Trabajo de Fin de Grado
Ingeniería Aeroespacial

La producción fotovoltaica de electricidad en la Unión Europea: un enfoque económico

The photovoltaic production of electricity in the European Union: an economic approach

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Escuela Técnica Superior de Ingeniería
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El tribunal nombrado para juzgar el Trabajo arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

El Secretario del Tribunal

Fecha:

A ti, Papá
A mi familia y amigos

Agradecimientos

Con este trabajo finaliza una etapa que empezó allá por 2013, por la que han pasado multitud de personas. Quiero agradecer a mi tutor, Ángel Arcos Vargas, por haber confiado en mí para realizar este trabajo.

También a todos esos amigos que han pasado por mi vida en estos años, especialmente a mis compañeros de carrera, del CMU San Juan Bosco, de la Asociación Juvenil de Debate Daoíz y Velarde y por último a la fila de locos de Hakuna.

Álvaro Anega Trucios

Sevilla, 2019

Abstract

In the present context, the needs of explore new sources of energy arise, and also improve the performance of colleting the energy from known sources. It is an undeniable fact solar energy has become one of the most important forms of energy all around the world, easy to capture and converted into electricity only with the help of a photovoltaic cell.

Throughout this work we will perform an economic analysis of the production of photovoltaic solar energy, defining previously some theoretical concepts related with electricity generation by means of photovoltaic cells, as well as commenting studies which have inspired the project, studies about the comparison between photovoltaic technologies.

In order to carry out this economic analysis we will select twenty locations in European Union countries and will calculate the yearly produced energy with the informatic tool PVGIS, describing before the key concepts of its manual and the economic formulas to the mentioned analysis.

The Levelized Costs of Energy (LCOE) will be calculated to compare the profitability of each photovoltaic technology: fixed, one-axis tracking systems (vertical or inclined) and two-axis tracking systems; appart from elaborating five maps of the European Union with the costs of energy production in each country, one for each technology and also an optimal map.

Finally, a sensitivity analysis will be performed, in order to observe how, varying the wage of the country (and consequently investment and operation costs) or the yearly energy production, varies the costs of energy production.

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1 INTRODUCTION

Nowadays, it is an undeniable fact that the sun has become one of the most important renewable energy sources all around the world, providing huge resource for generating clean and sustainable electricity without emitting contaminants to the atmosphere. Solar is an inexhaustible energy which can be captured easily and converted into electric power with the only help of a photovoltaic panel. Some of the earliest applications of solar technology were actually in outer space where solar was used to power satellites, after that, it was being developed not only for residences, but also to solar-powered airplanes, such as the 'Sunrise II', a remotely controlled aircraft, designed by Robert J. Boucher, which implied the first solar-powered flight. [1]

The technological evolutions produced a decrease in the costs of manufacturing and operations, having as consequence that since 2009, the cost of solar photovoltaic (PV) electricity fell by around 80%, as the International Renewable Energy Agency report claims. [2]

In this project, we will carry out an economic analysis about the production of electricity by means of photovoltaic systems around the European Union countries depending on geographical aspects such as latitude, longitude and the technology of PV plates: inclination and azimuth angles, fixed or tracking plates (one and two-axis).

Before getting into our research, we should say a little about the sections that will be developed throughout this document: including a state of the art of the study, with previous researches related with the topic, theoretical basis (geographical terminology, an introduction to solar tracking technology and some basic notions about the production and functioning of electricity by PV plates), as well as the comparison of the different tracking technologies, containing two tables as summary.

In the next chapter, we will explain the method that will be used for the project: firstly, related to the calculation of the energy production at each EU country, the Photovoltaic Geographical Information System (PVGIS), an informatic tool powered by the Joint Research Centre (JRC), which is the European Commission's science and knowledge service; this system presents interactive maps and estimations of electricity production and global irradiation. Then, we present the mathematical tool applied to carry out the analysis of costs of energy produced and its main indicator: the Levelized Cost of Energy (LCOE).

After that, in the results chapter, the list of locations will be included, followed by the corresponding data and graphs relating energy production, solar irradiation, costs, type of tracking system, etc. At the end of the chapter, a subsection presenting the results of a sensivity analysis will be included.

Finally, in the last chapter, some conclusions that have been drawn after the research are presented.

