Development of a tool for the estimation of rooftop solar photovoltaic generation

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Abstract

In this project, a tool capable of estimating the solar photovoltaic energy generation potential of any building has been developed, considering its characteristics, the typical meteorological information of the chosen location, and the shadows cast on the roof.

To carry it out, work has been done on the integration of two different parts using the Python programming language.

The first part consists of the evolution of a first shading module created by the Center for Numerical Methods in Engineering (CIMNE). This program studies the obstacles located around the interested roof and how they affect the solar radiation on the roof depending on the solar position. The validation of the functioning of the shading module has been carried out by comparing the results obtained with the obstacles adjacent to the building under study and considering the sun's path at different times of the day and times of the year.

In the second part, a module has been developed to estimate the hourly generation of a possible photovoltaic installation. This program has been created from the generation of a Python code from the SAM (System Advisor Model) software, considering the shading matrix obtained in the first module. The validation of the power generation estimation module was carried out by comparing the results of the code created with the executions using the aforementioned SAM software.

To make these estimations, the characteristics of the installation to be simulated have been defined (solar panels, inverters, installation losses, etc.).

The validation of the entire program has been carried out by comparing the output of the radiation after shading on the roof of the complete execution and the same parameter estimated by PVGIS (a web page that provides information on solar radiation and the performance of photovoltaic systems). Both PVGIS and the program created that estimates the solar potential of roofs use the same meteorological data.

Resum

En aquest projecte, s'ha desenvolupat una eina capaç d'estimar el potencial solar de generació d'energia fotovoltaica de qualsevol edifici, tenint en compte les característiques de la coberta, les dades meteorològiques típiques de la ubicació escollida i les ombres projectades sobre la coberta.

Per fer-ho s'ha treballat en la integració de dues parts diferenciades mitjançant llenguatge de programació Python.

La primera part consisteix en l'evolució d'un primer mòdul d'ombres creat pel Centre Internacional de Mètodes Numèrics a l'Enginyeria (CIMNE). Aquest programa estudia els obstacles situats al voltant de la coberta d'interès i com afecten a la radiació solar sobre la teulada en funció de la posició solar. La validació del funcionament del mòdul d'ombres s'ha realitzat comparant els resultats obtinguts amb l'anàlisi dels obstacles confrontats a l'edifici estudiar i tenint en compte la trajectòria del sol a les diverses hores del dia i èpoques de l'any.

En la segona part, s'ha desenvolupat un mòdul que estima la generació horària d'energia d'una possible instal·lació fotovoltaica. Aquest programa s'ha creat a partir de la generació d'un codi Python des del programari SAM (System Advisor Model) tenint en compte la matriu d'ombres obtinguda en el primer mòdul. Per a verificar el correcte funcionament d'aquest mòdul s'han comparat els resultats del codi creat amb les execucions a través de l'esmentat programari SAM.

Per dur a terme aquestes estimacions, s'han definit les característiques de la instal·lació a simular (panels solars, inversors, pèrdues de la instal·lació…).

La validació del mòdul sencer s'ha realitzat comparant l'output de la radiació després d'ombres de l'execució completa i el mateix paràmetre estimat per PVGIS (una pàgina web que proporciona informació sobre la radiació solar i el funcionament de sistemes fotovoltaics). Tant el PVGIS com el programa que estima el potencial solar de les cobertes utilitzen les mateixes dades meteorològiques.

Table of contents

Index of tables

Index of figures

List of abbreviations /Glossary

- TMY: Typical meteorological year
- CIMNE: Center for Numerical Methods in Engineering
- CIEMAT: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
- PVGIS: Photovoltaic Geographical Information System.
- SAM: System Advisor Model.
- LIDAR: Light Detection and Ranging
- PV: Photovoltaic
- SDG/ ODS: Sustainable Development Goals / "Objetivos de Desarrollo Sostenible"

1. Introduction

1.1 Object

This project aims to create a tool that estimates the generation potential of solar PV on rooftops. This tool will allow users to estimate the electrical energy that could be generated on their roofs, considering the shades of other objects on the rooftop surface.

Apart from the specific and tangible objectives, this project also aims to learn on a personal level how digitalization and monitoring systems for electric management work.

1.2 Scope

The project is divided into two principal parts: The evolution and testing of a shading module, and the creation of a module that provides an estimation of the photovoltaic energy that can be generated on a rooftop, both parts will be integrated into one module.

The scope of every branch of the project is detailed as follows:

1.2.1 Evolution of the shading module

The scope of the evolution of the shading module provided by the CIMNE [1], which estimates the production of a building according to its characteristics (location, orientation, azimuth...) by studying the shades projected to any rooftop in function of the sun position.
- Understand and execute the shading module provided by the CIMNE Bee group.
- Test the operation of the code by analyzing the results on different kinds of rooftops.
- Work with its parameters for using it at the following step.

1.2.2 Creation of a PySAM module

In this part, a tool that estimates the generation in terms of energy has been created taking into consideration the shading studied in the previous step. Its scope is:

- Estimate the generation with the program SAM using its interface.
- Create a PySAM code for executing simulations easily.
- Join the created PySAM code with the shade module.
- Discuss and treat the results obtained.

These two parts will be joined in one tool and this one will be validated with real buildings.

1.3 Requeriments

- Estimate the solar potential of any rooftop based on shades.
- Work with the SAM tool.
- Estimate the generation potential of a photovoltaic installation.
- Analyse the obtained results.

The following software has been used to carry out the project:

- PyCharm: Editor on which the modules have been created and executed. [2]
- Anaconda: Open-source distribution of the Python and R programming languages for scientific computing. [3]
- SAM: System Advisor Model (SAM) is a free techno-economic software model that facilitates decision-making for people in the renewable energy industry. [4]
- PVGIS: PVGIS is a website that gives information about solar radiation and the operation of photovoltaic systems. [5]
- Docker: Docker is a software platform that allows you to quickly build, test and deploy applications. Docker packages software into standardised units called containers that include everything needed for the software to run. [6]
- GitHub: GitHub is a development platform for developers and companies able to build, ship, and maintain softwares. [7]

1.4 Justification

This project aims to work on individual or collective photovoltaic installations and increase their efficiency.

Self-consumption systems are based on the production of electrical energy from an endless and renewable source such as solar.

These installations contribute to a future where the electricity grid is decentralized.

This work will be carried out jointly with the research center CIMNE - BeeGroup [8]. This center is working on the shared energy self-consumption project "EKATE Electricidad Fotovoltaica y Gestión del Autoconsumo Compartido" [9] , and the development of a tool for the rooftop solar PV generation will contribute to the development of part of this project, whose objective is demonstrate and develop efficient and smart electric energy management services based on photovoltaic renewable energy generation and shared self-consumption, using "Blockchain" and "Internet of Things (IoT)" technology.

2   Background and state of the art

It exists different resources to obtain information about the buildings for studying a possible photovoltaic installation such as vector cartographic maps, digital cadastral services, or state geographic information systems. The information that these resources contain is the building height, type and layout. All this data is not enough to define a building for the estimation of the photovoltaic potential, it is also necessary to determine the size and the tilt of the rooftop. [10]

In order to characterize properly the buildings, 3D city models like LIDAR technology have been used. LIDAR (Light Detection and Ranging) is a method that defines a 3D object by targeting it with a laser and measuring how much time it lasts for the reflected light at the surface to return to a receiver. The quality of the LIDAR information depends on the density of points targeted. This technology can provide information about the shape of any 3D element.

It is also necessary to assess the solar radiation on a surface. The global radiation incident is formed by three components, the direct, the diffuse and the reflected radiation. The solar radiation is affected by the latitude, the elevation, the season, the time of the day, the weather, the topography or surrounding objects and the characteristics of the ground. What's more, the solar trajectory is usually interrupted by obstacles that cast shades on the ground.

Nowadays, there are three possible methods to assess the solar potential of rooftops considering shades:

1. A detailed method based on 3D imaging of buildings and angular intersection with the solar trajectory.
    This method is normally used by engineering and research companies. It cannot be applied massively.

    Examples of platforms that use this method:
    -   PVSYST: It is a software package for the study, sizing and analysis of photovoltaic systems, it includes a database of meteorologic and photovoltaic system components. [11]

    -   SKETCHUP: This software is a tool that creates 3D geometry modelling used for sun modelling, sun exposure and shade analysis. It provides users the data of the sun position and shading over an object, so they can visualize how a photovoltaic installation is going to work. [12]

2. A method that uses Cadastre data to generate an approximation of several buildings of districts and cities. Inclination and orientation of rooftops must be introduced manually. The computations of the shadow effect are performed as angular projection of the sun position over the approximated geometry of the buildings.
    This method doesn't take into account the presence of obstacles apart from buildings like trees.

    Examples of platforms that use this method:
    -   Som Comunitat energetica: This platform is designed for the simulation of the creation of energy communities jointly with neighbours for discovering the energetic and economic savings that the installation is going to suppose. [13]

3. A method that uses LiDAR data to generate a 3D model of a city, it uses GIS (geographic information system) based applications to generate rasters (dataset of pixels representing characteristics of a geographical region) of shadings. This method generates solar maps of cities and districts.

   Examples of platforms that use this method:
   - CIEMAT (Centro de Investigaciones Energéticas, Medioambietales y Tecnológicas) gSolarRoof model: This model assess with precision the potential surface are for photovoltaic use in several types of buildings. This model can also calculate the maximum power that could be installed in the building, the energy that could be produced in a year and the CO_2 emissions avoided. [14]

The novelty of our tool is that it assesses the solar potential of rooftops with a methodology that it is in the middle of the 3 previous methods. Its characteristics are:

1. It needs very few data apart from the LIDAR files.
2. It automatically generates the 3D model
3. It provides very detailed data of the solar shading matrix with a minimum computational effort.
4. It also calculates the solar PV generation taking into account shading.

Its limit is that it requires higher computational resources to be massively implemented. The obtained results are very accurate, equivalent to the first method but with less inputs and less human dedication.

3 Methodology for the creation of the solar estimation potential of rooftops tool

In order to create the tool to estimate the solar potential of roofs taking into account shading, the below steps have been followed:
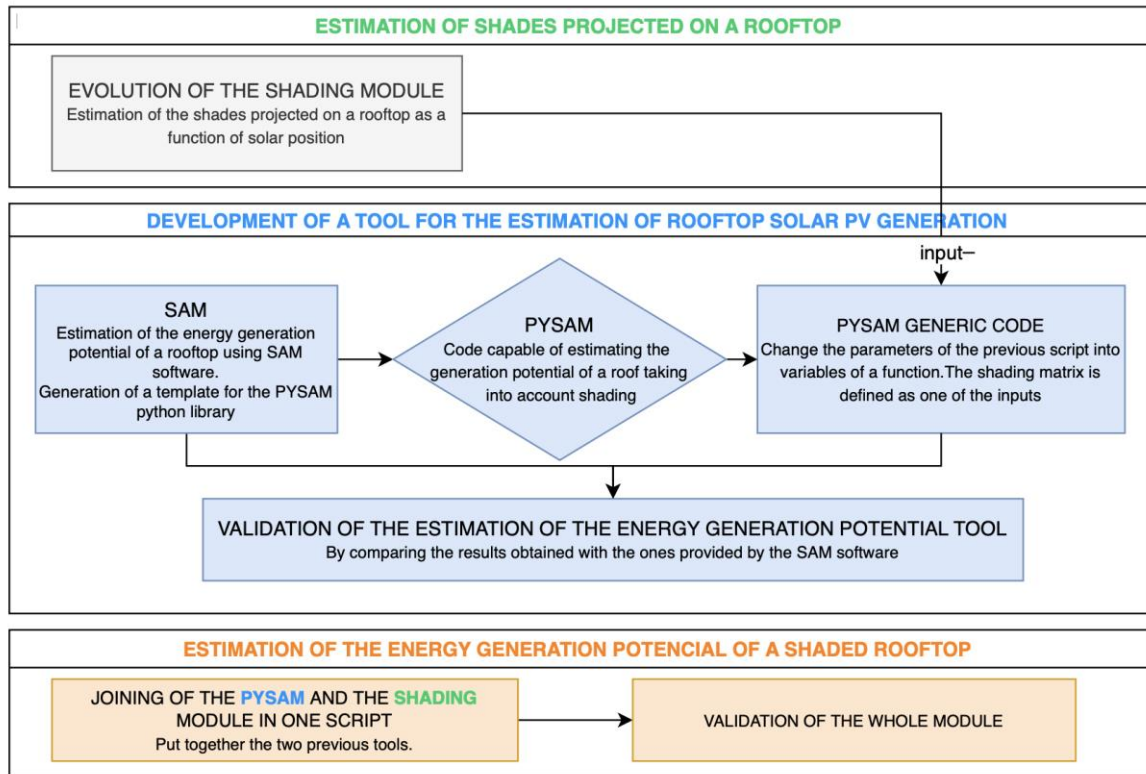
Figure 1 Flow chart of the development of the tool for the estimation of rooftop solar PV generation.

3.1 Estimation of shades projected on a rooftop

First of all, work has been performed with a Python script already created by the CIMNE – Bee Group, which is able to create a matrix that represents the percentage of shade in the selected rooftop in function of the solar azimuth and the solar altitude.

An evolution of this module has been carried out in order to minimize the execution time of the program. To achieve it, the shading percentage on the roof, depending on the solar position, has been modified. The measurement range for each 3° azimuth and 3° solar altitude has been changed to 9° for both parameters.

For the implementation and the execution of this Python code, a Docker container has been created for having all the necessary software on it.

Docker packages software into standardized units called containers that include everything needed for the software to run, including libraries, system tools, code and runtime.

3.2 Development of a tool for the estimation of rooftop solar PV generation

The second step consists of creating another module in a Python script based on PYSAM. This module is in charge of estimating the energy generation taking into account the matrix obtained in the execution of the previous script.

PYSAM is a Python module that makes it easy to read and manipulate mapped short-read sequence data stored in SAM files.

3.2.1 Execution from System Advisor Model interface

System Advisor Model (SAM) is a software model that can simulate many types of renewable energy systems to facilitate decision-making for people.

SAM can model different types of systems such as Photovoltaic systems, battery storage, wind power, marine energy wave, solar water heating, geothermal power generation and biomass combustion for power generation.

SAM can also model financial systems for residential and commercial projects, power purchase agreement projects and third-party ownership projects.

Firstly, a first run has been carried out using the SAM software through its interface, as it is know, this application is validated. This will allow us to compare the results obtained with our tool and validate its functionality.

A detailed PV model has been created in SAM, as it is the one that can read a shading matrix as input. No financial project has been chosen, as the project aims to determine the maximum energy production without considering the economic investment involved. In this SAM software, the parameters and variables of a generic installation have been introduced.

3.2.1.1 Inputs introduced in SAM

This model requires as inputs:

- Typical meteorological year (TMY) file. This fail contains a set of meteorological data of values for every hour in a year for a given location. The data are selected from hourly data in a longer time period (normally 10 years or more).
  Apart from the meteorological data, this file has implicit the following information:
    - Latitude [decimal degrees]
    - Longitude [decimal degrees]
    - Elevation [m]
  This file has to be downloaded from the PVGIS interface and is different for every location.
- Model of modules, number of modules per string in subarray and number of strings in parallel in subarray that will be used in the installation. To ensure that the process has as minimum variability as possible, a generic model of modules has been chosen for all executions, these modules are the same ones that the PYSAM script will use. The modules used are the following:
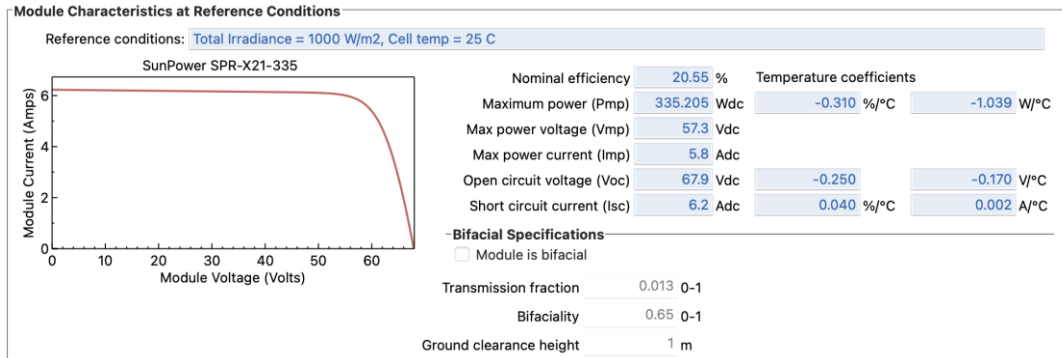
Figure 2 Screenshot of the SAM interface showing the modules chosen for the executions. [4]

- Number and model of inverters that will be used in the installation. To ensure that the process has as minimum variability as possible, a generic model of the inverter has been chosen for all executions, these modules are the same ones that the PYSAM script will use. The inverters used are the following:
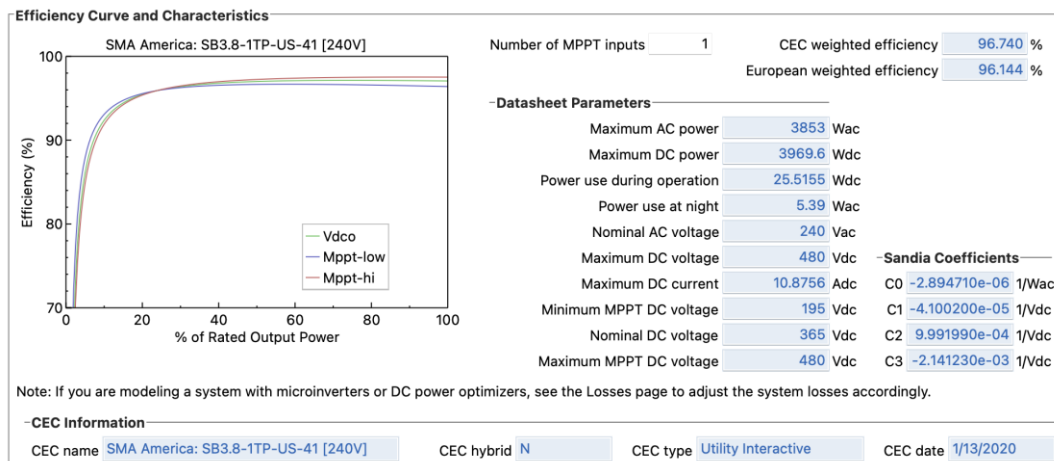
Figure 3 Screenshot of the SAM interface showing the modules chosen for the executions. [4]

- Shade matrix, obtained from the previous shade execution. This input will be different for every building.

- Tilt of solar panels. Being 0º horizontal panels and 90º Vertical panels. This input will be different for every execution.

- Azimuth of solar panels. Being 0º for the north, 90º for the east, 180º for the south, and 270º for the west, as in the shadind module. These values depend on the building.

- Ground coverage ratio (GCR): Ratio between the PV modules area and the total ground area. In all executions and in the PYSAM code GCR shall always be considered as 0,3.

7
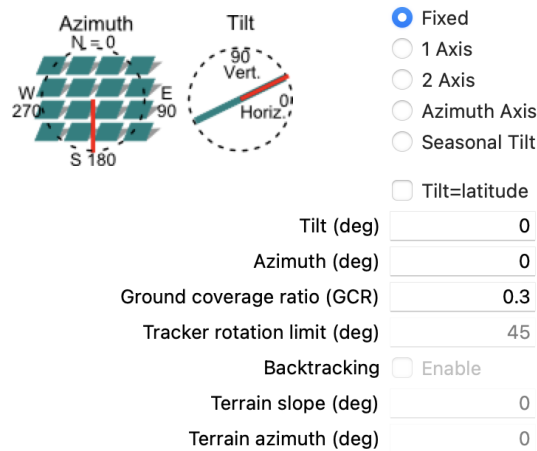
Figure 4 Screenshot of the SAM interface showing the criteria of Azimuth and Tilt, and how the inputs are introduced. [4]

- Losses. To ensure that the process has as minimum variability as possible, a generic value of losses will be set for all executions, these values are the same ones that the PYSAM script will use. Default values of soiling:
  - Average annual soiling loss: 5%
  - Total DC power loss: 4.440%
  - AC losses: AC wiring: 1%

Figure 5 Screenshot of the SAM interface showing the default values of losses for all the executions. [4]

3.2.1.2   Outputs obtained from SAM software simulation

Once all the data is introduced in SAM, the model can be simulated. The results obtained from the simulation are:

- Annual energy (year 1) [kWh]: The total amount of kWh that could be generated in the first year.

- DC capacity factor (year 1) [%]: Ratio of the annual average of kWh energy production divided by the maximum annual energy production when it operates at its peak rated capacity every hour of the year.

8

- Energy yield (year 1)[kWh/kW]: The amount of energy actually collected by the photovoltaic installation, taking into account external factors such as heat, dirt and shade.

- Performance ratio (year 1) [-]: The performance ratio is given as a percentage and expresses the ratio between the actual yield and the nominal yield of the PV system. It, therefore, indicates what proportion of the energy is actually available for power generation after energy losses have been deducted.

- Monthly energy generation [kWh]: The total amount of kWh that could be generated every month of one year.

- Hourly Data: System power generated [kW]: The total amount of kW that could be generated every hour during a year.

3.2.2 Generation of PYSAM generic code

The SAM software has the option of generating a template from the SAM interface with default values already entered, so that the generated code can be executed out of the platform.

