THE ADVANTAGES OF SOLAR TRACKER

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Abstract: Solar tracking systems allow greater efficiency of a photovoltaic system by continuously adjusting its position in relation to the sun, thus increasing the generation of electrical energy. The integration of photovoltaic solar tracking systems in a photovoltaic plant allows the energy needs of users to be met more widely in a smaller area. This integration is facilitated by the existence of technologies such as access to the Internet via Wi-Fi, which allows the development of systems to be included in the domain of "Cloud" and Automation 4.0. In this study, an "open circuit" solar tracker, the first of its kind designed in Brazil on a plant scale, was designed and developed, which runs the tracking algorithm in the service programmed in a PLC, which has a Wi-Fi module integrated. This study opens the possibility of integrating power generation systems in the Cloud domain, which among other things, allows constant monitoring of the system's behavior with Solar tracking.

Keywords: Solar Tracker, Photovoltaic System, Automation 4.0

INTRODUCTION

Due to the sizeable environmental impact caused by using fossil fuel to generate electrical energy, it became necessary to search for new renewable sources.


Moreover, the actual global environmental restrictions promote the search for renewable sources, mainly wind and solar energy. The technology development to obtain electricity due to the sun were intensify, at first, by telecommunication company to attend systems installed on remoted places. Another booster agent was the space race. The first solar deal happened in 1954 to a satellite.

Over time, new technologies were implemented in order to improve generation efficiency, among which the use of solar trackers stands out, with the function of monitoring the position of the sun throughout the day (East-West). This strategy provides an efficiency/generation gain over the fixed solar panel farms (Lee & Rahim, 2013). To adjust the angle of attack of the solar incidence in relation to the surface of the solar panels, some methods such as trackers and trackers with two axes have been emerging. Thus, the generation system is able to follow the movement of the sun throughout the day.

Besides approaches to increase the productivity of systems, the price of power unity or Watt has become lower with the advancement of technology. For residential systems, the cost of the Watt is $ 2.80 for direct current (DC) and $3.22 for alternate current (AC). The commercial cost is now around $1.85 in DC or $ 2.13 in AC (Allamehzadeh, 2019).

Systems that have two degrees of freedom are already a reality, being able to track the exact path of the sun using sensors triggered by sunlight and motors to perform the movement of the solar panels. However, just following the sun and obtaining the best generation angle is insufficient. In order to have a large part of the radiation pierce in the silicon of the photovoltaic modules, it is necessary to clean the glass of the surface of the solar panels. Thus, cleaning strategies are also being studied to ensure maximum absorption of sunlight. For a dynamic system, there are less accumulation of dirt on the surface of the photovoltaic modules. (Said, Alaoui, et al, 2018).

Besides using physical/mechanical methods to optimize the efficiency of photovoltaic systems, the maximum power point tracking (MPPT) strategy is fundamental for photovoltaic systems, since one of the characteristics of solar irradiation is its intermittence. In this way, the MPPT control ensures that maximum energy is constantly extracted under any conditions of irradiation and temperature. Several algorithms have been proposed in the literature to perform the MPPT, such as disturbance and observation (P&O), Incremental Conductance (IncCond), Artificial Neural Network (RNA), Control by Fuzzy Logic (CLF) (Poojitha et al, 2019).
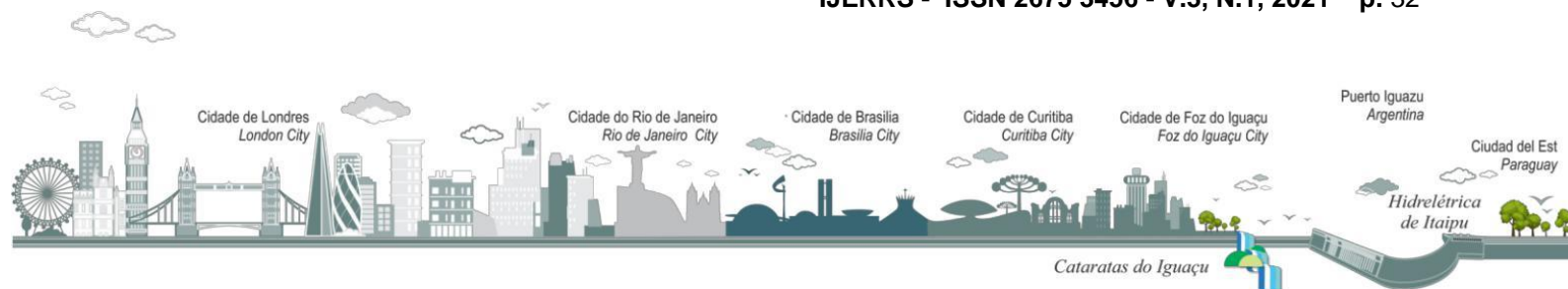
STATE OF ART

