



PERFORMANCE OF SINGLE AXIS SOLAR TRACKING SYSTEM FOR PHOTOVOLTAIC ENERGY GENERATION

Vanessa de Fátima Grah¹, Isaac de Matos Ponciano², Ezequiel Saretta³, Dinara Grasiela Alves⁴ & Tarlei Arriel Botrel⁵

ABSTRACT: More and more, alternative energy has gained attention in the national and international energy industry, turning solar photovoltaic (PV) energy in a promising source to generate electricity. In Brazil, 2 million of people live in rural areas without electricity, what limits the social, economic and agriculture development in these locals. The goal of this work was to propose a new design of concept of one axis three-steps sun tracking system (east-west) that operate manually, and to evaluate its productivity increment in PV energy when compared with static PV generators. The three steps tracking angle throughout a day, the PV generator angle that best fits the irrigation season, and the position movement of the PV generators were all calculated before installing the equipment in the field. The PV modules were installed in an experimental field of the Department of Biosystems Engineering-ESALQ, the irrigation season was settled as the period of months with lower precipitation in Piracicaba during 2012. The manual three-steps tracking system was composed by steel cables attached to the PV generators structure, so that in the morning they got tilted 50° to east, between the hours next the noon they got tilted to north (0° in relation to east-west axis), and in the afternoon they got tilted 50° to west. The increment of energy varied among 1.5 and 6.1 MJ m⁻² day⁻¹ (15 to 19%), according the daily sky condition, demonstrating that the manual three-steps tracking PV generators with optimized tilt angle β for the irrigation season were more efficient than fixed generators.

KEYWORDS: Solar energy, energy efficiency, partial segment.

DESEMPENHO DE UM RASTREADOR SOLAR DE UM EIXO PARA GERAÇÃO DE ENERGIA FOTOVOLTAICA

RESUMO: Cada vez mais as energias alternativas vêm ganhando destaque na matriz energética nacional e internacional, dentre elas, destaca-se a energia solar fotovoltaica (FV) a qual é uma fonte promissora de geração de energia elétrica. No Brasil mais de 2 milhões de pessoas vivem na área rural sem energia elétrica o que limita o desenvolvimento social, econômico e agrícola desses locais. O objetivo deste trabalho foi propor um novo conceito de sistema de rastreamento solar de três passos de um eixo (leste-oeste) com operação manual, e avaliar o incremento de energia FV produzida quando comparado com geradores FV estáticos. Antes da instalação dos geradores a campo foram calculados os três ângulos de rastreamento ao longo do dia; o ângulo do gerador fotovoltaico que melhor se adéqua à estação de irrigação e a hora da troca da posição dos geradores. Os módulos FV foram instalados em uma área experimental do Departamento de Engenharia de Biosistemas - ESALQ, a estação de irrigação foi definida como sendo os meses de menor precipitação em Piracicaba no ano de 2012. O sistema rastreador manual de três passos consistiu no uso de cabos de aço presos a estrutura dos geradores FV de modo que na parte da manhã ficavam inclinados a 50° para o leste, entre os horários próximos ao meio dia ficavam inclinado para o norte (0° em relação ao eixo leste-oeste) e na parte da tarde ficavam inclinados a 50° para o oeste. O incremento de energia variou conforme a condição diária do céu, entre 1,5 a 6,1 MJ m² dia⁻¹ (15 a 19%), demonstrando que o sistema rastreador de três passos em geradores FV com ângulo β otimizado para a estação de irrigação foi mais eficiente que geradores fixos.

Palavras-Chave: Energia solar, eficiência energética, segmento parcial.