In our project, a Python 3 code has been generated from SAM, as it is the same language used in the shade script. This code has implicit all the parameters introduced, and if this code is executed, the obtained results are the same as in SAM.

In order to create a generic code that does not depend on the interface and can be executed in any location and building, the following modifications have been done to the generated code:
- Convert the code into a function.
- Leave as default parameters all the variables detailed in the last point as generic.
- Convert the parameters that change in each case into input variables of the function:
  - TMY file (opened from an established repertoire)
  - Tilt of the rooftop
  - Azimuth of the rooftop
  - Matrix shading
  - Area
  - Latitude
  - Number of rooftops

3.3 Integration of both scripts

Once both scripts are working properly, they should be merged to close the loop and optimize the execution by achieving the following improvements:
- Minimize inputs: When the scripts are executed separately each one requires the following inputs:
  - Inputs of the shading estimation tool:
    - Coordinates of the rooftop
    - LIDAR (LAZ) file of the rooftop
  - Inputs of Power generation estimation tool:

- TMY file
- Tilt of the rooftop
- Azimuth of the rooftop
- Number of rooftops
- Area of the rooftops
- Latitude
- Shading matrix

Except for the TMY file, all parameters are calculated in the shading estimation tool, so linking the two scripts allows avoiding intermediate manual steps and minimizes the total inputs to:

- Coordinates of the rooftop
- LIDAR (LAZ) file of the rooftop
- TMY file

- Minimize the number of executions from two to one.

- Minimize the manually treatment of data.

- Obtain the desired outputs:

  o Shading matrix
  o Number of panels
  o Number of inverters
  o Nameplate capacity
  o Annual energy (year 1)
  o Monthly energy (year 1)
  o Capacity factor (year 1)
  o Energy yield (year 1)
  o Performance ratio (year 1)
  o Hourly power generation (kW)
  o Hourly radiation after shading (kW)
  o Hourly radiation before shading (kW)

4 Operation of the tool for the estimation of rooftop solar PV potential

The different parts of the created tool work as follows:

4.1 Operation of the shading module

1. Selection of the building: Entering the coordinates of the rooftop as an input of the script and the LIDAR corresponding file.
   The LIDAR files used for the executions are downloaded manually from the Spanish National Central of Geographic Information, which is a free database. [15] The density of points for Catalonia (the region of study in this project) is around 0.5 points per m^2. This low value can give non very precise results.

2. Determine the different planes using a RANSAC (Random sample consensus) algorithm: This algorithm tries to find all the rooftops and segments the roof into different planes.

It is necessary to determine the different roof planes, as orientation and slope have a significant impact on the solar potential.

The RANSAC algorithm is an iterative method for calculating the parameters of a mathematical model of a group of data observed.

This algorithm has a random part as it randomly takes 3 points for the creation of the plane, so the results can differ a lot in every simulation.

3. Find the building characteristics: tilt, azimuth and area for each plane.
Once determined the planes, the tilt and the azimuth are obtained by using the normal vector of each plane.

- Tilt: 0º for flat planes, 90º for vertical planes.
- Azimuth: The azimuth for the module is considered 0º for the north, 90º for the east, 180º for the south, and 270º for the west.
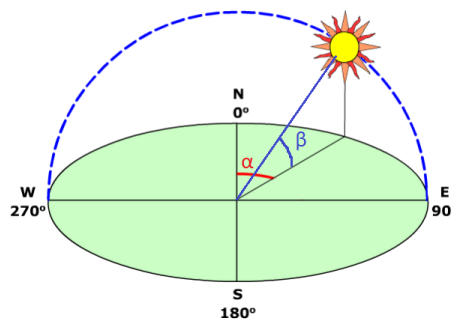
Figure 6 Criteria used for the solar azimuth (α) and the solar altitude (β) in the created tool. [15]

4. Shading: Create a matrix of shading for the following step.
The creation of a 3D model of the building and its surrounding objects is created in two steps.
   4.1. The area of study is selected: 50 meters on the east and west sides, 80 meters on the south side and 20 meters on the north side. These values have been chosen as the southern objects are the most significant in shading. A LAS file with las2shp is created in the selected area. Las2shp is a tool that can work with LIDAR files. From this shapefile, an STL file is created. STL files describe the surface geometry of three-dimensional objects.
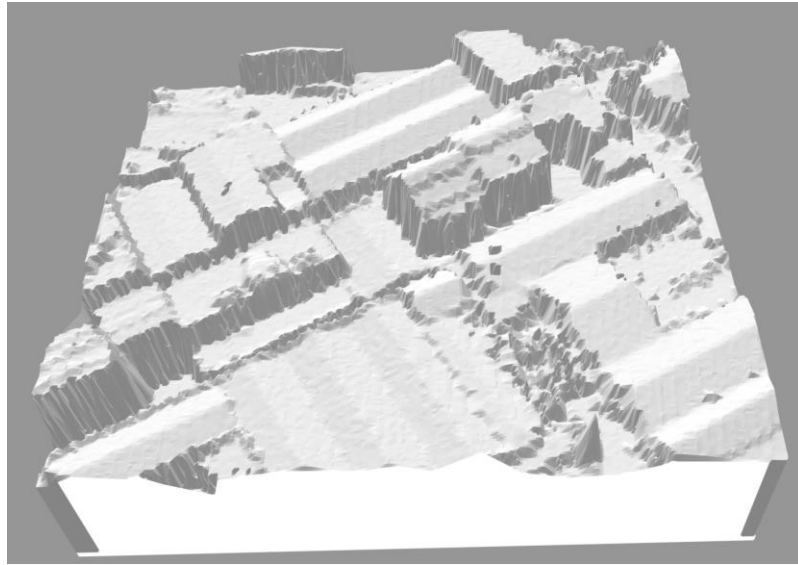
Figure 7 Example of an STL file created in an execution.

4.2. The creation of the shading matrix is done with the Python library trimesh with the mean of several matrix shading with the mean of several shading matrices. Each matrix is developed by taking random points on the rooftop and calculating the shading for every specific point. The shading of each point is evaluated by tracing a ray for a specific azimuth and a specific elevation and then by finding whether it crosses the mesh.

This operation is repeated for every altitude and azimuth value at a range of 9º. The matrix is created with these values.

4.1.1 Hypothesis taken

1. Parameters to join rooftops: 2 rooftops are joined:
   - If tilts of both are below 12º and difference of mean height is below 5 meters.
   - If the difference of orientation is below 10º, difference of tilt below 5º and difference of mean height is below 5 meters.

2. Delete points if its height is at least 7 meters below the average height. 7 meters is a value taken randomly. It is considered to be sure to not have really strange points, like points from a terrace.

3. Delete a plane if its slope is bigger than 60º or if its azimuth is between 270º and 90º and its slope is bigger than 15º.

4. Modification of the classification if at least 7 out of the 8 nearest neighbors have another classification.

5. Area of each rooftop

$$Area\ of\ each\ rooftop = \frac{number\ of\ points\ belonging\ roof}{point\ density} * 0.95$$

Considering the fact that the edge points don't cover only the building

$$Area\ of\ whole\ building = \frac{total\ building\ points}{point\ density} * 0.95$$

6. Area for the neighbourhood: 50 meters on West and East, 80 meters on South and 20 meters on South.

4.2 Operation of the PYSAM module

Estimation of the energy that could be generated in a photovoltaic installation.

Creation of a Python file using as inputs the previous calculated data. This PYSAM file is created through a generated code from the SAM software.

1. The area used for the installation of the solar modules is a 80% of the total available area.
2. Every string is composed by 7 modules.

4.3 Operation of the whole joined tool

Both parts have been joined in a Python script in order to avoid the inputs and outputs treatment manually.
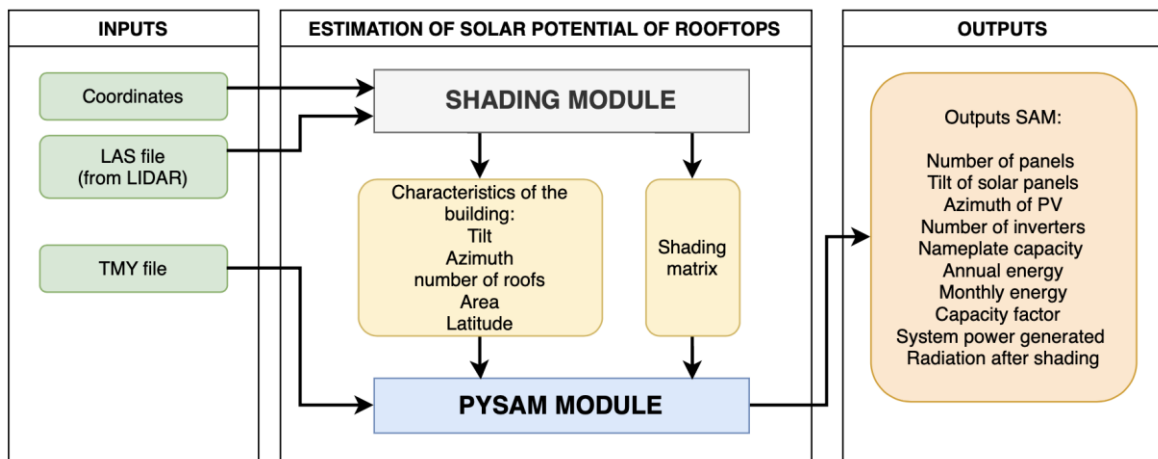
Figure 8 Flow chart showing the inputs, outputs and middle data during the execution of the whole module.

4.3.1 Inputs entered

1. Coordinates: The coordinates must be introduced manually when executing the file as follows:

   python3 Notebooks/main.py "[(41.512240, 2.038412), (41.512240, 2.03876), (41.512380, 2.038758), (41.512389, 2.038419)]"

2. LAS file: This file must be located in a defined repertoire. The LIDAR files used for the executions have to be downloaded manually from the free Spanish National Central of Geographic Information.

   On this website, the "LIDAR 2a Cobertura" digital elevations model has to be selected choosing the map option. A polygon of the interested surface has to be

drawn on the map. Once selected just the files that belong to the topic RGB have to be downloaded.

Figure 9 Screenshot from the Spanish National Central of Geographic Information, showing the digital model of elevations that have to be chosen. [16]
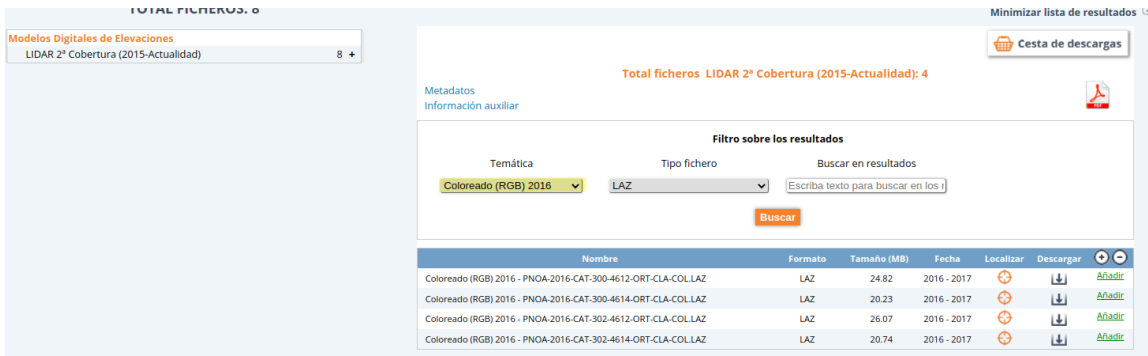
Figure 10 Screenshot from the Spanish National Central of Geographic Information, showing the digital model of elevations that have to be chosen. [16]

3. TMY file: This file was to be downloaded from the PVGIS interface. It has to be located in a defined repertoire.
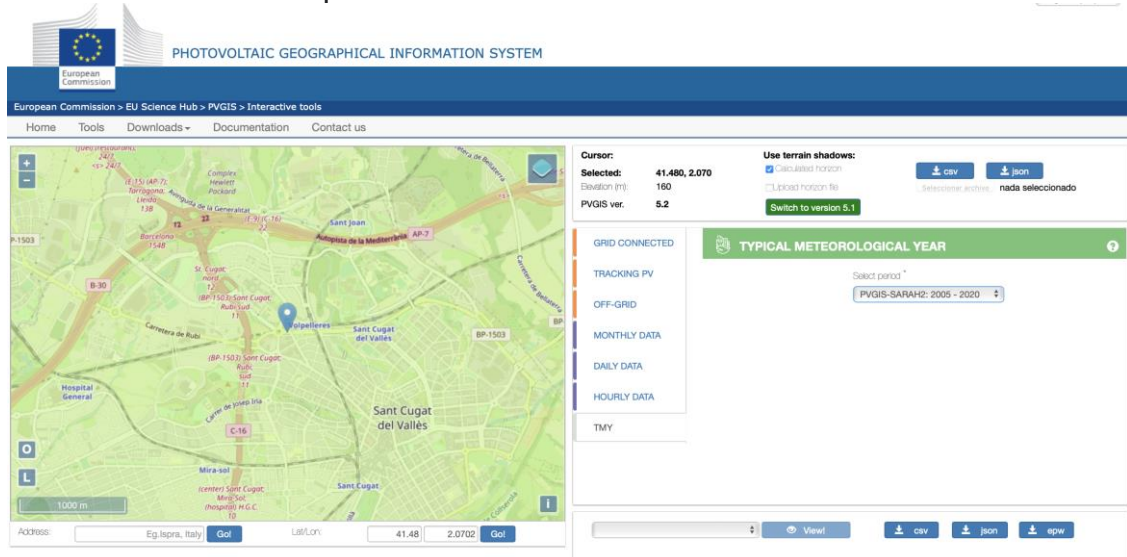
Figure 11 Screenshot from PVGIS webpage, showing the interface from where the TMY have been downloaded. [5]

4.3.2 Outputs of shading module and inputs of PYSAM module

The first shading module gives as outputs the following data. This information will be used as input for the second module:

1. Characteristics of the building in a text file.

Figure 12 Example of the characteristics of the building output.

2. Shading matrix in CSV format.

Table 1 Example of a processed shading matrix.

ALTITUDE (°) \ AZIMUTH (°)	9	18	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270	279	288	297	306	315	324	333	342	351	360
9	98,8	100,0	100,0	100,0	100,0	100,0	100,0	96,0	98,0	100,0	100,0	100,0	100,0	100,0	99,6	99,2	100,0	96,0	91,7	92,1	94,4	99,2	99,6	98,8	97,2	88,5	85,7	86,9	96,8	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
18	99,6	100,0	94,8	82,5	70,2	69,8	65,5	51,6	72,2	99,2	100,0	100,0	100,0	100,0	97,6	82,5	71,8	67,1	56,0	63,5	68,7	71,8	65,5	37,3	34,9	29,0	23,8	21,0	28,2	55,6	82,1	96,8	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
27	63,5	56,7	54,0	49,2	44,0	40,5	34,1	30,6	27,0	48,8	82,9	96,8	100,0	100,0	93,3	78,6	71,4	62,3	54,4	51,6	52,0	42,9	22,6	7,1	18,3	17,1	13,5	9,5	7,5	12,3	20,2	32,5	50,8	68,3	83,7	89,7	91,7	90,5	88,1	79,8
36	24,6	34,1	31,3	30,6	28,2	21,8	16,3	13,5	9,1	7,1	20,2	38,1	57,9	71,0	67,9	63,5	60,3	48,8	46,4	38,5	24,6	13,5	5,6	4,0	13,1	9,9	7,5	7,1	6,7	4,0	7,5	13,1	17,9	21,0	37,7	53,2	52,0	50,8	50,0	34,9
45	13,5	15,1	17,9	12,7	8,7	5,6	4,4	4,0	4,4	3,6	3,6	6,3	13,5	17,9	21,8	23,4	24,6	18,7	15,5	11,5	7,1	4,8	3,6	3,6	5,2	4,4	5,6	4,8	5,2	3,6	3,6	6,0	12,3	13,1	17,1	17,1	26,2	33,7	32,5	18,3
54	0,4	1,6	1,6	3,2	3,6	3,6	3,6	3,6	3,6	3,6	3,2	0,0	1,2	0,4	2,0	2,0	2,0	1,2	2,0	2,0	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	4,0	5,6	3,2	3,6	3,6	3,2	0,8	
63	0,0	0,0	0,0	1,2	3,2	3,6	2,0	2,0	2,4	1,6	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,4	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,2	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0
72	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	2,4	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,2	2,0	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
81	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,2	1,2	1,2	1,2	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
90	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

4.3.3 Outputs obtained

The outputs obtained from the whole executions are the following:

1. A text file with the following results of the simulation:
   - Area of one module
   - Number of panels
   - Tilt of solar panels
   - Tilt of rooftop(s)
   - Azimuth of PV
   - Azimuth of rootop(s)
   - Area of rooftop(s)
   - Number of inverters
   - Nameplate capacity
   - Annual energy (year 1)
   - Monthly energy (year 1)
   - Capacity factor (year 1)
   - Energy yield (year 1)
   - Performance ratio (year 1)
   - System power generated (kW)

```
●●●                                    outputs_SAM
area_one_module =  [4.7751748639073845]
Number of panels =  [175]
Tilt of solar panels=  [19.3]
Tilt of rooftop(s)=  [19.3]
Azimuth of PV =  [148.86171099390063]
Azimuth of roptop(s) =  [148.86171099390063]
Area of rooftop(s) =  [358.03437546617124]
Number of inverters =  16
Nameplate capacity = 58.660875 kWdc
Annual energy (year 1) = 76261.11186600877 kWh
Monthly energy (year 1) =  [2579.136771374828, 3618.0398932001717, 6470.272592857843,
7961.597064556177, 10213.737360269764, 10059.49211412338, 10199.327767383302, 9043.27930231673,
6155.362007716878, 4639.361701249466, 2949.9494403352364, 2371.5558506301236]
Capacity factor (year 1) =  14.840566864026938
Energy yield (year 1) = 1300.0336572887597 kWh/kW
Performance ratio (year 1) =  0.6611041476349503
System power generated (kW) =  [[0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0],
[2.7260710916014674], [6.631682171414691], [13.45665531408822], [17.33502626486072],
[18.00274368924589], [14.8758364290075187], [10.09975369514739], [1.2123627005731017], [0.0],
[0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0],
[0.0], [9.476784963769594], [10.611866473902502], [12.907206232047214], [17.563777113612574],
[18.102675395360954], [11.753286490360194], [6.897789436983668], [0.16896231399468], [0.0],
[0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0], [0.0],
[0.0], [2.8692166639379983], [10.417224563756303], [8.694591112473859], [6.739819253201183],
[3.529537503639723], [3.1939191065089294], [10.43209427679402], [0.12139409035203708], [0.0],
```

Figure 13 Example of the SAM outputs. The system power generated output is not showed in complete due to its length.

2. A CSV file with the hourly generation data of the first year. Same values as System power generated but in a different format.

3. A CSV file with the hourly radiation after shading data of the first year.

5 Results and validation of the tool for the estimation of solar PV generation

For the validation of the tool for the estimation of rooftop solar PV generation, several executions have been carried out in different types of rooftops and projected shades.

All the simulations are done in Coordinated Universal Time (UTC).

It has to be known that in Catalonia, the region where the tool has been validated the local time is UTC+1(from October to March) in winter and UTC+2 in summer (from March to October).

In each rooftop the following validations have been done:

- **Validation of the shading module by analyzing the shading matrix output.**
  This step has been carried out by interpreting the shading matrix obtained from the tool for the estimation of rooftop solar PV generation. It is known that the solar position is function of the hour of the day and the month of the year in the locations used for the validation:
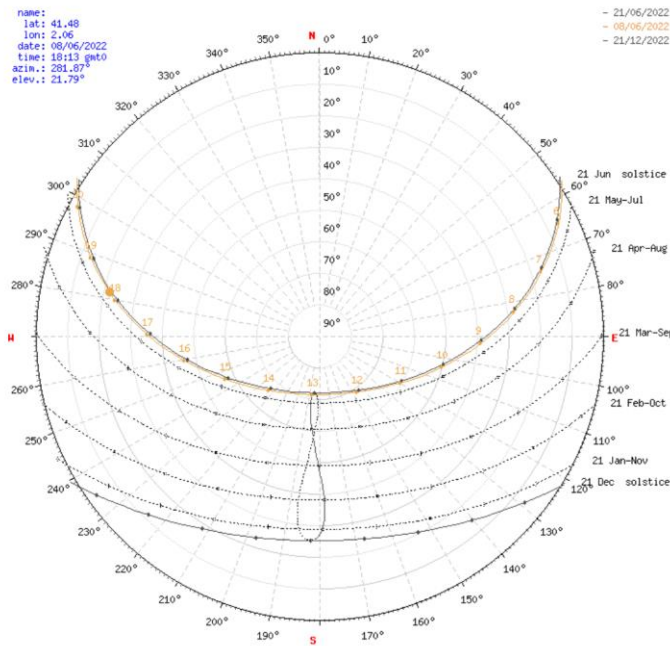
*Figure 14 Solar trajectory during the year in the location where all the executions for the validation
have been performed. The radius shows the solar altitude and the circumference angles show the
azimuth. [17]*

- **Validation of the PYSAM code by comparing the power output generation and
  the radiation after shading output with the results obtained from SAM software
  at the same location.**
  In this validation, the power generation output of the tool for the estimation of solar
  PV generation has been compared to a power generation output from an execution
  through SAM software configuring the same inputs in both cases.

