Revista Iberoamericana de las Ciencias Biológicas y Agropecuarias
Ciba
ISSN: 2007 - 9990

Comparativa de la eficiencia entre un sistema fotovoltaico con seguimiento solar y un sistema fotovoltaico fijo

Comparison between a photovoltaic solar tracker efficiency and a fixed photovoltaic system

Comparação da eficiência entre um sistema fotovoltaico com rastreamento solar e um sistema fotovoltaico fixo

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Resumen

Para generar de forma eficiente energía eléctrica utilizando paneles fotovoltaicos es indispensable que estos sean instalados de forma correcta. Para ello, se pueden implementar sistemas de control de posicionamiento (seguidor solar) mediante un algoritmo de búsqueda del punto máximo de energía, lo cual sirve para mejorar la eficiencia del sistema. Por tal motivo, en el presente trabajo se analiza el diseño y la construcción de un sistema fotovoltaico con seguimiento solar de dos ejes. El objetivo es determinar la eficiencia de este sistema frente a uno estático. El seguidor solar construido cuenta con celdas independientes que actúan como sensores y alimentan a los motores encargados de girar el panel fotovoltaico tanto en el eje vertical como en el horizontal. Para la adquisición de la energía generada por los dos sistemas de paneles solares se utilizó la tarjeta Arduino Nano 3.0 y diversos módulos. Los resultados de las pruebas realizadas se examinaron mediante el programa computacional SigmaPlot y la comparativa de grupos (ANOVA) de una vía. Asimismo, se realizó una prueba de rangos múltiples, que emplea el método de comparación múltiple de medias de Tukey. Luego se confrontaron los datos recabados durante un periodo de 29 días. Los resultados demostraron que en ese lapso la eficiencia promedio alcanzada por el sistema con seguimiento solar fue de 33 %, mientras que con el sistema fijo fue de 26.28 %. Además, se observó que, durante las primeras horas de cada día, el sistema fotovoltaico fijo logró generar más energía eléctrica que el sistema fotovoltaico con seguimiento solar.

Palabras clave: eficiencia, potencia, seguidor solar, sistema fijo, sistema fotovoltaico.

Abstract

The optimal installation of photovoltaic panels plays an important role for the efficient generation of electrical energy. To find the maximum energy point of a photovoltaic panel, the positioning control system (solar tracker) can be implemented by means of a technique or a search algorithm to improve the generation system efficiency. In the present work the design and construction of two shafted photovoltaic solar tracker system was addressed. The aim is to determine the efficiency of this system and compare with a fixed or static photovoltaic system. The solar tracker has independent cells that act as sensors and feed the DC motors responsible of turning the photovoltaic panel in both the vertical and the horizontal axis. For the acquisition of the power generated by each solar panel, an Arduino Nano 3.0 card and different modules were used, as well as the environment itself Arduino programming was also utilized. The results were examined through the SigmaPlot computer program. These results were analyzed by comparing groups (ANOVA) in one way, followed by a multiple range test, which uses Tukey's multiple measures comparison method. Field tests were conducted for a period of 29 days, and the results of both systems were compared. The results showed that, the average efficiency reached by the system with solar tracking during the experimental period, was 33%, while the fixed system achieved an average efficiency of 26.28%, therefore it is deduced that the percentage of the efficiency of the solar tracker system for this period was greater than the fixed system by 7%, approximately. Finally, it was observed that, during the first hours of each day, the fixed photovoltaic system managed to generate more electricity than the photovoltaic system with solar tracking.

Keywords: efficiency, power, solar tracker, fixed system, photovoltaic system.

Resumo

Para gerar energia elétrica eficientemente usando painéis fotovoltaicos, é essencial que eles sejam instalados corretamente. Para isso, sistemas de controle de posicionamento (rastreador solar) podem ser implementados por meio de um algoritmo de busca para o ponto máximo de energia, que serve para melhorar a eficiência do sistema. Por este motivo, no presente trabalho é analisado o projeto e a construção de um sistema fotovoltaico com rastreamento solar de dois eixos. O objetivo é determinar a eficiência deste sistema contra um sistema estático. O rastreador solar integrado possui células independentes que atuam como sensores e alimentam os motores responsáveis por girar o painel fotovoltaico no eixo vertical e horizontal. Para a aquisição da energia gerada pelos dois sistemas de painéis solares, utilizou-se a placa Arduino Nano 3.0 e vários módulos. Os resultados dos testes realizados foram examinados através do programa de computador SigmaPlot e da comparação de grupo unidirecional (Anova). Da mesma forma, foi realizado um teste de múltiplas faixas, que utiliza o método de comparação de médias múltiplas de Tukey. Em seguida, os dados coletados durante um período de 29 dias foram comparados. Os resultados mostraram que, nesse período, a eficiência média alcançada pelo sistema de rastreamento solar foi de 33%, enquanto no sistema fixo foi de 26,28%. Além disso, observou-se

que durante as primeiras horas de cada dia o sistema fotovoltaico fixo conseguiu gerar mais energia elétrica do que o sistema fotovoltaico com rastreamento solar.

Palavras-chave: eficiência, energia, rastreador solar, sistema fixo, sistema fotovoltaico.

Fecha recepción: Julio 2017 **Fecha aceptación:** Enero 2018

Introduction

The generation of energy is one of the most important environmental issues of today. This is mainly due to the indiscriminate use of fossil fuels to obtain electricity, which represents more than 80% of the energy produced in the world (Dick Hedberg, 2010, Noa-Diéguez, Álvarez-Sánchez and Pérez-Rodríguez, 2015) . According to the statistics of the International Energy Agency (IEA, for its acronym in English), the planet produces 21,431 TWh, and in Mexico 259 TWh. This means that 75% of the energy originated worldwide comes from materials such as coal, oil and natural gas. In Mexico, this proportion is higher, approximately 77% (International Energy Agency [IEA], 2010).

However, the massive exploitation of non-renewable sources has caused catastrophic consequences, such as the greenhouse effect, global warming and the deterioration of terrestrial and marine ecosystems. Faced with this situation, the interest in using clean sources, of which solar radiation is one of the greatest potential -especially in the intertropical regions- is growing more and more, because it can produce twice the energy of fossil fuels. However, the problem is that today's generators only have an efficiency of approximately 10% (Mousazadeh et al., 2009). This is one of the reasons why so much time and work is invested not only in research, but also in the development of more and better renewable energy technologies, such as that produced by the wind, the sun, as well as the thermal or the one generated by biofuels (Iglesias and Morales, 2013).