Solar trackers can be classified according to different criteria, such as the type of movement, degrees of freedom, and the control method (AL-Rousan, 2018). As for the type of movement, solar trackers are classified into passive and active. Passive trackers are based on the difference in density that results when a substance changes its temperature and not electronic components to control the movement of the tracker. As a commercial example of these types of trackers, the Zomeworks Corporation has been manufacturing them since 1969 (Randall, 1984). However, these trackers are highly dependent on climatic conditions, which can decrease their effectiveness. Because of this, active solar trackers are the most used option today. Active trackers are dependent on motors, gears, and other drivers to carry out the movement of the structure. Regarding the degrees of freedom, solar trackers are classified into single and two axes. Different configurations can be designed for each of these types. The main settings are settings in Figure 01.
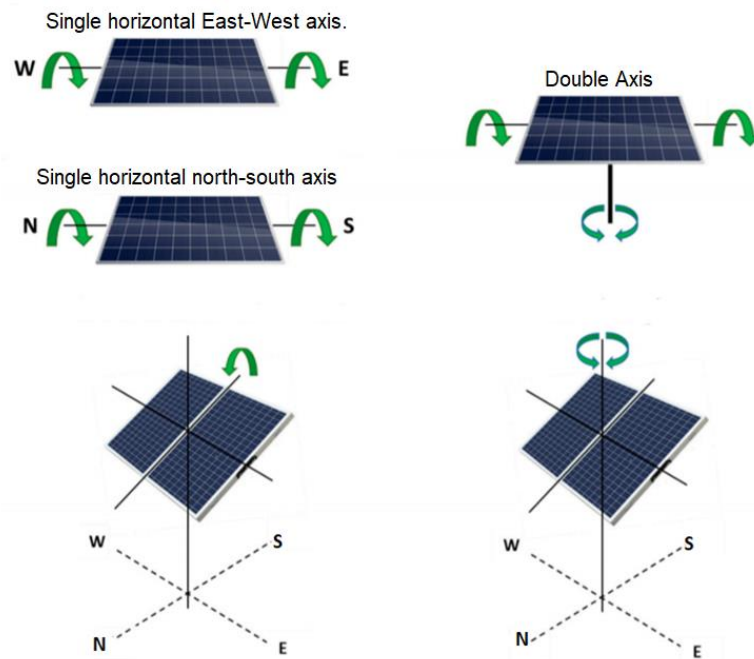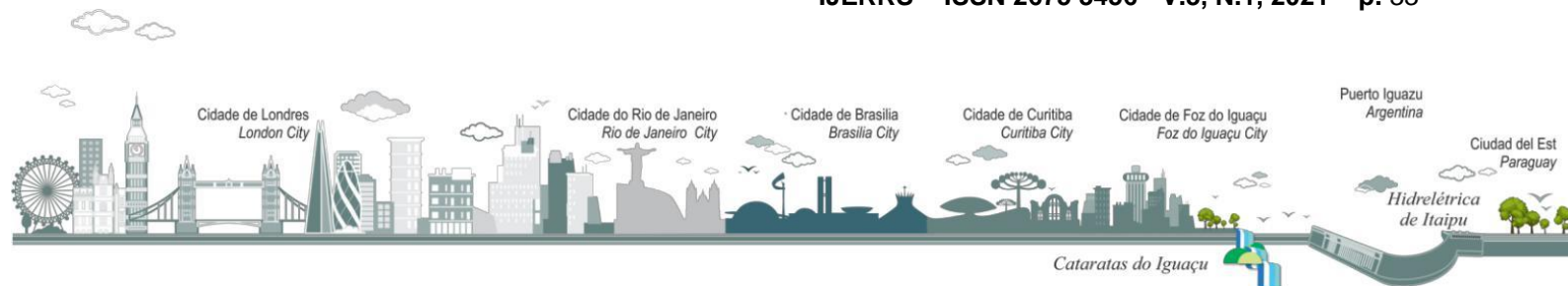

Figure 01: Example of types of trackers

- Single horizontal East-West axis.

- Single vertical axis with inclination equal to the latitude.

- Single vertical axis with inclination equal to the latitude.

- Single horizontal north-south axis.

The two-axis tracker is the one that allows the percentage of energy gains compared to the fixed system, as it keeps the photovoltaic modules perpendicular to the sun's rays during the day. However, the double rotational movement adds cost and difficulty of maintenance. To simplify the structure and control, single-axis trackers are more used for plant implementation. Concerning the control method, solar trackers are classified into sensor drive systems, microprocessor driver systems, open closed circuit driver systems, intelligent driver systems, and a combination of any of the systems mentioned (Huang, 2013).

Sensor driver systems employ photo sensors that provide a feedback signal (voltage or current) that can be used to trigger the solar tracker. Microprocessor driver systems use algorithms and mathematical equations to calculate the position of the sun and generally employ programmable logic controllers (PLCs) or peripheral interfaces such as a Human Machine Interface (HMI). A combination of PLC and photosensors can be used to reduce system tracking errors with programming logic alone. The control algorithm can be open-loop or closed-loop. Open-loop algorithms do not require sensors, as they use dates and time as fixed variables, their safety is the limit switches installed at their ends, while closed-loop algorithms depend on the feedback provided by the sensors such as pyrometer. Intelligent driver systems use algorithms based on fuzzy logic or artificial neural networks to improve control characteristics (Sidek, 2017). Open-loop systems are a good option for active control in applications that do not require high tracking accuracy, such as flat-panel PV systems. This method avoids the need for sensor maintenance and is very stable, even in cloudy conditions. As the project proposed in this study is open-loop, then the prototypes reported in the literature for open-loop tracking systems will be summarized.

A single-axis solar tracker with 3 open-loop positions was designed and tested (Huang, 2013). He used a PIC microprocessor, with a timer integrated circuit (IC), a direct current (DC) motor controlling the movement of the tracker, and additional electronic components mounted on a printed circuit board (PCB). A fixed time was defined for each of the three inclination angles, and a rotary type of resistor was used to detect the angular position of the PV module.

A two-axis open loop solar tracker for its implementation with a Fresnel lens to concentrate sunlight on a Stirling engine was proposed in (Yang, 2017). A single-chip microprocessor (AT89S52) was used to store the information provided by a global positioning system (GPS) module (EM-406A) and a real-time clock (RTC) and to calculate the corresponding altitude and azimuth angles. Two different stepper motors adjusted the positions of the axes and additional photovoltaic modules, in which they provided the energy to move the structure.
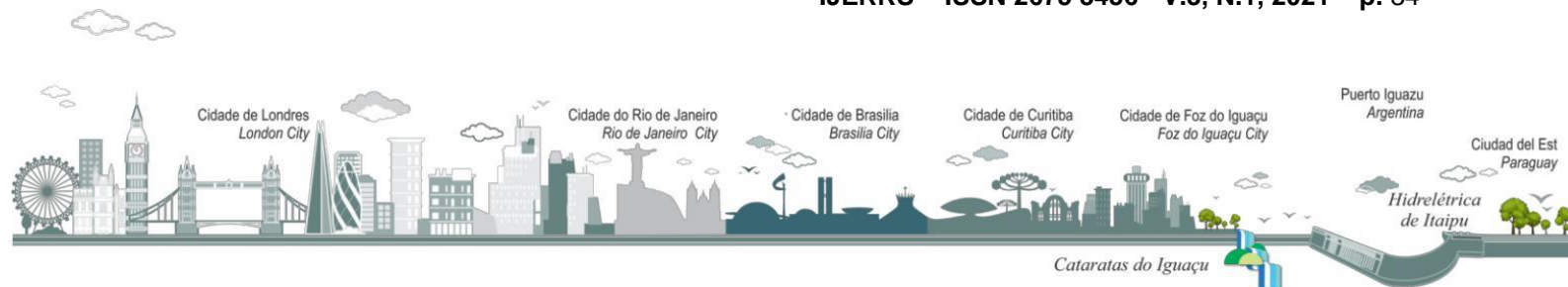
A small prototype of a two-axis open circuit solar tracker was tested (Melo, 2017), implementing two different algorithms that control the intervals between readjustment movements: one algorithm using a fixed interval time, while the other calculates the difference between the actual position of the sun and the position of the last movement to decide whether a new movement is necessary. The differences in performance of both open-loop algorithms were very small for daily searches numbered over five.

