The Effect of a Tracking System in the Efficiency of the Photovoltaics Solar Cells Panels

Miguel Baptista Bolas Cadete Neto

miguel.c.neto@tecnico.ulisboa.pt

September 2021

Abstract

There is an increasingly concern about the usage of energy sources with negative environmental impact. This concern resulted in a big investment in renewable sources of energy and a consequent decrease of investment in fossil fuels. Solar energy is one of the biggest energy sources in the world. The most common way to harvest it is through PV[1] converters. CPVT[2] are an alternative that as recently gained popularity due to the increase of multijunction solar cells efficiency. This increase is even more significant because CPVTs focuses solar radiation on its solar cells, reducing the area of PV cells needed for the system. To increase the efficiency of the system, solar tracking system are usually installed, to follow the apparent movement of the sun in the horizon through the day. In this way, adding a tracking system to a CPVT increases its efficiency. The goal of this dissertation is to display it. To simulate a CPVT in an innovative way, as well as the tracking system, the system is implemented in a MBA[3], in Netlogo, a popular programming language to implement these models. These types of models have a level of granularity bigger than other types of models used in this kind of systems. The model developed can accept as input any GPS Location, as well as different reflector model geometries. Results show a significant increase of efficiency of this system when you add a solar tracking system.

Keywords: Netlogo, MBA, Solar Concentration, Tracking Systems, CPVT Systems.

1. Introduction

In these days, the need to meet global energy demand is an increasingly huge challenge. The majority of the worldwide consumed primary energy comes from fossil fuels. The dependence of this energy source is problematic because it is finite since its speed consumption is much higher than its speed generation. On the other hand, burning fossil fuels produces greenhouse gases, particularly carbon dioxide, which results in global warming of our planet, which can lead to disastrous effects for humanity.

Due to all these adversities and due to a constant increase in energy consumption demand worldwide, renewable energies are an alternative that is not associated with all the previously identified problems of fossil fuels. Solar energy is one of the main sources of energy in a global level. Although global solar energy production is lower than other

---

[1] Photovoltaic
[2] Photovoltaic Thermal Solar Concentrators
[3] Model Based in Agents

renewable energy sources, notably wind and hydropower, its projected growth is higher than the previous two. This potential growth is justified due to the amount of solar radiation available on Earth. This corresponds to an amount 10000 times greater than all human energy consumed during the history of mankind. On the other hand, solar energy is a flexible technology because it is either possible to install large PV parks or concentration thermoelectric solar plants (CSP), as well as decentralized PV systems on the roof of any house[1].

The objective of this dissertation is to create a model of a solar tracking system in a CPVT and verify its impact on the efficiency of the CPVT. On the other hand, the model explores the impact of installing the CPVT system in different locations, as well as different reflectors modules geometry, different times of the year. The expected results are a significant increase in the efficiency of the system CPVT, due to the implementation of a solar tracking system.

2. Simulation Model

The model of the solar tracking system of the CPVT system is defined through an MBA with Netlogo.

2.1. MBAs

An MBA is a form of computational modeling in which an observed event is modeled through agents, through the environment and through the interactions of the preceding elements.

An MBA provides a description of a phenomenon detailed over time and not only the final state of the system, as is the case in MBEs. The big difference lies in the fact that MBAs model each individual and the interactions of each one, which makes it possible to examine the history of each individual member of the model, as well as any groups of agents. Thus, an MBA has a higher level of detail than an MBE.

2.2. Solar Tracking System of a CPVT

The program developed in this dissertation simulates the operation of a solar tracking system of a CPVT, composed of PV Panels, a reflective object, as well as the solar tracking system itself.

As this model is developed in two dimensions, the CPVT solar tracking system has one axis. Due to the limitations of a two-dimensional model, it is assumed that the CPVT is placed in a horizontal tilt position directly appointed to the Sun, in the place and time where the model is simulated. The system follows the apparent movement of the Sun throughout the day by rotating the East-West axis.

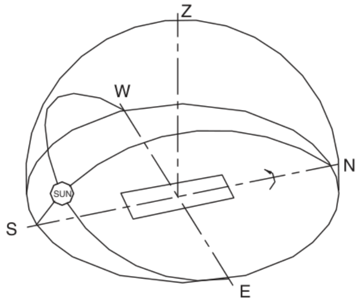

Figure 1- East-West axis tracking system with tilt = 0°, taken from [2].

