surface on which the modules are located. In addition, bifacial technology also seeks to use high-performance photovoltaic cells in order to maximize the flow of electrons. The great advantage of bifacial cells is the increase in module efficiency by up to 25% and even up to 30%. One of the most relevant factors of bifacial technology and that makes the big difference compared to single-facial modules is the albedo. This is defined as the percentage of incident sunlight -mainly diffuse radiation- reflected by a surface and determines in turn the amount of reflected radiation on the ground available to be used by the lower face of the panel (Martín, 2022). Figure 5.8. shows the use of light thanks to its two faces.

Figure 5.8 Bifacial panels



Source: Martín, 2022

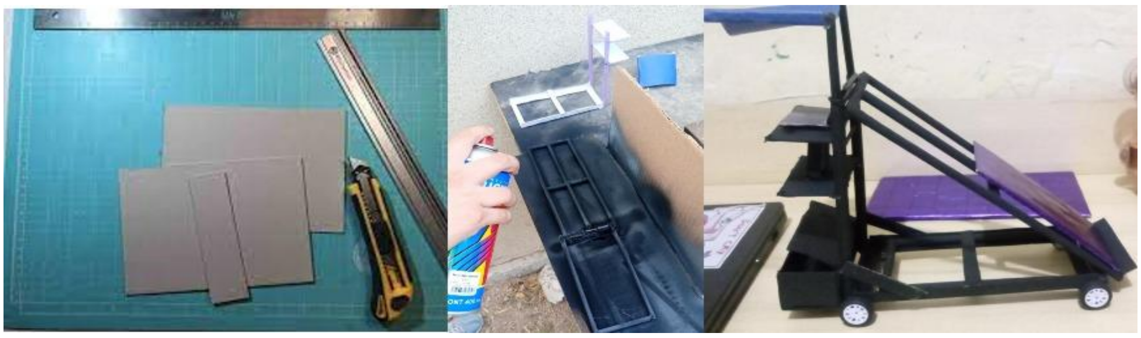
The design and construction of this mobile laboratory arises from the need of students to analyze and work with photovoltaic modules, the main objective is to build a structure that facilitates the study of photovoltaic modules, to optimize the transport of the PVMs, and the investigation of the phenomena that affect the operation of a panel, as well as the variables that occur in the environment. Specifically, the aim is to design an ergonomic and comfortable system for the user who will carry out the study with PVMs, through the elaboration of a previous design using 2D drawing programs (AutoCAD), as well as a scale prototype. It is intended to build the mobile unit taking into account the durability and strength of the materials, as well as the ability to handle the module safely. As well as to evaluate the practicality of the mobile laboratory through the study of the efficiency of a module by performing various tests.

This paper deals with the design and construction of a mobile structure for the transport and analysis of photovoltaic modules, as well as the experimentation with it. The first chapter introduces the important topics and concepts for the understanding of the work, while the second chapter indicates the materials and procedures used to design and build both a prototype and the final structure, as well as the costs involved and the experimentation techniques used. On the other hand, Chapter 5.3 discusses the results obtained from the different measurements made with the use of the mobile laboratory, where inferences are made about the factors that affect the performance of a solar module. Finally, Chapter 5.4 contains the conclusions regarding the operation of the mobile laboratory and the evaluated performance of the photovoltaic module.

5.2 Methodology

The development of the laboratory began with the creation of a model using different materials such as cardboard, sticks, fabric and straws, when the pieces were already with their respective measures, they were cut out, the model was painted and then joined to give it the details that would be the incorporation of tires, shelves, shade and a drawer, this is shown in figure 5.9.