An automated two-axis solar tracking positioning system was proposed in (Sidek, 2017) controlled by a microcontroller unit (MCU) and with peripherals, such as an encoder and a GPS. The MCU consisted of a master controller (PIC18f4680) in charge of performing the algorithm, arithmetic calculations, and database generation, with two additional slave mode microcontrollers in charge of controlling the moto driver and obtaining feedback from the encoders for adjusting altitude and azimuth. A compass was added to provide the system with a true north reference so that, along with GPS, tracking systems could be implemented anywhere in the world.

A two-axis open-loop solar tracker was evaluated and compared to a fixed system (Senpinar, 2012). A three-phase alternating current (AC) motor was used for the East-West axis, while a DC motor was used for the north-south axis. An encoder that provides feedback to an input/output data card (I/O) was used to record measurements for storage on a computer.

The review of the technical characteristics of the existing open circuit solar trackers reveals that Cloud technology was not applied in this field to integrate solar trackers in smart plants as well as their use in Latin America. The present study tries to fill this knowledge gap.

Theoretical analysis of energy gains from solar tracking

The percentages of energy gains of a tracking system compared to a fixed system are dependent on the type of tracker, location, and station. The different ideal irradiations collected by the different types of solarimetric stations, trackers were analyzed for Cascavel, West of Paraná State - Brazil -24 ° 57'54.96 "S, -53 ° 25'47.50" O. Ilumisol's new headquarters. The method inputs were the twelve-monthly mean daily global horizontal irradiation values (GHId) in $kWh/m^2 day$

 taken from the Forecast of the National Aeronautics and Space Administration Worldwide Energy Resources website (NASA POWER, 2019). Typical profiles of global horizontal irradiance (G(0)) in kW/m² for the day in the middle of each month at 5-minute intervals were calculated as (Whillier, 2020).
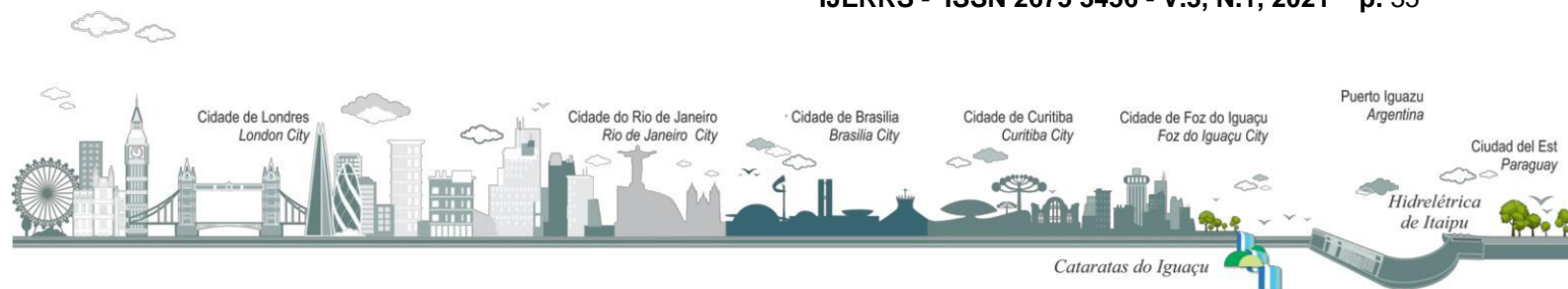
$$G(0) = (\pi/24) \cdot [(\cos \omega - \cos \omega_s)/(\omega_s \cdot \cos \omega_s - \sin \omega_s)] \cdot (a + b \cdot \cos \omega) \cdot GHId$$

$$a = 0.4090 - 0.5016 \cdot \sin(\omega_s + 1.047)$$

$$b = 0.6609 + 0.4767 \cdot \sin(\omega_s + 1.047)$$

Where ω is the angle of the solar time in radians and ωs is the angle of the solar time at sunrise for the day. Trigonometric terms are expressed in radians. The position of the sun for each value ω was determined by the elevation angle (γs) and the azimuth angle as (ψs) (Walraven, 1978).

$$\sin \gamma_s = \sin \delta \cdot \sin \varphi + \cos \delta \cdot \cos \varphi \cdot \cos \omega$$

$$\cos \psi s = \frac{\sin \gamma_s \cdot \sin \varphi - \sin \delta}{\cos \gamma_s \cdot \cos \varphi}$$

Where δ is the Earth's declination angle and φ is the latitude of the location. The horizontal diffuse (D(0)) and beam (B(0) irradiance were then calculated. First, the extraterrestrial horizontal irradiance (Bo(0)) was obtained by:

$$B_o(0) = B_o \cdot \varepsilon \cdot \cos \gamma_s$$

Bo is the solar constant and ε the eccentricity of the Earth's orbit on the day considered. The clarity index was defined as:

$$K_t = G(0)/B_o(0)$$

The D(0) was estimate using a correlation proposed by (Iqbal, 1983).

$$D(0) = (0.958 - 0.982 \cdot K_t) \cdot G(0)$$

And the component B(0) is the difference between G(0) and D(0). The next step consists of calculating the position angles of the photovoltaic modules: orientation in relation to the North (α) and inclination (β). These angles can be obtained for each position of the sun (γs,ψs) considering the type of solar tracker (Kalogirou, 2014).
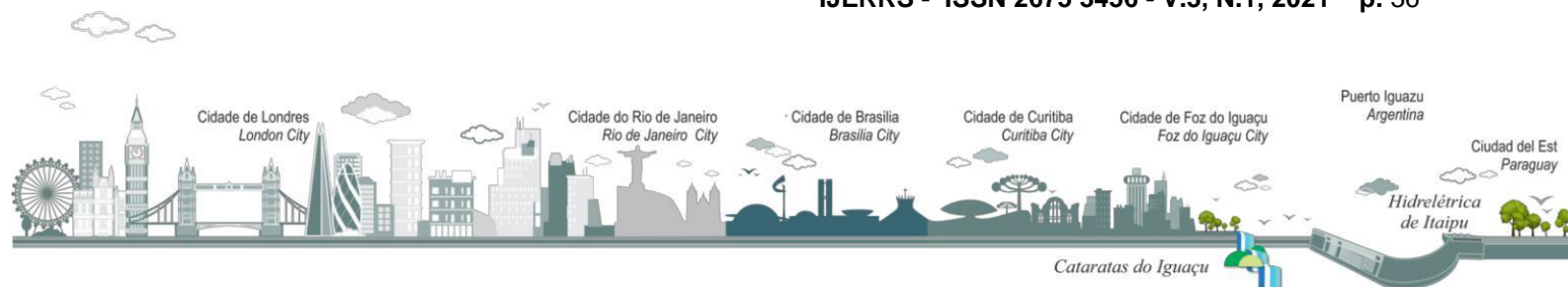
$$\alpha = \begin{cases} 0, & -\pi/2 < \psi_s < \pi/2\,\pi \qquad \text{otherwise} \\ tan\beta = cos\psi_S/S\gamma \end{cases}$$

