A STUDY ON THE INFLUENCE OF LOCALITY IN THE VIABILITY OF SOLAR TRACKER SYSTEMS

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Abstract— Photovoltaic solar energy has been explored as a solution to meet the growing demand for electricity from a clean and renewable source. However, the low energy-conversion efficiency of photovoltaic panels is one of the factors that hamper the competitiveness of this energy source compared to the others. Solar trackers are used to improve the performance of photovoltaic systems; however, they have a higher installation cost and maintenance. This article presents a review of several types of solar trackers, as well as simulations of a 1 MWp power plant in seven cities of Brazil, to evaluate the influence of locality in the viability of solar trackers systems. The results showed that Bom Jesus da Lapa - BA presents the best performance among the cities tested, both technically and economically. Also, solar-powered plants with solar trackers have better economic viability than fixed-panel power plants in all cities studied.

Keywords— Solar energy, solar trackers, photovoltaic panels, photovoltaic plants, renewable energy sources.

Resumo — A energia solar fotovoltaica tem sido explorada como uma solução para o atendimento da crescente demanda de energia com uma fonte limpa e renovável. Porém, a baixa eficiência de conversão de energia dos painéis fotovoltaicos é um dos fatores que dificultam a competitividade dessa fonte de energia frente às demais. Os seguidores solares são utilizados com o intuito de melhorar o desempenho dos sistemas fotovoltaicos, entretanto, são sistemas que possuem maior custo inicial e de manutenção. Este artigo apresenta uma revisão de vários métodos de seguidores solares, além de uma simulação de uma usina de 1 MWp em sete cidades do Brasil, a fim de avaliar a influência da localidade na viabilidade de seguidores solares. Os resultados obtidos mostraram que Bom Jesus da Lapa – BA apresenta o melhor desempenho dentre as cidades testadas, tanto técnica quanto economicamente. Além disso, as usinas com seguidores solares apresentam melhor viabilidade econômica que as usinas com painéis fixos em todas as cidades estudadas.

Palavras-chave— Energia solar, seguidores solares, painéis fotovoltaicos, usinas fotovoltaicas, fontes renováveis de energia.

1 Introduction

Producing energy from renewable sources is vital for the environment, as it reduces greenhouse gas emissions and dependence on fossil fuels. Among the various types of renewable energy sources, solar energy is one of the most promising (Seme *et al.*, 2017).

Currently, photovoltaic systems are already being used as distributed generators, both for isolated loads and connected to the power distribution system. Those systems are ideal for application in urban environments, as they do not emit pollutants or acoustic noise. In addition, they can be installed in environments already used for other purposes, such as in roof-tops of residences or shopping malls.

Despite their advantages, a downside attributed to photovoltaic generation is the low energy conversion efficiency (Roberto Zilles *et al.*, 2012). That problem can be minimized with the implementation of solar tracking devices, which aim to increase generation efficiency by keeping panels perpendicular to solar radiation most of the time (Vieira *et al.*, 2016). According to Nsengiyumva *et al.* (Nsengiyumva *et al.*, 2018), a 12-20% increase in energy output can be achieved with the use of single-axis trackers, and up to 43.9% with dual-axis trackers. However, the performance improvement of a system depends on the application conditions and the installation site (Ghosh *et al.*, 2010).

2 Classification of solar trackers

Solar trackers are usually classified in the literature according to their tracking technology and their degree of freedom. The divisions can be observed in Figure 1.

2.1 Tracking technology

2.1.1 Passive solar trackers

These systems are designed to track the sun without any electronic device. They can use fluids that expand when heated by the sun. These fluids are contained in cylindrical containers connected by tubes on the sides of the panel, as can be seen in Figure 2. The expansion of the fluid at different levels due to the position of the sun creates a displacement of the fluid's weight between the two sides of the tracker, causing the movement towards the sun (Nguyen, 2014). Narendrasinh Parmar et al. (Narendrasinh Parmar *et al.*, 2015) developed a solar tracker based on this principle and obtained an energy gain of approximately 25% when compared to fixed panels.