NOMENCLATURE

φ - Geographic latitude (deg)
δ - Declination angle (deg)
ω - Hour angle (deg)
θ_z - Zenith angle (deg)
α - Solar altitude (deg)
ψ - Solar azimuth (deg)
β - Tilt angle of plane to ground (deg)
θ_i - Incidence angle of light rays (deg)
ρ - Tracking angle (deg)
γ - Aperture azimuth angle, 90° in the morning, 0° at noon and -90° in the afternoon (deg)
σ - Ground albedo (-)
L_l - Local latitude (deg)
L_p - Pattern longitude (deg)
β' - Angle between the tracking plane and the ground after the plane is rotated by the ρ angle (deg)
ΔE - Energy increment (MJ day)
ω_{NS} - sunrise hour angle (deg)
$I_{T,A}$ - Total Irradiance incident on a tilted surface (MJ day)
$I_{B,A}$ - Beam Irradiance incident on a tilted surface (MJ day)
$I_{D,H}$ - Diffuse Irradiance on a horizontal surface (MJ day)
$I_{T,H}$ - Total Irradiance incident on a horizontal surface (MJ day)

1 INTRODUCTION

The technology involving photovoltaic energy generation has been rapidly improved in the last years, especially through the development of technological industries. Photovoltaic energy has shown a potential for cost reduction and better conversion efficiency, and it is believed to become one of the primary source of energy supply in the future (Chang, 2010). According to data from the United Nations (2010), solar energy is expected to become cheaper than conventional energy sources in the near future, due to two main factors: continuous development of photovoltaic technology, and to fossil fuels raising prices. In this scenario, Brazil has the advantage of being a tropical country, with 92% of its land located above the Tropic of Capricorn, which provides a great potential for photovoltaic energy generation. Solar radiation in Brazil ranges from 8 to 24 MJ m⁻² day⁻¹, and the seasonal variations in the Northeast region are small, which may lead to technical and economical advantages (TIBA et al., 2000).

An effective instrument to the sustainable development of rural areas in developing countries is the electricity availability, especially in arid region (QOAJDER and STEINBRECHT, 2010). According to the Brazilian Institute of Geographic and Statistic, until 2000, about 10 million Brazilians that live in rural areas had no access to electricity, most of them living far from supply networks, mainly in North and Northeast. Fortunately, this number decreased to about 2.3 million in 2010. In Brazil, electricity distribution among the different regions can be assessed in terms of the social economic condition: in places where there is no electricity network, the family income is lower than three minimum wages (IICA, 2011).

Energy and water have been the most important input in the Brazilian productive chain in current days, mainly in agriculture production. This way, it is important to

consider that the water can be a powerful factor that retain people in the countryside (MOREIRA et.al, 2012). Besides that, in rural areas without access to conventional electric energy, such alternatives as the use of solar energy are feasible and a highly relevant solution (GABRIEL FILHO et.al, 2013). Thus, the availability of electricity may improve the economic situation of these regions, as well as health pattern, education, communication, and the access to clean water. This fact is important mainly to small family farms, which food production is significant mostly in social than economic aspect (FEITOSA et al., 2014).

The current photovoltaic cells have their efficiency of transforming solar energy into electrical energy under the expectations, and there is not yet any technology that might improve this performance (DEMAIN; JOURNEÉ; BERTRAND, 2013). The attempts to improve photovoltaic energy generation consist in optimizing the installation angle in order to have sunlight reaching the PV generator surface perpendicularly throughout the day (KALDELLIS et al., 2012). This way, the energy-generating cells may obtain a constant maximum power. To set the angles to an optimum, a control system is necessary to track the sun and adjust the angles of the generators. Over the last 35 years, studies about tracking systems, optical elements to concentrate the solar radiation, and about especially cells for use under high solar concentration have been performed by several researches (VIANA et. al, 2012).

Basically, there are three fixing configurations of PV generators: i) static generator, ii) partial tracking system, moving only one axis (single axis); and iii) total sun tracking system which moves in two axis (double axis), varying both the inclination and the azimuth angle of the generator. According to Chun-Sheng (2008), researches showed that single axis sun tracking systems can increase the electricity production in 20%, while the double axis type, in 40%. The selection criteria for each type of tracking system, as well as if it will be automatic

or manually operated, depend on factors such as financial resources, availability of technical assistance for constant maintenance and repairs, and available of manpower to movement the PV generators. In terms of automatic tracking systems, Alvarenga (2006) stated that is important to evaluate if the PV increment in productivity associated to automatic tracking system compensates the cost. Besides, many problems can happen in automatic systems that do not occur with manual system, like control system complications, higher consumption of energy, higher cost of maintenance, and less reliability (Ai et. al, 2003). Consequently, it is more suitable to use a manual tracking.