- Single vertical inclined axis:

$$\alpha = \psi_s$$

$$\beta = \varphi$$

- Single East-West horizontal axis:

$$\alpha = \begin{cases} -\pi/2, \omega < 0\,\pi/2 \qquad \text{otherwise} \\ \tan \beta = \sin \psi_s / \tan \gamma_s \end{cases}$$

- Single East-West inclined axis:

$$\tan \alpha = (\cos \gamma_s \cdot \sin \psi_s)/[\sin(\gamma_s + \varphi) \cdot \sin \varphi]$$

$$\tan \beta = \tan \varphi / \cos \alpha$$

- Double axes

$$\alpha = \psi_s$$

$$\beta = \pi/2 - \gamma_s$$

Once the position angles of the photovoltaic modules were known, the method estimated the beam (B), diffuse components (D) and albedo (A) of the solar irradiance in the plane of the collectors. was obtained by:

$$B = [B(0) \cdot \cos \theta]/ \sin \gamma_s$$

$$\cos \theta = \sin \delta \sin \varphi \cos \beta - \sin \delta \cos \varphi \sin \beta \cos \alpha + \cos \delta \cos \varphi \cos \beta \cos \omega$$
$$+ \cos \delta \sin \varphi \sin \beta \cos \alpha \cos \omega + \cos \delta \sin \alpha \sin \omega \sin \beta$$

Where θ represents the angle of the solar rays in relation to the normal of the photovoltaic modules. For the calculation of D, Hay's diffuse sky anisotropic model was used by (Hay J.E, 1979).
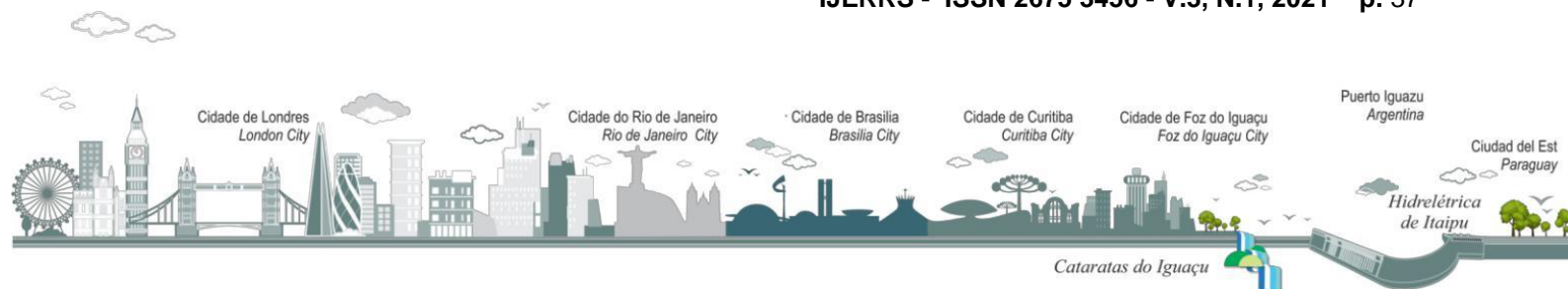
$$D = D(0) \cdot [K_b \cdot R_b + (1 - K_b) \cdot (1 + \cos \beta)/2]$$

$$K_b = \min \{B(0)/B_o(0), 1\}$$

$$R_b = \max \{\cos \theta / \sin \gamma_s, 0\}$$

and A was obtained by an isotropic model with an albedo coefficient of 0.2:

$$A = 0.2 \cdot [(1 - \cos \beta)/2] \cdot G(0)$$

Prototype design and implementation

The construction of the prototype can be divided into four areas: the support and movement structure, the control circuit, the tracking algorithm based on the system by a Delta controller and the monitoring system. Each area will be described in the following subsections.

Table 1. Technical data of the photovoltaic module as provided by the manufacturer.

Model: CS3W-390P

Maximum power (Pmax)	390 W
Voltage at maximum power point (Vmp)	38.3 V
Current at maximum power point (Imp)	10.19 A
Open-circuit voltage (Voc)	46.8 V
Short-circuit current (Isc)	10.74 A

PHYSICAL DRAWING

As for the support and movement structure, it was designed by the Engineering Company Ilumisol using the SolidWorks software, considering the dimensions of the photovoltaic modules used, see Table 1. It was decided that a structure would be able to support 72 modules with dimensions of 2132mm x 1048mm, aiming to create a more efficient and simple design to implement as a commercial product. The Figures below represent a Canadian Solar model CS3W-390P of our sun-tracking prototype. Isometric and side views of the structure are shown.
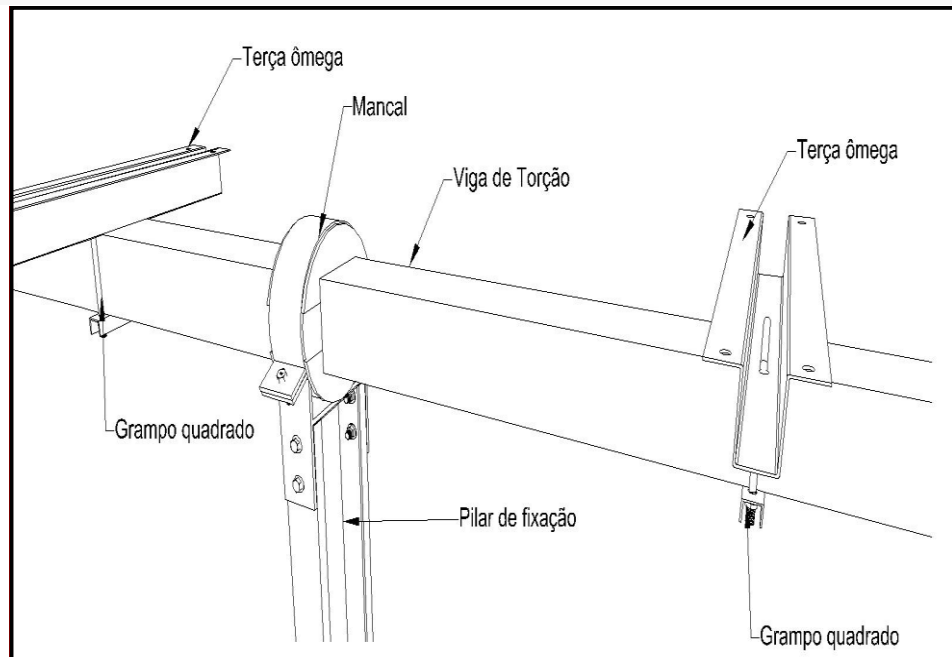
Figure 02 Tracker Mechanical Building structure