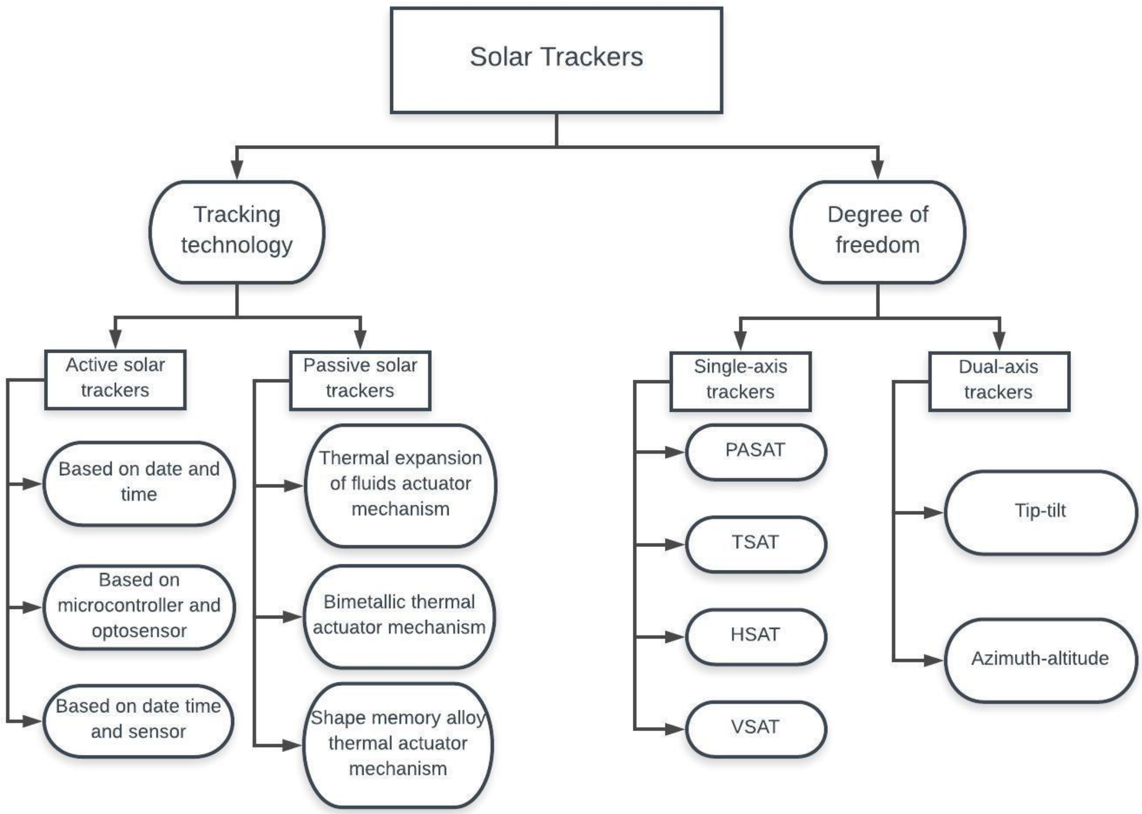

Figure 1. Classification of solar trackers according to their tracking technology and degree of freedom.

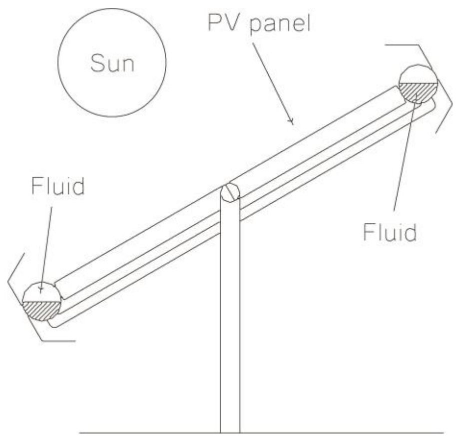

Figure 2. Passive solar tracker using cylindrical tubes filled with a fluid. Adapted from (Clifford and Eastwood, 2004).