The purpose of this work was to propose a new concept design for a single axis three-steps manually operated sun tracking generator, evaluate the energy productivity expected increment and compare it to static generator productivity.

2 MATERIAL AND METHODS

The experiment was carried out at the experimental area of the Department of Biosystems Engineering of Luiz de Queiroz College of Agriculture, University of São Paulo, located in Piracicaba-SP, Brazil (22°42'30" S; 47°38'00" W; 546 m). The area is indicated at the center of Figure 1.



Figure 1 - Experimental area localization
Source: Google Earth

2.1 CONCEPTUAL DESIGN OF THE SUN

As shown in Figure 2, the three-steps sun tracking (3-ST) is single axis PV generator oriented northward by tilt angle β , best fitted for the irrigation season, that will be hereinafter described.

Daily adjustments of the tracking angle ρ , which is equivalent to the inclination between the west-east direction and the 3-ST plane, allowed the perpendicular incidence of the beam radiation through the day. Three tracking angles were calculated for three periods of the day, and set by rotating the generators: one for the morning hours, other for hours around noon, and the last for the afternoon.

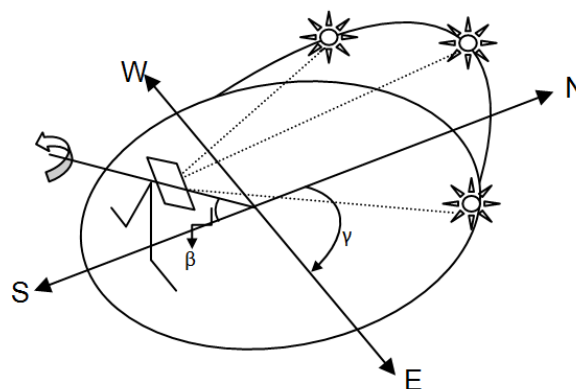


Figure 2 - Design of the three-steps tracking system (3-ST), with partial segment. Adapted from Ai et.al (2003).

Such adjustments of the tracking angles ρ were manually done using steel cables (Figure 3).

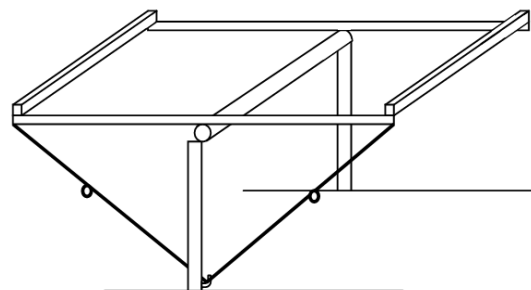


Figure 3 - Adjustment of PV structure by cables.

The same structure presented in Figure 3 was used for a static generator, which was aligned east-west during the day. This way, for 3-ST performance evaluations it was considered the energy conversion increment between the two scenarios: 1°) Conventional situation, with static PV generators and tilt angle (β) optimized for the lower solar radiation season; 2°) Proposed situation, with PV generators in 3 tracking angles (morning, noon, and afternoon) and tilt angle optimized for the lower solar radiation season.

2.2 OPTIMIZATION OF SUN TRACKING ANGLES AND TIMES OF ADJUSTMENT

In order to determine the tracking angles, and the hours of angle changes throughout the day, the data of Horizontal Global Irradiance from 2012, obtained from the Weather Station of the Department of Biosystems located nearby (2.0 km) from de experimental area, was used. Tilted irradiance was calculated from the data of horizontal irradiance for both the fixed and the tracking generators. The clear days, cloudless, from 2012, were selected according to the atmospherical characterization adapted from Iqbal (1983). Months of 2012 with lower rainfalls and more necessity of irrigation were determined as the irrigation season. A historical data series of 95 years from the weather station confirmed that 2012 presented the lowest average rainfall amount.

Some sun angle positions to the center earth are important to assemble a photovoltaic (PV) system, especially those with a tracking mechanism, such as: latitude angle (Φ), declination angle (δ), and the hour angle (ω), Figure 4.