The mechanical structure that has the drive set, it consists of a planetary gearbox (reducing motor) mounted on the rotating gear below the equipment figure.
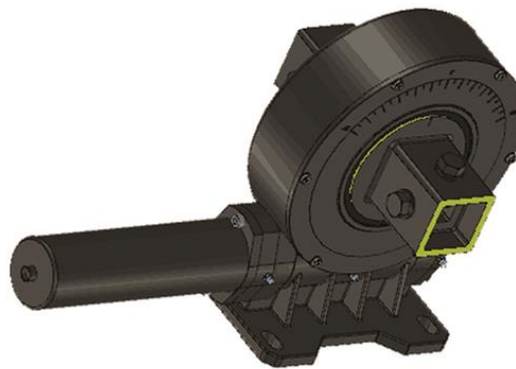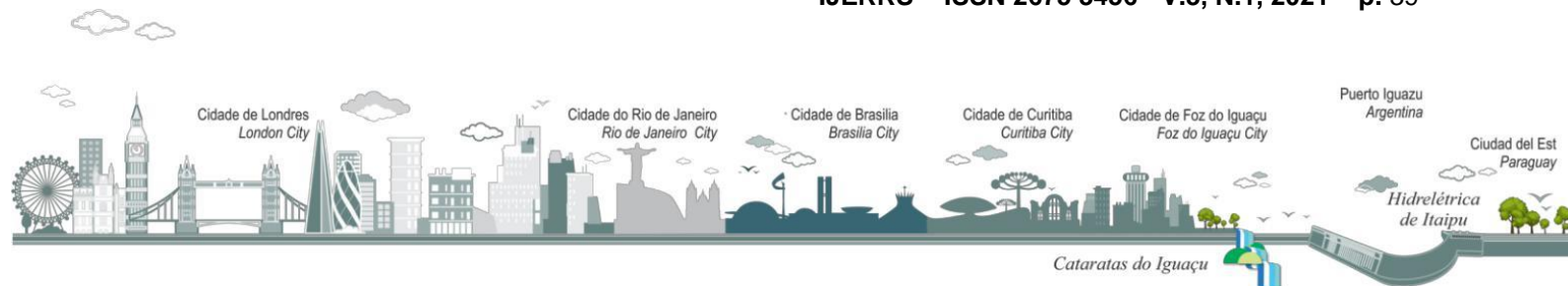

Figure 03: Tracker motor

CONTROLLING SYSTEM

As for the control system used for solar tracking, a Delta AS300 PLC was used, where the programming algorithm was developed using the control for days and hours of

positioning the sun. The system was developed using ISPSoft V3.11, the software. Figure 04 illustrates the programming of the logic algorithm.
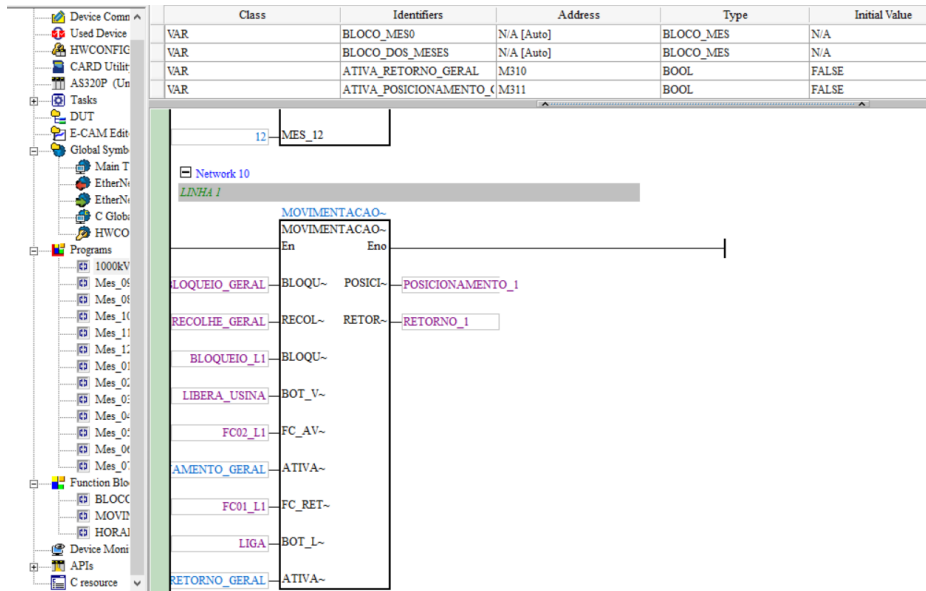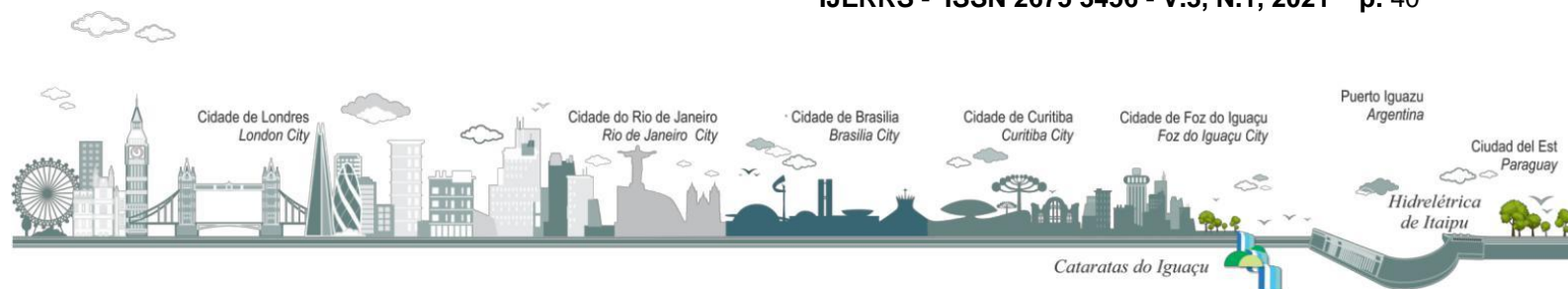