At the end of the document, two annexes are also presented: the first one with the exact geographical locations in which the calculations have been carried out, with Google Earth snapshots and information not only about geographical coordinates, but also with minimum and maximum average temperatures. In the second annex, we can consult the detailed data and graphs as result of PVGIS in every location: tables for fixed and tracking technologies, monthly energy production and daily irradiance in both best and worst months.

2 STATE OF THE ART

First of all, we should stop to explain some concepts which are important to know before deepening in our study, making reference to the documents which have been inspiration for the project, becoming the prelude of all the work that will be carried out.

2.1 Previous concepts

2.1.1 Photovoltaic plate functioning

PV plates are formed by modules, and these by PV cells, which are composed by different layers and sheets. Sunlight strikes the PV cells of the plate and an electrical field is created between the layers, generating an electrical circuit. The greater the sunlight is, the greater the flow of electricity will be; in addition, direct light it is not needed, because it also works on cloudy days. The produced current is continuous and is often transformed to alternating current by means of an inverter, making it suitable to distributing and consuming. [3]

Consequently, there exist two ways of improving the PV installation performance: acting on the energy transformation processes that take place in the panel or increasing the radiation received by the panel, being the second one in which we will focus along the research.

2.1.2 Geographic and geometric parameters

In this section, in order to understand all the calculations that will be carried out, some parameters must be defined, geographical and geometrical as well.

- *Latitude:* angular distance north or south from the earth's equator measured through 90 degrees. [4]

- *Longitude:* angular distance measured on a great circle of reference from the intersection of the adopted zero meridian with this reference circle to the similar intersection of the meridian passing through the object. [4]

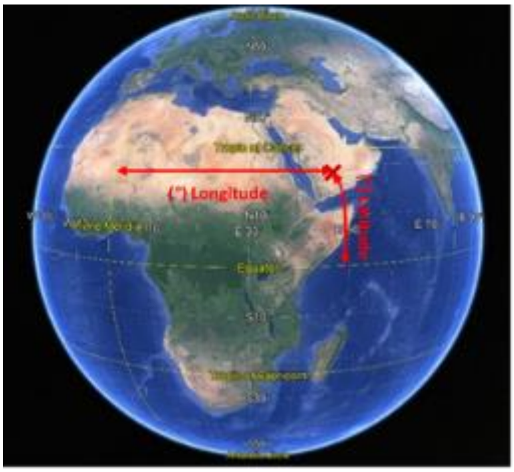


Fig. 1: Latitude and longitude

Source: Google Earth

In accordance with the position of the PV plate, it is defined by two parameters:

- *Inclination angle (also called slope):* tilt of the PV cell compared to a horizontally mounted PV cell. [5]

- *Orientation angle (also called azimuth):* describes the orientation in respect to the southern direction. [5]

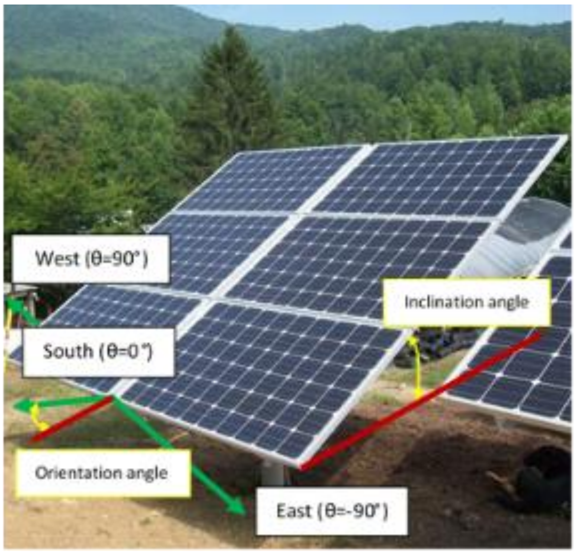


Fig. 2: PV plate parameters: Inclination and orientation angles

Source: alibaba.com. Labels and lines: prepared by the author.

2.2 Fixed or tracking technology

As mentioned before, some technological evolutions relative to PV plates have been focused in order to improve the solar irradiation received by the plate. Nowadays, we could find as well as movable installations, in which PV plates imitate the movement of the sun, whether by moving around one or two axes.

A fixed PV installation is one in which the panels do not change their position over time [6], placed at a fixed angle which is usually the optimum tilt. To obtain maximum efficiency from the solar panels they need to be pointed in the direction that captures the most sun. Fixed tilt arrays, being immobile, are simple in construction, easy to design and maintain [7].