  For quantifying the similarity, a Python script has been created. This code opens
  from a specific repertoire the following files. These files have to be located there
  manually.
    - Output hourly power generation from SAM
    - Output radiation after shading from SAM
    - Output hourly power generation from the created tool for the
      estimation of rooftop PV generation (PYSAM module).
    - Output radiation after shading from the created tool for the estimation
      of rooftop PV generation (PYSAM module).

  The program gives as output the following files in HTML format:
    - A superimposed plot of the radiation after shading from SAM and
      from the tool for the estimation of rooftop solar PV generation.
    - Linear regression plot of the radiation after shading from SAM and
      from the tool for the estimation of rooftop solar PV generation.
    - A superimposed plot of the power generation from SAM and from the
      tool for the estimation of rooftop solar PV generation.
    - Linear regression plot of the power generation from SAM and from
      the tool for the estimation of rooftop solar PV generation.

  This script uses the plotly Python library for the plot of the hourly results and the
  trend line that quantifies the similarity between SAM and PYSAM values.

18

Both results have to be very similar because they are using the same approximations, as both are working through the SAM software.

Target trend line values:
- $R^2 = 1$. This value means that both hourly values are proportional and aligned.
- Slope = 1. This value means that both hourly lists have the same value.

- **Validation of the whole tool by comparing the radiance after shading provided by the tool for the estimation of rooftop solar PV generation with the PVGIS software**.
For the validation of the whole tool (shading module + PYSAM module) the output of hourly radiation after shading is compared with the hourly radiation values obtained from PVGIS.
In some cases, the hourly radiation before shading values have also been used during the validation.

PVGIS is a web site that gives information about solar radiation and Photovoltaic system performance at nearly any place in the world.

PVGIS has been chosen for the comparative as the TMY values used by the created module are obtained from there, so this comparative assures that the weather values are the same in the executions from both platforms. The variability between the results of the PVGIS and the module created is due to the fact that the approximations are made using two different software packages (PVGIS and SAM).

When simulating from PVGIS the following inputs are needed: The azimuth and the tilt of the rooftop, the criteria used for the azimuth in PVGIS is different than the one used in SAM and in the created module.
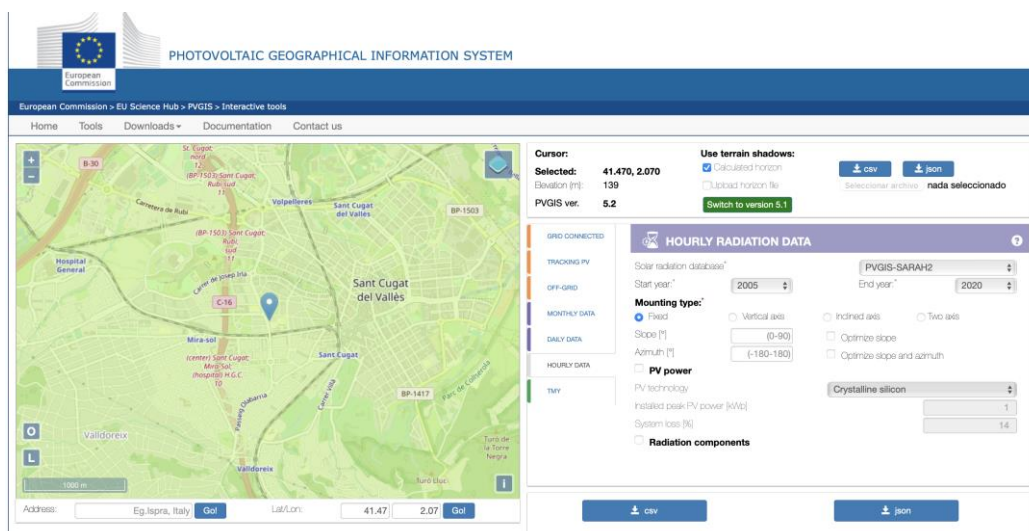
Figure 15 Screenshot from PVGIS webpage, showing the interface from where the hourly data have been downloaded. [5]

*Table 2 Comparation of the criteria used in the tool for the estimation of solar potential and the
PVGIS platform.*

	AZIMUTH CIRTERIA USED BY THE ESTIMATION OF SOLAR POTENTIAL MODULE	AZIMUTH CRITERIA USED BY THE PVGIS WEBPAGE
North	0º	+/- 180º
East	90º	-90º
South	180º	0º
West	270º	90º

So it has to be taken into account that the azimuth to put in PVGIS has to be:

$$Azimuth_{PVGIS} = Azimuth_{PYSAM} - 180º$$

PVGIS gives as output an hourly list of radiation per m^2.

For quantifying the similarity between PVGIS and the whole module, a Python script has been created. This code opens from an specific repertoire the following files. These files have to be located there manually.

- o Hourly radiation from PVGIS. This value is multiplied by the area of modules of the rooftop in the script.

- o Output hourly radiation after shading from the created tool for the estimation of rooftop solar PV generation.

The program gives as output the following files in HTML format:
- o A superimposed plot of the radiation after shading from PVGIS and from the tool for the estimation of PV generation.
- o Linear regression plot of the radiation after shading from PVGIS and from the tool for the estimation of PV generation.

This script uses the plotly library for the plot of the hourly results and the trend line that quantifies the similarity between the results.

Target trend line values:

- R^2 = 1,000 . This value means that both hourly values are proportional and aligned.
- Slope = 1,000 . This value means that both hourly lists have the same value.

Despite the target values, it is assumed some variability caused by the different methodology used.

These validation tests have been done on the following rooftops:

5.1 Validation tests over a flat, unshaded rooftop

First of all, a flat and apparently unshaded rooftop is chosen for the validation.

Figure 16 2D view of the building used for the execution of a flat and an unshaded rooftop. Oriented according to the cardinal points. [18]

Figure 17 3D view of the building used for the execution of a flat and an unshaded rooftop. [18]

5.1.1 Validation of the shading module

- Characteristics of the building output:
  - Slope : 1,278 º
  - Azimuth : 254,829 º
  - Area rooftops : 439,353 m^2

The slope output confirms that the rooftop is almost flat, as expected.

- STL file: The obtained STL file representing the neighbourhood evaluated shows that there aren't taller budlings interrupting the solar trajectory until the rooftop.

Figure 18 STL file of the building chosen for the execution and its surroundings.

- Shading matrix output:

Table 3 Shading matrix obtained for the flat and unshaded rooftop validation.

The shading matrix obtained from the execution indicates that there are no shadows cast on the roof regardless of the solar position, as expected when choosing the building.

The operation of the shading module is validated on a flat, unshaded roof.

![UPC Universitat Politècnica de Catalunya BarcelonaTech logo]
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BARCELONA**TECH**
Escola Superior d'Enginyeries Industrial,
Aeroespacial i Audiovisual de Terrassa

5.1.2 Validation of the PYSAM code

5.1.2.1 Comparison of the hourly power generation output

Figure 19 Power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

As shown in the figure, the superimposed plots of the output of generation created by the PySAM code of the tool for the estimation of rooftop solar PV generation and generation values of the SAM software are exactly the same.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM:
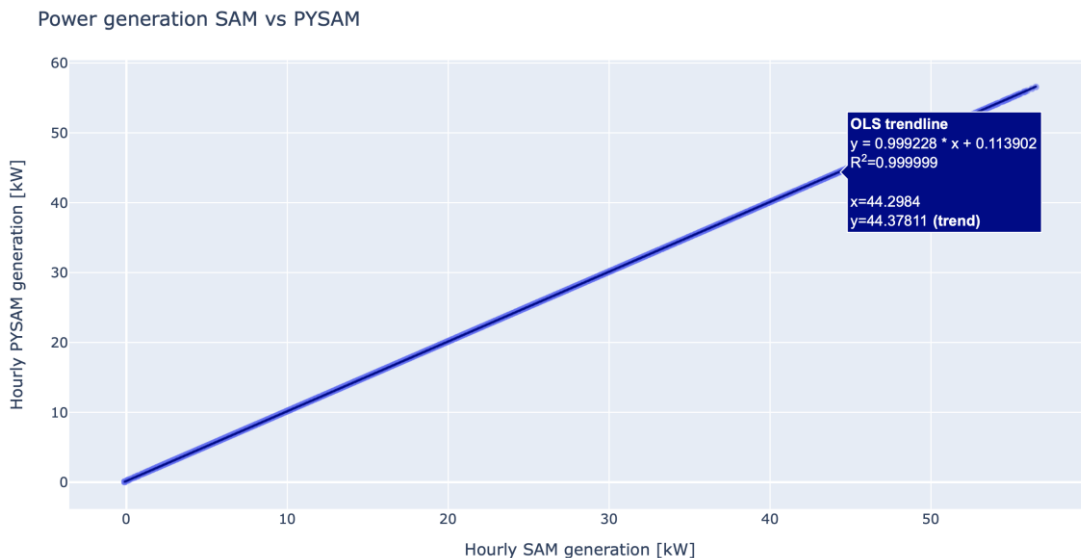
Figure 20 Linear regression of the power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000→ The obtained values of SAM are the same as those of PYSAM.

5.1.2.2   Comparison of the hourly radiance after shading output

RADIATION AFTER SHADING SAM vs PYSAM

Figure 21 Radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

The superimposed plots of the output of radiance after shading created by the PySAM code and the radiance after shading of the SAM software are exactly the same.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.

RADIATION AFTER SHADING SAM vs PYSAM
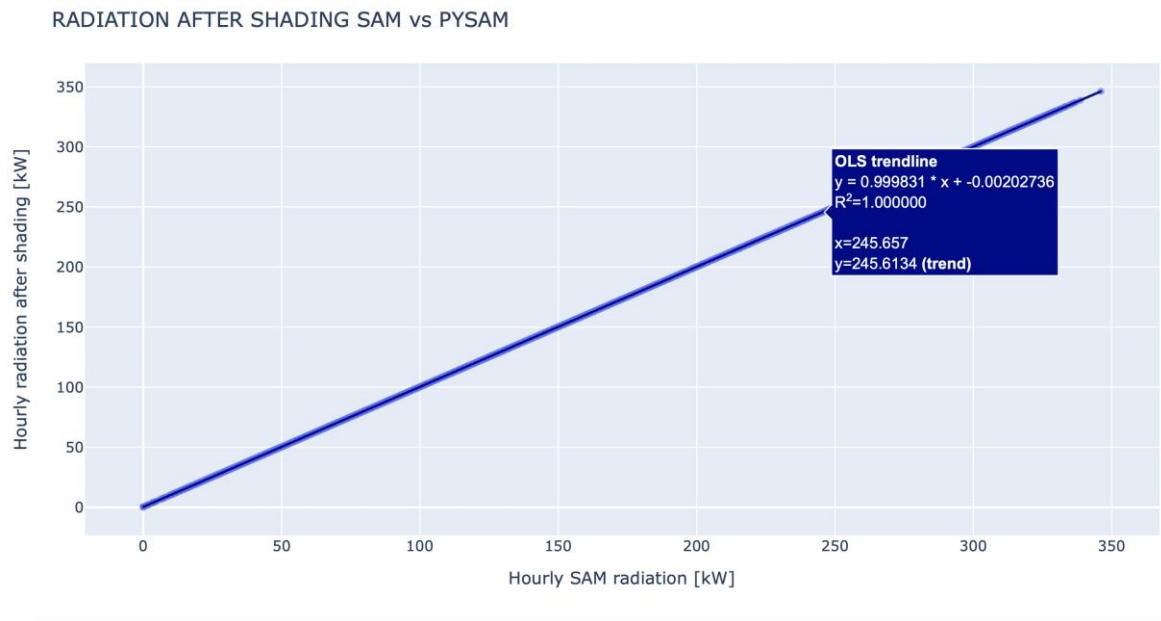
Figure 22 Linear regression of the radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values of SAM are the same as those of PYSAM.

The operation of the PYSAM module is validated on a flat, unshaded roof.

5.1.3 Validation of the whole tool

Comparison of the radiation after shading values given by the tool for the estimation of rooftop solar PV generation with the radiation values estimated by the PVGIS software in the same surface.

In this case, as detailed in the point 5.1.1., there is no shading on the rooftop so the obtained results have to be very similar in both cases.

*Figure 23 Radiation hourly values from PVGIS and radiation after shading hourly values from the
tool for the estimation of solar PV generation.*

If the graphs are superimposed, it can be observed that both plots are very similar.

In order to quantify their similarity, the following linear regression has been performed
comparing the results of PVGIS and the created tool.

*Figure 24 Linear regression of the radiation hourly values from PVGIS and from the radiation after
shading hourly values from the tool for the estimation of solar PV generation.*

The trend line of this plot shows the following information:

- R^2 = 0,970 ≈ 1 → The dots are closely aligned, which means that the values of PVGIS and the tool for the estimation of rooftop solar PV generation are proportional.
- Slope = 0,958 ≈ 1 → The slope value is slightly less than 1, which means that the PVGIS values are slightly higher than those provided by the created tool.

The difference between the values is attributed to the fact that the estimations made by the tool created are different from the ones made by PVGIS.

The operation of the whole module is validated on a flat, unshaded roof.

5.2 Validation tests over a flat, shaded rooftop

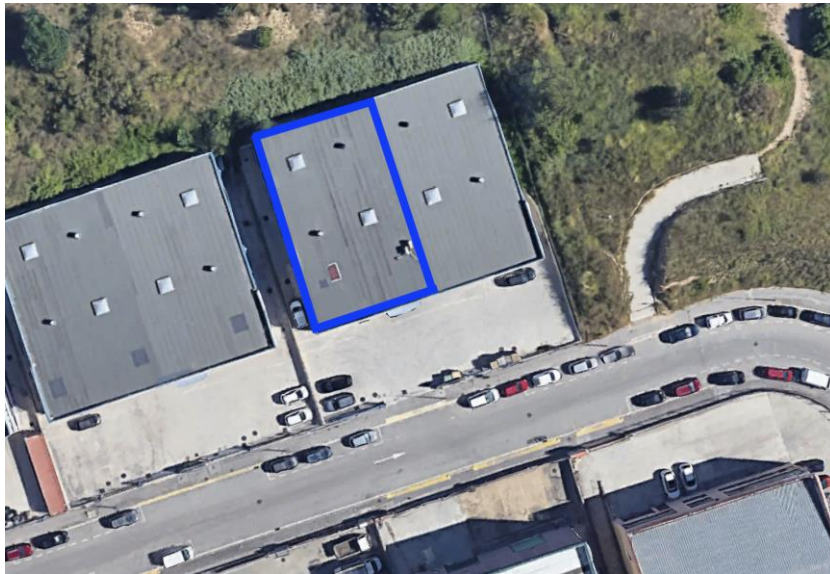A flat and apparently shaded rooftop is chosen for the validation.
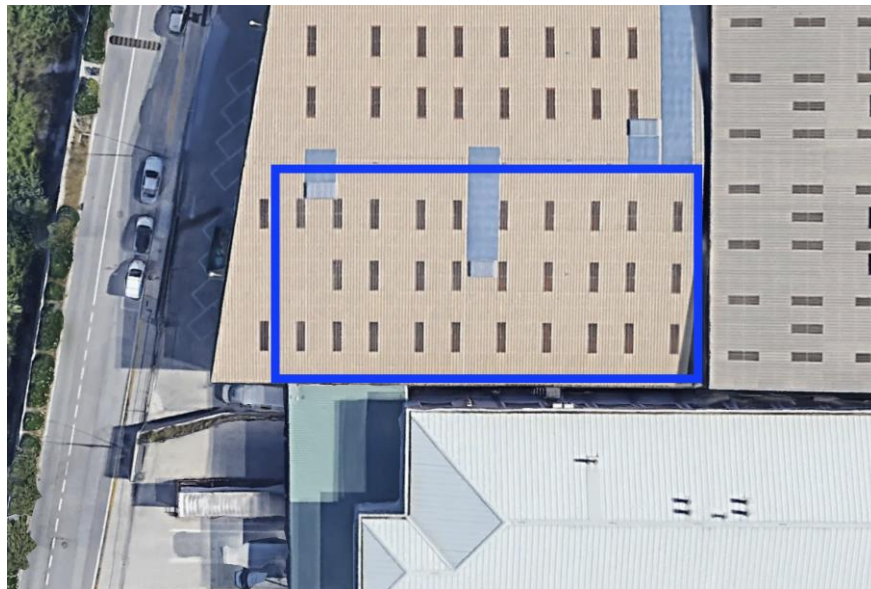
Figure 25 2D view of the building used for the execution of a flat and shaded rooftop. Oriented according to the cardinal points. [18]
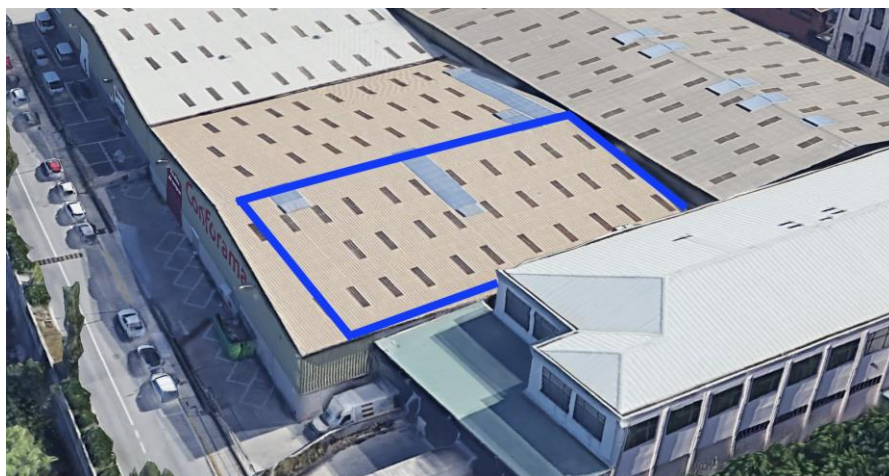
Figure 26 3D view of the building used for the execution of a flat and shaded rooftop. [18]

5.2.1 Validation of the shading module

- Characteristics of the building output:

  - Slope : 5,734 º
  - Azimuth : 182,476 º
  - Area rooftops : 783,797 m^2

The slope output confirms that the rooftop can be considered flat and the azimuth confirms the south orientation.

- STL file: The obtained STL file representing the neighbourhood evaluated shows that there are a taller budling in the south and another one at the east interrupting the solar trajectory until the rooftop for lower values of solar altitude.
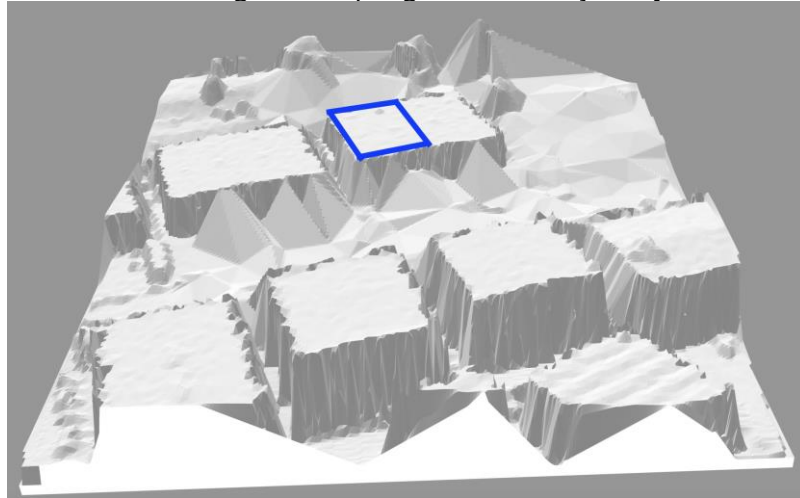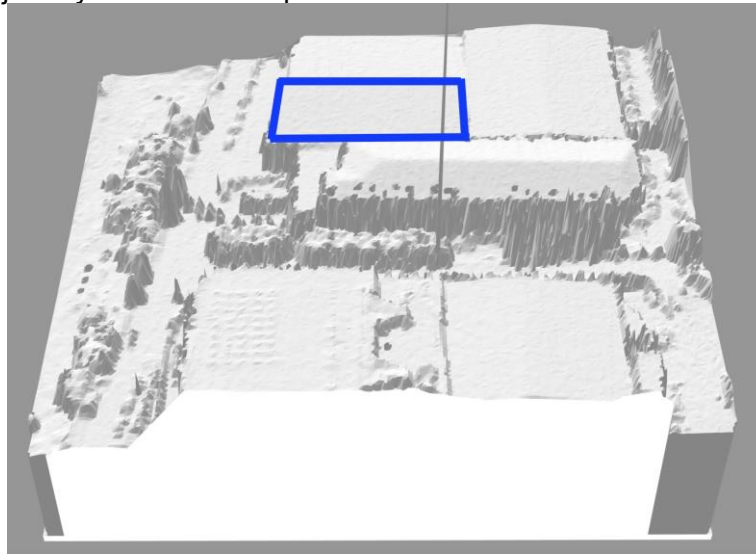

Figure 27 STL file of the building chosen for the execution and its surroundings.

- Shading matrix output:

Table 4 Shading matrix obtained for the flat and shaded rooftop validation.