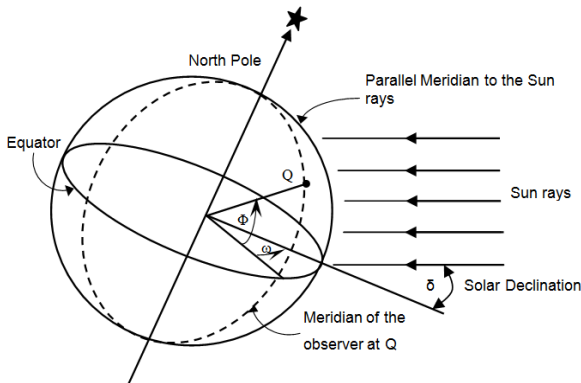


Figure 4 - Illustration of angles of Sun position in relation to Center Earth Coordinates. Adapted from Ai et.al (2003).

There are still other angles referring to an arbitrary location on the surface of the earth: zenith (θ_z), solar altitude (α) and the azimuth (ψ), Figure 5.

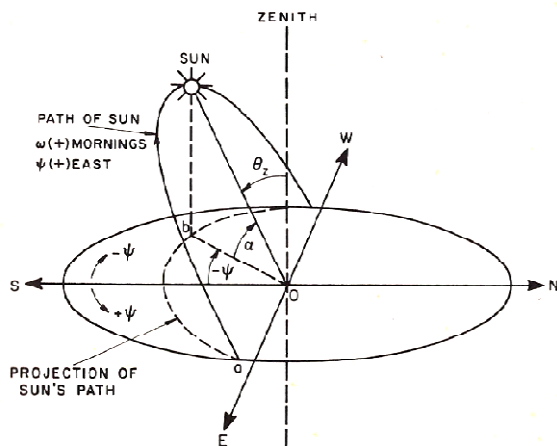


Figure 5 - Definition of zenith, solar altitude, and azimuth

Source: Iqbal (1983), for an observer in the North Hemisphere

These angles are important to predict the angle formed between the sun rays and the generator normal vector (perpendicular), which is called angle of incidence (θ_i), Figure 6.

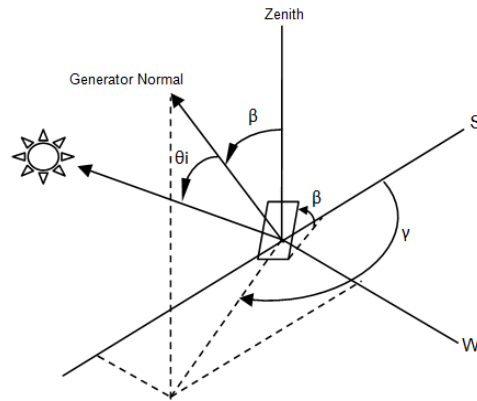


Figure 6 - Demonstration of the incident angle on a tilted surface

The θ_i is of great importance for solar projects, since it allows the maximum amount of energy to reach the photovoltaic generator. Another important one is the tracking angle (ρ), which can be a function of one or two tracking axis. By this angle, the sun rays reach the generator perpendicularly according to the type of the tracking system. Hour, zenith, and altitude solar angles were calculated through traditional equations obtained from trigonometric relations (Iqbal, 1983). The equations proposed by Cooper (1969) and Stine & Geyer (2001) were used, respectively, for solar declination and solar azimuth. The incidence angles of the sun rays on the tracking generator were obtained according to the methodology proposed by Stine & Geyer (2001), using Equations (1), (2), and (3). For the fixed generator calculations, only Equation (2) was used.

$$\cos \theta_{i \text{ morning}} = \sin \alpha \cos \beta' + \cos \alpha \sin \beta' \cos(\gamma - \psi) \quad (1)$$

$$\cos \theta_{i \text{ noon}} = \sin \alpha \cos \beta + \cos \alpha \sin \beta \cos(\gamma - \psi) \quad (2)$$

$$\cos \theta_{i \text{ afternoon}} = \sin \alpha \cos \beta' + \cos \alpha \sin \beta' \cos(\gamma - \psi) \quad (3)$$

The angle β for both static and 3-ST system was calculated using equation 4 (DOUSOKY; EL-SAYED; SHOYAMA, 2011). This equation considers the optimization of the PV energy generation from during a certain period of the year. In this case, the irrigation season, between Julian days 122 and 271.