Clifford and Eastwood (Clifford and Eastwood, 2004) developed a passive solar tracker turned on by two aluminum and steel bimetallic strips. Those strips are positioned symmetrically on each side of a horizontal axis. When the strip gets exposed to the sun and absorbs heat, the aluminum will expand more than steel due to its higher coefficient of thermal expansion, generating the movement of the photovoltaic panels towards the sun. There was a 23% increase in power generation compared to fixed panels, which could achieve an extra gain of 2% with the application of a night-return mechanism so that the panel turn to the right position at sunrise.

Passive solar tracker systems are easy to implement because they are made of less complex structures, requiring little maintenance. However, they produce a low energy gain when compared to active solar trackers due to their low tracking accuracy. A further disadvantage of those devices is the impossibility of application in cold climate regions since they require heat for their operation (Nsengiyumva et al., 2018).

2.2.2 Active solar trackers

They use electric motors or gear mechanisms to perform solar tracking. They can use microprocessors and sensors, date and time-based algorithms, or a combination of both to detect the position of the sun. These devices, unlike passive solar trackers, consume energy to ensure their operation, although they produce a higher energy gain (Sumathi *et al.*, 2017).

Date and time-based solar tracking detect the position of the sun using algorithms that considers date, time, and location as input data. Reda and Andreas (Reda and Andreas, 2004) developed an algorithm to calculate the zenith and azimuth angles of the sun. This algorithm is an adaptation, focusing only on the sun, of an algorithm described by Jean Meeus (Meeus, 1998) that focused on the planets and stars in general. The algorithm is able to calculate the angular position of the sun between the years -2000 and 6000 with uncertainties of ± 0.0003°.

Solar trackers can also use microprocessor interfaced with sensors. These systems measure the intensity of light through sensors and transmit signals to the microprocessor, which drives the motors for proper motion of the photovoltaic panels. Seme *et al*. (Seme *et al.*, 2017) implemented a dual-axis solar tracker that uses four light-dependent resistors (LDRs), whose resistance decreases when the light intensity increases. A pair of LDRs is used to enable east-west movement, while the other pair is used to enable north-south movement. The electrical circuit is based on the comparison of two LDRs. When there is a greater light intensity focusing on the LDR positioned to the west, the microprocessor drives the motor from the axis perpendicular to the ground (azimuth axis) to move the panels in that direction. The same happens in the second axis of the tracker, called the elevation axis. Four limit switches were also used to prevent entanglement of the cables, these devices allow the movement of the east-west axis only by 270 °, and the movement of the north-south axis only by 65 °. The results were satisfactory for the tracking accuracy of the sun, with the exception of some deviations caused by shadows incident on the sensors in the morning. From 1:30 p.m., the solar tracker approached the sun's trajectory to less than 1 degree. In terms of electric energy, the solar tracker produced 27% more compared to a fixed system.

Some solar trackers use a combination of sensors and date and time-based algorithms to locate the position of the sun. An example was developed by Mereddy et al. (Mereddy *et al.*, 2016). Their solar tracker has two rotation axes and uses LDRs to detect the position of the sun, except in cloudy atmospheres, when the sensors can't detect the position of the sun accurately, then it automatically activates the algorithm based on date and time. An energy gain of 36% was observed with the use of this sun tracking mechanism, which can be very useful in large-scale plants.

2.2 Degree of freedom

Regarding the degree of freedom, solar trackers can be classified as single-axis and dual-axis solar trackers.