Figure 04: programming logic

The panel was assembled with a 30 A charge controller to charge two 12V / 7Ah lithium batteries connected in series adding the 24V charge for the Solar Tracker motor activation.
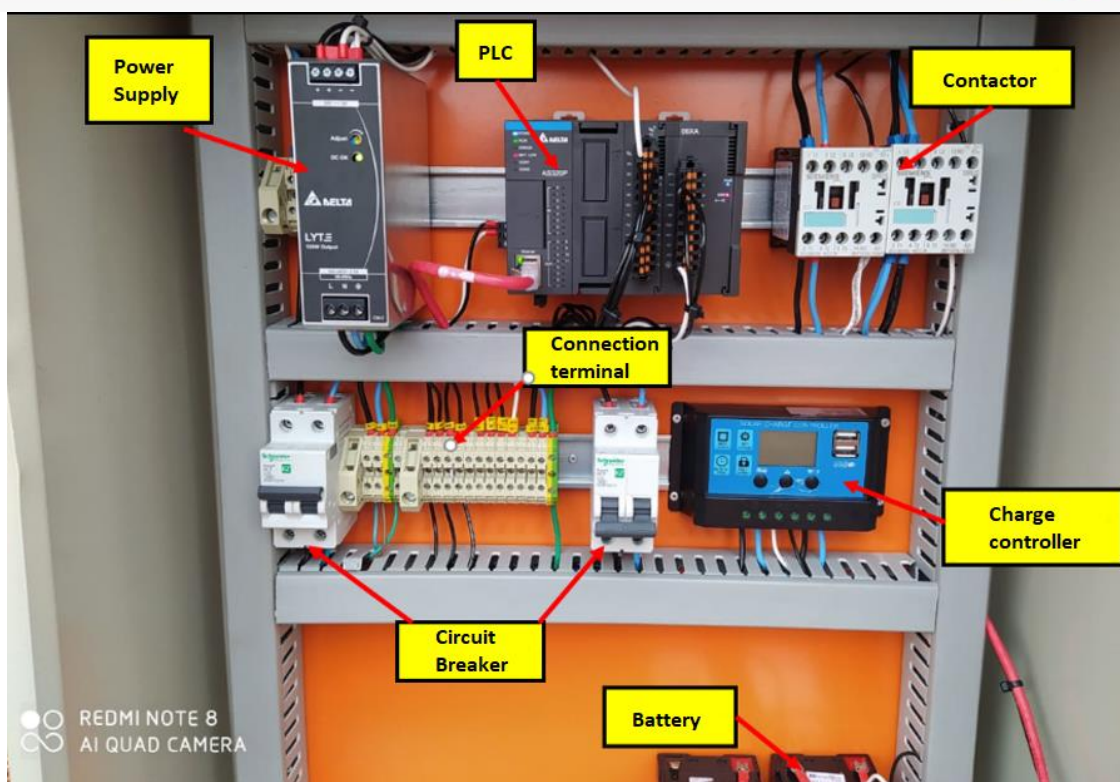
Figure 05: assemble of automation panel

MONITORING SYSTEM

To evaluate the tracker's performance, the short-circuit current of one of the installed PV modules was measured. For this system, a Minipa brand multimeter was used, to which an ACS758 current meter was connected to the monitored module outputs. This meter was previously calibrated, which guaranteed the reliability of the measurements. The values found between 0 and 11 A and voltage of 0 and 46V. And it was decided that the current measurements would be taken every 15 minutes. The collected values were saved in a spreadsheet. It is important to mention that the monitoring system was independent of the control system.

As mentioned before, data collection took place in the city of Cascavel, in the west of the state of Paraná. The city of Cascavel is 711m above sea level, where the climate is warm and temperate. The climate classification is Cfa according to (Köppen and Geiger, 2006). In Cascavel, the average annual temperature is 18.2 ° C. The average annual rainfall is 1822 mm. Measurements were made for nine days in October 2020, corresponding to days 01, 02, 03, 04, 05, 06, 07, 08, and 09. These days were selected due to the absence of clouds, which facilitated the measurement of gains power. Solar
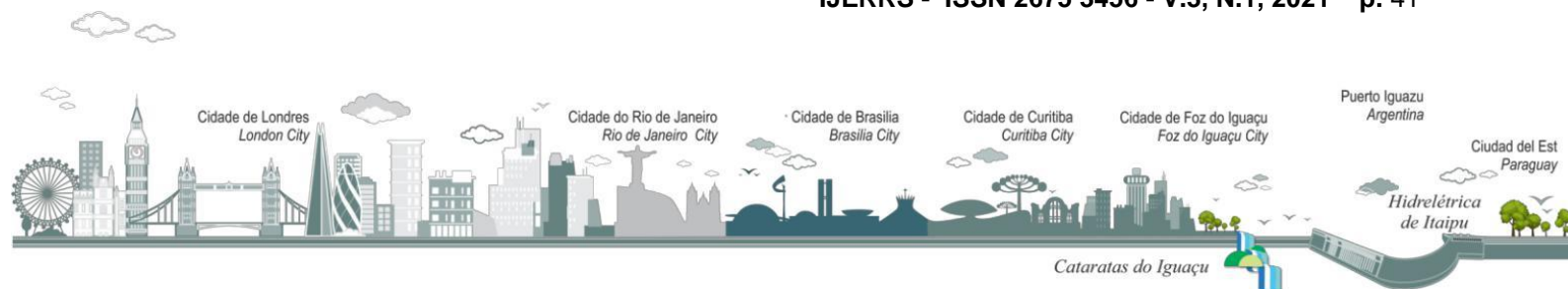
noon occurred at 12:45 pm, local time on those days, increasing the angle of solar height. Figure 06 shows the movement of the solar tracker over a business day.