	AZIMUTH (º)																																							
	9	18	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270	279	288	297	306	315	324	333	342	351	360
27	18,1	18,1	21,1	21,9	20,0	56,3	71,5	65,6	55,9	46,7	34,8	58,9	71,1	73,0	74,4	70,0	57,0	48,5	50,4	45,2	43,7	39,3	37,8	34,8	32,2	24,4	16,3	8,1	3,3	1,9	0,0	0,0	0,0	1,9	5,2	8,1	12,2	14,8	16,7	18,1
36	5,6	6,3	7,8	8,1	10,0	37,4	45,6	39,6	35,2	23,3	20,7	35,2	51,1	61,9	65,9	55,6	33,7	31,9	33,3	31,1	30,4	28,1	27,0	23,7	14,4	8,9	6,3	3,7	3,3	0,7	0,0	0,0	0,0	0,4	1,9	3,3	4,4	5,2	5,6	
45	1,1	1,1	2,6	8,9	24,4	37,4	34,1	31,9	24,8	15,9	13,0	25,9	32,2	48,9	57,4	54,4	28,1	15,2	15,9	12,6	10,7	11,1	8,9	6,7	6,7	5,9	3,7	3,3	3,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	1,1	1,1	
54	0,0	0,0	0,4	7,0	19,3	26,3	25,9	20,0	14,1	11,1	9,6	18,9	20,0	25,6	33,7	30,7	17,0	10,4	7,8	5,6	4,4	5,6	4,4	4,4	4,1	3,3	3,3	3,3	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
63	0,0	0,0	0,0	0,4	3,7	8,9	12,6	11,5	10,0	8,1	6,3	10,7	12,6	14,1	13,3	10,0	5,9	6,7	5,9	4,4	3,3	4,4	3,3	3,3	3,3	3,3	2,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
72	0,0	0,0	0,0	0,0	0,0	0,7	1,5	4,4	4,8	4,4	4,1	5,2	4,4	3,3	3,0	3,3	3,7	4,1	4,4	3,3	3,3	3,7	3,3	3,3	3,3	2,6	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
81	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,7	1,1	1,5	2,2	2,2	1,9	1,1	1,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
90	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	

It can be seen that for Southeast values of azimuth there are some significant values of shade that are going to reduce the radiance values.
This result was expected due to the two buildings surrounding the selected rooftop.

The operation of the shading module is validated on a flat, shaded roof.

5.2.2 Validation of the PYSAM code
5.2.2.1 Comparison of the hourly power generation output
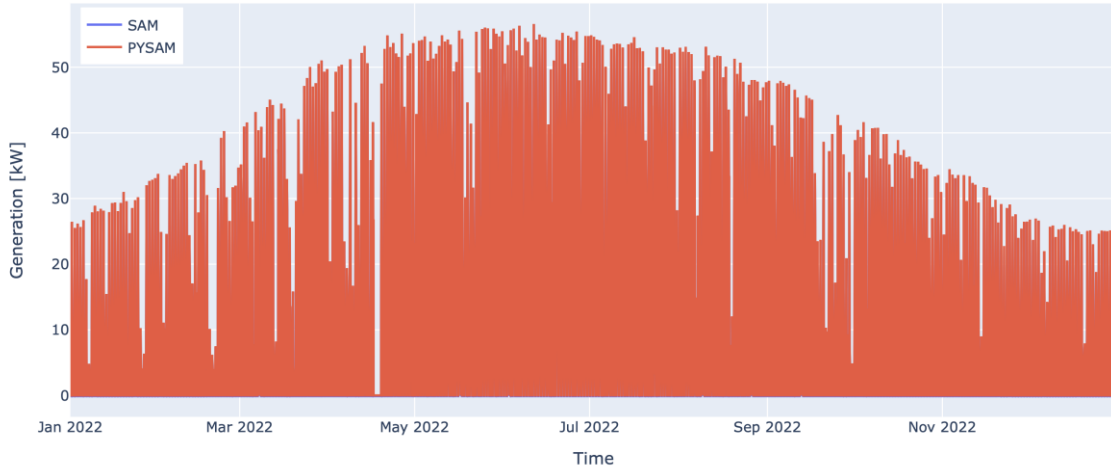
POWER GENERATION SAM vs PYSAM
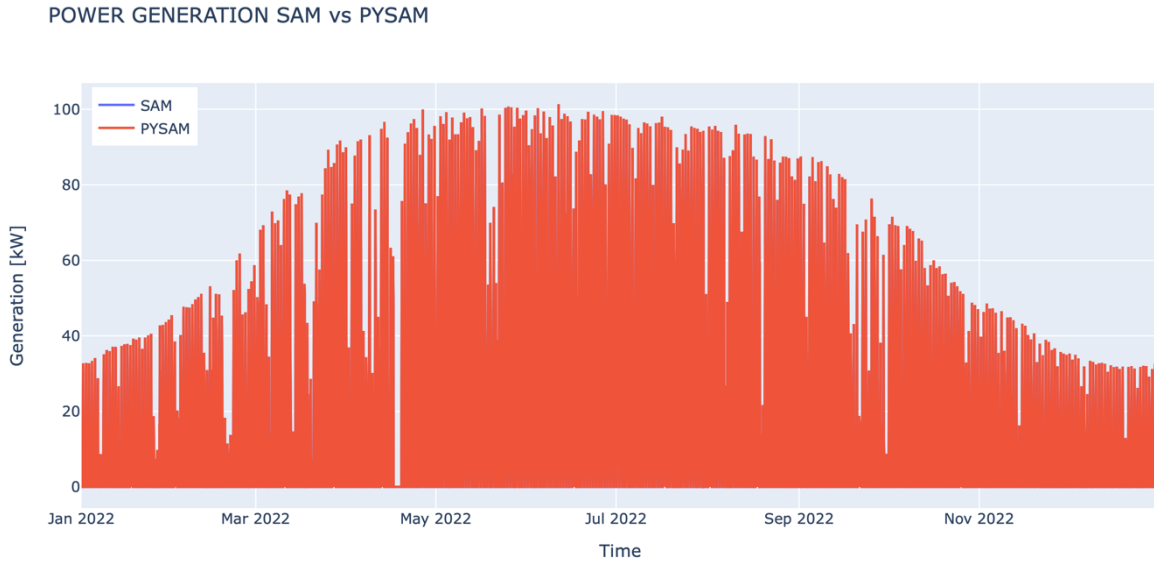
Figure 28 Power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The superimposed plots of the output of radiance after shading created by the PySAM code and the radiance after shading of the SAM software are exactly the same.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.

Power generation SAM vs PYSAM

OLS trendline
y = 1 * x + -2.0301e-05
R^2=1.000000

x=41.3545
y=41.35449 (trend)
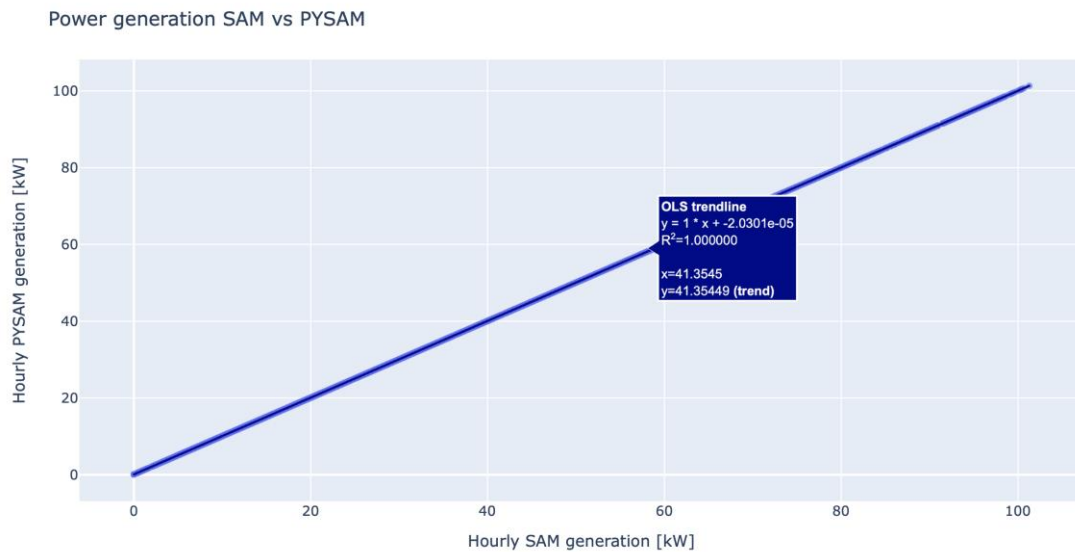
Figure 29 Linear regression of power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values of SAM are the same as those of PYSAM.

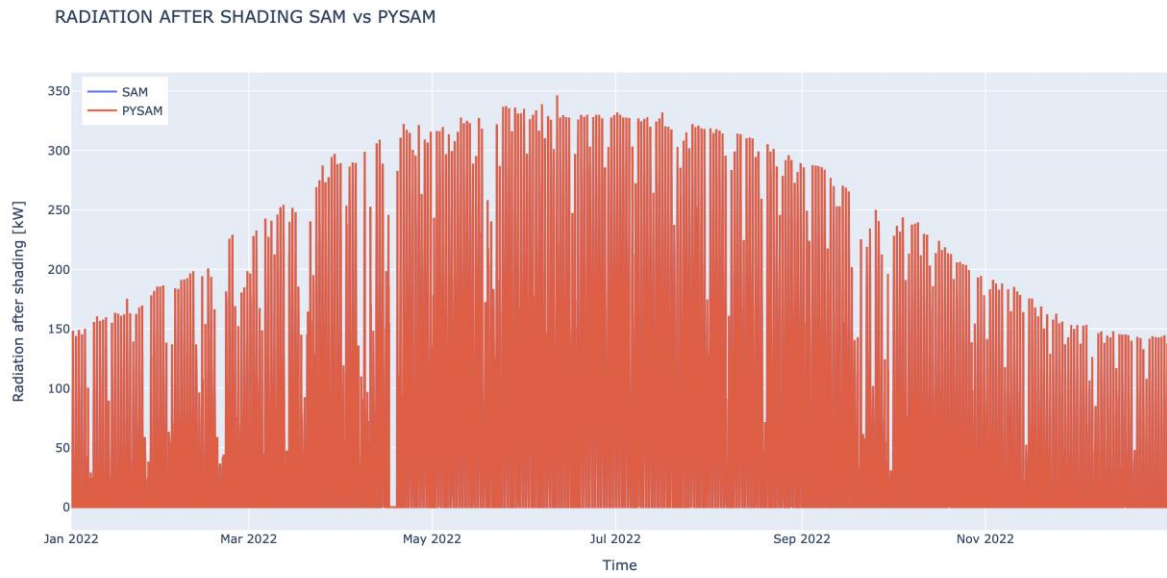## 5.2.2.2 Comparison of the hourly radiance after shading output

RADIATION AFTER SHADING SAM vs PYSAM
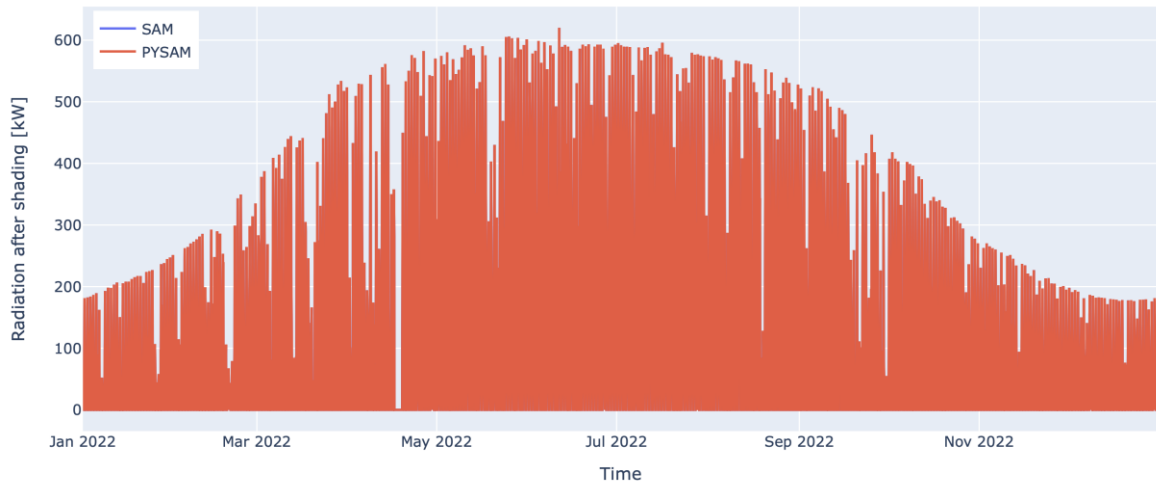
Figure 30 Radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

As shown in the graph, the plot of the output obtained from the output of radiance after shading created by the PySAM code of the tool for the estimation of rooftop solar PV generation is the same as the one generated with the SAM software.

If the graphs are superimposed, it can be observed that both plots are exactly the same.
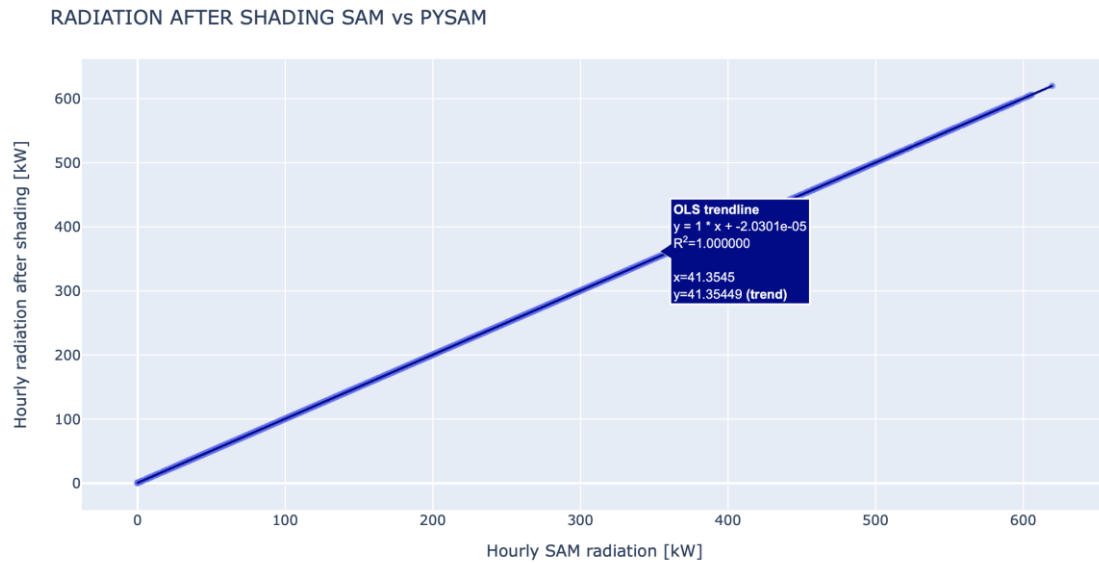
Figure 31 Linear regression of radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2 = 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values of SAM are the same as those of PYSAM.

5.2.3 Validation of the whole tool
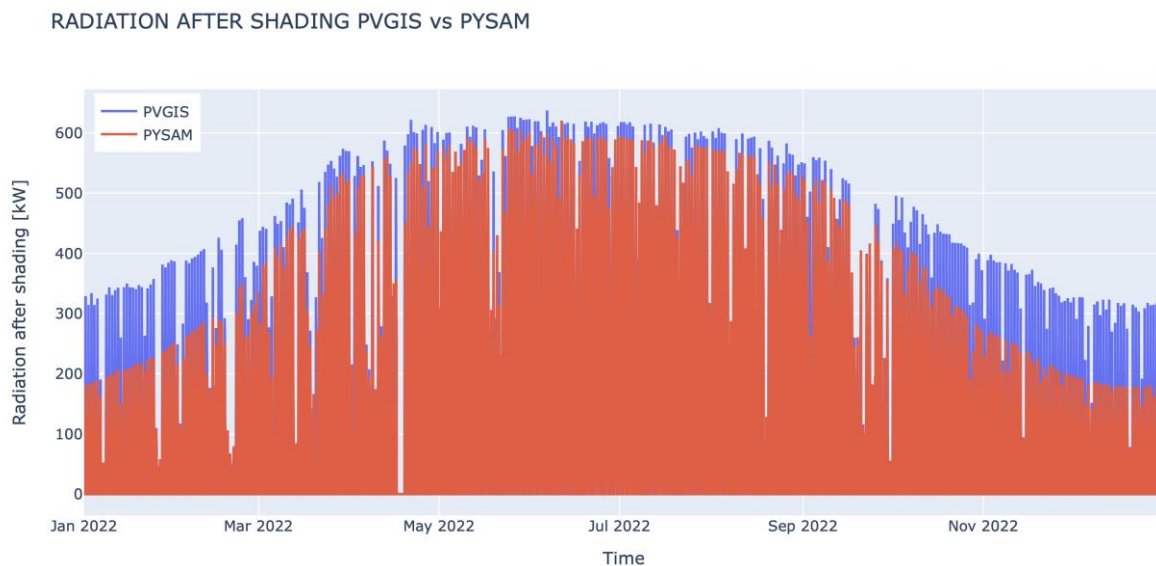
Figure 32 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation.

In this case, when the values are compared, there are some considerable differences due to shading.

If the graph comparing PVGIS results and radiation before shading is plotted it can be observed that both values are more similar:

RADIATION BEFORE SHADING PVGIS vs PYSAM
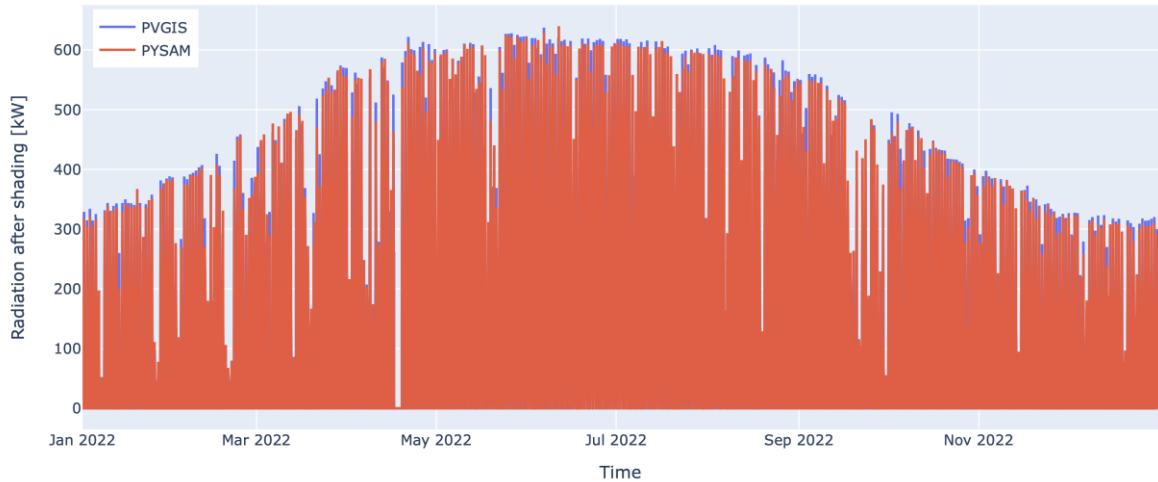
Figure 33 Linear regression of the radiation hourly values from PVGIS and from the radiation after shading hourly values from the tool for the estimation of solar PV generation.

As there is a taller building on the east of the rooftop, there are shades for lower values of solar azimuth (mornings).