$$\beta = \phi - \delta \quad (4)$$

the 3-ST angle β' between the tilted plane and the ground, after rotating ρ degrees, was calculated according to by Ai et al. (2003) Equation (5).

$$\sin \beta' = \sin \beta \sqrt{1 + \frac{\sin^2 \rho}{\tan^2 \beta}} \quad (5)$$

The tracking angle (ρ) optimizes energy generation after the movement of the generator ($-\gamma$ in the morning and γ in the afternoon). The selection of ρ consisted in choosing the value that provided the higher increment of energy obtained on a tracking tilted surface compared to a static tilted surface, using the total incident irradiance. The incident irradiance on a tilted surface was calculated using the Stine and Geyer (2001) equation, according to

the Liu and Jordan (1963) method and improved by Klein (1977). The total incident irradiance on a horizontal surface data were obtained from the historical series of a weather station in Piracicaba. Diffuse irradiance on a horizontal surface was calculated by Grace (2006) equation, which follows the Liu & Jordan (1963) isotropic model. Finally, equation (6) provided ρ values by increments of energy (ΔE).

$$\Delta E = I_{B,A+} \left[I_{D,H} \left(\frac{1 + \cos \beta'}{2} \right) + \sigma_{T,H} \left(\frac{1 - \cos \beta'}{2} \right) \right] - I_{B,A+} \left[I_{D,H} \left(\frac{1 + \cos \beta}{2} \right) + \sigma_{T,H} \left(\frac{1 - \cos \beta}{2} \right) \right] \quad (6)$$

The β angle and β' are settled, and the tracking angle varied from 0° to 90° (steps of 10°). The ρ angle which presented the greatest energy increment was used on the proposed system during the irrigation season. Regarding the sunrise hour angle (ω_{NS}), the times to rotate the PV generator with the tracking angle are determined using the calculations exposed on Table 1, proposed by Ai et al. (2003).

Table 1 - Calculation to change the tracking angle three times

Tracking angle	Regulation time (Solar time)	Hour angle interval (deg)	Rotation angle (deg)
ρ_{morning}	$12 - \frac{1}{15} \omega_{NS} $	$- \omega_{NS} \rightarrow -\frac{1}{3} \omega_{NS} $	$-\frac{2}{3} \omega_{NS} $
ρ_{noon}	$12 - \frac{1}{45} \omega_{NS} $	$-\frac{1}{3} \omega_{NS} \rightarrow \frac{1}{3} \omega_{NS} $	0
$\rho_{\text{afternoon}}$	$12 + \frac{1}{45} \omega_{NS} $	$\frac{1}{3} \omega_{NS} \rightarrow \omega_{NS} $	$\frac{2}{3} \omega_{NS} $

The hour angle $|\omega_{NS}|$ used on Table 1 can be calculated according to the equation proposed by Klein (1977). Since the tracking system was manually moved, three tracking angles were selected to be used as base to rotate the modules: ρ_{morning} to the westward orientation from sunrise until the first regulation time, when the generator was adjusted to ρ_{noon} , aligning it east-west, and then, $\rho_{\text{afternoon}}$ at the second regulation time, until sunset.

2.3 Evaluating The Productivity Increment Of Pv Energy

Besides the 3-ST, other static generator was built to evaluate the tracking system expected energy increment. The static system remained fixed, northward orientated over all season. The two systems were comprised by two separated sets of five PV modules each, as show in Figure 7. In addition, both generators were tilted with the angle β , optimized to irrigation season. The only difference between the systems was the movement of the 3-ST, according to the tracking angles ρ .



Figure 7 - Static modules with two sets of five PV generators each

Two pyranometers (Kipp and Zonen Company-SP - lite model) were installed on the top of the front set of each generator, on the same plane of the modules surface (Figure 8). Then, a datalogger acquired and stored solar irradiance data from each sensor. Comparing the data from pyranometers installed to the static and to the 3-ST PV generators, it was possible to evaluate the energy increment of PV generated using a manual three-steps tracking system.