In recent decades, the field of renewable energy sources has become important for sustainable development. In this context, solar energy is presented as an efficient and economical alternative - in comparison with other traditional forms of electric power - hence the need for greater use has increased (Machado Toranzo, Lussón Cervantes, Leysdian Carralero Gold, Bonzon Henríquez and Escalona Costa, 2015; Noa-Diéguez et al., 2015).

According to Neha, Gugri, Mishra and Dubey (2013), the amount of solar energy received annually by land represents ten thousand times the consumption of the planet in that same period. This means that the sun - besides being the main actor of the biological processes on earth - is a powerful and inexhaustible source of energy, which can be exploited by means of an adequate system of capture and conversion to another type of energy, such as electrical, thermal, among others (Arroyo Romero y Cortés Montes de Oca, 2015; Noa-Diéguez *et al*., 2015).

In this sense, photovoltaic panels are one of the simplest methods to convert the energy of the sun into electricity, because in this transformation no dangerous byproducts are created for the environment (Domínguez González, 2012). These panels work when sunlight excites the electrons inside the cells, which generates electrical energy. For this, nevertheless, the angle of incidence of the solar rays plays a determining role, since a correct installation of the panel improves its efficiency. In effect, for different values of the angle of incidence in a panel, the output of this will change, so that the maximum output value is obtained when the sun's rays are perpendicular to the panel (Escobar Mejía, Holguín Londoño and Osorio, 2010; Kahn, 2012). For this reason, in order to find the maximum output of a photovoltaic panel, positioning control systems (solar tracker) can be implemented by means of a technique or search algorithm of the maximum energy point to improve the efficiency of the system (Enríquez, Andújar and Bohórquez, 2010, Escobar Mejía et al., 2010, Grupta, 2011, Panait and Tudorache, 2008).

The solar tracker is a technological device whose function is to increase the production of energy. For that, it uses photovoltaic panels and other concentration devices by means of mechanical, electrical and electronic systems that follow the trajectory of the sun. In this way, it captures the maximum solar radiation for as long as possible. Photovoltaic systems with tracking can have one or two axes. The first can only follow the solar azimuth, but not the solar altitude; while the latter can fulfill both functions, hence they are more efficient (Ahmet Senpinar, 2012, Koussa, 2011).

For this reason, in the present work the design and construction of a photovoltaic system with solar tracking of two axes is analyzed. The objective is to determine the efficiency of this when compared with that of a fixed photovoltaic system.

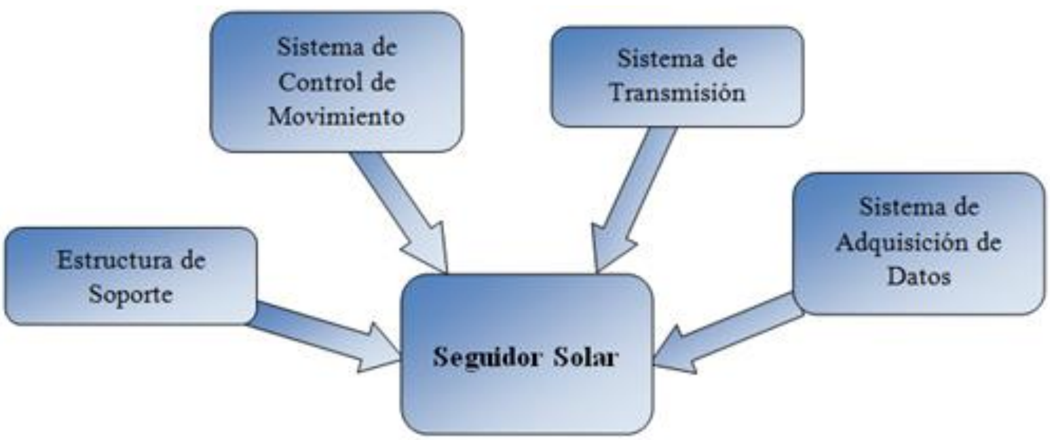
Methodology

The photovoltaic system with solar tracking

The system with solar tracking (also called solar tracker) proposed in this paper is of two axes, and consists of four basic parts (figure 1):

1. Support structures.
2. Motion control system.
3. Transmission system (power stage).
4. Data acquisition system.

Figura 1. Estructura y sistemas del seguidor solar



Fuente: Elaboración propia

Support structure

The metallic structure that supports the photovoltaic system with built-in solar tracking is made of tubular metal material, metal angles and rectangular tubular profile. This provides firmness to the solar tracker, supports both the motion control system and the transmission system, and offers attachment points and grip of these. Figures 2 (a), 2 (b), 2 (c), 2 (d) and 2 (e) show the design made using SolidWorks software.

Figura 2. Estructura de soporte para el sistema fotovoltaico con seguimiento solar

a b c

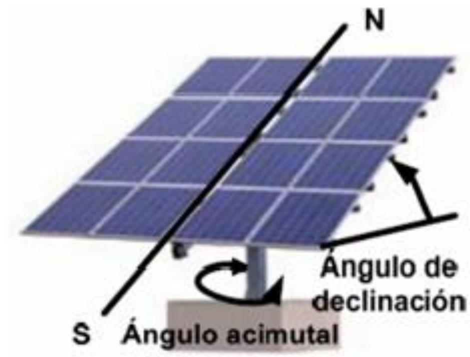
d e

Fuente: Elaboración propia

Motion control system

This system is responsible for obtaining the azimuthal angle corresponding to the movement of the vertical axis and the declination or elevation angle of the movement of the horizontal axis of the photovoltaic panel (figure 3).

Figura 3. Ángulo acimutal y de declinación del seguidor solar



Fuente: Núñez Flores (2012)

Next, the system that controls the movements of the photovoltaic panel is explained. The system uses a pair of independent solar cells with technical specifications of 6 Vcc, 110 mA and 0.6 W each. These solar cells act as sensors to provide vertical (azimuthal) motion; they are located one to ninety degrees from the other and are located on top of the solar panel (figure 4). Depending on which of the two solar cells receives more light, then it will be the azimuthal movement that the photovoltaic panel will have. Another pair of independent solar cells are used as sensors to provide horizontal movement; these cells have the same functioning as the sensors that give the azimuthal movement.