The objective of the model's solar tracking system is to quantify the number of solar beams that focus on the PV panels and to represent the process in which this system identifies the tilt position in which the CPVT has the highest solar incidence.

This process is referred as scanning tilt positions. These tilt positions correspond to the tilt of the system in relation to East-West axis. In this scan, it is first defined which different tilt positions to test. For each tilt position, a solar incidence test is performed. This test consists of quantifying the number of solar beams that focus on the PV module. The scanning is composed of solar incidence tests for all selected tilt positions and identifying the tilt position with the highest solar incidence.

The CPVT have two PV modules, which are together, one on top of the other, the upper with upward orientation (0º in Netlogo), while the lower one is oriented down (180º in Netlogo), to capture as many solar beams as possible, as seen in Figure 2. On one hand, solar beams that directly focus on CPVT are captured by the upper module while reflected beams in the CPVT reflecting module are collected by the bottom module.

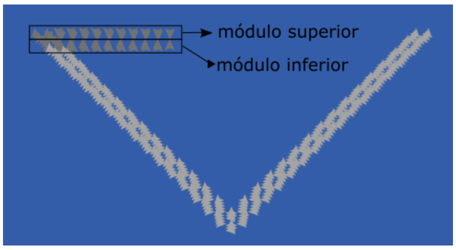

Figure 2 - Highlight of the CPVT Module FV with a triangular geometry reflector module.

The function of the reflector module is to concentrate solar radiation on the lower FV module of the CPVT. In this model, the reflective material of the CPVT System is anodized aluminum due to its low cost and production flexibility. Its weighted reflection index varies between 88 % to 91 %, and in this model is considered 90 %, an approximate value of 89.3%, corresponding to the weighted hemispheric reflection index, a value that takes into account the degradation of the material over time[2].

In this model, two geometries of reflector modules are considered to illustrate and demonstrate its influence on the incident radiation in the PV modules of the CPVT. The geometries considered are triangular and semicircular.

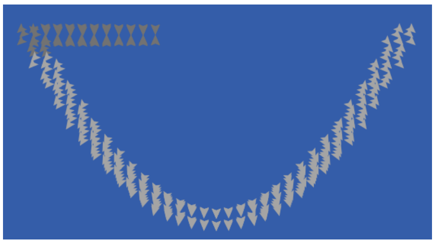

Figure 3 - CPVT of reflector module with a semicircular geometry with a tilt position of 0º.

2.2.1. Definition of Agents

In this model, CPVT is represented by turtles because these agents move during the operation of the CPVT solar tracking system. These turtles belong to a breed named concentrator, differentiating them from other turtles of the model and are divided into two categories: those belonging to the reflector module, and those belonging to the PV module. The relevant properties of these agents are the location, heading, and if they belong to the reflector object or the PV module.

The number of turtles that define the CPVT needs to be large enough for turtles to exist in all patches that represent the CPVT for all tilt positions, so that no beams can walk through the CPVT without interacting with it. The turtles that represent the reflector object are differentiated from those representing the PV module through a variable. This variable corresponds to 1 if the turtle belongs to the PV module and 0 if it belongs to the reflector object. Turtles belonging to the FV module are represented by a darker gray relative to the turtles of the reflector object so that the user can differentiate between them in the interface.

The initialization of the solar beams consists of the creation of breed beams turtles, so that they cover the top and the lateral limits of the program interface, representing the solar beams that can reach the CPVT. These turtles are represented in yellow on the interface. The direction of these beams corresponds to the angle of incidence, and this is calculated using as input the users introduced data: date, time and Latitude. The solar position algorithm calculates the Solar Azimuth (α_S) and Solar Altitude (A_S). It is necessary to convert these values to an angle of incidence of the solar beams from the perspective of the CPVT, which is done through an algorithm, adapted to Netlogo from [1].