One of the most important advances has been the research about how to create a system that follows the apparent path of the sun's motion, integrating a PLC programmed with a stellar database [8].

Essentially, a solar-tracker is a machine with a fixed part and another movable which lays out a collecting solar surface as perpendicular as possible to the sun throughout the day and within its motion range [6]. We can identify two types:

- One-axis tracker: with only a degree of freedom in their movement. There are several types (fixed in azimuth and steerable in slope or fixed in slope and steering in azimuth around a vertical or inclined axis).
- Two-axis tracker: with two degrees of freedom, permitting a more accurate solar tracking.

Fig. 3: 1-axis tracker (left) and 2-axis tracker (right)

Source: solarbay.com.au (1-axis) and mecasolar.com (2-axis), arrows elaborated by the author.

Now, it is time to make reference to some researches which have investigated about tracking systems and have carried out studies in order to compare fixed and 1 or 2-axis trackers and their production.

The first study that we should consider was promoted by R. Eke and A. Senturk (2012) from Mugla

Sıtkı Kocman University in Turkey; in which they conducted a performance comparison between a double-axis sun tracking system and a fixed PV system.

"*In the study, performance results of two double axis sun tracking photovoltaic (PV) systems were analyzed after one year of operation. Two identical 7.9 kWp PV systems with the same modules and inverters were installed at Mugla University campus in October 2009. Measured data of the PV systems were compared with the simulated data. The performance measurements of the PV systems were carried out first when the PV systems were in a fixed position and then the PV systems were controlled while tracking the sun in two-axis (on azimuth and solar altitude angles) and the necessary measurements were performed (...)"*

"*The electricity yield was 11.53 MWh for fixed tilt PV system and 15.98 MW h for the PV system on the double axis sun tracker. It was calculated that 30.79% more electricity was obtained in the double-axis sun-tracking system when compared to the latitude tilt fixed PV system. The difference between the estimated values and measured values were lower than 5%"* [9].

P.J. Axaopoulos and E.D. Fylladitakis (2014), from the Technological Educational Institute (TEI) of Athens, Greece, performed a research "*comparing the performance of a two-axis tracking system to that of an identical fixed inclination system facing south at optimal annual inclination angle for three locations across Europe: Athens (Greece), Stuttgart (Germany) and Aberdeen (UK), characterized by different climate conditions.*

The monthly and annual energy output of a real-world small-scale electricity generation photovoltaic installation with a rated power of 6.4 KWp was calculated, taking into account all electrical and temperature losses, as well as the power consumption of the two-axis tracker which was deducted from the annual generation of the system.

For each geographic location, the optimal annual inclination angles were calculated correlated to the latitude of the location. Finally, and economic analysis based on current economic data and local legislation was performed and economic analysis diagrams was presented to help evaluate any future changes of the feed-in tariff rates and capital cost, as well as possible feed-in tariff rate and capital cost subsidies. This study determined that investing on grid connected photovoltaic systems critically depends not only on the area's climatic conditions but also on the national legislation and regional energy prices" [8].

By means of real data of the TEI in Athens (38.0N, 23.675E) and a computer program for Stuttgart (48.83N, 9.2E) and Aberdeen (57.17N, 2.08W), some climatic data were recorded. The monthly global and diffuse irradiation on horizontal surfaces are presented in the following graph, "*showing us that, the global radiation decreases with increasing latitude; however, during summer, this ratio is not as strong as it is during winter, due to the influence of longer days in the north*" [8].