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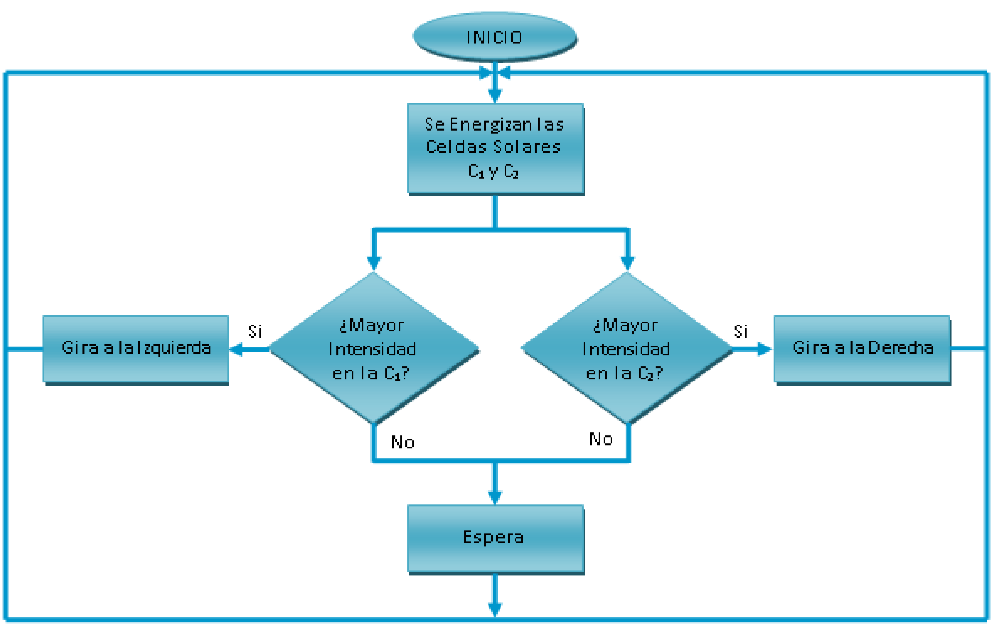
ISSN: 2007 - 9990

Figura 4. Sensores para el movimiento vertical y horizontal del seguidor solar

Fuente: Elaboración propia

In Figure 5 the flow diagram for the motion control of the constructed photovoltaic system is illustrated.

Figura 5. Diagrama de flujo para el control de movimiento del sistema con seguimiento solar



Fuente: Elaboración propia

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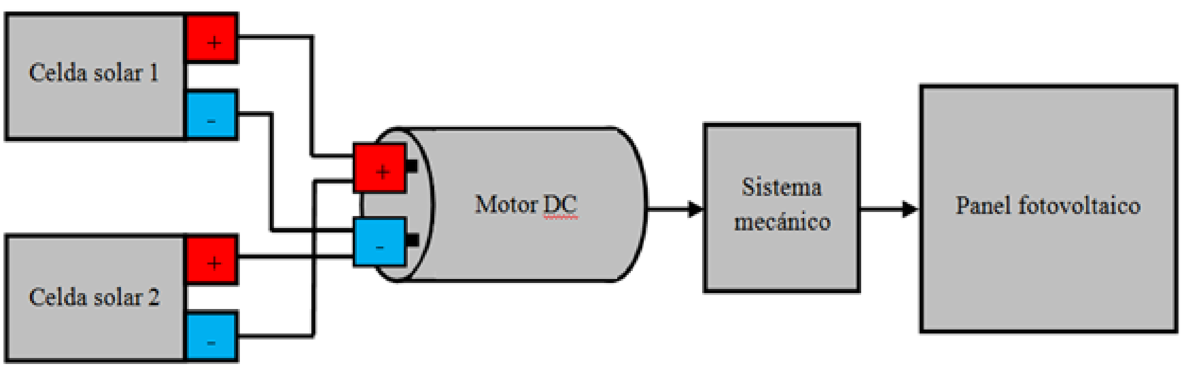
Transmission system (power stage)

This system is constituted by a set of stars and chains - as shown in figures 2 (d) and 2 (e) - that move by direct current motors. The solar tracker uses two motors for its operation: one for vertical movement and the other for horizontal movement. The direction of movement of the motors is defined by the difference in power emitted by the solar cells. The connection of the solar cells to each of the motors that provide the vertical and horizontal movements is shown in figure 6, and is explained as follows: solar cell 1 is connected to the motor with direct polarization (positive of the solar cell with the positive of the motor, and negative of the solar cell with the negative of the motor); this causes that when the sun radiates to this solar cell, it turns the motor in the sense of the hands of the clock. The solar cell 2 is connected in reverse bias (positive of the solar cell with the negative of the motor, and negative of the solar cell with the positive of the motor); When the sun radiates to this second solar cell, it turns the motor counterclockwise. Now, when the sun radiates with the same intensity to the two solar cells, the motor remains motionless.

Figura 6. Sistema de transmisión para el movimiento vertical y horizontal del panel fotovoltaico