Figure 8 - Pyranometer installed on the same plane of the Photovoltaic generator.

Each PV generator operated at 17.7 V and 7.91 A so the potential of generating was up to 140 W of power. Generators were connected in parallel in each set to increase the current, and the two sets were connected in series to increase the voltage. Hence, each system could provide a peak of 1400 W. Charge controllers (model C40 from Schneider Electric) were used to equalize the operation by regulating voltage of two batteries, with a DC-AC current inverter (PROSINE 1000 from Xantrex Company). Two batteries of 45 Ah each (Freedom model from Heliar Company), connected in series, temporarily stored energy for the controller to allow starting a pumping system, which consumed the energy.

3 RESULTS AND DISCUSSION

The irrigation season was defined as being the months from May to September based on the Piracicaba’s 2012 average rainfall (Figure 9). However, June had a great amount of rainfall, which was an atypical event.

In the irrigation season of 2012, most days had Kt values of 0.65, which is a characteristic of days with clear sky, according to the classification of Escobedo et al. (2009).

Teramoto and Escobedo (2012) states that solar radiation is one of the most affected meteorological variables by the presence of clouds in the sky. Therefore, it is important to identify the pattern of nebulosity to understand the dynamics of energy falling on the photovoltaic generators. Global atmospheric transmittance or Clearness index (Kt) (Kasten, 1966), which is the ratio between the global solar radiation and the radiation at the top of the atmosphere, indicates the percentage of cloud cover (Souza et al., 2012).

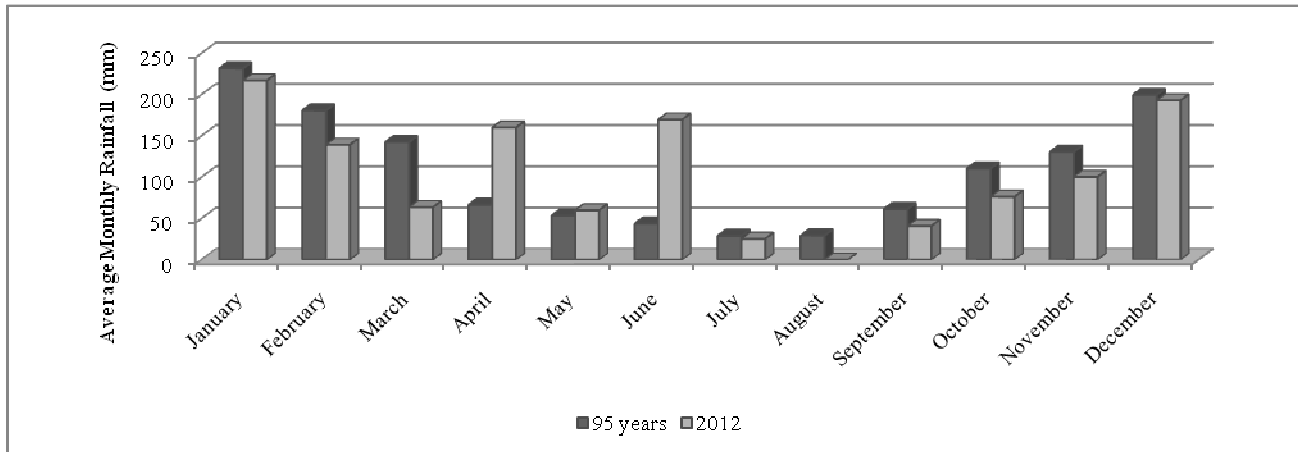


Figure 9 - Precipitation data from 2012 and the previous 95 years from ESALQ’s weather station.

The angle β calculated, the value between the generator surface and the Zenith, was 38° for both systems. This way, the generators could obtain the potential energy from the sunrays, regarding to their efficiency.



Figure 10 - Three steps tracking system.

Figure 11 shows the increment of PV energy using manual 3-ST systems compared to static PV generators through 40 days during the irrigation season. The daily increment energy was 15% and for clean sky days it reached 19%. According to Lave and Kleissl (2011) the gains can also be higher in regions with more clear sky days, where optimizing tracking angle may strongly impact the irradiation. This also happens in regions with irrigation season well defined, when the precipitation is low or null, and the clear sky predominates over months.