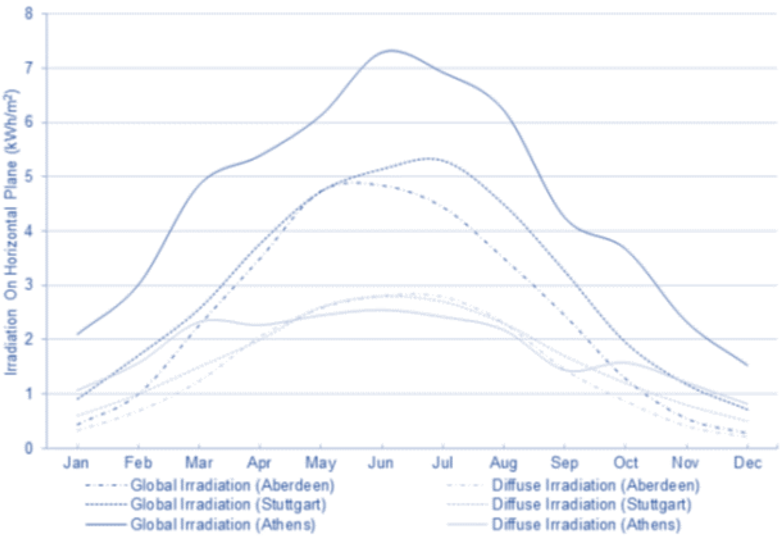


Fig. 4: Daily Average Global and Diffuse Irradiation on Horizontal Plane in Athens, Stuttgart and Aberdeen.

Source: [8]

Furthermore, we can see that the diffuse irradiation is affected positively by latitude in summer and the fraction of the diffuse to global irradiation increases in winter.

After that, "*the global irradiation incident on the inclined plane was also represented for systems both fixed at optimal inclination angles and mounted on two-axis trackers, making clear that the energy generation increase induced by a two-axis is inversely interrelated to the percentage of diffuse to global irradiation*". [8]

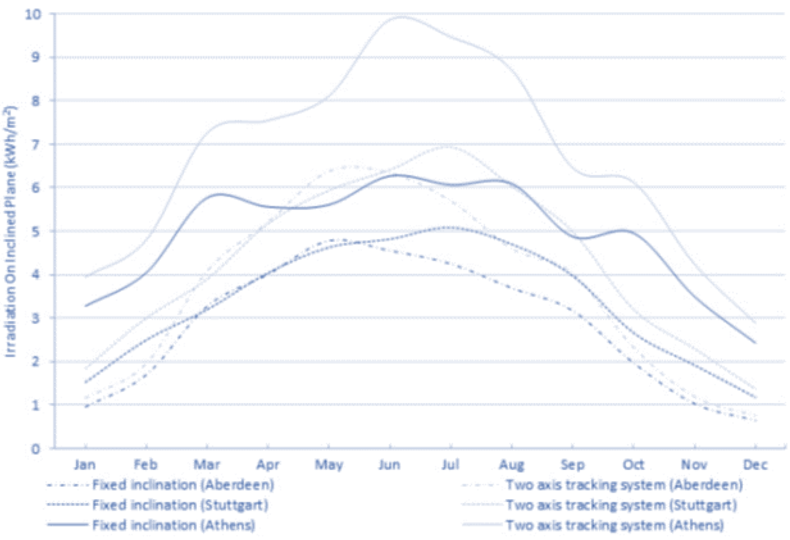


Fig. 5: Irradiation on inclined plane for both fixed inclination and two-axis tracking panels

Source: [8]

Moreover, we have to refer in particular to a special chapter of the research, where it is done an economic analysis for electrical energy generated, based on Life Cycle Cost Analysis (LCCA).

"*This method is widely applied for determining energy systems economics. With this method all costs and benefits are discounted to their present values. The appraisal requires the synthesis of both photovoltaic system performance results and a number of economic parameters. Required performance data have been calculated using the aforementioned simulation model*". [8]

Given the change of most of the economic parameters with time and geographic area, "*it is difficult to make reliable predictions about future trends on the value of money; consequently, a sensitivity analysis based on net present value is undertaken to evaluate the economics of energy generated under various investment costs and feed in tariff price fluctuations*" [8]. We will not go into this anymore, but it is important to note that some parameters were calculated: the net cash flow of each year (CF_T), the Bank Loan periodic payments (PP) and the Net Present Value (NPV).

Focusing on the results, we can divide them into two categories: energy generation and economic analysis. In the first one, the annual energy generation performance of the photovoltaic systems is presented, energy generation percentage increase and the performance ratio increase are also calculated.