Fuente: Elaboración propia

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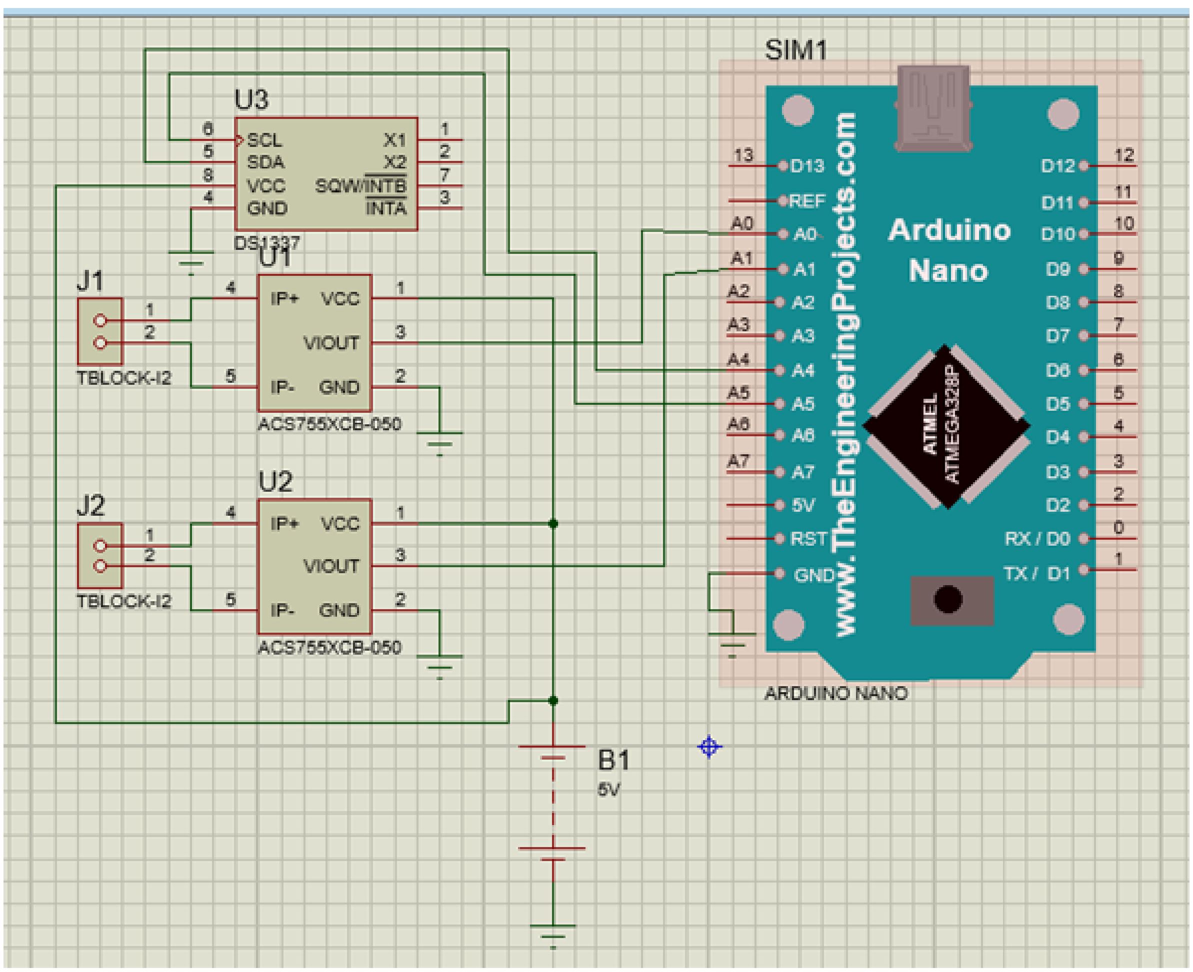
Data acquisition system

For the acquisition of both the amperage and the voltage emitted by each of the two photovoltaic panels (with solar and fixed tracking), an Arduino Nano 3.0 card, a DS3231 real-time sensor, two ACS712 current sensors and several connectors were used. These electronic components are interconnected through a printed circuit board (PCB), which was called a data acquisition card. Figure 7 shows the connection diagram of this card, which was used during the field tests to obtain the current, the voltage and, therefore, the power generated by both systems.

Figura 7. Diagrama de conexiones de esta tarjea de adquisición de datos



Fuente: Elaboración propia

The fixed photovoltaic system

The fixed photovoltaic system used in this work is a photovoltaic panel of 65 W of power, positioned with a fixed elevation angle equal to 19.771o. Figure 8 shows this system, which was installed in the city of Autlán de Navarro, Jalisco, to perform the field tests of this investigation. It should be noted that the elevation angle of this panel was obtained with the help of SunEarthTools.com and Solar Topo applications, both available on the Net at no cost.

Figura 8. Sistema fotovoltaico fijo

Fuente: Elaboración propia

Experimental development

The field work of this investigation was carried out with the experimentation of the two photovoltaic systems treated in this work (both of 65 W) during a period of 29 days (from February 14 to March 15, 2017). To carry out the field tests, the two systems were installed at the address of Adán Uribe 111B, located in the city of Autlán de Navarro, Jalisco, with a geographic location of 19,771° of latitude. To measure the voltage and current generated, a data acquisition system was implemented based on the Arduino platform, which allowed us to perceive its measurements and calculate the power simultaneously using formula 1.

$$P = VI \quad (1)$$

Where

P = Electric power (W)

V = Voltage (V)

I = Electric current (A)

To determine energy efficiency, formula 2 was used, which is included in the international standard ISO 50001 on energy management systems, published in September 2011 by the International Organization for Standardization. (International Organization for Standardization [ISO], 2011).

$$Eficiencia\ energética = \frac{Resultado}{Entrada\ total\ de\ energía} \quad (2)$$

Where

Result = Power generated by the photovoltaic panel (W)

Total energy input = Maximum power of the photovoltaic panel (W)

The information obtained through the data acquisition card (voltage and current) was exported to an Excel spreadsheet, where graphs of efficiency behavior by both photovoltaic systems were made. The efficiency is given in percentages, for which formula 3 was used. Experimentation was carried out between 09:00 hours and 19:00 hours, since before and after that time, minimum values were acquired. The interval between each of the measurements was 15 minutes.

$$Eficiencia\ energética = \left(\frac{Resultado}{Entrada\ total\ de\ energía}\right) \times 100\ \% \quad (3)$$

Finally, to analyze the results, the SigmaPlot computer program was used. The descriptive statistics reported the efficiency of each of the photovoltaic systems evaluated per hour and later per day. The results of each experimental set were examined to find significant statistical differences between the methods evaluated in each treatment by means of a one-way comparative analysis of groups (Anova), followed by a multiple-range test, which uses the multiple comparison method of Tukey stockings.

Results and Discussion

The information presented in this work corresponds to the efficiency of both systems of photovoltaic panels in the most unstable days of the aforementioned months, that is, a partially cloudy day (February 19, 2017) and a sunny day (March 14, 2017). same year). This section presents the information gathered during the preliminary test and that corresponding to a partially cloudy day and a sunny day, as well as that obtained during the 29 days of the experiment (from February 14 to March 15, 2017).

Preliminary test

The differences in the efficiency achieved by the two systems during the preliminary test carried out on February 15, 2017 are shown in figure 9. In this it can be seen that for the observed time range the photovoltaic system with solar tracking generated greater electrical power than the fixed photovoltaic system. In fact, at 1:30 p.m. that day, the system with solar tracking reached its maximum efficiency (65.18%), while at 12:00 hours it obtained the highest efficiency compared to the fixed system (17.11%).