Figure 06: Morning position (a), Afternoon position (b)

Figure 06. Movement of the solar tracker over the course of a day. Morning position (a), afternoon position (b).

A fixed PV module oriented to the north (same manufacturer and model for those installed in the tracking structure) was installed close to the site at Unioeste - Universidade Estadual do Oeste do Paraná, with the same inclination of the tracker axis, comparing the irradiation collected by the tracker and fixed system. (Directly on the ground). This fixed module was monitored in the same way as the tracking system. Which allows an indirect estimate of the irradiance collected by each system, because the short-circuit current is approximately proportional to the irradiance in the photovoltaic modules (considering that the temperature coefficient of the short-circuit current, <0.05% / ∘ Ç). Therefore, the irradiance incident in a PV module (G) can be expressed as:

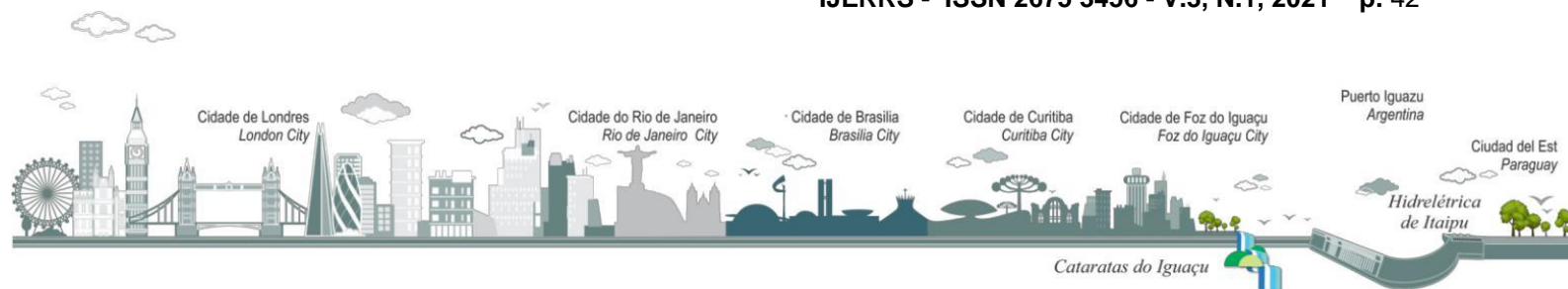$$G = (Isc, meas / Isc, STC).1000 \, W/m^2$$

Table 2. Daily irradiation was collected by the tracking and fixed systems during the 9 days, a percentage gain of irradiation obtained by the tracking system, and a difference in the percentage gain of the average gain.

Day	Tracker kWh/m²	Fixed system kWh/m²	Percentual gain %	Average difference %
1	10.51	8.02	31.07	1.18
2	10.95	8.21	33.36	3.47
3	10.40	7.91	31.48	1.59
4	10.26	7.85	30.65	0.76
5	9.95	7.86	26.55	−3.34
6	10.63	8.12	30.99	1.10
7	9.61	7.57	26.91	−2.98
8	10.16	7.80	30.32	0.43
9	9.55	7.50	27.23	−2.66
Daily average	10.22	7.87	29.89	0.00

The irradiance gains of the tracking system compared to the fixed system during the 9-day experimental follow-up can be analyzed in more detail by examining the minimum, the average, and the maximum gains over local time (Figure-07). The average gain curve had two maximums (located approximately in the ranges from 8:00 am to 9:00 am and from 5:30 pm to 6:30 pm). These were the operational points with the best performance improvement due to the tracking movement. These points differed from sunrise (around 6:30 am) and sunset (around 7:15 pm) due to the limits of the rotational angle avoided more perpendicularity compared to the sun's rays during these events. It can also be noted that the uncertainty in measurements (understood as the difference between the minimum and maximum gains at a given local time) was greater in the first and last hours of the day compared to the interval around noon. This may be due to low irradiance errors inherent in the current sensors and the rapid change in the level of irradiance during the first and last hours of the day. As can be seen, the uncertainty bars were quite small in the interval around noon, when most of the energy was generated by the photovoltaic system.
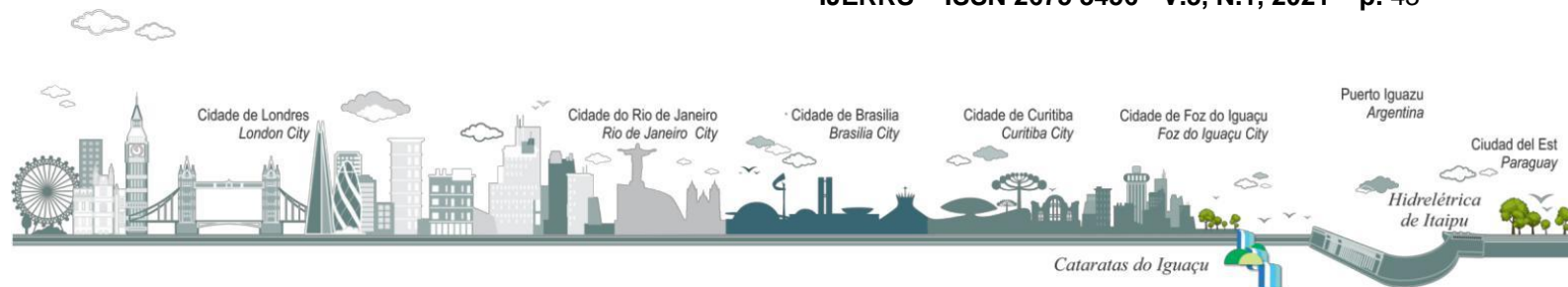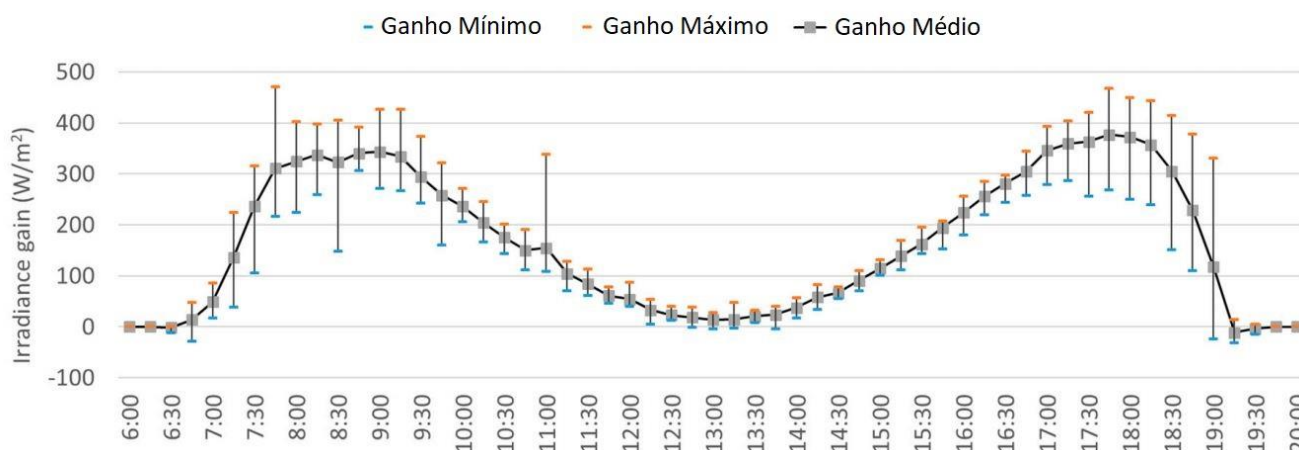
Figure-07: Analysis of the average irradiance gains of the tracking system compared to the fixed one over the day for the 9-day experiment and the difference between the maximum and minimum gains represented by the bars.