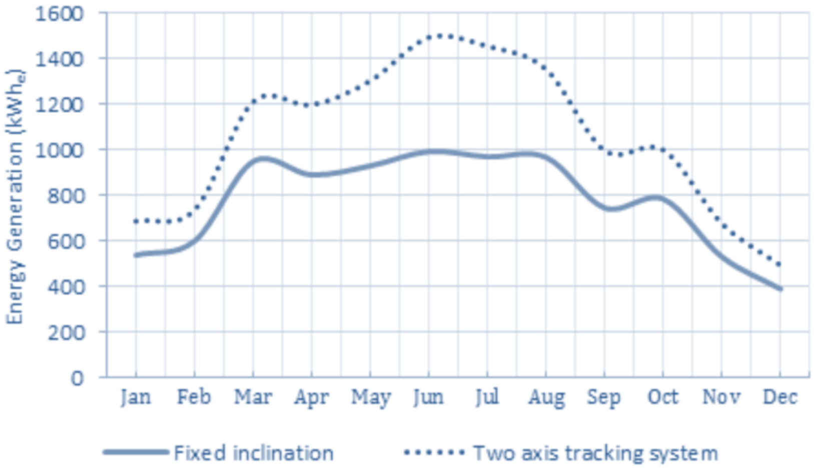


Fig. 6: Monthly Energy Generation (Athens)

Source: [8]

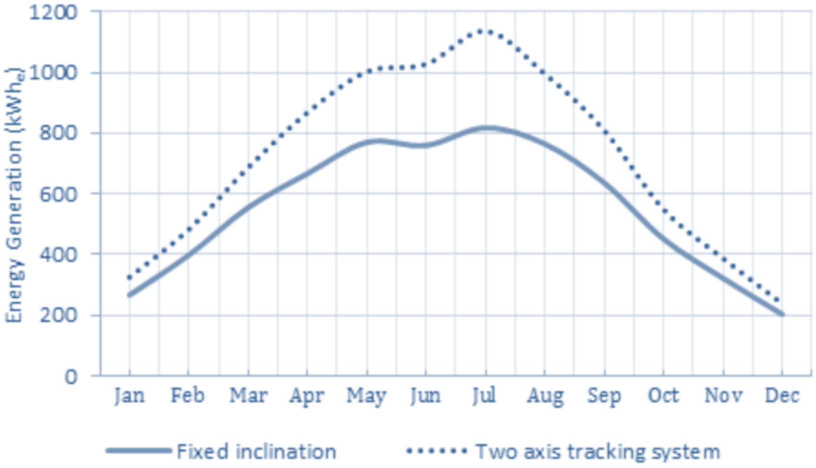


Fig. 7: Monthly Energy Generation (Stuttgart)

Source: [8]

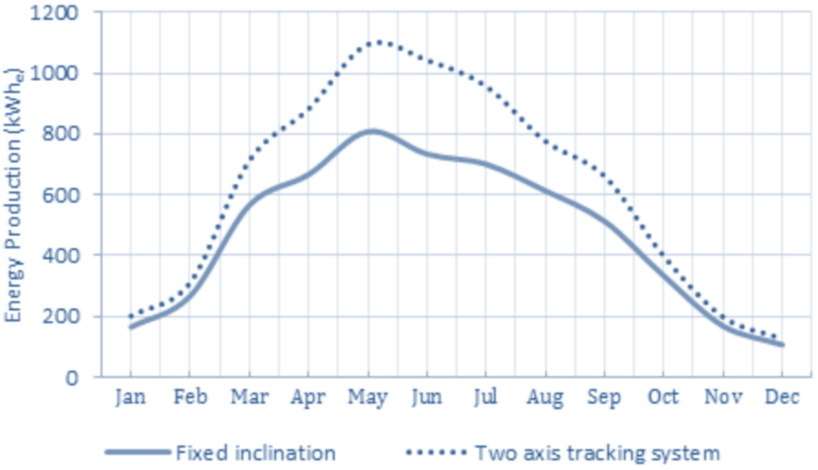


Fig. 8: Monthly Energy Generation (Aberdeen)

Source: [8]

From figures 6, 7 and 8, we can conclude that the energy generated by the tracking system is greater than that of the fixed system, particularly during the summertime period between the two equinoxes.

"*Outside of that period, it decreases significantly as latitude increases. Consequently, in January and December in Aberdeen, the energy generated by the tracking system is almost identical to that of the fixed system because the portion of diffuse radiation to the global radiation is very large. It is also noteworthy to mention that in Aberdeen the utilization of a two-axis tracker increases the annual energy generation more than in Stuttgart because of the long summertime days and extended sunshine hours during that period. Therefore, it becomes apparent that even if the annual diffuse to global irradiation ratio increases, the annual energy generation percentage increase that a two-axis tracking system would yield will not necessarily shrink as it is dependent on more than one parameter*" [8].