As there is a taller building in the south of the rooftop, shade is casted in the surface for lower values of solar altitude: It can be observed that in the Winter season the values are less similar. In order to analyze it, one week of every season is compared before and after shading as follows:

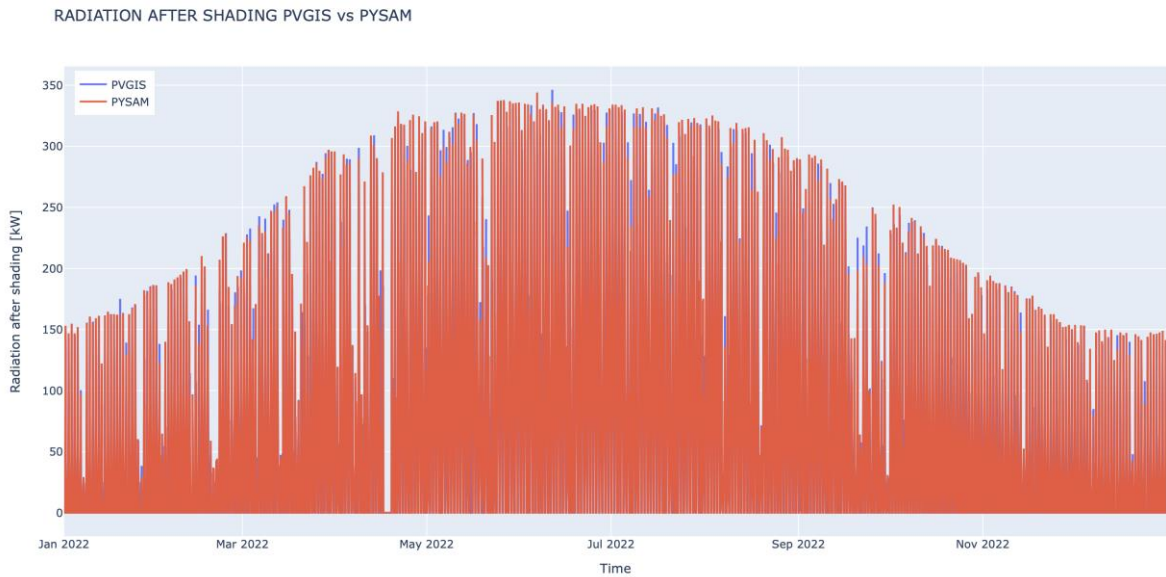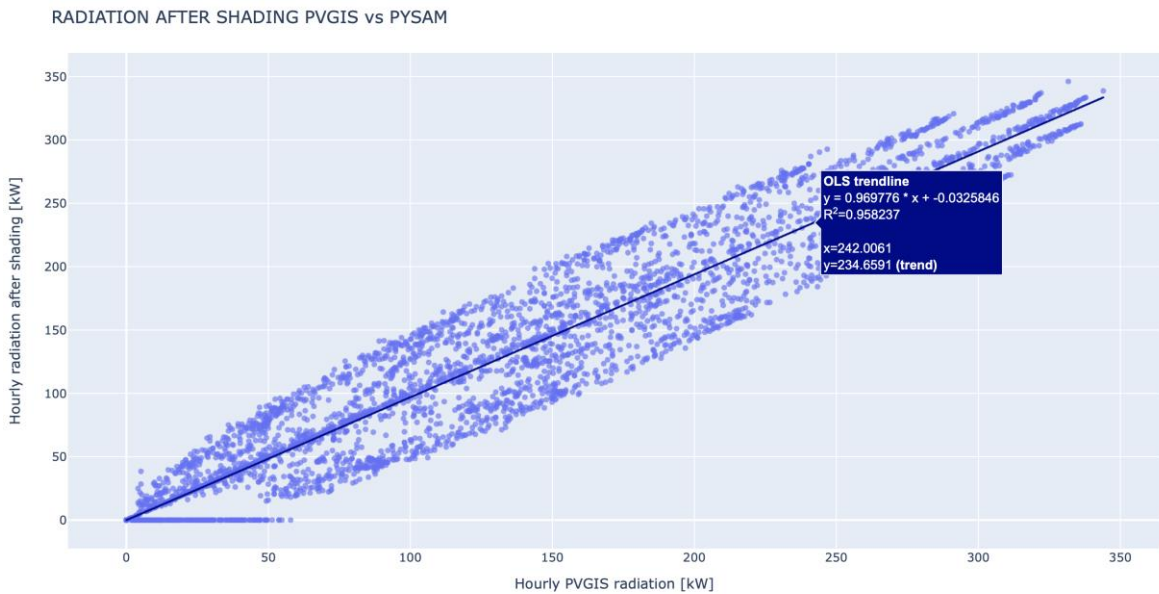- Winter: January

RADIATION BEFORE SHADING PVGIS vs PYSAM
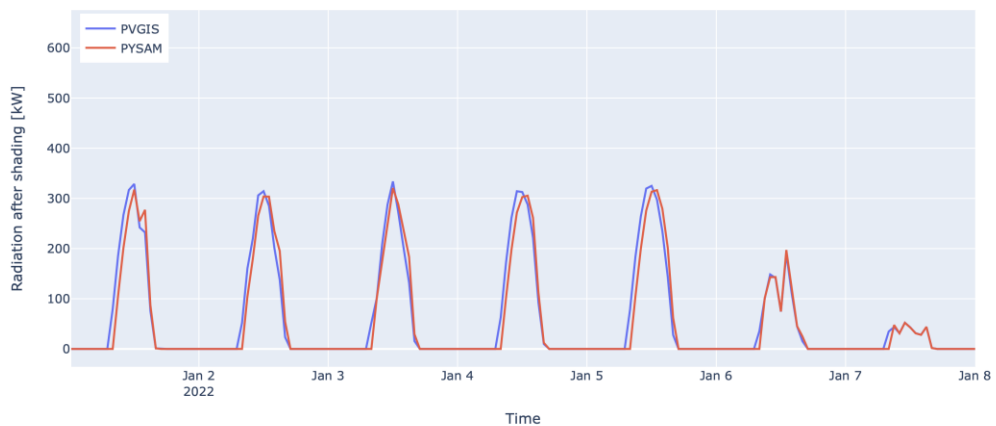
Figure 34 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from January the 1st to January the 8th .

32

RADIATION AFTER SHADING PVGIS vs PYSAM
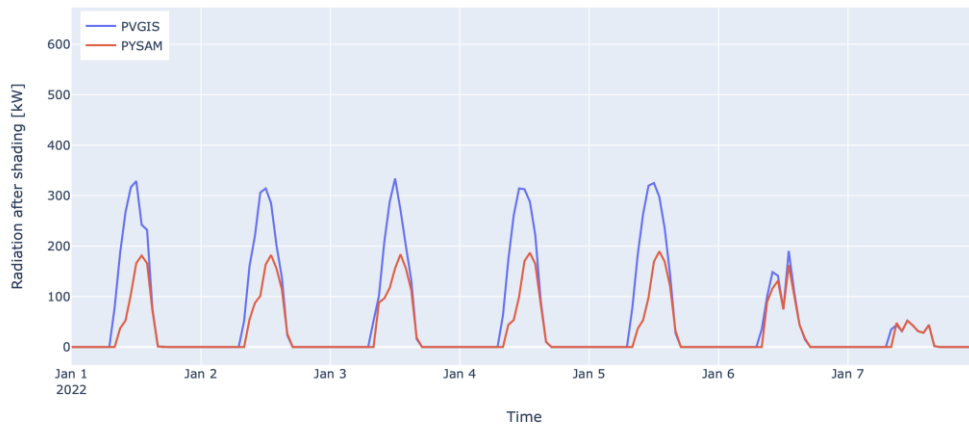
Figure 35 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from January the 1ˢᵗ to January the 8ᵗʰ .

The plots show that in winter the radiation after shading peak is approximately 50% of the radiation before shading, this is caused by the sun altitude during this season and the obstacle in the south of the studied rooftop.
The peak radiation after shading in winter reaches a value of approximately 175 kW.

There is some differences observed in the mornings due to the east obstacle.

- Spring: April

RADIATION BEFORE SHADING PVGIS vs PYSAM
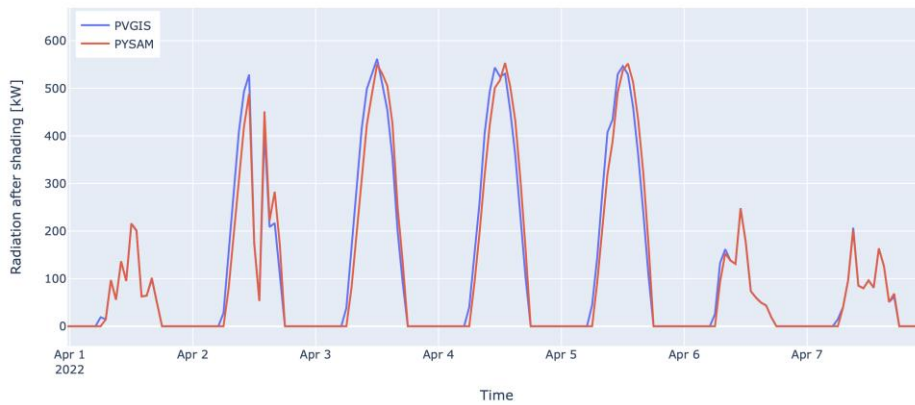
Figure 36 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from April the 1ˢᵗ to April the 8ᵗʰ.
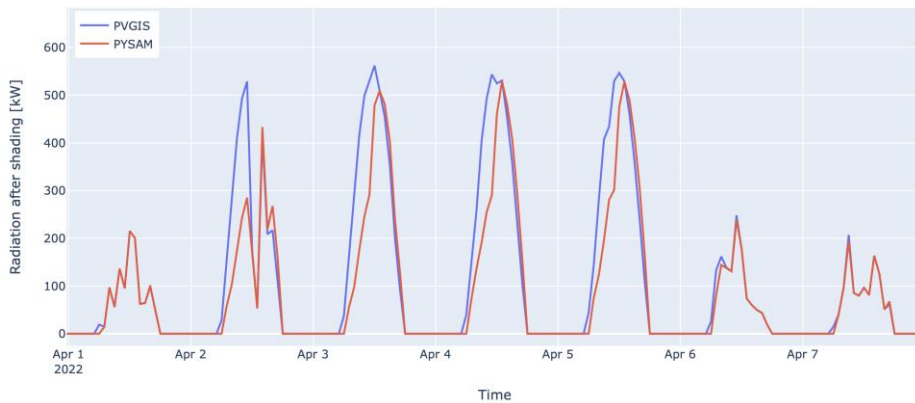
Figure 37 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from April the 1st to April the 8th.

The radiation peak before and after shading is approximately the same because in this season the sun altitude is greater than in winter, so the building in the south of the studied rooftop doesn't create shading on it.
The peak radiation after shading in spring reaches a value of approximately 510 kW.

The differences between both plots are only seen in the mornings due to the obstacle in the east of the building.

- Summer: July
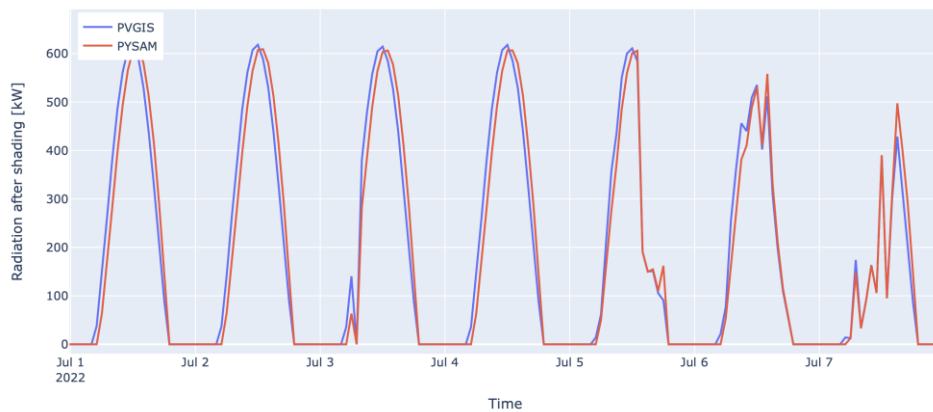
Figure 38 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from July the 1st to July the 8th.
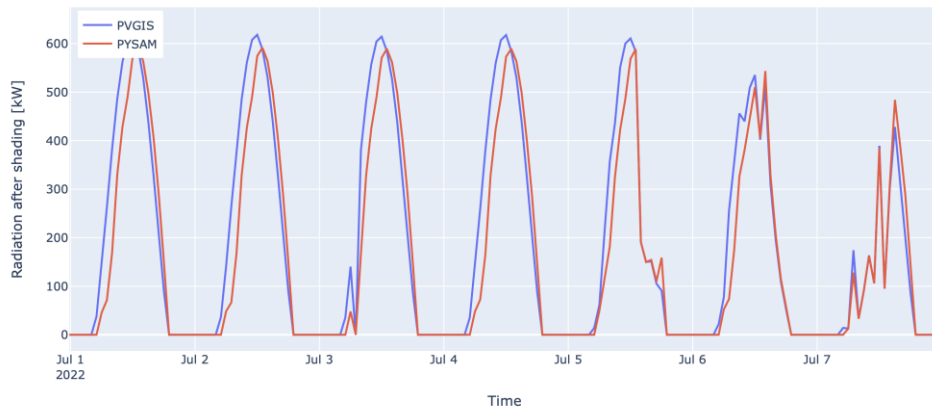
Figure 39 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from July the 1st to July the 8th.

The radiation peak before and after shading is approximately the same because in this season the sun altitude is large enough to overcome the building to the south of the studied rooftop.
The peak radiation after shading in summer reaches a value of approximately 600 kW

The differences between both plots are only seen in the mornings due to the obstacle in the east of the building.

- Autum: October
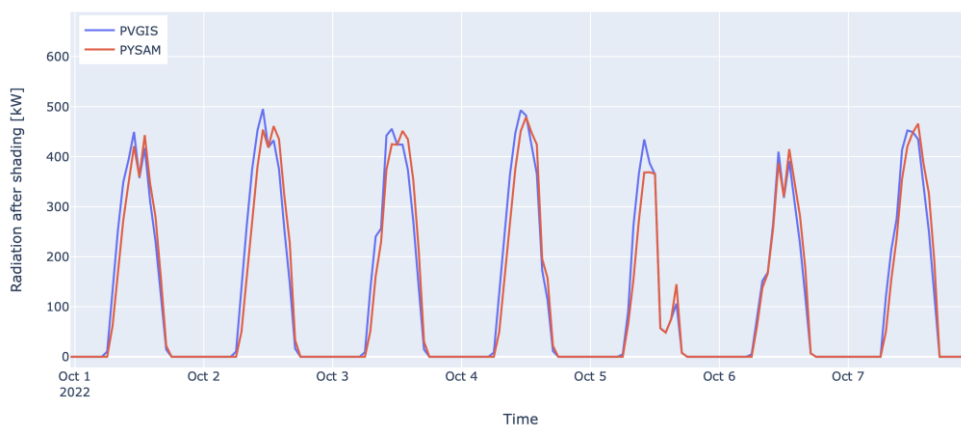
Figure 40 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from October the 1st to October the 8th.

RADIATION AFTER SHADING PVGIS vs PYSAM
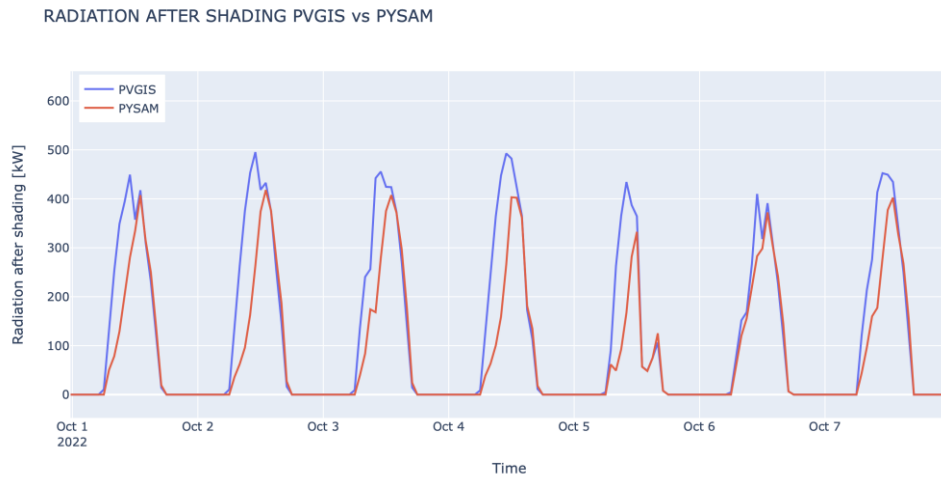
Figure 41 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from October the 1st to October the 8th.

The peak radiation after shading is slightly lower than the peak radiation before shading because in this season the altitude of the sun is lower than in summer, so it does not overcome the building on the south side of the studied roof at all times of the day.

The peak radiation after shading in spring reaches a value of approximately 410 kW.

The differences in radiation in the mornings are due to the eastern obstruction of this building.

If the outputs irradiance before shading and irradiance after shading obtained from the tool for the estimation of rooftop solar PV generation of rooftops of a sunny day are compared:

RADIATION BEFORE SHADING PVGIS vs PYSAM
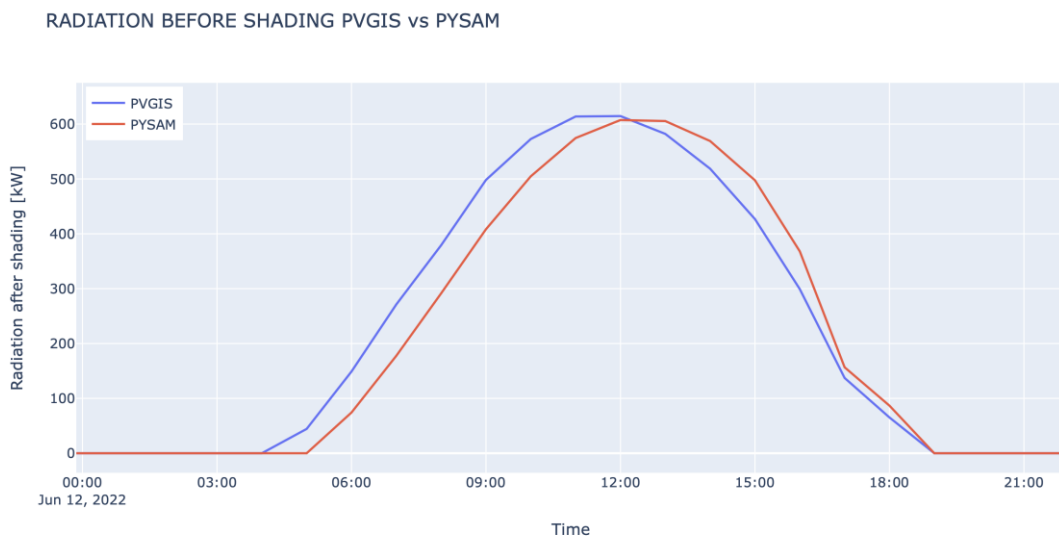
Figure 42 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation on the 12th of June.

36
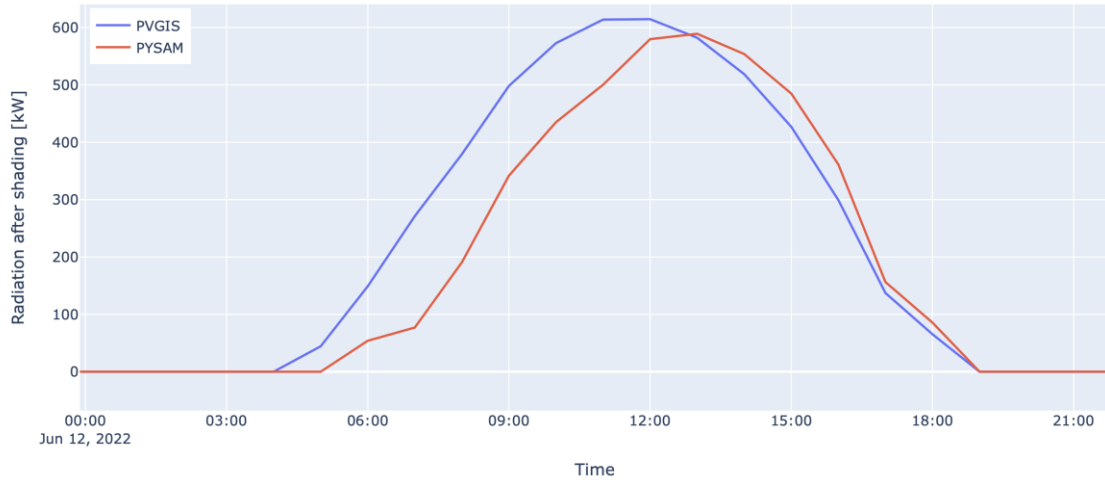
Figure 43 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation on the 12th of June.

If hourly values of a sunny day are compared before and after shading, it can be observed that in the morning the difference between PVGIS and PySAM values is greater in the plot that takes into account shading, but in the afternoon both plots are equal.

The trend line done with PVGIS and radiation after shading values is as follows:
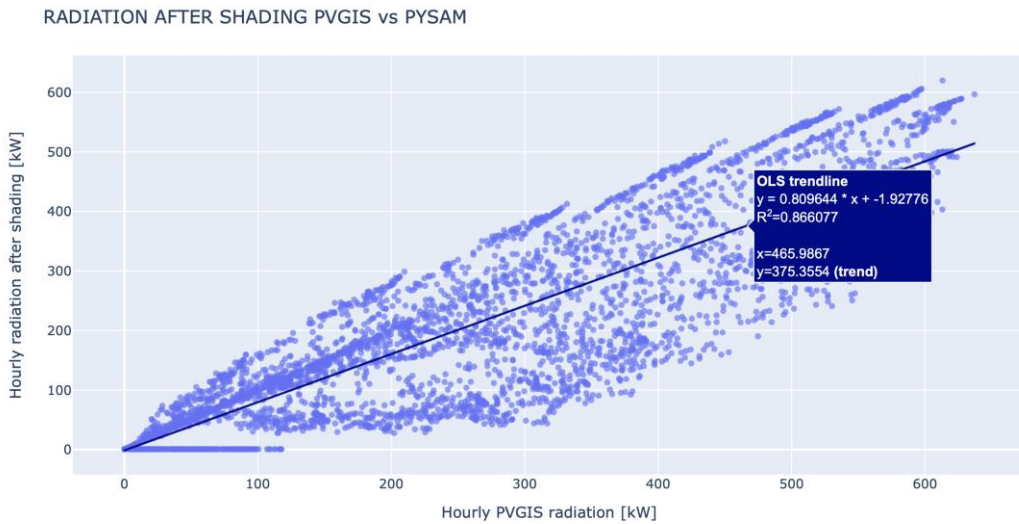
Figure 44 Linear regression of the radiation hourly values from PVGIS and from the radiation after shading hourly values from the tool for the estimation of solar PV generation.

The trend line of this plot shows the following information:

- $R^2 = 0,866 \rightarrow$ This plot, shows that the correlation between the data compared is not linear, this conclusion was expected because just one is considering shading and shade is different in every hour of the year.

37

- Slope = 0,810 → The slope value is less than one, this means that the PVGIS values are greater than the hourly radiation after shading values provided by the crated tool. This value was also expected because shading limits the radiation.