During the development of the model, the number of solar beams created in each patch that was chosen to cover the top and side limits of the program interface is chosen. After testing different values, it was defined that at the beginning of each test, each patch of the limits of the world of the model creates 10 turtles of the beam type. This means that for each CPVT tilt position test, 3010 beams are created in the model. This value corresponds to a compromise between creating as many beams as possible to minimize the variance of results obtained with the amount of information that the model processes, which affects the speed of execution of the model due to the software and processing limitations of each users' computer.

The only action that turtles of solar beam breed perform is a step, which means advancing to the "front", this "front" corresponds to the direction defined by the heading of these. If the beam reaches one of the world limits of the model, this beam is eliminated.

2.2.2. Agent-Agent Interaction Definition

It is also necessary to define all the agent-agent interactions, which in this model can only occur between the solar beams and the collector. The reflector material of the CPVT System is anodized aluminum and its reflection index corresponds to approximately 90 %. [2]

If a beam turtle is in the same patch as a collector breed turtle, one of two interactions occurs between these agents: reflection of the beam or absorption of this. If the turtle collector is a part of the FV module, the beam is always absorbed. This interaction corresponds to its destruction and this beam is counted as incident. On the other hand, if the collector turtle belongs to the reflector module, there is a probability of 10 % of the beam being absorbed by the CPVT. In this case, the beam is also eliminated, but is not counted as an incident as it is not absorbed by the FV module. If the beam is not absorbed, it is reflected by the reflector module. The new direction of the solar beam is altered accordingly to the law of reflection. The new direction of the turtle solar beam corresponds to the reflected angle (β), in which the incident angle corresponds to the previous direction of the solar beam(θ) and the surface normal corresponds to the heading of the turtle breed collector.

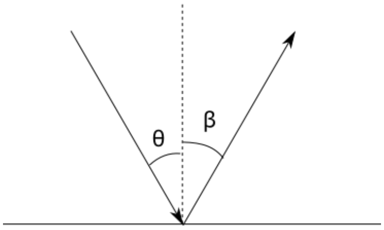

Figure 4 Illustration of the Law of Reflection, taken from [3].

Adapting this Law to the notation of angles of Netlogo, the orientation of the solar beam is calculated as follows:

$$\begin{aligned}&\text{Heading of reflected angle } = \\ &180 + \text{Reflection Normal} + \\ &(\text{Reflection Normal} - \\ &\text{Heading of incident angle}).\end{aligned} \tag{2-1}$$

In the formula above, the Heading of incident angle corresponds to the orientation of the solar beam before reflection and the Heading of the reflected angle corresponds to the orientation of the solar beam after reflection. The Reflection Normal corresponds to the heading of the turtle collector in the zone where the solar beam has focused.

2.2.3. Temporal evolution

To run the model, user must click the Setup button. During Setup, the model is reset. All turtles that represent the CPVT are created. The CPVT is rotated -135º to its initial position. After the user presses the Setup button, the Interface is in a state like Figure 5.

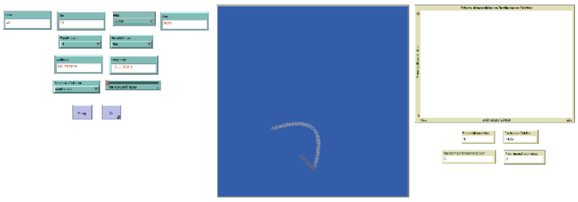

Figure 5 - MBA interface before its execution.

Then, user must click the Go button to start the time evolution of the model.

The first solar incidence test is then performed to calculate the number of incident beams in the concentrator for the initial system position. This test begins with the creation of solar beams at the upper and lateral boundaries of the interface. The beams move through the interface with the direction of the angle of incidence calculated by the solar position algorithm and advance 0.1 steps on each tick[4] of the model. The beams end up colliding with the turtles of the collector, where the collision procedure is run, absorbed by one of the turtles of the FV module or reaching one of the limits of the interface. The test ends when all solar beams are eliminated.

At the end of the test, the number of incident beams is recorded in a list and through a point on a graph of incident beams in relation to the tilt position of the system illustrated in the graph of Figure 6.