2.2.1 Single-axis solar tracker

These systems have only one axis of rotation. They may be horizontally aligned (HSAT), vertically aligned (VSAT), horizontally aligned with tilted (HTSAT) and polar (PASAT).

a. Horizontal single-axis tracker (HSAT) - In HSAT the axis of rotation is horizontal to the ground and positioned on the north-south line (Singh *et al.*, 2018). This solar tracker is most appropriate for low latitude regions. A typical HSAT can be seen in Figure 3a.

b. Vertical single-axis tracker (VSAT) - In VSAT the axis of rotation is vertical to the ground. These systems are more appropriate for regions of high latitudes and need to be installed with larger spacings to prevent mutual shading (Nsengiyumva *et al.*, 2018). A VSAT can be seen in Figure 3b.

c. Horizontal single-axis tracker with tilted (HTSAT) - The only difference between these systems and HSAT is the tilt of the axis of rotation. They are suitable for regions with higher latitudes and also, it occupies less space when compared to other types of single-axis solar trackers (Nsengiyumva *et al.*, 2018). A typical HTSAT can be seen in Figure 3c.

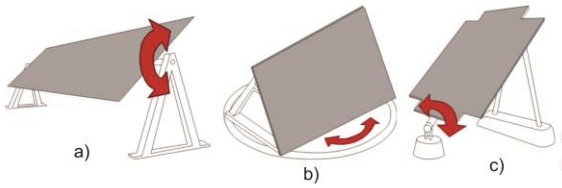

Figure 3. a) HSAT b) VSAT c) HTSAT. Source: (Seme et al., 2017).

d. Polar tracked single axis tracker (PASAT) - In PASAT the tilted axis is aligned with the polar star (Singh *et al.*, 2018). In this system, the tilted angle must be equal to the latitude of the project site (Nsengiyumva *et al.*, 2018).

Li *et al*. (Li *et al.*, 2011) developed a study to investigate the performance of an HSAT in China. A mathematical analysis was performed to estimate the daily collectible irradiation in three systems: with fixed panels, with dual-axis solar tracker, and with HSAT. The results showed that the annual gain of the HSAT was related to the orientation of the tracking axis. The south-north axis sun tracking presented a better performance at improving the energy collection in tracked systems. The gain obtained waved from 10-24% compared to the fixed system, while the east-west axis sun tracking obtained a gain of 8%. They also found that the performance of HSAT decreases according to the latitude, therefore, they present a greater viability when installed in regions whose latitudes are lower.

To investigate the performance of a VSAT compared to a fixed panel system and a dual-axis solar tracker system, Li *et al*. (Li *et al.*, 2011) proposed a mathematical procedure in order to estimate annual collectible radiation. The calculations showed that, compared to the fixed panel system, the VSAT obtained a gain of 28% in areas with abundant solar resources and 16% in areas with scarce solar resources, highlighting that VSAT was suitable to be employed in regions with abundant solar resources.

2.2.2 Dual-axis solar tracker

Dual-axis solar tracker systems have two axes of rotation that are usually perpendicular to each other. The primary axis is considered the axis fixed to the ground, while the secondary axis is considered to be referenced to the primary. They produce more energy than single-axis solar tracker systems because they can track the sun both horizontally and vertically (Mereddy *et al.*, 2016). For this reason, these systems require more complex control systems to ensure their operation, implying high acquisition and maintenance costs. One disadvantage is the forces applied to them, mainly due to the weight of the photovoltaic panels and wind resistance (Ramos, 2016). The dual-axis solar trackers can be tip-tilt type and azimuth-altitude type.

a. Tip-tilt dual-axis tracker - In this system, the photovoltaic arrangement is mounted on top of a pole, as shown in Figure 4, and has a fixed azimuth axis (Singh *et al.*, 2018). The disadvantage of the tip-tilt tracker is that the post supports the weight of all panels, limiting the number of panels in a string.

b. Azimuth-altitude dual-axis tracker - This type of tracker has the primary vertical axis to the ground and it is called the azimuthal axis, while the secondary axis is normal to the primary axis and is called the elevation axis (Singh *et al.*, 2018). Unlike the tip-tilt, it has the weight of the panels distributed along the primary axis, therefore is capable to support a greater number of panels. A typical azimuth-altitude system can be seen in Figure 5.