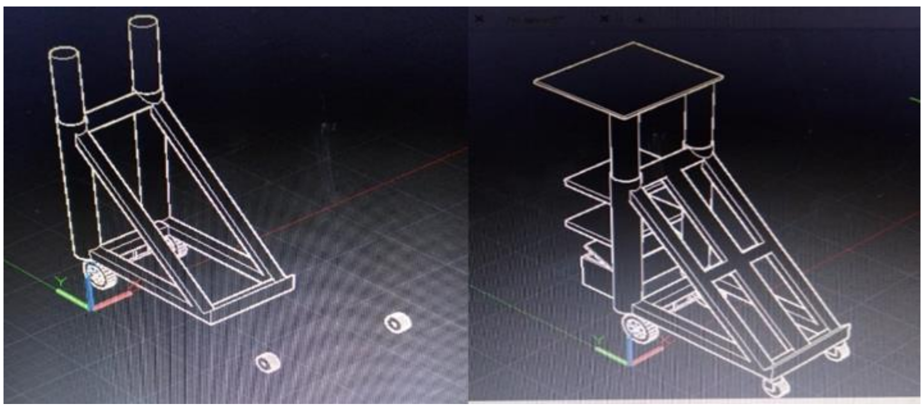
Figure 5.9 Elaboration of mockup



Source: Own elaboration

In addition, the virtual design of the 3D prototype was elaborated in the AutoCAD program of what would be the laboratory as shown in Figure 5.9.

Figure 5.10 Digitized prototype



Source: Own elaboration

Once the design was finalized, the materials were quoted and compared and the construction of the laboratory began. Table 5.2 lists the materials used for the constructed laboratory, as well as the quantities required in each case. During construction the tools used were a flexometer, a magnetic square, mechanical clamps, iron presses, a hammer, a torpedo level, polisher (4" cutting and grinding discs), drill, inverter, 60/13-3/32 electrodes and wire brush. The safety equipment used for handling the tool included an electronic mask, leather gloves, a boot with a dielectric sole, a work coat, gloves and safety goggles.

Table 5.2 Material for the construction of the mobile laboratory

Material	Quantity used	Size
Sill	6 m	2” (1/4)
Angle	6 m	2” (1/8)
Quadrangular PTR	15 m	1 ¼” (14)
Circular conduit pipe	1.6 m	1’’
Circular conduit pipe	1.4 m	1 ¼”
Rod	1.1 m	½’’
Rotating rims	2	6”
Wagon wheel rims	2	8’’
Carousel rims	8	1’’
Brackets	4	20 cm
Shelves	2	(35x75) cm^2
Butterfly clamps	2	¾’’
Bicycle horns	1	45 cm
Gray enamel	1	1 L
Red enamel	1	¼ L
Car sunshade	1	One size fits all

Source: Own elaboration

We began by measuring the sections of PTR, sill, angle, and circular tube that would serve both for the structure of the project and for the base where the panels would be reloaded. Once the pieces were measured and cut, they were welded together.

Figure 5.11 Taking of measurements and welding

Source: Own elaboration

To achieve a better result, the corners of the structure were polished, removing the imperfections generated by the welding and then, in the lower part of the base, two pieces of angle of 35 cm each were added, which would function as the support for the drawer, and then the pieces were joined together.

Figure 5.12 Joining the pieces

Source: Own elaboration

With the shade in place and most of the structure ready, it was painted to later add details such as shelves, drawer, tires, the angles were measured from 10° to 45° and handles were added to facilitate the transport of the laboratory.