This weather pattern can be found in the Brazilian Cerrado. Carrilho Sobrinho et. al (2013) found 80 and 90% of clear and partially cloudy sky, respectively in a Cerrado area, between June and July.

Caton (2014) emphasizes that there are many studies in the literature of various array orientations and tracking strategies but little agreement as to the relative benefits. Compared to a fixed-slope array, a full two-axis tracking system is reported to result in gains of 40%, 30%, 44%, 29.3%, and between 33-43% (Hankins, 1995; Helwa et.

al, 2000; Neville, 1978; Kacira et. al, 2004; Gordon & Wenger, 1991; respectively). For single-axis tracking system, reported benefits dependent on re-adjustment frequency, e.g., for a polar axis system (Vilela et. al, 2003; Gordon e Wenger, 1991) the were around 11% to 32%.

Lave and Kleissl (2011) illustrated that some of this variation is due likely to latitude and local weather pattern, they compared double axis system to fixed slope array and it showed a range of gains between 25-45% , where these gains increase with latitude. Caton (2014) evaluating different tracking system, including double-axis and single-axis, observed that when re-orientation the axis over the year or monthly did not

showed significant differences in the increment of energy but showed a significantly benefit with hourly re-orientation. Among the systems studied, the author found a gain between 2.3% to 15%, being the major increment form hour tracking system.

Fraidenraich and Barbosa (1999) evaluated a solar tracking in PV generator installed in Recife –PE (latitude de 8° S) and observed an annual benefit of 26% compared to fixed slope array. Also in Recife, Vilela et al. (2003) evaluated a partial tracking system (east-west) and compared to fixed slope generators, and found an annual increment of 20% in the energy generated.

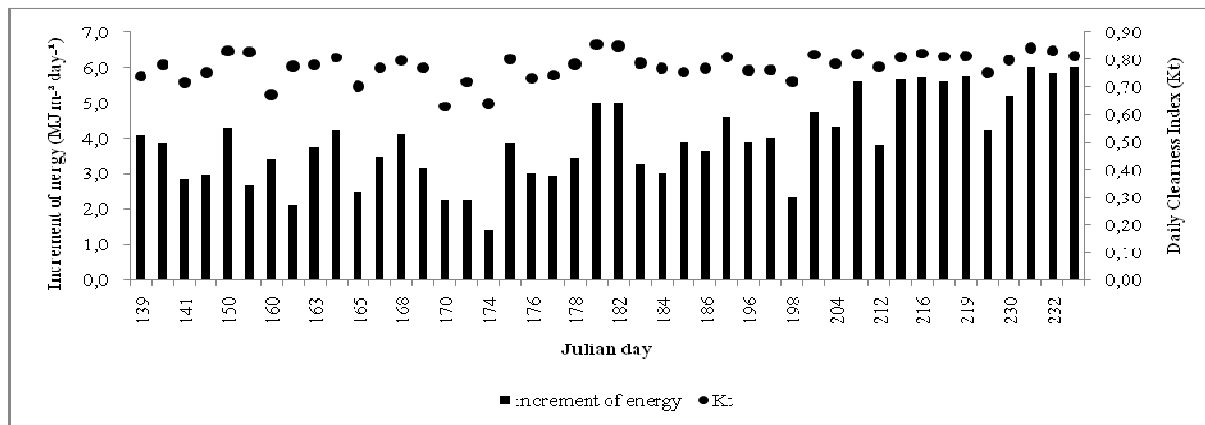


Figure 11 - The increment of photovoltaic energy using manual three-steps tracking systems compared to static photovoltaic generators.

4 CONCLUSIONS

The PV system with the manual tracking produced 1.852 MJ m⁻² and the fixed generators, 1.005 MJ m⁻², resulting in an increment of 177 MJ m⁻².

The calculation procedures proved to be adequate for estimating tracking angles and the optimum tilt angle (β) for the irrigation season, using only data of one year of global horizontal irradiation.

For the estimation of energy generated, the manual three-step tracking PV generators were more efficient than fixed generators, proving that this type of tracking system is a feasible alternative for the city of Piracicaba-SP.

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