On the other hand, from 10:30 am to 10:45 am, and from 1:45 pm to 2:15 pm, the same efficiency was registered for both systems because in those periods they captured the same amount of energy produced by an intense cloudiness

Regarding the average efficiency generated that day, the system with solar tracking registered 33.62%, while the fixed system obtained 26.38% on average. It should be noted that the falls in the efficiency of both systems (figure 9) correspond to cloudy periods (see the records corresponding to the interval from 09:45 hours to 10:15 hours).

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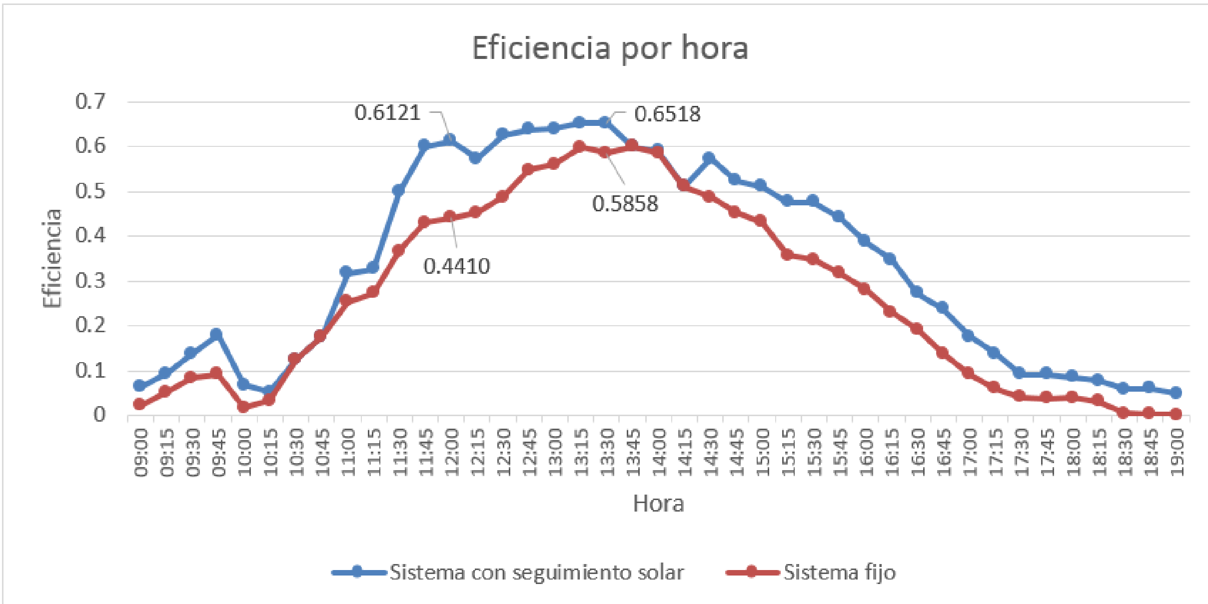
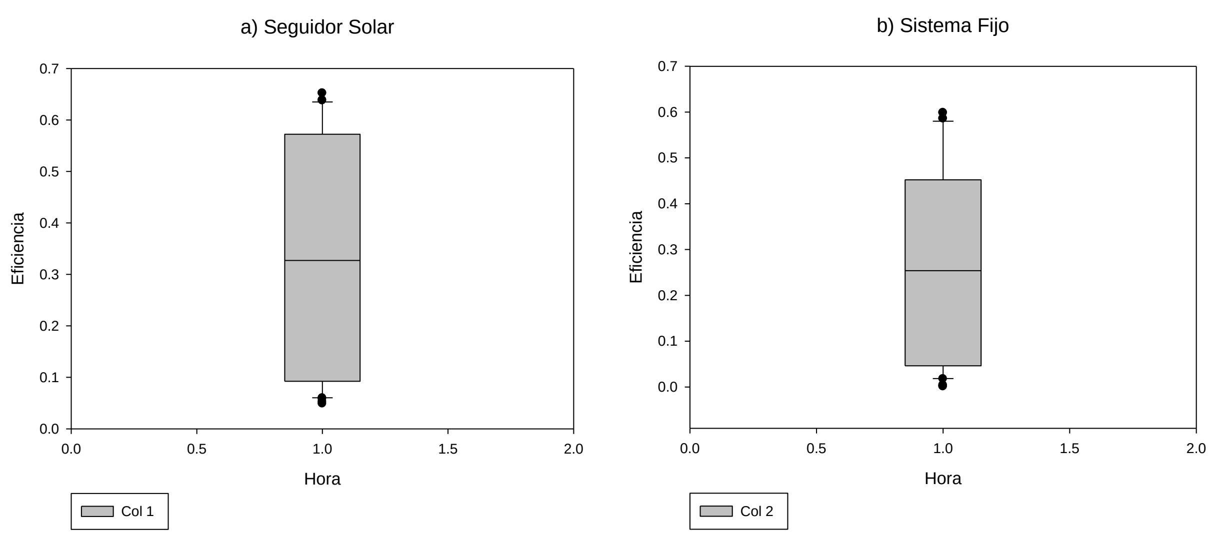
Figura 9. Gráfica del comportamiento de la eficiencia lograda el 15 de febrero de 2017



Fuente: Elaboración propia

On the other hand, Tukey's analysis for comparisons of the means of both systems showed a minimal significant difference between them, as shown in figures 10 (a) and 10 (b).

Figura 10. Gráficos de la diferencia mínima significativa (Tukey) entre a) el seguidor solar y b) el sistema fijo