When you finish recording the minimum tilt position test, the CPVT rotates several degrees that the user has set in VariationTilt, in the interface, clockwise. Successive tests are performed as the CPVT rotates clockwise until it reaches the maximum tilt value, which corresponds to +135º. You can view the world and outputs of the model while running the model, as seen in Figure 6

---

[4] Denomination of time step in Netlogo

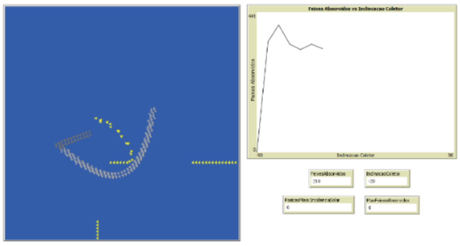

Figure 6- World and MBA output control options during its execution.

After the solar incidence tests of the system have been completed, the tilt position of the CPVT in which the highest incidence of solar beams occurred is determined. It corresponds to the element in the system tilt position list for which the index is the same as that of the maximum value incident beam log list, and the CPVT rotates to it.

3. Results

As described in the previous chapter, different tests are performed in the model in various locations through the year to evaluate the performance in these locations as well as the impact of implementing the solar tracking system in the CPVT.

A test was performed in Lisbon in 21 of June in 2021 and other in 21 of December in 2021, both with a triangular reflective module, to compare the performance of the system in different times of the year.

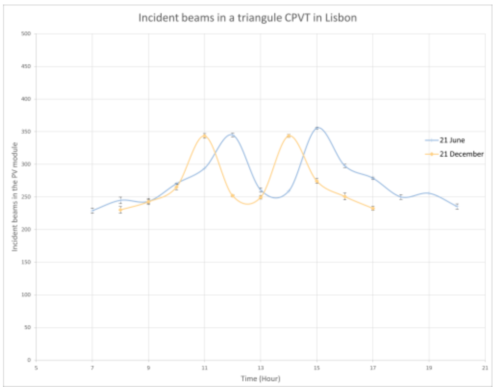

Figure 7 – Incident beams in a triangular CPVT in Lisbon on June 21 and December 21.

In the figure above, the test of June 21 shows the number of incident beams in the CPVT model with solar tracking system increases from dawn until around noon, decreases greatly from 12:00 to 14:00, increases again from 14:00 to 15:00 and then progressively decreases until dusk. The values are lower between 12:00 and 15:00 because there are not as many beams reflected by the reflector module for the lower PV panel. It is also possible to determine between 12:00 and 15:00 it is expected that the value of solar irradiance received by the system is higher and that the counting of incident beams is not the most accurate to relate to solar irradiance, since the model does not consider that the reflected beams have less energy than the beams that directly focus on the upper FV module, due to the energy of a reflected beam being lower.

Based on Figure 7, Incident beams between December 21 and June 21 are very similar through the day (there is a one-hour gap between the two tests due to daylight saving time being in effect only on June 21 test). The value of the incident beams is slightly higher on June 21 due to the solar beam height being higher on this day. Despite this small difference, the predicted result is a greater variation of incident beams between these two tests. This inaccuracy occurs due to the test being performed on two dimensions, so it is not considered that the system is tilted horizontally in the same way all year, it is adjusted every day as already referred in subchapter 2.2. The error is higher on December 21 compared to June 21, due to the inclination of the vertical component of incident beams in June being closer to the fixed horizontal tilt of systems placed in this location.

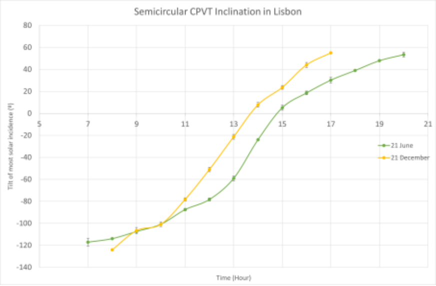

Figure 8 - Inclination of a triangular CPVT in Lisbon on June 21 and December 21.

In Figure 8, it is possible to observe that in both tests, CPVT rotates from the left (negative tilt position value) to the right (positive tilt position value) through the day, following the apparent movement of the sun in the horizon. Based on Figure 8, we can observe the variation of the tilt position of higher incidence in the system through the day, which is similar on the two days, however there is a gap of a few degrees between days due to the position of the Sun on the horizon throughout the day being different, as well as the length of the day. The time zone on June 21 is one hour ahead of December 21, due to the first occur during daylight saving time, unlike the last case.