FINAL CONSIDERATION

It is possible to observe that the first sun tracking system proposed through the automation of the Solar Tracker for the integration of plants can provide a substantial increase in energy production (29.8% in October in Cascavel - PR), presenting a different behavior to that found in the fixed system in Cascavel - PR. The design of the control system can operate anywhere in the world automatically, due to the algorithm, making this system innovative and flexible in terms of implementation. Although the mechanical structure of the solar tracker is not a novelty, the automation architecture 4.0 with cloud is a modern and innovative technology, and such an approach cannot be found in the literature.

The proposed system is suitable for integration in power plants, which often have a Wi-Fi connection available. Another advantage of the system is the possibility of displaying its behavior through the DOP-100 HMI, as this platform allows viewing the number of requests made by the control circuit, as well as the amount delivered. In this way, it is possible to know the position of the tracker at any time. Although, in applications for small plants or buildings, this may not be very limiting. One area of improvement that could be identified is the construction of a support structure for photovoltaic modules, with a special focus on cost reduction. This can be accomplished using cheaper materials, of similar performance, or better, through a redesign of the structure, managing to find a more accessible design and with the same level of support as the structure used.

REFERENCES

Randall, J.; Lieberman, M. Passive trackers for photovoltaics. In Proceedings of the Annual Meeting—American Section of the International Solar Energy Society, New Orleans, LA, USA, 7–12 October 1984; pp. 529–533.

Huang, B.-J.; Huang, Y.-C.; Chen, G.-Y.; Hsu, P.-C.; Li, K. Improving solar PV system efficiency using one-axis 3-position sun tracking. Energy Procedia 2013, 33, 280–287.

Said, A., Alaoui, S. M., Rouas, Y., Dambrine, G. & Menard, E. (2018). Innovative Low Cost Cleaning Technique for PV Modules on Solar Tracker. IEEE 2018.

Melo, A.G.; Filho, D.O.; De Oliveira Júnior, M.M.; Zolnier, S.; Ribeiro, A. Development of a closed and open loop solar tracker technology [Desenvolvimento de tecnologia de rastreamento solar com controle em malha fechada e em malha aberta]. Acta Sci. Technol. 2017, 39, 177–183.

Sidek, M.H.M.; Azis, N.; Hasan, W.Z.W.; Ab Kadir, M.Z.A.; Shafie, S.; Radzi, M.A.M. Automated positioning dual-axis solar tracking system with precision elevation and azimuth angle control. Energy 2017, 124, 160–170.

Gutiérrez, S.; Rodrigo, P.M. Energetic analysis of simplified 2-position and 3-position North-South horizontal single-axis sun tracking concepts. Sol. Energy 2017, 157, 244–250.

Senpinar, A.; Cebeci, M. Evaluation of power output for fixed and two-axis tracking PVarrays. Appl. Energy 2012, 92, 677–685.

Whillier, A. The determination of hourly values of total solar radiation from daily summations. Arch. Meteorol. Geophys. Bioklimatol. Ser. B 1956, 7, 197–204.

Walraven, R. Calculating the position of the sun. Sol. Energy 1978, 20, 393–397.

Poojitha, K., Ashwini, L., Anjali, B. S. & Ramprabhakar, J. (2019). Solar tracker using maximum power point tracking algorithm, 2019 International Conference on Intelligent Computing and Control Systems, ICCS 2019 (Iciccs): 1528–1531.

NASA Prediction of Worldwide Energy Resources (NASA POWER). Available online: https://power.larc. nasa.gov/ (accessed on 20 February 2019).

Whillier, A. The determination of hourly values of total solar radiation from daily summations. Arch. Meteorol. Geophys. Bioklimatol. Ser. B 1956, 7, 197–204.

Walraven, R. Calculating the position of the sun. Sol. Energy 1978, 20, 393–397

Iqbal, M. An Introduction to Solar Radiation; Academic Press: Toronto, ON, Canada, 1983

Kalogirou, S.A. Solar Energy Engineering: Processes and Systems, 2nd ed.; Academic Press: Cambridge, MA, USA, 2014.

https://www.canadiansolar.com/wpcontent/uploads/2019/12/Canadian_Solar-Datasheet-BiHiKu_CS3W-PB-AG_EN.pdf

Hay, J.E. Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Sol. Energy 1979, 23, 301–307

https://www.canadiansolar.com/wp-content/uploads/2019/12/Canadian_Solar-Datasheet-BiHiKu_CS3W-PB-AG_EN.pdf

Ochoa, I.Z.; Gutierrez, S.; Rodriguez, F. Internet of things: Low cost monitoring beehive system using wireless sensor network. In Proceedings of the 2019 IEEE International Conference on Engineering Veracruz, ICEV 2019, Boca del Rio, Veracruz, 14–17 October 2019.

Gutierrez, E.; Gutierrez, S.; Becerril, J.A.; Rodriguez, F. Low cost prototype for monitoring and remote control in greenhouse for homes. In Proceedings of the 2018 IEEE International Autumn Meeting on Power, Electronics and Computing, ROPEC 2018, Ixtapa, Mexico, 14–16 November 2018.