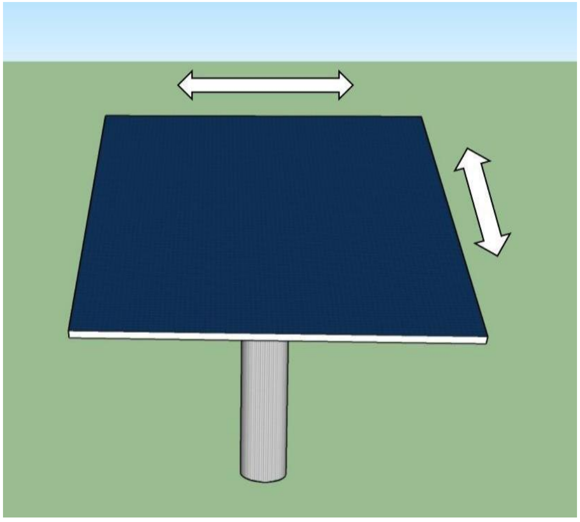

Figure 4. Tip-tilt dual-axis solar tracker.

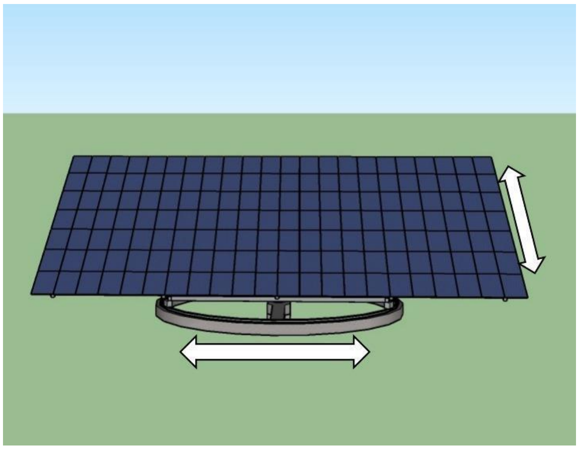

Figure 2. Azimuth-altitude dual-axis solar tracker.

Kivrak *et al*. (Kivrak *et al.*, 2012) developed a double-axis solar tracker with open-loop control. The system was compared experimentally to a system of fixed panels tilted 37°, in the climatic conditions of Denizli, Turkey. The measurements were performed from the months of May to June and the system with solar tracker obtained an energy gain close to 64% in comparison to the fixed system. It is important to note that, instead of using fixed loads or batteries connected to the photovoltaic panels, measurements were made using a Boost converter with Maximum Power Point Tracking (MPPT) algorithm. The explanation is that rechargeable batteries keep the panel's voltage almost constant, then require the same power for fixed or tracked photovoltaic panel, leading to errors in analyzing the performance of solar trackers. The authors of the article stated that solar tracking systems should be used regardless of whether or not they are expensive, simply because they reduce the area needed to build a plant by up to 60%.

Sidek *et al.* (Sidek *et al.*, 2017) presented a study on an azimuth-altitude dual-axis tracker. The system was designed and manufactured as shown in Figure 6. A DC motor was used to rotate the panel on the azimuthal axis and a linear DC motor was used to move the panel on the elevation axis. The tracker performance is analyzed in comparison to a fixed-tilted photovoltaic system. It was observed that, in relation to the fixed system, the tracker obtained a gain of 26.9% and 12.8% on sunny days and cloudy days, respectively.

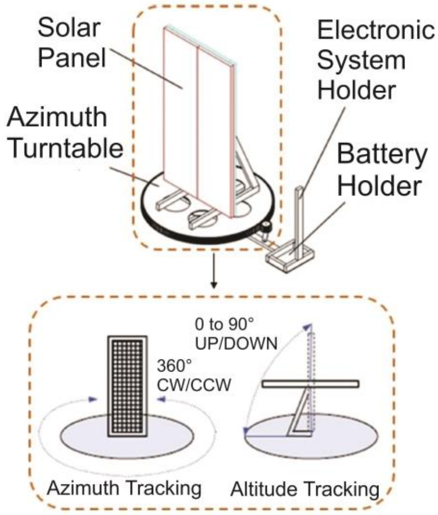

Figure 3. Design of dual-axis azimuth-altitude tracker. Adapted from Sidek *et al*. (Sidek *et al.*, 2017).