Fuente: Elaboración propia

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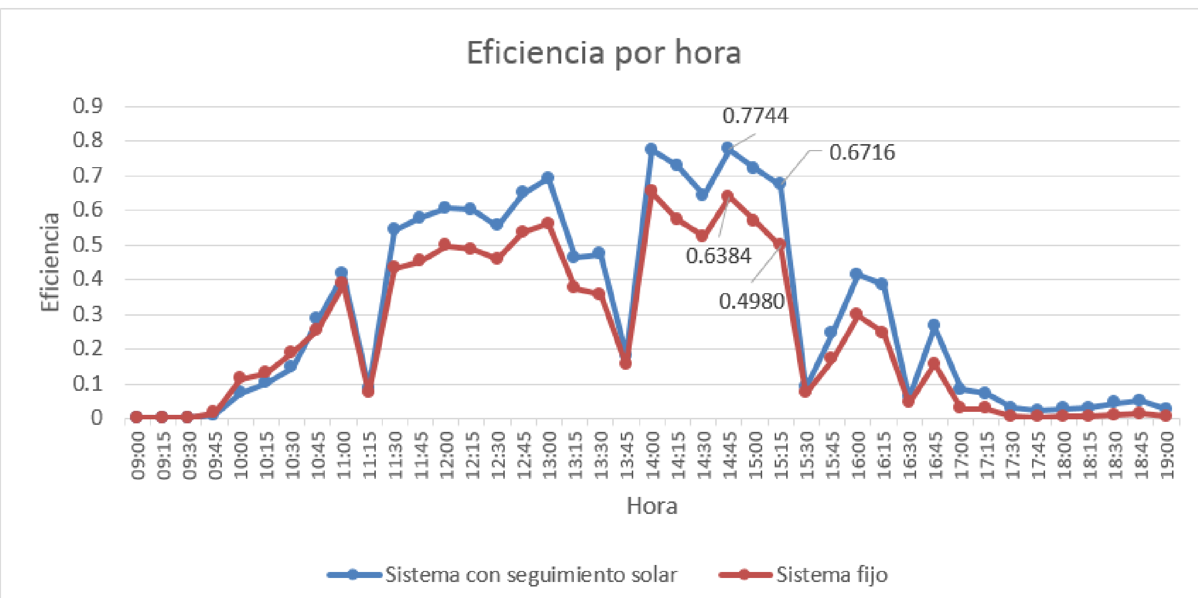
Partly cloudy day

The efficiency achieved by the two photovoltaic systems during a partially cloudy day (February 19, 2017) is shown in figure 11. In this it is observed that from 9:00 am to 10:30 am the fixed photovoltaic system generated greater electrical power that the system with solar tracking. This was because every day, with the sunset, the photovoltaic panel with solar tracking ended facing west (west), so that the next day the sun did not radiate enough cells used as sensors. This caused that the necessary energy was not transmitted to the motor to turn the photovoltaic panel towards the east (where the sun begins its journey). It was also observed that for the rest of this day (except for some periods where there were intense cloudiness) the photovoltaic system with solar tracking generated more electrical power than the fixed photovoltaic system. In fact, at 14:45 hours of that day the system with solar tracking reached its maximum efficiency (77.44%), while at 15:15 it recorded the highest efficiency compared to the fixed system (17.36%).

Regarding the average efficiency generated that day, the system with solar tracking registered 30.72%, while the fixed system achieved 24.42% on average. This data shows that in days with different cloud cover the system with solar tracking can generate more energy than the fixed system.

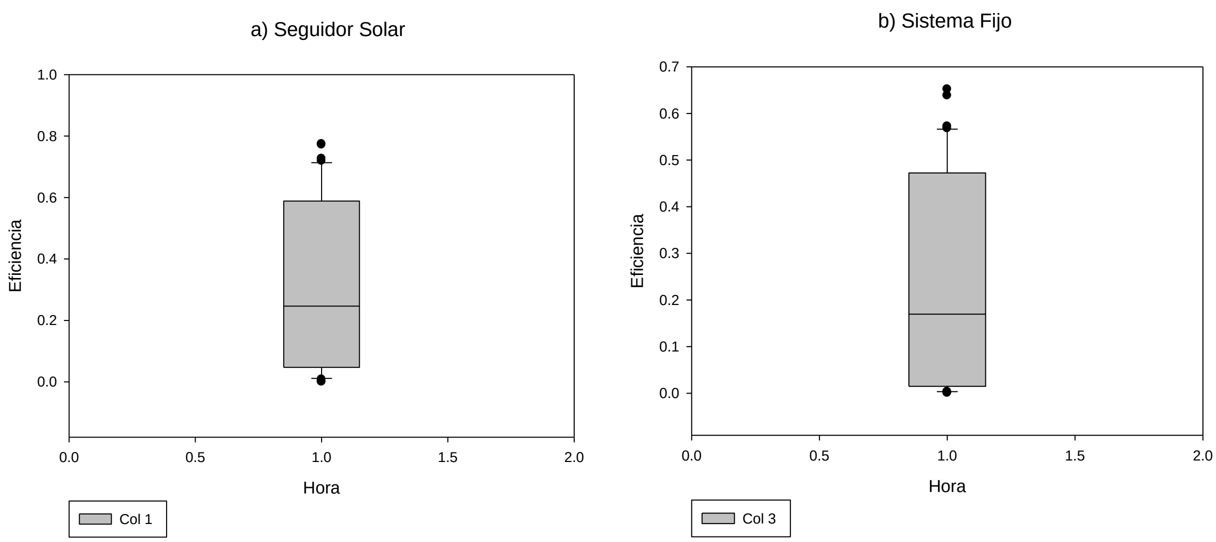
Figura 11. Gráfica del comportamiento de la eficiencia obtenida el día 19 de febrero de 2017



Fuente: Elaboración propia

Also, Tukey's analysis for the comparisons of the means of the two systems shows a minimum significant difference between both, see figures 12 (a) and 12 (b).

Figura 12. Gráficos de la diferencia mínima significativa (Tukey) entre a) el seguidor y b) el sistema fijo



Fuente: Elaboración propia

Sunny day

This research was considered as a sunny day on March 14, 2017 due to the almost zero clouds in the city of Autlán de Navarro. The efficiency obtained by both systems during that day is shown in figure 13. In this it is observed that from 09:00 hours to 10:15 hours the fixed photovoltaic system generated more electrical power than the system with solar tracking due to the reason already noted on the cloudy day.