To compare the system solar incidence between a reflector module with triangular geometry and one with semicircular geometry, two simulations of the model were made where inputs were all equal except the geometry of the reflector module of the system, which were the two cases descripted above.

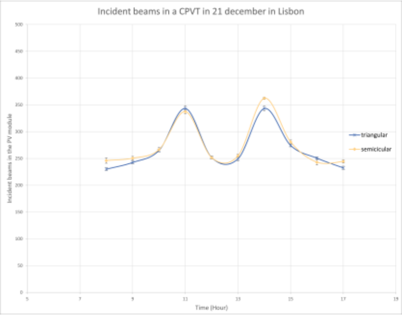

Figure 9 - Incident beams in a CPVT model for Lisbon on December 21.

When analyzing Figure 9, there were more incidence beams in the model with semicircular geometry (2737.7 in total in the semicircular to 2683.3 in the triangular, both values are the average of ten runs), due to the way solar beams reflect in the reflector modules, so the solar beams reflect more to the lower FV module in comparison to the triangular reflector module.

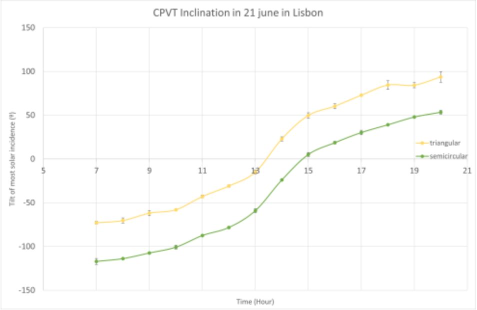

Figure 10- Inclination of a CPVT in Lisbon on June 21.

Based on Figure 10, it is visible that there is a constant gap between CPVT inclination curves throughout the day, which corresponds to approximately 50º. This variation exists because the reflector of semicircular geometry has a different focus point from the triangular module, so the semicircular geometry reflector reflects more beams to the system when it is more inclined to the left relative to the triangular geometry reflector module. In an annual perspective, the number of beams incident in the system was calculated for the 21st day of each month.

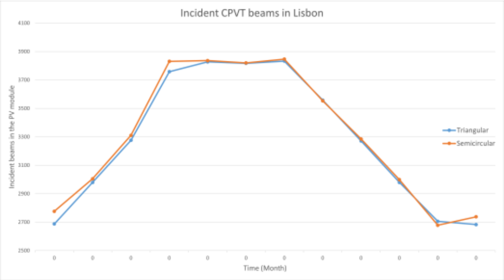

Figure 11 – Incident beams in the CPVT model in Lisbon.

By looking at the previous figure, you can conclude that the summer months have more incident beams, as expected. On the other hand, CPVT with semicircular geometry has a slightly higher performance than triangular geometry. Tests were also performed with the same model, but only for the 0º vertical tilt position, to represent the CPVT system without tracking the solar position, that is, the same vertical tilt position. In relation to the horizontal axis, this position is the intermediate between East and West, which corresponds to the position with the highest solar incidence around noon.

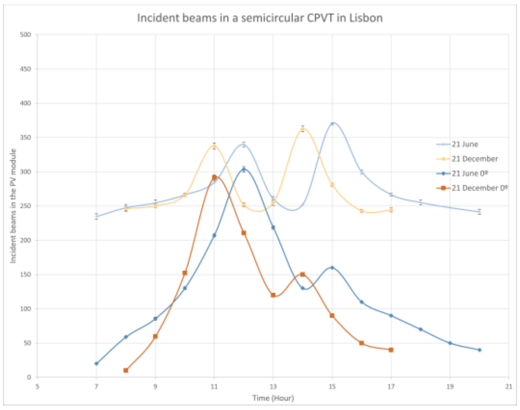

Figure 12 - Incident beams in the CPVT model with and without sun tracking in Lisbon on June 21 and December 21.

When looking at Figure 12, it is possible to verify that there is a larger number of incident beams in the CPVT system when it has a solar tracking system, as expected. Around noon, the number of incident beams is similar with or without tracking system, due to the fixed CPVT being positioned to maximize the incidence of solar radiation for that time. For the other hours of the day, the difference between the incident beams is very large.