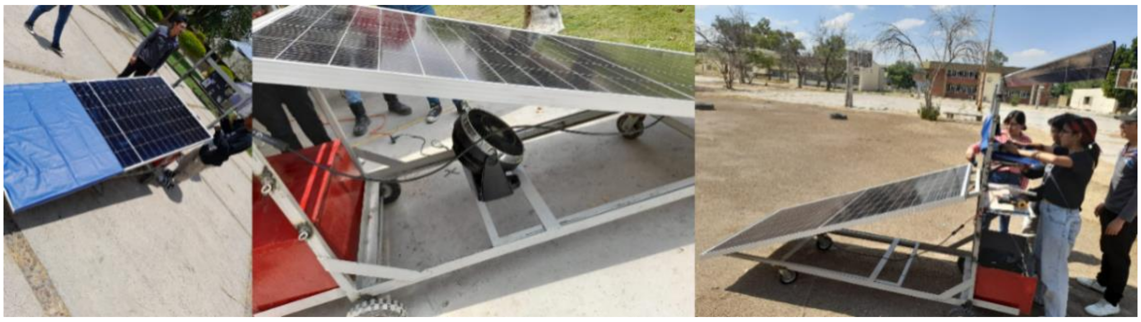
Figure 5.13 Finished structure

Source: Own elaboration

Finally, with the structure assembled and working, several tests were carried out in which different factors such as panel ventilation, shading, angles and soils were varied in order to demonstrate the effectiveness of the panel for the transport and analysis of the VFM as shown in Figure 5.13 For these tests the equipment required was a hand-held pyranometer, infrared thermometer, solar panel multimeter, a fan, anemometer and the JAM72S10 410/MR 410 W solar panel.

The first case analyzed was to determine the partial shading effect of the module by using a tarp to shade the panel cells horizontally and then shading it vertically. In the second analysis, the albedo effect was determined by using 4 different shades of flooring around the module, transporting it to different areas of the institute. The efficiency of the module was also determined by positioning it at each tilt angle available in the laboratory. And finally, the performance of the module was analyzed with and without cooling using a fan.

Figure 5.14 Laboratory tests



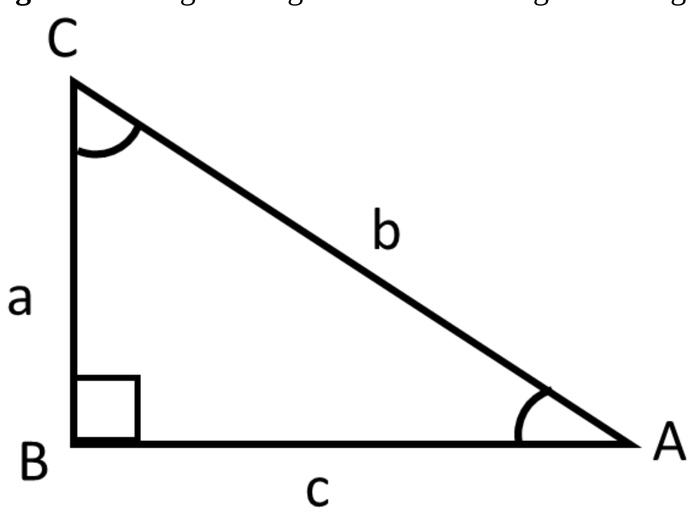
Source: Own elaboration

5.3 Results and discussion

To define the dimensions of the laboratory, it is necessary to take into account that the structure is intended to carry a 2.1m x 1m VFM surface. In addition, the height of the structure is defined considering that the panel will be adjusted from 10 to 45°.

Based on the above considerations, the variables are defined, and calculations are performed using the following trigonometric identities. Figure 5.15 shows a right triangle representing the silhouette of the mobile laboratory, where the hypotenuse (b) represents the length required to vertically lay the module and A is the angle of inclination to be given to the module.

Figure 5.14 Right triangle with defined angles and legs.



$$sen = \frac{co}{h},\ co = a, \quad h = b \tag{3}$$

$$cos = \frac{ca}{h}, \quad ca = c, \quad h = b \tag{4}$$

$$tan = \frac{co}{ca}, \quad co = a, \quad ca = c \tag{5}$$

The height and length required for the structure when having an angle of inclination of 45° is calculated below, where ∢A=45°, b=2.1m, co = height and ca = length.

$$sen\theta = \frac{\mathrm{a}}{\mathrm{b}} \therefore a = sen\theta * \mathrm{b} \tag{6}$$

$$co = sen\ (45°) * 2 = 1.48m \quad (7)$$

$$cos\theta = \frac{c}{b} \therefore c = cos\theta * b \quad (8)$$

$$ca = \cos(45°) * 2.1m = 1.48m \quad (9)$$

To find the distance to lengthen the base of the structure now the calculations are performed with the minimum angle of inclination to which the module will reach, i.e. 10°, where ∢A=10°, b=2.1m, co = height and ca = length.