For the validation of the comparative, the trend line plot has been done with the PVGIS radiation output and the tool for the estimation of rooftop solar PV generation output of radiation before shading:

RADIATION BEFORE SHADING PVGIS vs PYSAM
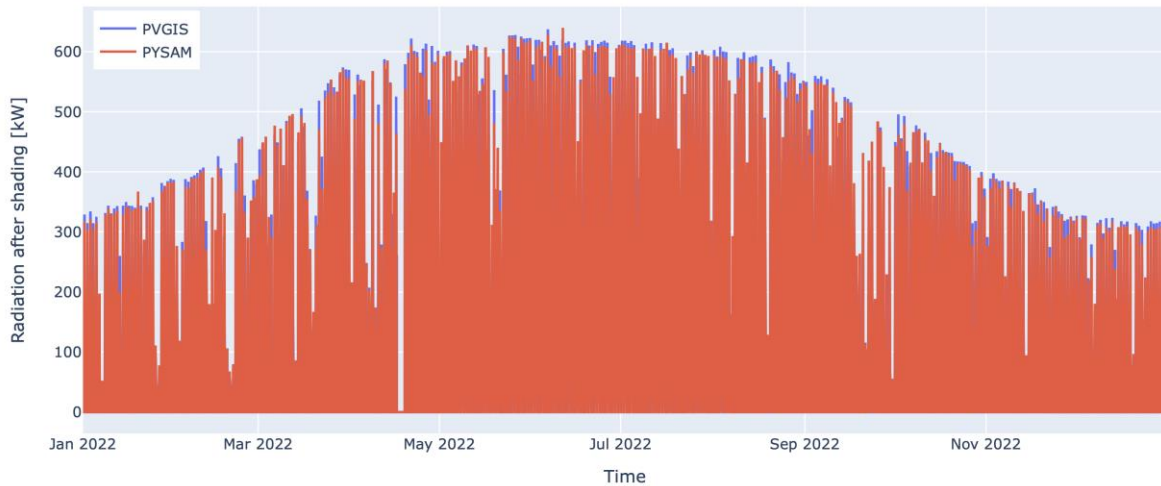
Figure 45 Radiation hourly values from PVGIS and from the radiation after shading hourly values from the tool for the estimation of solar PV generation.

RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 46 Linear regression of the radiation hourly values from PVGIS and from the radiation before shading hourly values from the tool for the estimation of solar PV generation.

The trend line of this plot shows the following information:

- R^2= 0,969 ≈ 1 → The dots are closely aligned, which means that the values of PVGIS and the tool for the estimation of rooftop solar PV generation are proportional.
- Slope = 0,973 ≈ 1 → The slope value is approximately 1, which means that the PVGIS values are similar to those provided by the created tool.

The operation of the whole module is validated on a flat, shaded roof.

5.3 A sloped, unshaded rooftop

In this validation, an apparently sloped and unshaded roof has been executed. A south-facing roof has been used to avoid shadows from the building itself.

Figure 47 2D view of the building used for the execution of a sloped and an unshaded rooftop. Oriented according to the cardinal points. [18]

Figure 48 3D view of the building used for the execution of a sloped and an unshaded rooftop. [18]

5.3.1 Validation of the shading module

- Characteristics of the building output:
    o Slope : 17,028 º
    o Azimuth : 181,554 º
    o Area rooftops : 78,964 m²

The slope output confirms that the rooftop is tilted and the azimuth the south orientation (≈180º)

- STL file: The obtained STL file representing the neighbourhood evaluated shows that there aren't taller budlings or trees interrupting the solar trajectory until the rooftop.

Figure 49 STL file of the building chosen for the execution and its surroundings.

- Shading matrix output:

Table 5 Shading matrix obtained for the sloped and unshaded rooftop validation.

ALTITUDE (º) \ AZIMUTH (º)	9	18	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270	279	288	297	306	315	324	333	342	351	360
9	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	93,9	99,2	87,4	96,6	99,2	98,1	98,5	99,6	93,5	70,5	64,0	64,4	72,0	75,5	76,2	78,2	73,6	80,5	83,9	92,3	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
18	100,0	100,0	100,0	100,0	100,0	100,0	99,6	90,8	74,7	58,2	42,9	31,0	65,9	39,8	70,1	69,0	53,3	63,6	51,7	48,3	43,3	42,5	41,8	41,0	42,9	41,4	39,1	33,3	33,3	34,1	57,1	81,6	97,3	100,0	100,0	100,0	100,0	100,0	100,0	100,0
27	100,0	100,0	100,0	97,3	94,3	85,1	64,4	42,9	31,4	12,3	11,1	11,5	11,5	14,9	22,6	27,6	29,1	33,0	33,3	33,3	33,3	32,2	28,7	27,6	27,2	23,8	21,1	19,2	19,9	15,3	23,0	43,3	58,2	79,7	90,8	97,7	100,0	100,0	100,0	100,0
36	80,5	77,8	72,4	59,8	49,4	38,7	27,6	18,4	11,1	0,0	4,6	6,9	9,2	10,3	12,3	13,8	16,1	18,8	21,8	24,1	26,8	24,9	22,2	19,9	16,9	13,8	11,1	11,5	12,6	15,3	10,3	13,8	20,3	30,7	36,8	51,3	57,9	68,6	73,9	78,2
45	40,6	36,4	33,7	31,0	27,6	20,3	12,6	7,3	2,7	0,0	3,8	6,9	6,9	9,2	10,3	10,7	11,9	12,6	13,8	13,8	13,8	13,8	12,6	11,9	10,3	10,0	7,3	6,9	6,9	0,0	3,1	7,3	16,1	19,2	21,8	28,7	34,5	37,5	41,0	
54	23,0	23,8	23,8	20,3	14,6	7,7	5,7	4,2	0,0	0,0	2,7	6,9	6,9	6,9	8,4	10,3	10,3	10,3	10,3	10,3	10,3	10,3	10,3	10,3	9,6	7,3	6,9	6,9	6,5	0,0	0,0	0,4	8,0	11,1	14,6	18,0	21,1	22,6	22,6	
63	11,5	10,3	9,2	6,9	3,8	3,4	1,9	0,0	0,0	0,0	1,9	6,9	6,9	6,9	6,9	6,9	8,0	9,2	9,6	10,3	10,3	10,3	9,2	8,8	7,7	6,9	6,9	6,9	6,9	5,4	0,0	0,0	0,0	0,4	6,9	8,0	8,4	9,2	11,1	11,5
72	5,7	4,6	3,4	2,3	1,5	0,4	0,0	0,0	0,0	0,0	0,8	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	3,8	0,0	0,0	0,0	0,0	2,3	4,2	4,6	5,7	5,7	
81	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,8	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,5	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
90	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,9	3,8	4,6	5,0	5,7	5,7	5,7	5,7	5,7	5,7	5,7	5,7	5,4	4,6	4,2	3,1	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Despite the matrix is showing some shade, there isn't sunlight for values of azimuth between 300º and 60º and for values of solar altitude lower than 20º.

If these values are removed, the matrix looks like this:

Table 6 Processed shading matrix obtained for the sloped and unshaded rooftop validation.

ALTITUDE (º) \ AZIMUTH (º)	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270	279	288	297
27	64,37	42,91	31,42	12,26	11,11	11,49	11,49	14,94	22,61	27,59	29,12	32,95	33,33	33,33	33,33	33,33	32,18	28,74	27,59	27,20	23,75	21,07	19,16	19,92	15,33	22,99	43,30
36	27,59	18,39	11,11	0,00	4,60	6,90	9,20	10,34	12,26	13,79	16,09	18,77	21,84	24,14	26,82	24,90	22,22	19,92	16,86	13,79	11,11	11,49	12,64	15,33	10,34	13,79	20,31
45	12,64	7,28	2,68	0,00	3,83	6,90	6,90	9,20	10,34	10,73	11,88	12,64	13,79	13,79	13,79	13,79	13,79	12,64	11,88	10,34	9,96	7,28	6,90	6,90	0,00	3,07	7,28
54	5,75	4,21	0,00	0,00	2,68	6,90	6,90	6,90	8,43	10,34	10,34	10,34	10,34	10,34	10,34	10,34	10,34	10,34	10,34	9,58	7,28	6,90	6,90	6,51	0,00	0,00	0,38
63	1,92	0,00	0,00	0,00	1,92	6,90	6,90	6,90	6,90	6,90	6,90	8,05	9,20	9,58	10,34	10,34	10,34	9,20	8,81	7,66	6,90	6,90	6,90	6,90	5,36	0,00	0,00
72	0,00	0,00	0,00	0,00	0,77	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	3,83	0,00	0,00
81	0,00	0,00	0,00	0,00	0,00	3,83	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,90	6,51	0,77	0,00
90	0,00	0,00	0,00	0,00	0,00	0,00	1,92	3,83	4,60	4,98	5,75	5,75	5,75	5,75	5,75	5,75	5,75	5,75	5,36	4,60	4,21	3,07	0,77	0,00	0,00	0,00	0,00

This matrix only has significant shadow values at its corners due to shading from the other roofs of the building. Even so, it can be predicted that the irradiance after shading results obtained by the created module, considering the shadows, will be slightly lower.

The percentage of shade in high altitude values and south azimuth values is probably estimated by the presence of the trees drawn in STL file at the south of the building.

5.3.2 Validation of the PYSAM code
5.3.2.1 Comparison of the hourly power generation output

Figure 50 Power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.

Figure 51 Linear regression of power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R2 ≈ 1,000 → The points are aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 0,999 ≈ 1 → The obtained values from SAM are the same as those of PYSAM.

5.3.2.2 Comparison of the hourly radiance after shading output

RADIATION AFTER SHADING SAM vs PYSAM
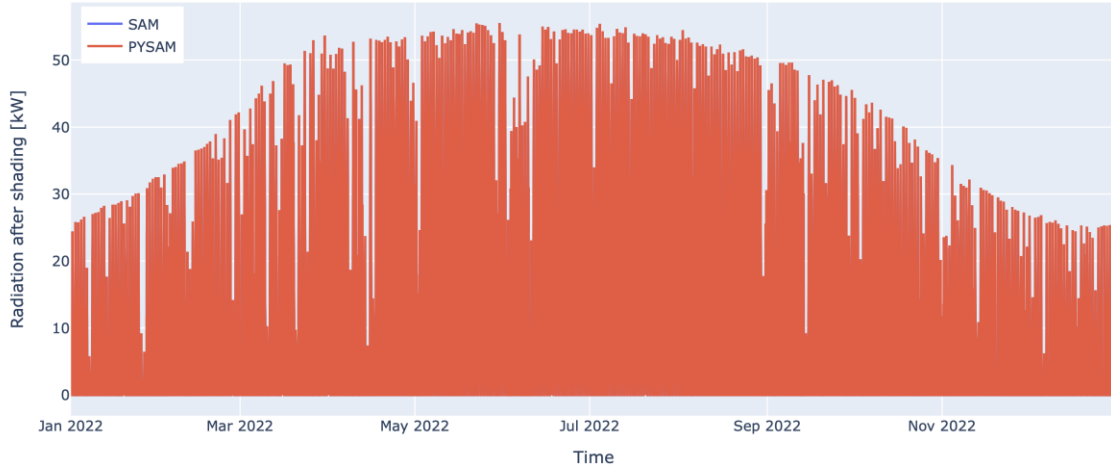
Figure 52 Radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

As shown in the figure, the plot of the superimposes graphs output obtained from the output of radiance after shading created by the PySAM code of the tool for the estimation of rooftop solar PV generation is exactly the same to the one generated with the SAM software.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.

RADIATION AFTER SHADING SAM vs PYSAM
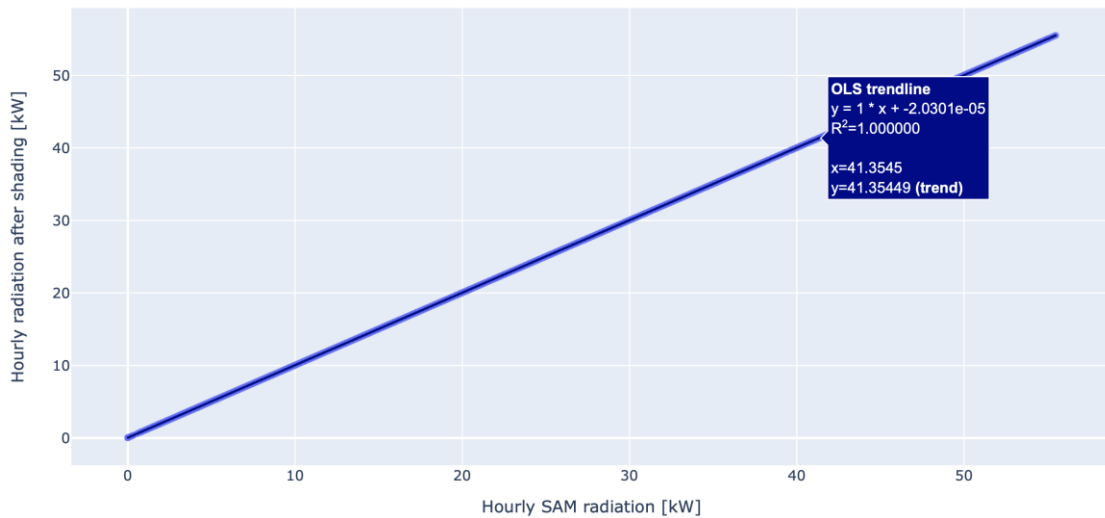
Figure 53 Linear regression of radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

43

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values from SAM are the same as those of PYSAM.

The operation of the PYSAM module is validated on a flat, unshaded roof.

5.3.3 Validation of the whole tool

If the graphs are superimposed, it can be observed that both plots are very similar:
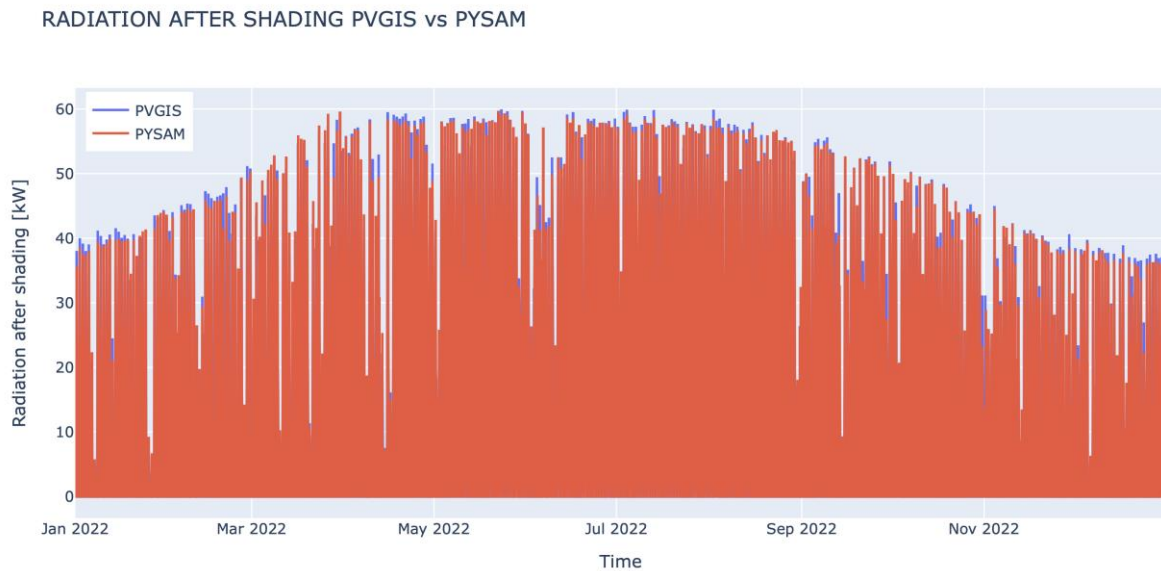
Figure 54 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.
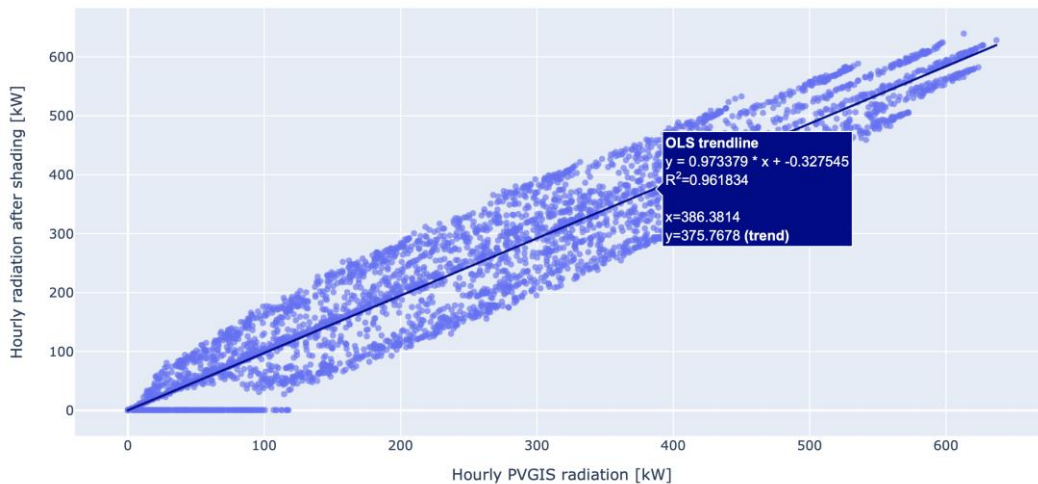
44

RADIATION AFTER SHADING PVGIS vs PYSAM
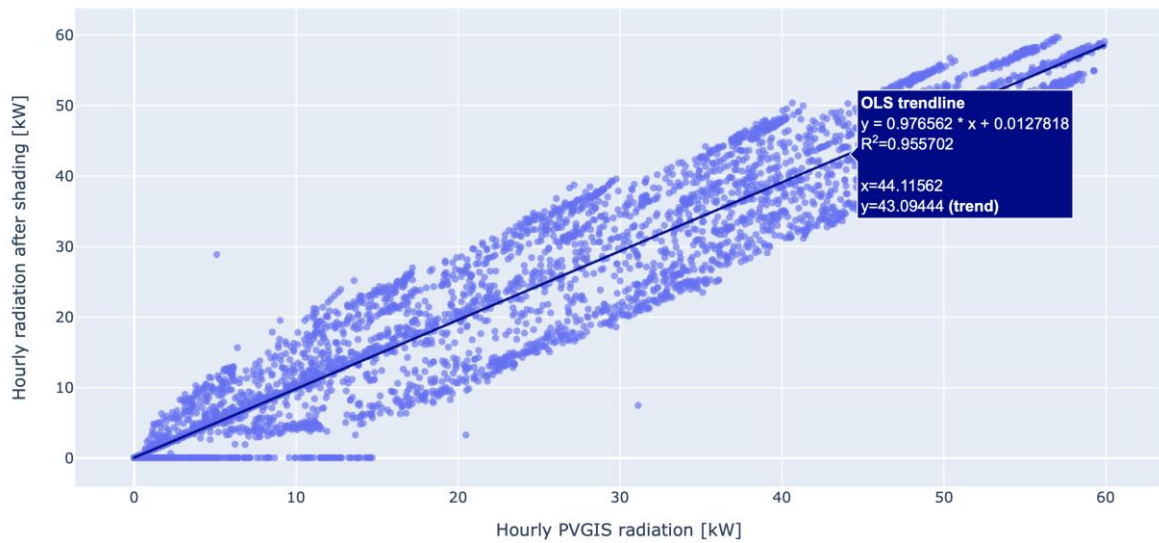
Figure 55 Linear regression of the radiation hourly values from PVGIS and from the radiation after shading hourly values from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R2= 0,956 ≈ 1 → The dots are closely aligned, which means that the values of PVGIS and the estimation of solar potential of rooftops tool are proportional.