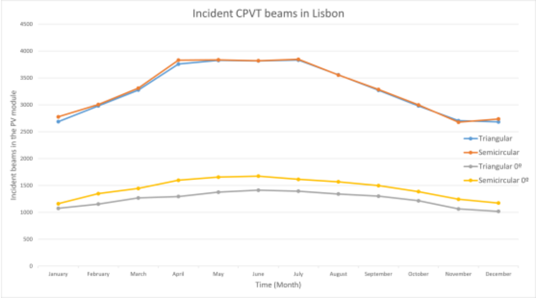

Figure 13 – Incident beams in the CPVT model in Lisbon with and without sun tracking.

When comparing the variation of incident beams in the CPVT throughout the year in Figure 13 (each value corresponds to the incident beams during the 21st of each month), it is possible to verify that there is a significant bigger number of incident beams in the CPVT system, when it has a solar tracking system, as expected. On the other hand, the difference between incident beams in the systems with different reflector geometries is quite small, being greater in the system without solar tracking.

Four tests were conducted in Buenos Aires to compare the CPVT performance in this location with Lisbon.

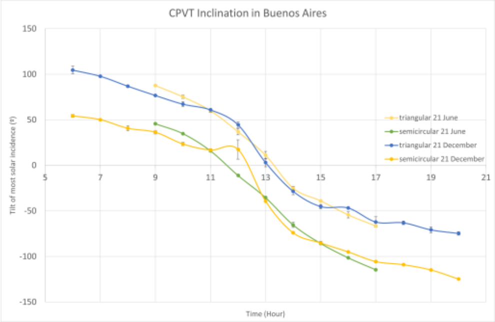

Figure 14 - Inclination of a CPVT in Buenos Aires.

Based on figure above, a system placed in the Southern Hemisphere facing North follows the apparent movement of the Sun from the right (East) to the left (West), contrary to a system that is placed in Lisbon. As in Figure 10, the variation of The Higher Solar Incidence Slope

Position between tests with reflectors with triangular geometry and reflectors with semicircular geometry is a value in the order of 50º.

A test like the one illustrated in Figure 13 was also performed in Buenos Aires to verify the variation of solar incidence in the CPVT system throughout the year.

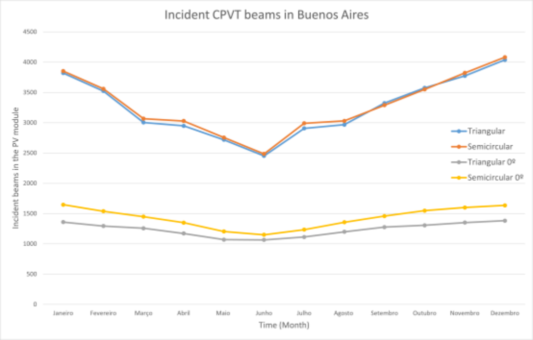

Figure 15 – Incident beams in the CPVT model in Buenos Aires with and without sun tracking.

There is a higher incidence of beams in the Summer of the Southern Hemisphere and lower in winter, as in Lisbon, bearing in mind that the summer months in Lisbon correspond to the winter months in Buenos Aires and vice versa. The maximum and minimum values of incident beams is similar in both locations, due to being at a similar distance to the Equator.

To verify the model in Singapore, tests were performed with the same inputs as the tests shown in Figure 14.

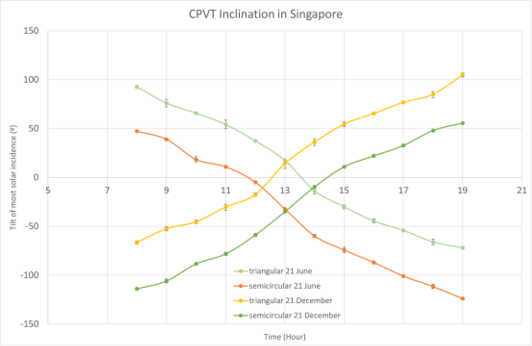

Figure 16 - Inclination of a CPVT in Singapore.