$$sen\theta = \frac{a}{b} \therefore a = sen\theta * b \quad (10)$$

$$co = sen\ (10°) * 2.1m = 0.36m \quad (11)$$

$$cos\theta = \frac{c}{b} \therefore c = cos\theta * b \quad (12)$$

$$ca = \cos(45°) * 2 = 2.06m \quad (13)$$

We have that the length of the base extends from 1.48 m to 2.06 m, therefore, the minimum length of the span protruding from the base to reach 2.06m is,

$$1.06 - 1.48 = 0.58\ m$$

The graduation that the laboratory will have to adjust the angle of inclination of the module will go from 10° to 45° in intervals of 5°. Table 5.1 shows the data of the height to be marked on the structure according to the desired angle.

Table 5.1 Gradation of the structure.

Angle (°)	Height (m)
45	1.48
40	1.35
35	1.20
30	1.05
25	0.89
20	0.72
15	0.54
10	0.36

Source: Own elaboration

Once the dimensions of the laboratory have been obtained, the costs of the materials necessary for its construction are shown in Table 5.1.

Table 5.2 Materials and costs for the construction of the laboratory

Material	Length	Caliber	Cost
Sill	6 m	2” (1/4)	$547.72
Angle	6 m	2” (1/8)	$532.90
Quadrangular PTR	15 m	1 ¼” (14)	$988.68
Rims	-	-	$1900.00
Paint	-	-	$240.00
Total			$4609.3

Source: Own elaboration

C. Experimentation using the portable laboratory

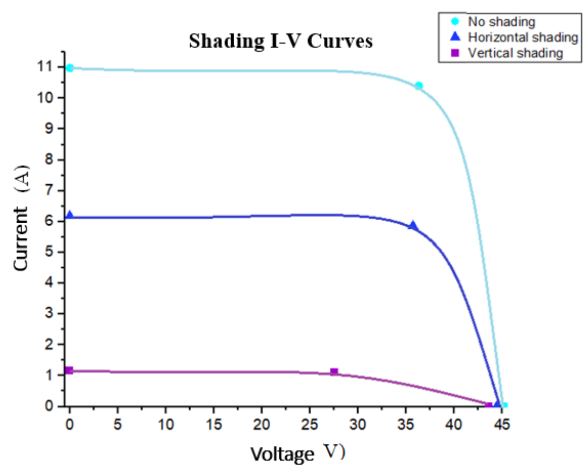
To test the feasibility of using the portable laboratory, the 410W JaSolar module was subjected to different tests. Table 5.3 shows the data obtained from the first form of experimentation, where the electrical parameters of the module were measured by directly receiving the irradiance, partially shading it horizontally and partially shading it vertically. Figure 5.16 shows the I-V curves generated according to each situation, while Figure 5.17 shows the efficiencies obtained in each case.

Table 3.3 Electrical parameters of the shaded panel

Parameters	Horizontal shading	Vertical shading	No shading
Voc [V]	44.4	43.6	45.3
Isc [A]	6.18	1.16	10.98
Pmax [W]	209	30.2	378
Vmp [V]	35.7	27.5	36.3
Imp [A] Imp [A	5.86	1.10	10.4
Efficiency [%] Efficiency [%] Incident radiation [W/m2	8.65	1.24	15.60
Incident radiation [W/m2] Incident radiation [W/m2	1208	1217.2	1211.2
Cell temperature [°C] Cell temperature [°C	43.8	48.3	45.6
Ambient temperature [°C]	24	24	24