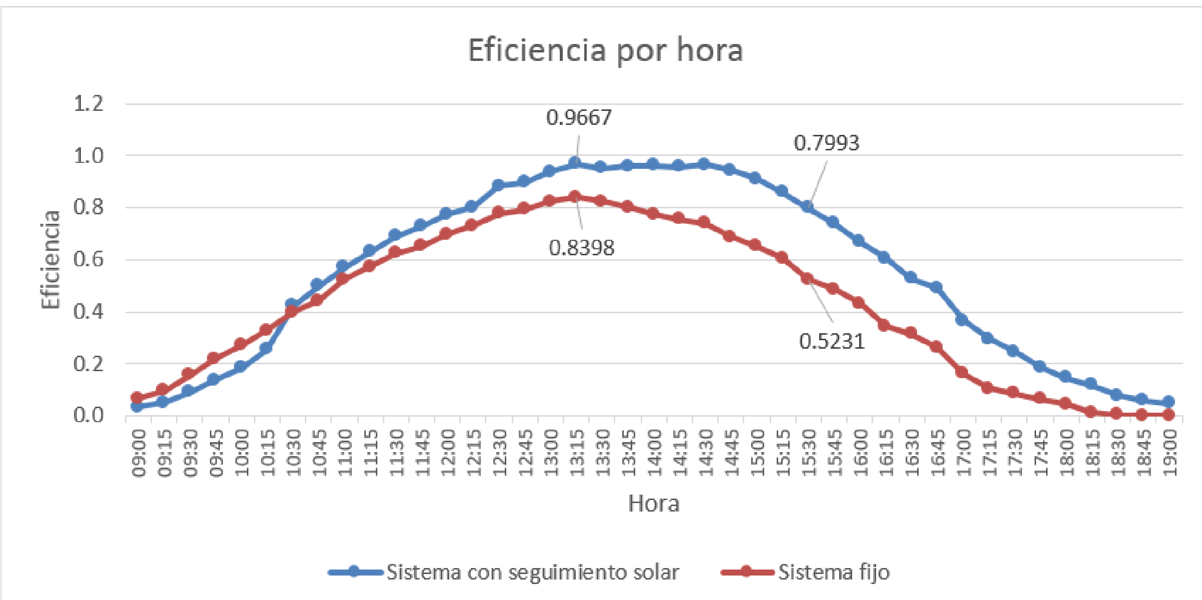
Likewise, it is appreciated that starting at 10:30 am the system with solar tracking generated more electrical power than the fixed system. Also, it is noted that at 13:15 hours the system with solar tracking achieved its maximum efficiency (96.67%), while at 15:30 hours it recorded the highest efficiency compared to the fixed system (27.62%).

Regarding the average efficiency generated that day, the system with solar tracking registered 54.72%, while the fixed system achieved 43.17% average. This data shows that on sunny days the system with solar tracking is more efficient than the fixed system, and that both systems are more efficient those days than during cloudy or partially cloudy days.

The behavior of both graphs (from 12:30 hours to 18:15 hours) indicates a considerable increase in the efficiency of the system with solar tracking compared to the fixed system. This was due to the fact that during the day there were no cloudiness that would lead to similar figures of energy in the two systems.

It should be mentioned that during the study period the fixed photovoltaic system was not aligned according to the corresponding solar altitude, since in no interval close to noon (including the sunny day) both photovoltaic systems achieved a similar efficiency. This reveals that at no time during the days of the experiment were the sunbeams aligned perpendicular to the fixed photovoltaic panel.

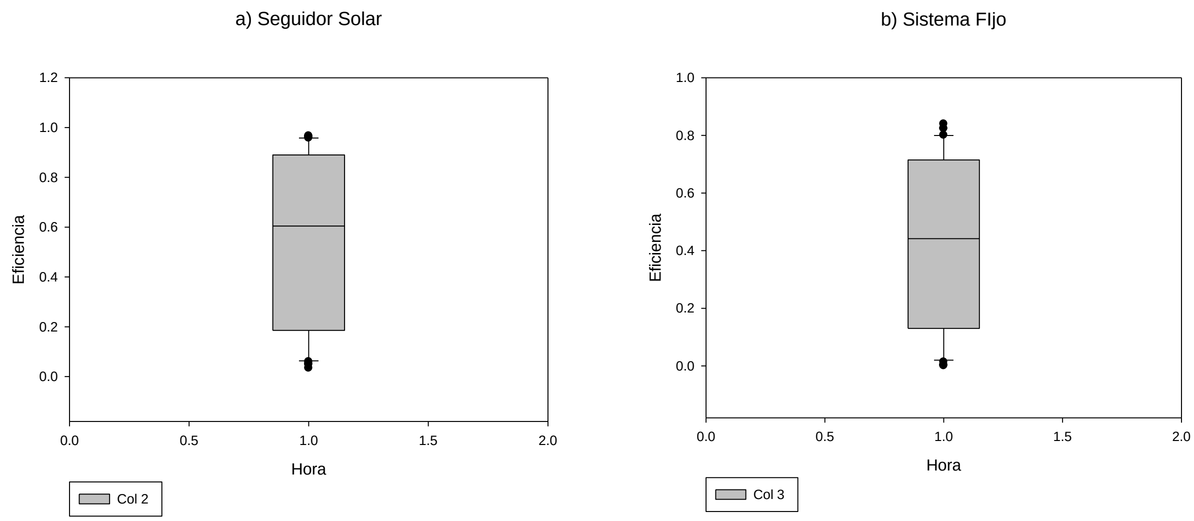
Figura 13. Gráfica del comportamiento de la eficiencia lograda el día 14 de marzo de 2017



Fuente: Elaboración propia

Also, Tukey's analysis for the comparisons of the means of both systems showed a minimum significant difference between them, this is observed in figures 14 (a) and 14 (b).

Figura 14. Gráficos de la diferencia mínima significativa (Tukey) entre a) el seguidor solar y b) el sistema fijo



Fuente: Elaboración propia

Period of 29 days

Figure 15 shows the average of the efficiencies obtained by both systems during the experimental period (from February 15 to March 15, 2017). In the figure it is observed that during all the days of the study the photovoltaic system with solar tracking generated more electrical power than the fixed photovoltaic system. Likewise, on March 14, the system with solar tracking achieved greater efficiency (54.72%) compared to the other days, and that same day achieved the highest efficiency (11.55%) compared to the fixed system.

On the other hand, on February 27, the system with solar tracking recorded the lowest efficiency (13.63%). Likewise, on February 16, the system with solar tracking obtained the lowest efficiency (4.26%) compared to the fixed system.

On the other hand, the average efficiency reached by the system with solar tracking during the experimental period was 33%, while the fixed system achieved an average efficiency of 26.28%. This allows to deduce that the efficiency of the system with solar tracking (during the experimental period) was greater than that of the fixed system in approximately 7%.

It should be noted that the falls in the efficiency of both systems (figure 15) are on cloudy days (eg, February 27, 2017) or partly cloudy (eg, February 19, 2017).