- Slope = 0,977 ≈ 1 → The obtained values of PVGIS are very similar than those obtained from the tool for the estimation of rooftop solar PV generation. With this value the hypothesis of unshaded rooftop can be validated.
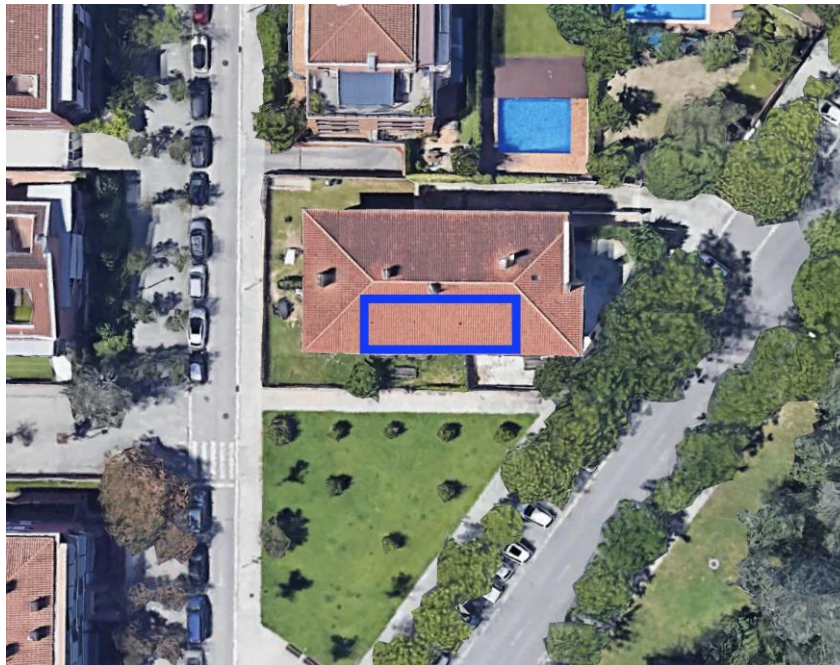
5.4   A sloped, shaded rooftop
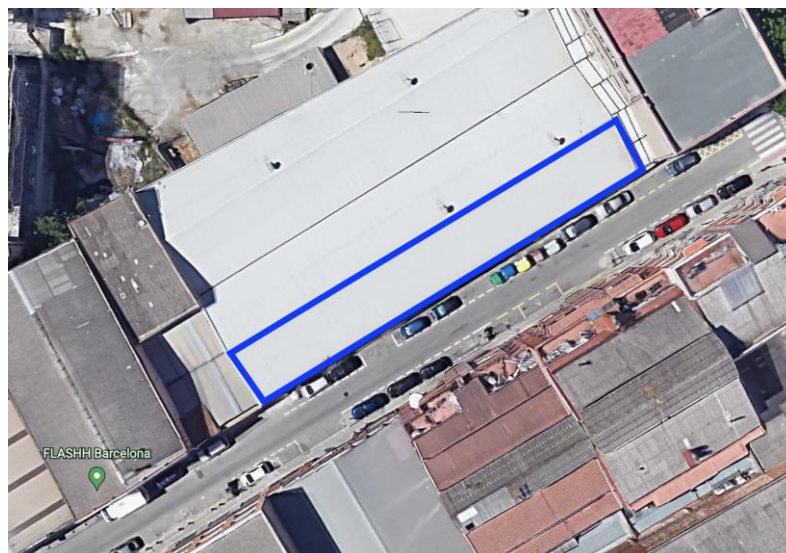
Figure 56 2D view of the building used for the execution of a sloped and shaded rooftop. Oriented according to the cardinal points. [18]

Figure 57 3D view of the building used for the execution of a sloped and shaded rooftop. [18]

5.4.1 Validation of the shading module

- Characteristics of the building output:
    - o Slope : 19,300 º
    - o Azimuth : 148,860 º
    - o Area rooftops : 358,030 m^2

The slope output confirms that the rooftop is tilted.

- STL file: The obtained STL file representing the neighbourhood evaluated shows that there are taller budlings in the south and in the east interrupting the solar trajectory until the rooftop for lower solar altitudes.

Figure 58 STL file of the building chosen for the execution and its surroundings.

- Shading matrix output:

Table 7 Shading matrix obtained for the sloped and shaded rooftop validation.

ALTITUDE (º) \ AZIMUTH (º)	9	18	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270	279	288	297	306	315	324	333	342	351	360
9	98,8	100,0	100,0	100,0	100,0	100,0	96,0	98,0	100,0	99,2	100,0	100,0	100,0	100,0	100,0	99,6	99,2	100,0	96,0	91,7	92,1	94,4	99,2	99,6	98,8	97,2	88,5	85,7	86,9	96,8	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
18	99,6	100,0	94,8	82,5	70,2	69,8	65,5	51,6	72,2	99,2	100,0	100,0	100,0	100,0	97,6	82,5	71,8	67,1	56,0	63,5	68,7	71,8	65,5	37,3	34,9	29,0	23,8	21,0	28,2	55,6	82,1	96,8	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
27	63,5	56,7	54,0	49,2	44,0	40,5	34,1	30,6	27,0	48,8	82,9	96,8	100,0	100,0	93,3	78,6	71,4	62,3	54,4	51,6	52,0	42,9	22,6	7,1	18,3	17,1	13,5	9,5	7,5	12,3	20,2	32,5	50,8	68,3	83,7	89,7	91,7	90,5	88,1	79,8
36	24,6	34,1	31,3	30,6	28,2	21,8	16,3	13,5	9,1	7,1	20,2	38,1	57,9	71,0	67,9	63,5	60,3	48,8	46,4	38,5	24,6	13,5	5,6	4,0	13,1	9,9	7,5	7,1	6,7	4,0	7,5	13,1	17,9	21,0	37,7	53,2	52,0	50,8	50,0	34,9
45	13,5	15,1	17,9	12,7	8,7	5,6	4,4	4,0	4,4	3,6	3,6	6,3	13,5	17,9	21,8	23,4	24,6	18,7	15,5	11,5	7,1	4,8	3,6	5,2	4,4	5,6	4,8	5,2	3,6	3,6	6,0	12,3	13,1	17,1	17,1	26,2	33,7	32,5	18,3	
54	0,4	1,6	1,6	3,2	3,6	3,6	3,6	3,6	3,6	3,2	0,0	1,2	0,4	2,0	2,0	2,0	1,2	2,0	2,0	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	4,0	5,6	3,2	3,6	3,6	3,2	0,8		
63	0,0	0,0	0,0	1,2	3,2	3,6	2,0	2,0	2,4	1,6	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,4	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,2	0,4	0,0	0,0	0,0	0,0	0,0		
72	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	2,4	3,6	3,6	3,6	3,6	3,6	3,2	2,0	0,4	0,0	0,0	0,0
81	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,2	1,2	1,2	1,2	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
90	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

The matrix of shadows obtained from the execution indicates that the surface is shaded for lower values of solar altitude as expected when choosing the building.

The operation of the shading module is validated on a flat, unshaded roof.

5.4.2 Validation of the PYSAM code

5.4.2.1 Comparison of the hourly power generation output

POWER GENERATION SAM vs PYSAM

Figure 59 Power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The superimposed plots of the output of radiance after shading created by the PySAM code and the radiance after shading of the SAM software are exactly the same.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.
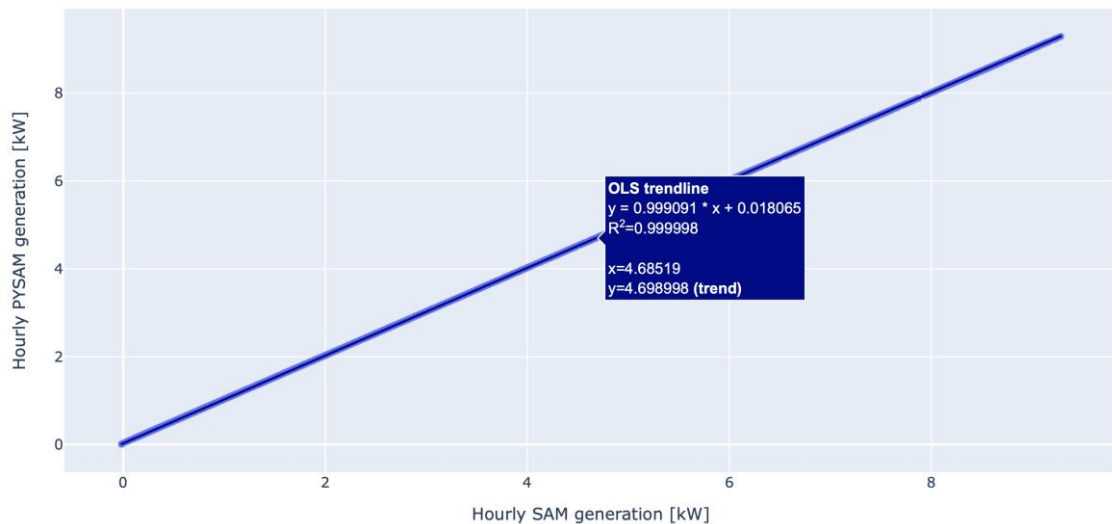
Figure 60 Linear regression of power generation hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values of SAM are the same as those of PYSAM.

### 5.4.2.2 Comparison of the hourly radiance after shading output

The plot of the output obtained from the output of radiance after shading created by the PySAM code of the tool for the estimation of rooftop solar PV generation is the same as the one generated with the SAM software.

If the graphs are superimposed, it can be observed that both plots are exactly the same:
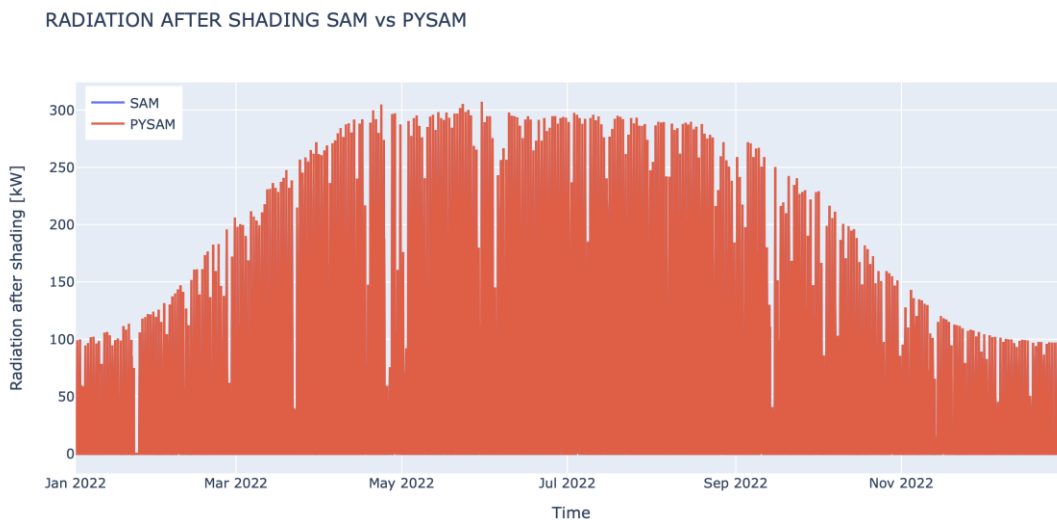

Figure 61 Radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

In order to quantify their similarity, the following linear regression has been performed comparing the results of PySAM and SAM.

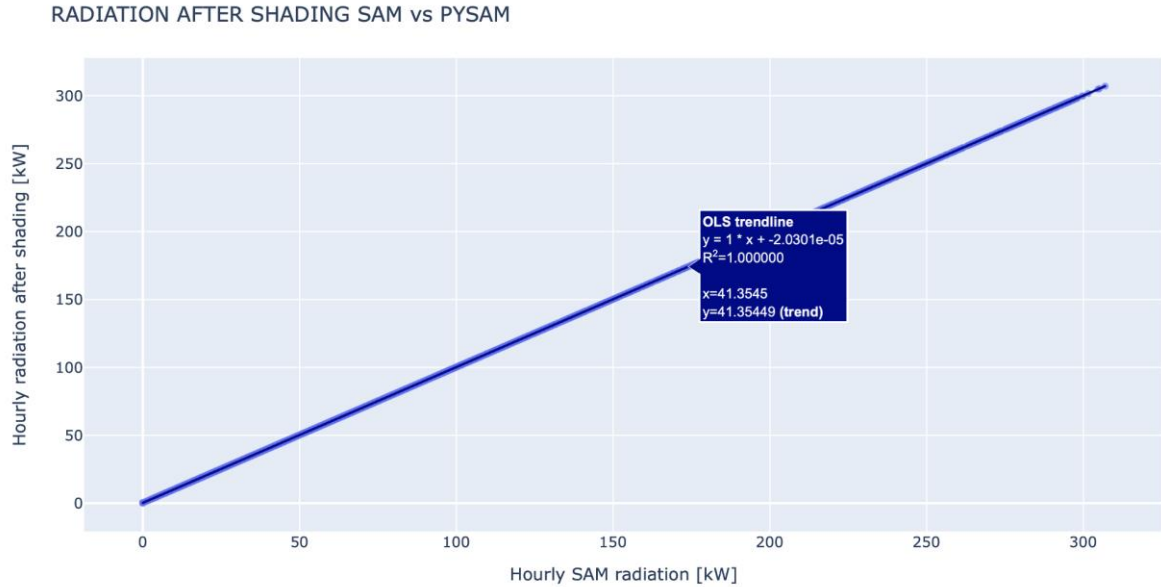RADIATION AFTER SHADING SAM vs PYSAM

Figure 62 Linear regression of radiation after shading hourly values from SAM and from the tool for the estimation of solar PV generation.

The trendline of this plot shows the following information:

- R^2= 1,000 → The points are completely aligned, which means that the values of SAM and PYSAM are proportional.
- Slope = 1,000 → The obtained values of SAM are the same as those of PYSAM.
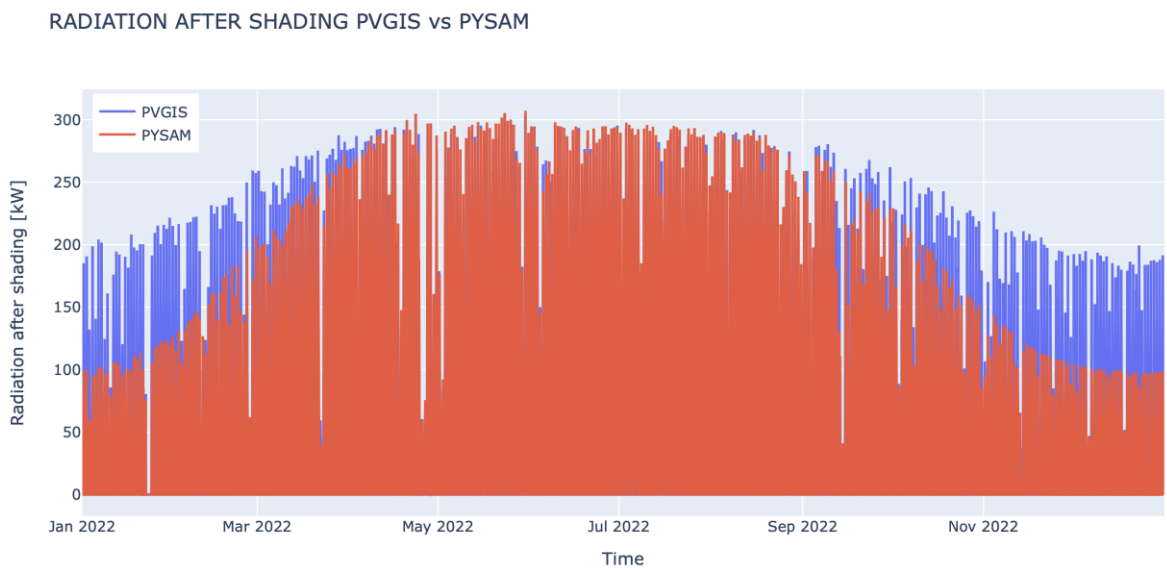
5.4.3 Validation of the whole tool

RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 63 Radiation hourly values from PVGIS and from the radiation after shading hourly values from the tool for the estimation of solar PV generation.

In this case, when the values are compared, there are some considerable differences due to shading.

If the graph comparing PVGIS results and radiation before shading is plotted it can be observed that both values are more similar:

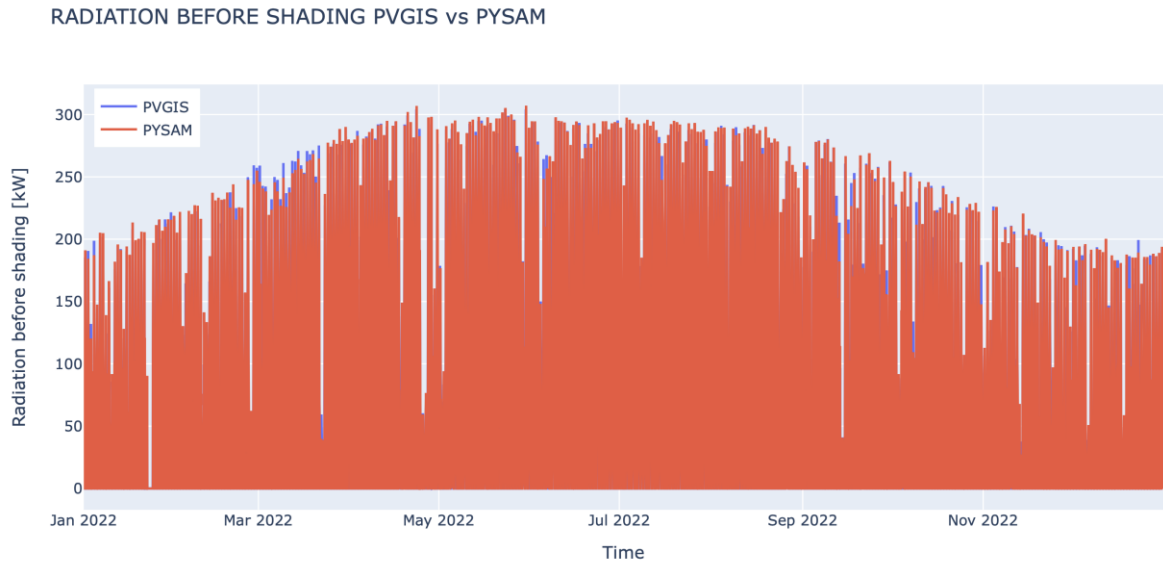RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 64 Radiation hourly values from PVGIS and from the radiation before shading hourly values from the tool for the estimation of solar PV generation.

As there is a taller building on the south of the rooftop, shade is going to be cast in the surface for lower values of solar altitude: It can be seen that in the Winter season, when the sun altitude is lower, the values are less similar. In order to analyze it, one week of every season is compared before and after shading as follows:

- Winter: January
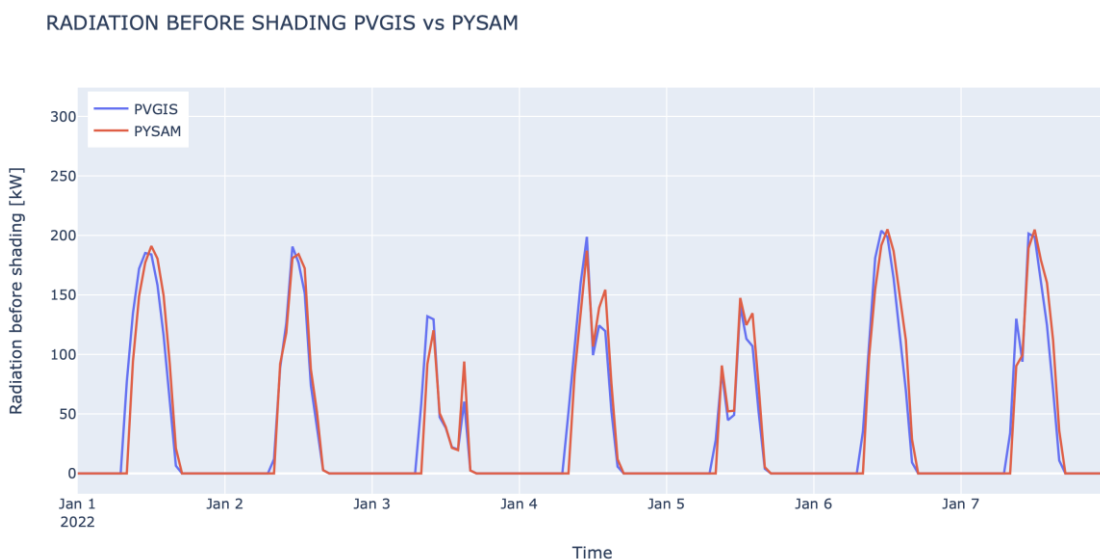
RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 65 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from January the 1st to January the 8th .
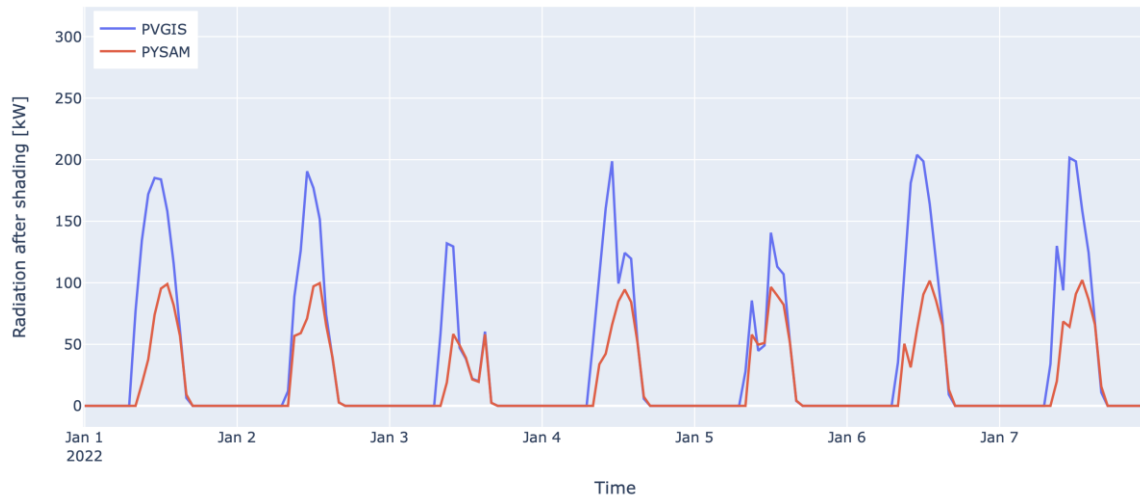
RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 66 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from January the 1st to January the 8th .

The plots show that in winter the radiation after shading peak is approximately 50% of the radiation before shading, this is caused by the low sun altitude during this season and the obstacle in the south of the studied rooftop.
The peak radiation after shading in winter reaches a value of approximately 100 kW.

There are also some differences observed in the mornings due to the east obstacle.