3 Influence of the locality on the viability of solar trackers

According to the review published by Mousazadeh *et al.* (Mousazadeh *et al.*, 2009), the use of solar trackers can increase the energy generated between 10 and 100% depending on the period of time and the geographic conditions. There are several geographic factors that influence the performance of a photovoltaic panel, such as overheating due to overexposure to solar radiation in high-temperature environments. Solar trackers can improve the efficiency and the energy gain of photovoltaic modules; however, they can present a negative influence in countries with hot weather. Eldin *et al.* (Eldin *et al.*, 2016) investigated the viability of solar trackers in hot and cold regions, more specifically in Egypt and Germany. The results showed that sun tracking is economically unviable in hot and sunny regions such as Cairo and Aswan in Egypt and highly recommended in cold regions such as Stuttgart and Berlin in Germany. In addition, large temperature variations throughout the year, present in some countries, make it more difficult to apply passive solar trackers.

Another factor of influence is the presence of clouds in the sky. Orgill and Hollands (Orgill and Hollands, 1977) state that, on extremely cloudy days, about 90% of global radiation is composed of diffuse radiation. Therefore, for a small amount of direct radiation, the use of passive solar trackers is not feasible. Instead, active solar trackers using appropriate strategies for cloudy days, such as date and time-based algorithms is more indicated (Clifford and Eastwood, 2004). It is important to emphasize the need for studies to limit energy consumption associated with unnecessary movements of solar trackers on cloudy days (Lazaroiu *et al.*, 2015). Koussa *et al.* (Koussa *et al.*, 2011) studied the performance of 5 configurations of solar trackers and 2 configurations of fixed photovoltaic panels. The daily electrical energy produced by the different systems was quantified separately for each sky state. It was found that for overcast days, all systems considered produced approximately the same amount of electrical energy and the horizontally positioned fixed panels presented the best performance. This result leads to an improved tracking algorithm that turns the panel to the horizontal position on cloudy days.

Bahrami *et al.* (Bahrami *et al.*, 2016) have developed a study to evaluate the effect of latitude on the performance of solar trackers. Sixty systems of seven different configurations were simulated across Europe and Africa. They found that the performance of east-west (EW) single-axis solar tracker was more influenced by the latitude than the other trackers. For latitude higher than 64°, the EW tracker is worse than the optimally fixed photovoltaic panel. Results also showed that the vertical-axis solar trackers perform much better at high latitudes. Therefore, it can be stated that the performance of the solar trackers is dependent on the geographic conditions.

4 Study of the technical and economic viability of solar trackers in seven cities in Brazil

In order to evaluate the influence of locality (latitude, longitude) on the viability of a solar tracker system, simulations of a 1 MWp power plant were performed using data from seven cities in Brazil: Pureza - RN (-5.4°, -35.7°), Bom Jesus da Lapa - BA (-13.3°, -43.8°), Montes Claros - MG (-16.7°, -43.92°), Franca (-20.5°, -47.5°), Manaus - AM (-3.0°, -60.2°), Santa Maria - RS (-29.7°, -54.0°), Teresópolis - RJ (-22.4°, -43.1°). The locations were chosen in different regions of the solarimetric map.

For all sites, the grid-connected plant was simulated in two cases. In the first case, the plant is composed of fixed panels and, in the second case, the plant is composed of single-axis solar trackers. The inclination of the photovoltaic panels of the fixed system was the optimum slope indicated by the PVSyst software. In both cases, 3330 panels of 300 Wp and 9 inverters of 100 kW were used. The equipment's specifications are shown in Table 1.

PVSyst software version 6.68 was used to size and to estimate the power generation in each location. The estimated amount of energy generated annually is expressed as "energy injected into the grid". The obtained results of energy injected into the grid were used to calculate the payback time and the profit after 25 years.