In the figure above, it is possible to verify that the variation of the slope position of the CPVT over the course of June 21 and December 21. On June 21, the Sun is North of Singapore, so the system is facing North and it follows the apparent movement of the Sun, as in Buenos Aires, as illustrated in Figure 14. On December 21, the Sun is South of Singapore, so the system is facing South, and it follows the apparent movement of the Sun, as in Lisbon, as illustrated in Figure 10

A test like the one illustrated in Figure 15 for Singapore was also performed to verify the variation in solar incidence throughout the year.

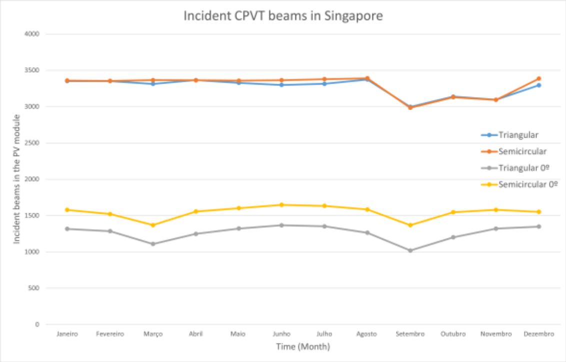

Figure 17 – Incident beams in the CPVT model in Singapore with and without sun tracking.

In the preceding figure, it is possible to verify that the number of beams incident in the system is similar throughout the year, due to Singapore being close to Equator. It is also possible to verify that CPVTs with tracking system benefit from reflector modules of semicircular geometry in relation to triangular shaped reflector modules, as well as CPVTs without tracking system, as in all other locations where the model has been tested.

By comparing tests from different days of the year to different locations, it is possible to verify that the model can adapt to different variations of the apparent movement of the Sun in any location in the world, due to the use of the algorithm for calculating the angle of incidence of solar beams in the CPVT model.

By performing year-round testing for different locations around the world, it is possible to conclude that as a location is further from the Equator, greater is the variation of the incident beams in the CPVT throughout the year. Therefore, it is more cost-effective to install this system in a location in a region closer to Equator as possible, so that there is not a very large fluctuation in energy production throughout the year, as well as more hours of sun. In the three locations tested, the number of incident beams increases significantly with the implementation of a solar tracking system in a CPVT system.

4. Conclusion

Despite the limitations of the accuracy of the results presented, it was possible to verify that the implementation of a solar tracking system in a CPVT considerably increases the efficiency of the same CPVT as expected. In addition, it was possible to compare the impact of different formats of the reflector module on the CPVT system, as well as to compare locations where to install the system. The model implemented in this dissertation is a starting point of a detailed study of CPVT systems. It is also possible to study the impact of a solar tracking system on CPVTs or even in different FV applications, as well as different types of solar tracking systems. On the other hand, this model is suitable for a pedagogical perspective, graphically demonstrating the principle of operation of a CPVT, as well as the operation of a CSP system. This model is the first iteration of an MBA of a solar tracking system of a CPVT system. For the results of this model to be more accurate, it is possible to create a three-dimensional model and simulate a two-axis solar tracking system instead of a one axis. It is also possible to introduce in the model a database with solar irradiance values around the world, to quantify irradiance values to solar beams. It can also be quantified that during the reflection of the solar beams in the reflector module, part of the beam is absorbed. It would make the simulation of the model more detailed implementing a FV cell model, applied to each cell of the FV module of the CPVT system. It is also possible to take advantage of the FV Cells individual modulation with the study of heat distribution in the different solar cells of a PV module. To compare the results with a real-life example, it would make the validation of this model more precise the creation of a CPVT with the dimensions of the SOLARUS AB system, so that you can compare the results of the model with experimental values of SOLARUS AB system. It is also possible to add to the MBA a control model of the solar tracking system, such as a microcontroller and the mechanical system associated with the solar tracking system.

References

[1] A. Smets, K. Jager, O. Isabella, R. Van Swaaij, e M. Zeman, *Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems*. UIT Cambridge, 2016.

[2] T. Fend, G. Jorgensen, e H. Küster, «Applicability of highly reflective aluminium coil for solar concentrators», *Sol. Energy*, vol. 68, n. 4, pp. 361–370, 2000.

[3] H. C. Verma, *Concept of Physics Part 1*. Bharati Bhawan, 2017.