Source: Own elaboration

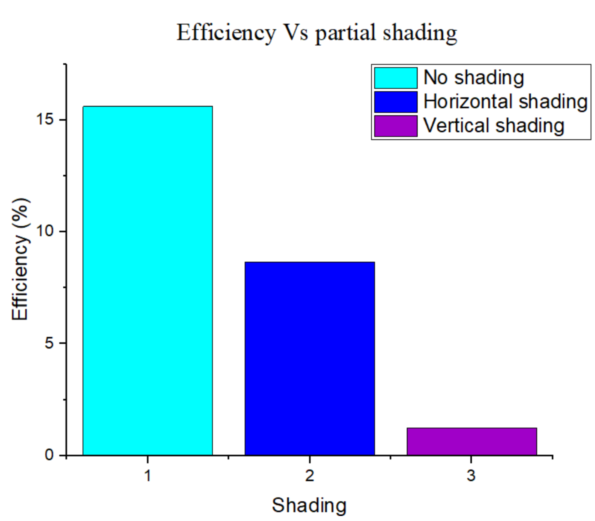
Figure 5.15 Comparison between the shaded I-V curves and the real curve



Source: Own elaboration in OriginLab

Fig. 5.15 Comparison between the shading I-V curves and the real curve.

Figure 5.16 Efficiency of the module affected by partial shading



Source: Own elaboration in OriginLab

The behavior of the shading curves with respect to the behavior of the curve without shading is notorious. The effect of vertical shading affects in a greater way the maximum power obtained since the interconnection of the cells is more affected in this way, where the continuity of the connection of several rows of cells is intervened, while the horizontal shading affects only a part of the interconnection of the cells. Also, it can be seen that the module efficiency decreases greatly with the two types of shading, being reduced by up to 1.24% in the case of vertical shading and by 8.65% in the case of horizontal shading. For this reason, photovoltaic installations should be located in areas free of objects that could cause these efficiency drops.

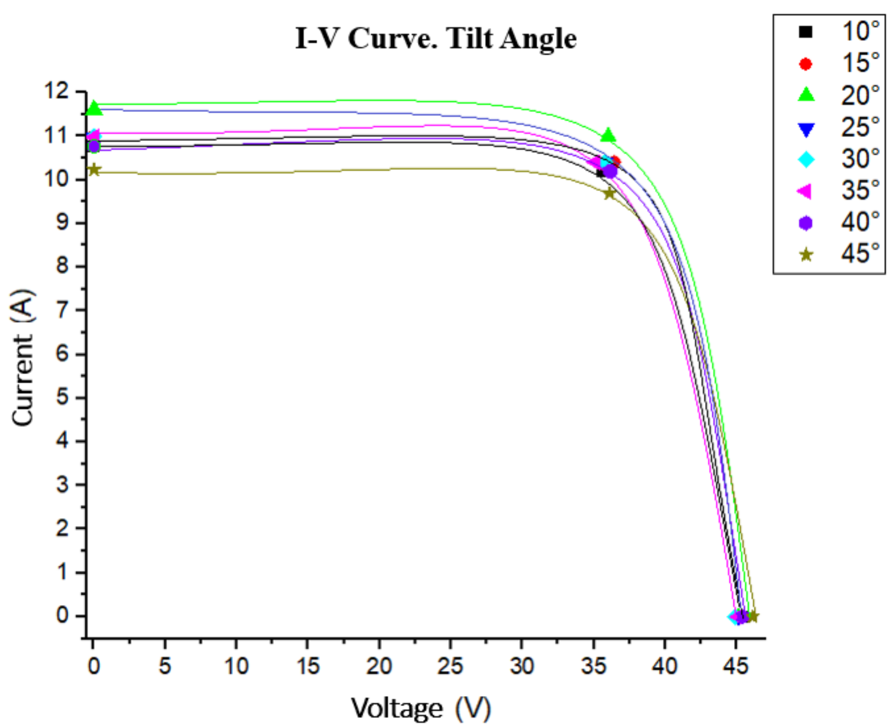
Table 3.4 lists the electrical parameters of the module at different tilt angles. For this test, the portable laboratory was used to simulate the installation of the module from 10 to 45° tilt, orienting the module to the south. Figure 3.4 shows the I-V curves obtained from the measurement at each angle at which the module was placed, which varied by 5° between each measurement. The efficiency of the module with respect to each inclination is shown in Figure 3.5.