The profit after 25 years is calculated by (1), when M is equal to 300 months (25 years). The payback time is calculated by the same equation, when M is the number of months necessary for the profit to be equal to the initial investment.

$$\sum_{m=1}^{M}(EIIG_M.ET_M - D_M) = P \tag{1}$$

$EIIG_M$: Energy injected into the grid for the M^{th} month.

ET_M: Energy tariff for the M^{th} month.

D_M: Contracted energy demand for the M^{th} month.

P: Profit.

Table 1. Equipment's specifications.

Equipment	Brand	Model	Power
Photovoltaic panel	Canadian Solar ®	CS3K-300MS	300 Wp
Inverter	Fronius International ®	AGILO 100.0-3 Outdoor	100 kW

The mean annual horizontal global and diffuse radiations of each site, according to the Meteonorm 7.1 database, are shown in Figure 7. The locations were positioned in the descending order of global radiation. The results of energy injected into the grid annually for each location are shown in Figure 8. It is observed that there is a relation between the energy injected into the grid and the global radiation because the energy injected into the grid is smaller in cities with lower global radiation. Manaus - AM and Teresópolis - RJ are exceptions to the previous statement. One possible explanation is those places have higher values of diffuse radiation due to their high humidity indexes.

From the results of power generation, it is possible to investigate the economic viability of solar tracker systems. In this work, that investigation is performed by analyzing the payback time and the profit after 25 years. For a 1 MWp plant, average values of R$ 4.28 million were considered for the fixed-panels system and R$ 4.8 million for the solar tracker system. The inflation considered is equal to 8% per year. The energy tariffs and contracted energy demands considered in the calculations are shown in Table 2.

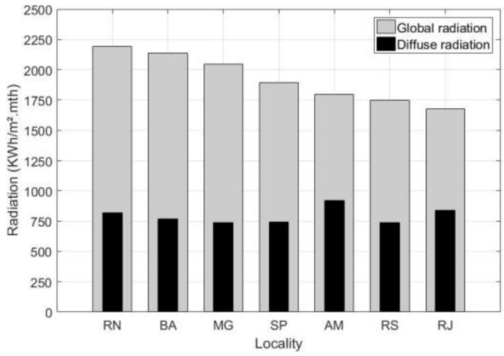

Figure 4. Horizontal global and diffuse irradiations for the tested locations.

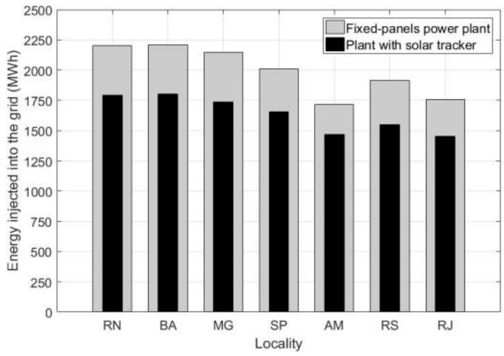

Figure 5. Energy injected to the grid by the fixed-panels power plant and plant with the solar tracker for the tested locations.

The payback time and the profit after 25 years for each location are shown in Figures 9 and 10, respectively. It should also be noted that in Pureza - RN and Bom Jesus da Lapa - BA, although the values of energy injected into the grid are close, the payback time and profit differ greatly, highlighting the influence of the energy tariff on the viability of the system. Pureza - RN has a higher payback time (55 months for the fixed-panels system and 48 for the system with solar tracker) than Bom Jesus da Lapa - BA (42 months for the system with fixed panels and 38 for the system with solar trackers), because the energy tariff in the state of Rio Grande do Norte is R$ 0.15 lower than the energy tariff in the state of Bahia. For this same reason, Franca - SP has the largest payback time. Even if it does not have the smallest generation of energy, it has the lowest energy tariff.

Table 2. Energy tariffs and contracted energy demands for each locality.