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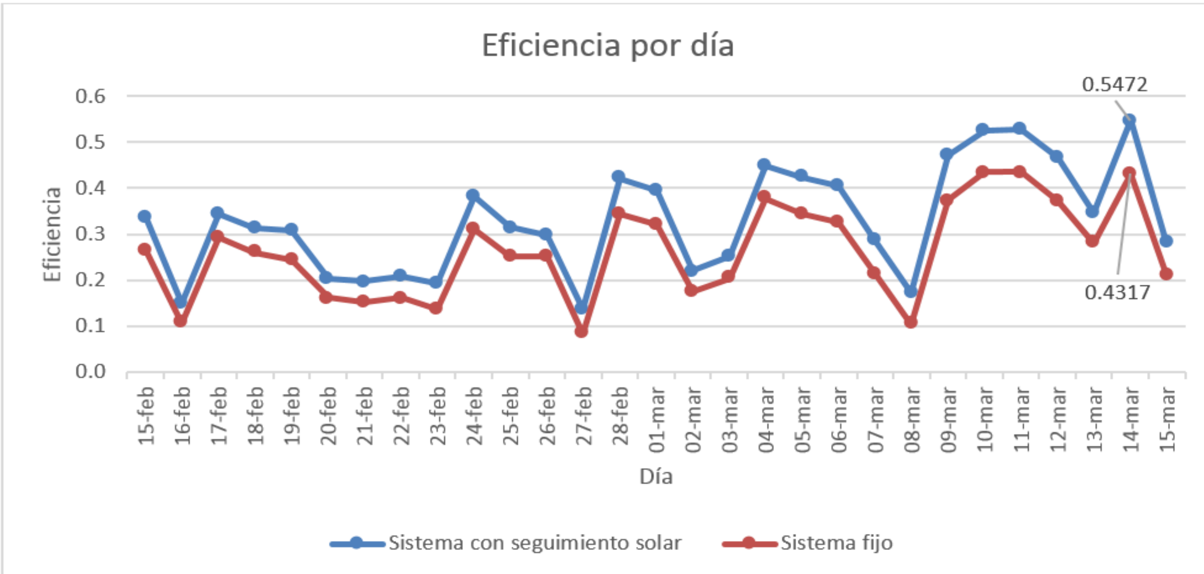
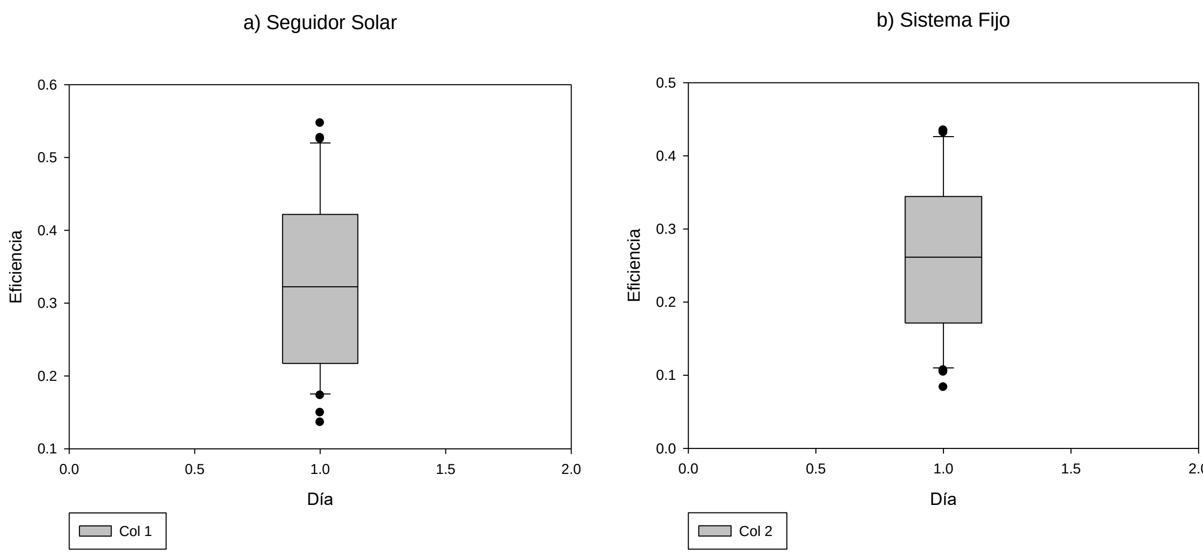
Figura 15. Gráfica de la eficiencia promedio diaria durante el periodo experimental



Fuente: Elaboración propia

Also, Tukey's analysis for comparisons of the means of both systems showed a minimal significant difference between them, this difference is observed in figures 16 (a) and 16 (b).

Figura 16. Gráficos de la diferencia mínima significativa (Tukey) entre a) el seguidor solar y b) el sistema fijo



Fuente: Elaboración propia

When performing the comparative analysis of groups (Anova) between both systems, the data obtained during the experimental period of 29 days yielded the following results, which are shown in table 1.

Tabla 1. Resultado del análisis de comparativa de grupos (Anova) entre ambos sistemas

Nombre del grupo	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**	
Col 1	29	0	0.330	0.117	0.0213	
Col 2	29	0	0.263	0.101	0.0184	
Fuente de variación		**DF**	**SS**	**MS**	**F**	**P**
Entre grupos		1	0.0677	0.0677	5.700	0.020
Prueba de normalidad:		aprobada (P = 0.241)				
Prueba de varianza igual:		aprobada (P = 0.418)				

Fuente: Elaboración propia

The differences of the mean values between the treatment groups are greater than would be expected by chance, since there is a statistically significant difference (P = 0.020). In other words, there is greater efficiency in the system with solar tracking than in the fixed system, since there is a significant difference between both systems.

Conclusions

The fixed photovoltaic system generated a greater amount of electricity in the first hours of each day (before 10:30 am) compared to the solar tracking photovoltaic system. This is because with the sunset, the photovoltaic panel with solar tracking ended facing west.

In the periods where there was intense cloudiness, the drop in efficiency in both photovoltaic systems showed approximately the same value. In other words, in those intervals the efficiency was similar for the two systems.

The maximum efficiency reached by both photovoltaic systems was obtained at 1:15 p.m., reaching values of 96.67% efficiency in the system with solar tracker and 83.98% efficiency in the fixed system. On the other hand, the biggest difference in the efficiency obtained between both photovoltaic systems was obtained at 15:30 hours.

During the experimental period of 29 days, the results obtained showed that, the average efficiency reached by the system with solar tracking was 33%, while with the fixed system it was 26.28%, that is, the solar tracking system was able to be more efficient than the fixed photovoltaic system by approximately 7%.

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