Table 5.4 Electrical parameters of the panel installed at different inclinations

Parameters	10°	15°	20°	25°	30°	35°	40°	45°
Voc [V]	45.5	45.4	45.1	45.1	44.9	45.1	45.4	46.1
Isc [A]	10.77	10.98	11.61	10.98	10.98	10.98	10.77	10.23
Pmax [W]	382	380	390	375	373	367	370	349
Vmp [V]	35.6	36.4	35.2	36	35.8	35.1	36.1	36.1
Imp [A] Imp [A	10.2	10.4	11	10.4	10.4	10.4	10.2	9.69
Efficiency [%]	14.53	14.75	15.08	15.31	15.31	15.34	15.21	14.12
Irradiance [W/m^2]	1317.6	1288	1292.7	1224	1217.6	1195.8	1215.6	1235
Cell temperature [°C]	45.1	43.6	48.1	51.4	51.2	47.4	45.8	42.5
Ambient temperature [°C	24	24	24	24	24	24	24	24

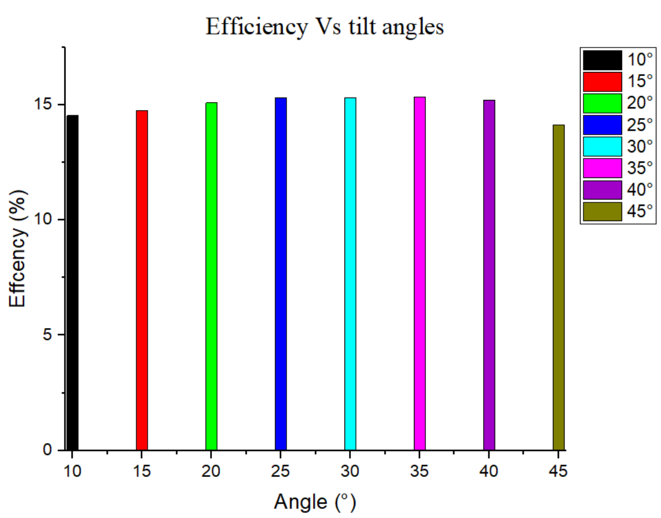
Source: Own elaboration

Figure 5.17 I-V curves generated by the module at different tilt angles



Source: Own elaboration in OriginLab

Figure 5.18 Efficiency of the module affected by different tilt angles



Source: Own elaboration in OriginLab

As ventilation is applied to the module, the cell temperature decreases and the open circuit voltage increases or is maintained even though the irradiance decreases. In Figure 3.9, it is shown that the module becomes more efficient using cooling. The relationship between cell temperature and open circuit voltage is inversely proportional, the lower the cell temperature the higher the voltage and vice versa.

5.4 Conclusions

In conclusion, the laboratory meets the desired characteristics, facilitates the transport of the module safely, as well as work tools since the laboratory has a tool drawer, in terms of mobility has two types of tires, the laboratory also has a removable shade, tool drawer has a dimension of (64x41x30)(cm^3) 3and is recessed, rear tires that are fixed and the front tires that are swivel tires to take it towards the desired direction and removable shade that can overhang up to 50 cm high.

The lab also helps make measurements much more efficient speaking of the time in which they can be made, the mobile lab has a tilt from 10º to 45º degrees with 5º degree intervals, this was graduated in this way to facilitate tilt adjustment.

It was observed that shading significantly affects peak power and module efficiency, with vertical shading being the most detrimental. The optimum tilt angle for the module was determined to be between 25° and 35°, while surfaces with higher albedo coefficient, such as green grass and gray pavement, resulted in higher efficiency. It was also shown that cooling by means of a fan increases the efficiency of the module.

These results demonstrate the importance of considering factors such as shading, tilt, and environmental conditions when designing and installing photovoltaic systems, in order to maximize energy generation and optimize performance.

5.5 References

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