Cities	**Contracted energy demand (R$/kW)**	**Energy tariff + taxes (R$/kWh)**
Pureza (RN)	13.85	0.55
Bom Jesus da Lapa (BA)	18.88	0.70
Montes Claros (MG)	11.05	0.64
Franca (SP)	11.06	0.52
Manaus (AM)	16.44	0.86
Santa Maria (RS)	20.21	0.78
Teresópolis (RJ)	17.61	0.81

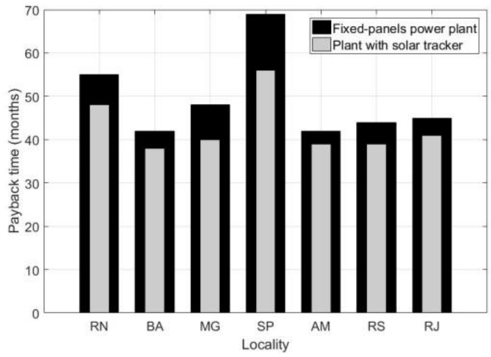

Figure 6. Payback time of the fixed-panels power plant and plant with the solar tracker for the tested locations.

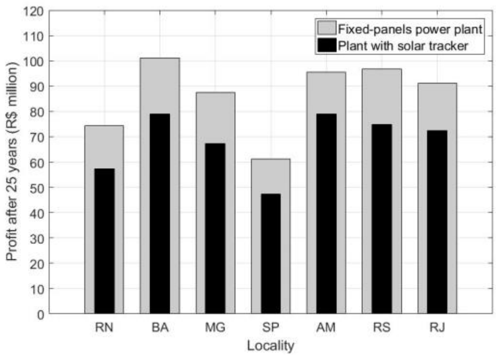

Figure 7. Profit after 25 years of the fixed-panels power plant and plant with the solar tracker for the tested locations.

Bom Jesus da Lapa - BA presented the best performance both technically and economically. Its system obtained the highest values of energy injected into the grid, being 1804 MWh for the system with fixed panels and 2210 MWh for the system with solar trackers. As well as the lowest payback time values, 42 and 38 months, respectively; and better profit values, R$ 79 million and R$ 101 million, respectively.

The payback time of a plant with solar trackers, for the studied locations, is shorter than the payback of a fixed-panels power plant, although its initial investment is higher. This is due to the energy gain provided by solar trackers. In some cases, such as Manaus - AM and Teresópolis - RJ, despite having low energy production, the use of photovoltaic plants with solar trackers becomes economically feasible because those states have high energy tariff values. They also use the same area as a fixed panel system to produce a greater amount of energy.

5 Conclusion

Solar trackers aim to improve the performance of a photovoltaic system by keeping the panels perpendicular to the sun's rays. In this article, the definitions of the different solar tracker topologies have been presented. The definitions were presented according to the tracking technology: passive or active; and the degree of freedom: single-axis or dual-axis. Passive trackers may be based on the thermal expansion of fluids or bimetallic strips or may use alloys with shape memory effect. Active solar trackers can utilize microprocessors and optical sensors, date and time-based algorithms, or a combination of both to detect the position of the sun. As for the degree of freedom, there are four types of single-axis solar trackers: HSAT, VSAT, HTSAT and PASAT; and two types of dual-axis solar trackers: tip-tilt and azimuth-altitude.

Lastly, simulations were performed to evaluate the influence of locality on the viability of solar trackers. The results showed that, between the tested locations, Bom Jesus da Lapa - BA presents the best performance, both technically and economically, since it presented better values of energy generation, being 1804 MWh for the plant with fixed panels and 2210 MWh for the plant with solar trackers. That location also presented better results of payback time and profit, being 42 months and R$ 79 million, respectively, for the fixed-panels power plant, and 38 months and R$ 101 million, respectively, for the plant with solar trackers.

The results also showed that plants with close values of energy injected into the grid may have different payback time and profit values if they are installed in locations with different energy tariff values. In addition, the payback time and the profit of a plant with solar trackers present better values than a plant with fixed panels for the tested regions, despite the higher initial cost. It shows the potential of using solar trackers in Brazil.

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