- Spring: April
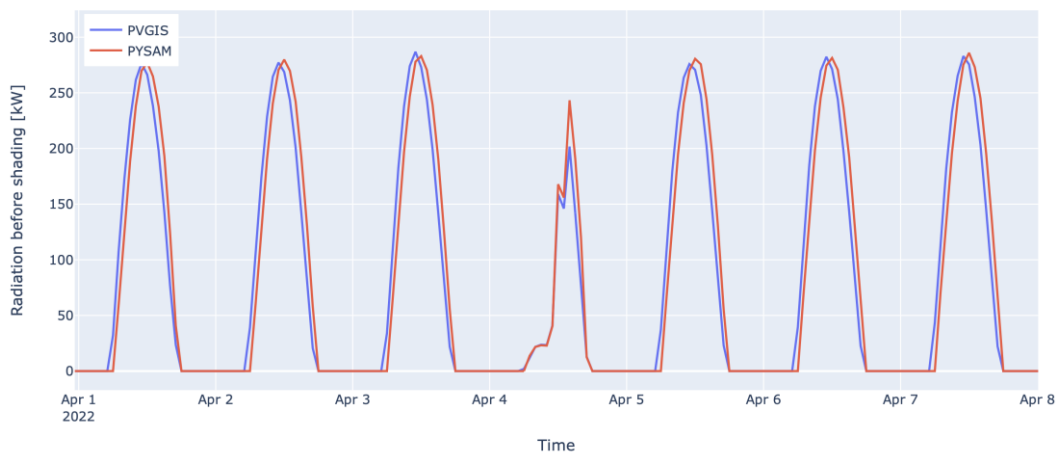
RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 67 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from April the 1st to April the 8th .

51

RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 68 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from April the 1st to April the 8th .

The radiation peak before and after shading is almost the same before and after shading because in this season the sun altitude is greater than in winter, so the building in the south of the studied rooftop just creates shading on it during the beginning and the end of the day.
The peak radiation after shading in spring reaches a value of approximately 275 kW.

The differences between both plots seen in the mornings are due to the obstacle in the east of the building.

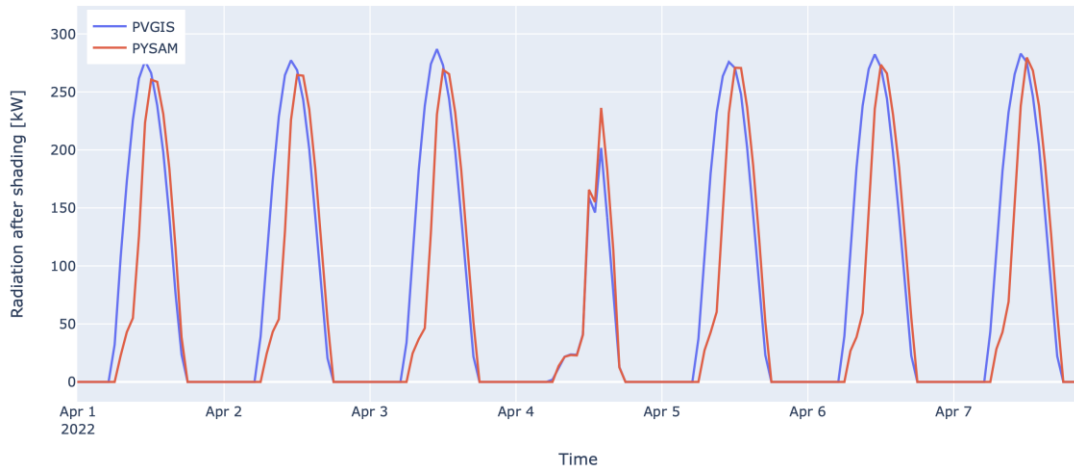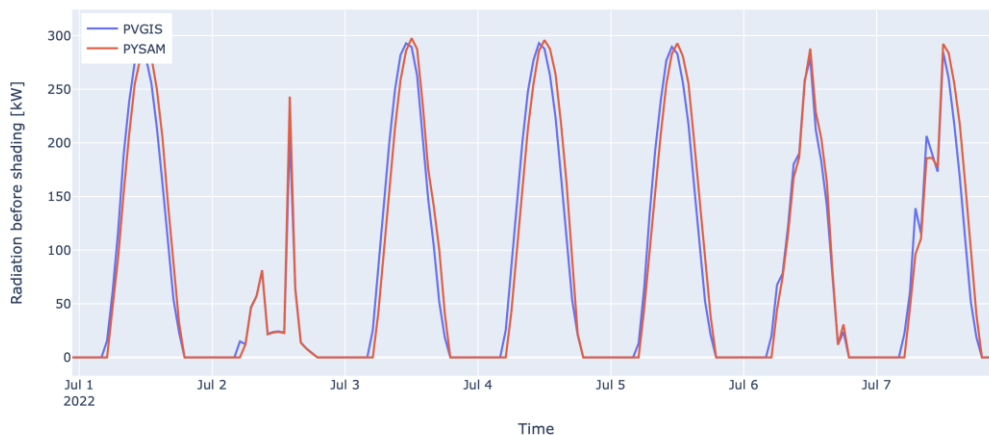- Summer: July

RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 69 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from July the 1st to July the 8th .
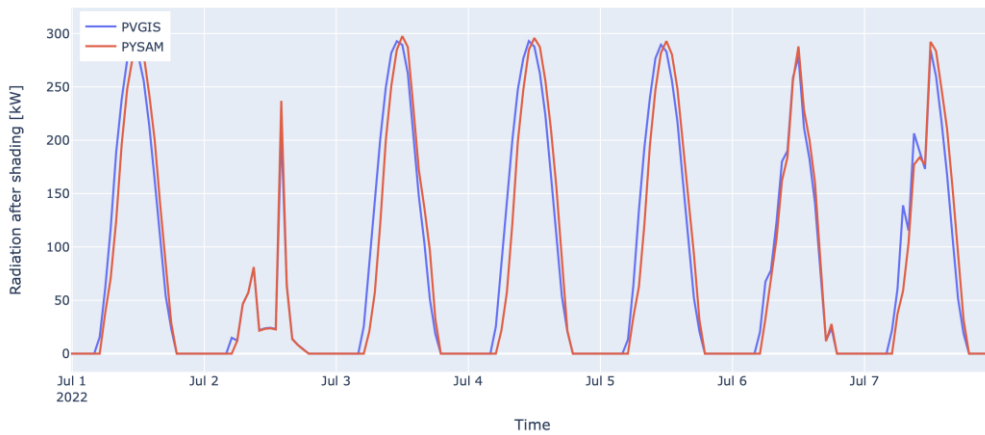
RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 70 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from July the 1ˢᵗ to July the 8ᵗʰ .

The radiation peak before and after shading is approximately the same because in this season the sun altitude is large enough to overcome the building in the south of the studied rooftop.
The peak radiation after shading in summer reaches a value of approximately 300 kW

The slight differences between both plots are only seen in the mornings due to the obstacle in the east of the building.

- Autum: October
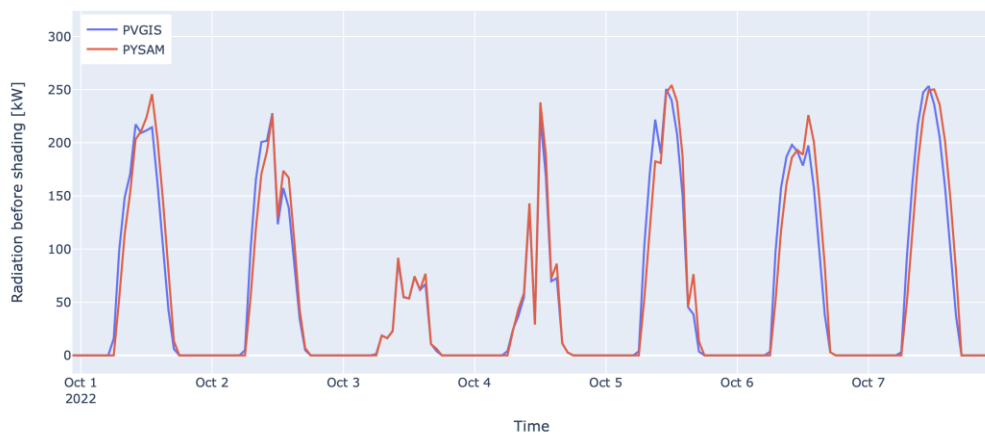
RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 71 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation, for days from October the 1ˢᵗ to October the 8ᵗʰ .

RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 72 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation, for days from October the 1st to October the 8th .
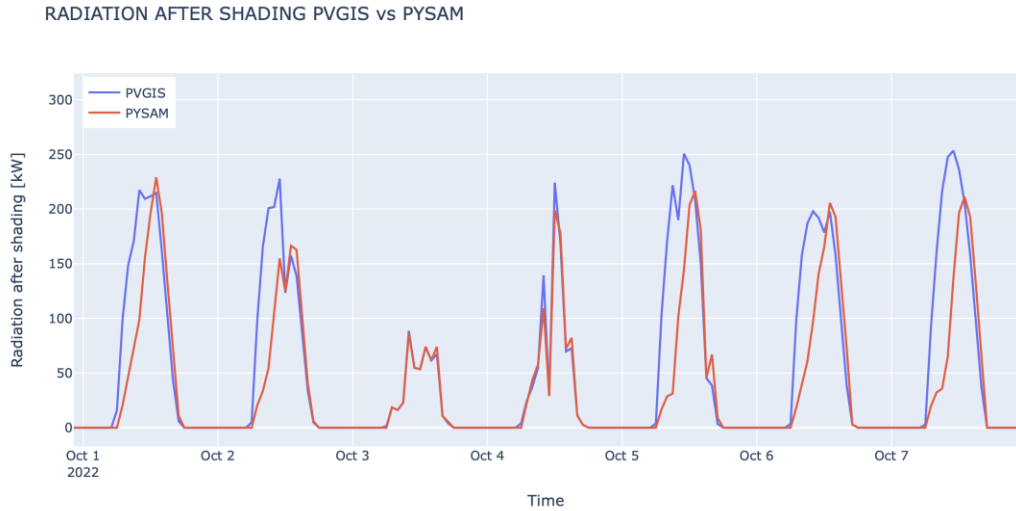
The peak radiation after shading is slightly lower than the peak radiation before shading because in this season the altitude of the sun is lower than in summer, so that it does not overcome the building on the south side of the studied roof at all times of the day.
The peak radiation after shading in spring reaches a value of approximately 230 kW.

The differences in radiation in the mornings are due to the eastern obstruction of this building. In this season the difference is much bigger, because the solar altitude is lower.

If the outputs irradiance before shading and irradiance after shading obtained from the tool for the estimation of rooftop solar PV generation of a sunny day are compared:
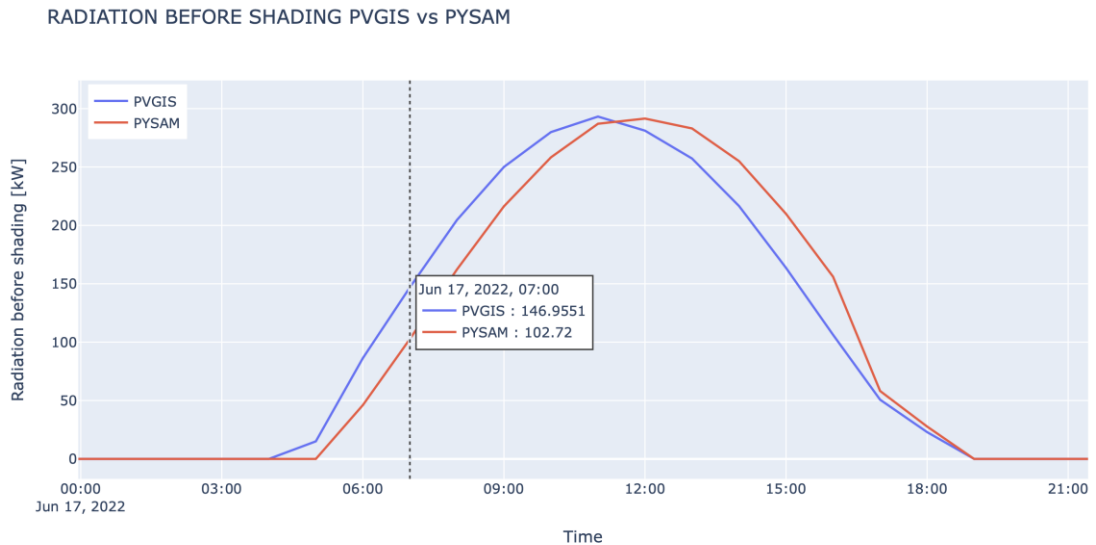
RADIATION BEFORE SHADING PVGIS vs PYSAM

Figure 73 Radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation on the 17th of June.
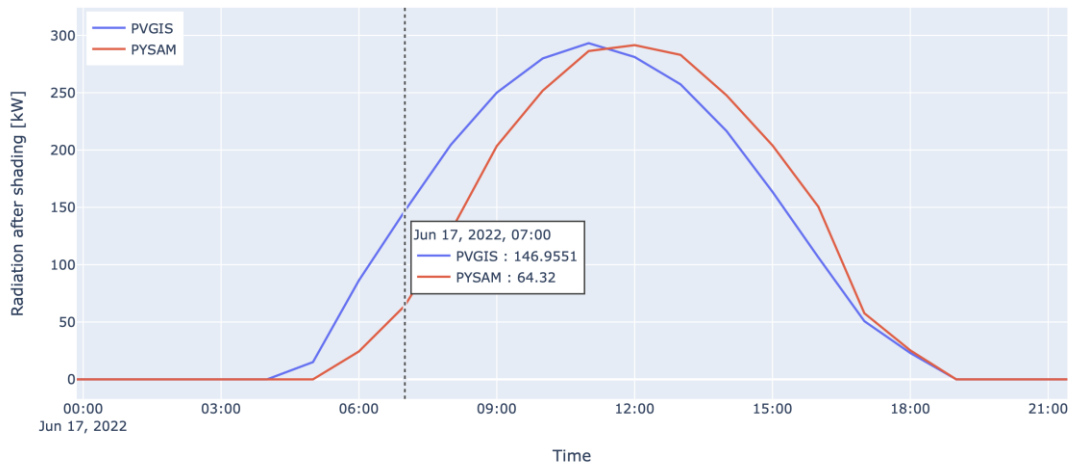
RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 74 Radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation on the 17th of June.

If hourly values of a sunny day are compared before and after shading, it can be observed that in the morning the difference between PVGIS and PYSAM values is greater in the plot that considers shading, but in the afternoon both plots are practically equal.

For example, at 7:00 am (UTC time) the radiation before shading takes a value of 102,72 kW, while the value before shading is 64,32 kW.

The trend line done with PVGIS and radiation after shading values is as follows:

RADIATION AFTER SHADING PVGIS vs PYSAM

Figure 75 Linear regression of radiation hourly values from PVGIS and radiation after shading hourly values from the tool for the estimation of solar PV generation.

The trend line of this plot shows the following information:

- R^2= 0,797 ≈ 1 → This plot shows that the correlation between the data compared is not linear. This conclusion was expected because just one is considering shading and shade is different every hour of the year.

- Slope = 0,805 ≈ 1 → The slope value is less than one, this means that the PVGIS values are greater than the hourly radiation after shading values provided by the crated tool. This value was also expected because shading limits the radiation.

For the validation of the comparative, the trend line plot has been done with the PVGIS radiation output and the solar potential estimation of rooftops output of radiation before shading:

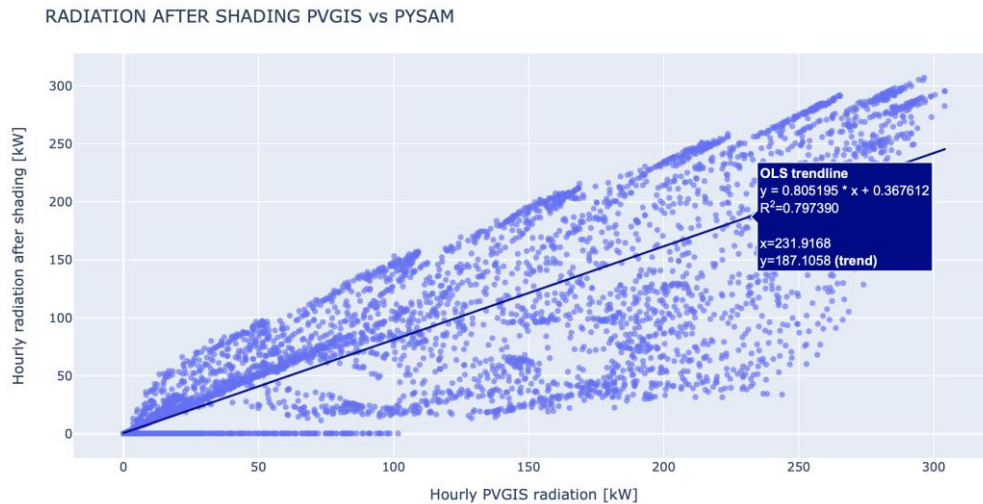RADIATION BEFORE SHADING PVGIS vs PYSAM
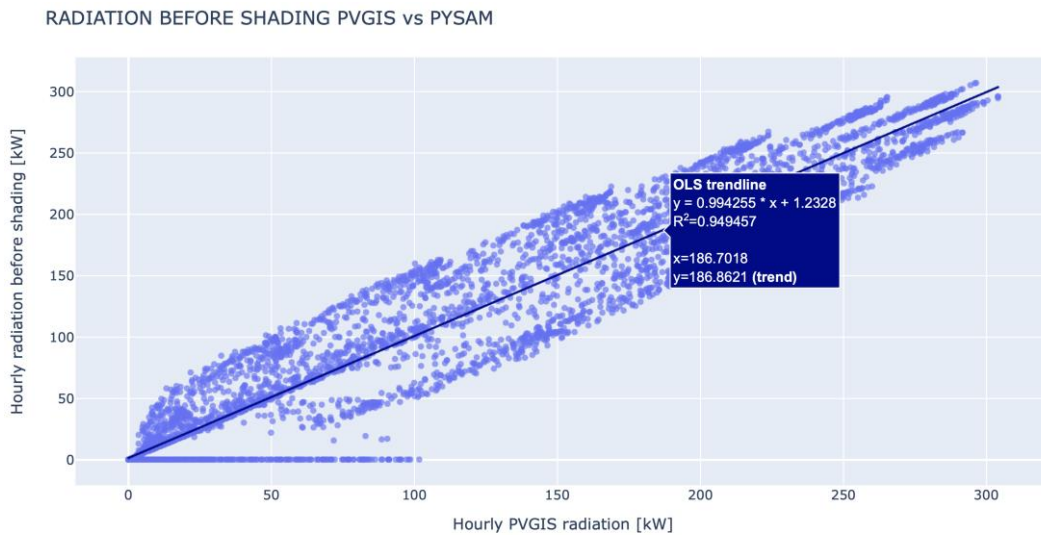
Figure 76 Linear regression of radiation hourly values from PVGIS and radiation before shading hourly values from the tool for the estimation of solar PV generation.

The trend line of this plot shows the following information:

- R^2= 0,949 ≈ 1 → The dots are closely aligned, which means that the values of PVGIS and the estimation of solar potential of rooftops tool are proportional.
- Slope = 0,994 ≈ 1 → The slope value is approximately 1, which means that the PVGIS values are similar to those provided by the created tool.

The operation of the whole module is validated on a flat, shaded roof.

6 Budget

The total technical cost of the development of a tool for the estimation of rooftop solar photovoltaic generation is of 4072,50 €. The costs are detailed in the following table and in the attached budget document.

Table 8 Total cost of the project

	Cost
Dedication	3.972,50 €
Equipment	100 €
TOTAL	**4.072,50 €**

7 Analysis and assessment of environmental and social implications

The Sustainable Development Goals (SDG) are a call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet. They are made up of 17 goals responsible for transforming the world. [19]

Figure 77 List of the 17 Sustainable Development Goals. [19]

The project developed has a positive impact to the environment because it aims society to use the solar renewable source for the electricity generation, by informing the user about the potential of their rooftop.

The tool created for the estimation of rooftop solar PV generation contributes to SDG 7 and 11:

- **Goal 7: Ensure access to affordable, reliable, sustainable and modern energy**
The developed project, contributes to an energy more accessible as is thought to estimate the potential of any building. It also contributes to a more sustainable and efficient energy, because the energy is obtained from an endless source and estimates the losses due to different variables such as shading.

More specifically, the project contributes positively to goal number 7.2. : "By 2030, increase substantially the share of renewable energy in the global energy mix"

Figure 78 Logo of the goal 7 of the SDG. [19]

- **Goal 11 → Make cities inclusive, safe, resilient and sustainable**
The tool created, aims to increase self-consumption in urban environments, either individually or collectively in energy communities. Making cities a more sustainable environment.
More specifically, the project contributes positively to goal number 11.3: "By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries."

Figure 79 Logo of the goal 11 of the SDG.

8 Conclusion

The tool created is able to give the characteristics of the building and an estimation of the solar photovoltaic generation of the roof with only a manual input of the coordinates, LAS files and a TMY file. The generation is calculated using System Advisor Model. The tool takes into account the shadows on the roof, so the hourly values of radiation are affected by shading depending on the solar position. Therefore, the generation is also dependent on the shading.

The operation of the tool has been tested in several buildings with different roof characteristics to validate its correct functioning.

To continue with the development of the tool, it would be interesting to improve the python code by synthesizing it to reduce the execution time. It would also be interesting to further automate the execution so that the LIDAR and TMY files of the indicated coordinates are downloaded automatically, significantly minimizing the inputs.

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