In Athens, the utilization of a two-axis tracker improved the annual energy generation of a PV system by 34.8%, in Stuttgart by 28.7% and in Aberdeen by 30.4%.

In terms of performance ratio, defined by $PR = \frac{E}{H_T * \eta_{STC}}$, which describes the percentage of energy generated (E) by the PV system with respect to the ideal performance, being H_T the incident solar irradiation on the inclined PV module surface and η_{STC} the efficiency of the module under Standard Test Conditions. The increases of PR are by 0.8% in Athens, by 1.1% in Stuttgart and by 1.3% in Aberdeen.

After economic analysis, some diagrams were made to display the economic viability of investing on a small-scale photovoltaic energy generation system in each of three locations and how future FIT and capital cost variations would affect the NPV of the investment, with the current analysis results being the reference point. Looking at them, it is concluded that, "*with the FIT rates effective then, photovoltaic stations remained a viable economic investment in Athens until the February of 2015, at which point the investment on a stand-alone photovoltaic system was of equal worth to a simple bank deposit. The FIT reductions of August 2012 however undoubtedly greatly reduced the appeal of investing on photovoltaics. The utilization of a two-axis tracker further increased the net present value of the investment over a 25-year analysis period*". [8]

"*The constant reductions of the feed in tariff rates during the previous few years turned land-based energy generation photovoltaic systems into an unappealing business investment in Germany and unprofitable in Scotland, making necessary the introduction of considerable government subsidies to become viable economic investments once again (…) It was clearly shown that investing on grid connected photovoltaic systems critically depends not only on the climatic conditions of the area but also on the national legislation and regional energy prices*". [8]

We should also consider the study promoted by DEGERiberica [10] (2016), in which an energetic comparative analysis about the use of one-axis horizontal solar trackers against fixed installations was carried out; the systems were installed in Zaragoza, Spain (latitude 41°N). The total nominal photovoltaic installed power was 7.15 KW.

The following cases of study were considered:

- A one-axis horizontal tracker (E-W) moving around axis N-S, facing East in the morning with a maximum inclination of 45° and facing West in the afternoon with a maximum inclination of 45°.
- A fixed plate with 35° of inclination oriented South. This angle is considered to be the optimum for this latitude in terms of maximizing annual generation.
- A fixed plate with 15° of inclination oriented South. This angle is considered to be the optimum for uses which need a better performance during the summer months. Furthermore, this angle coincides with the most of house roofs.
- A fixed horizontal plate (inclination 0°). This is the case of a flat roof and a horizontal pergola without inclination.

The monthly produced energy was indicated in a table and a graph was made, but we have preferred doing our own one, presented below.

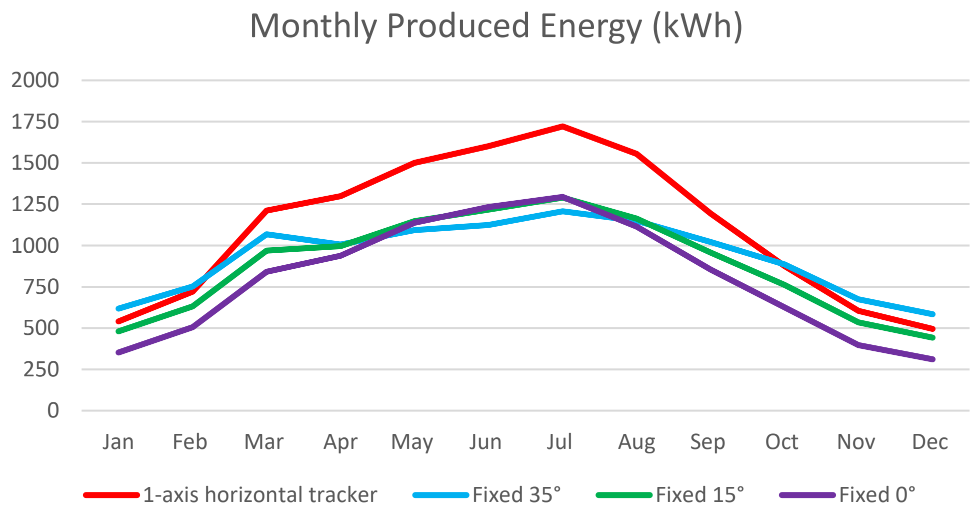


Fig. 9: Monthly Produced Energy (*Zaragoza, Spain)*

Source: Data [10], graphics elaborated by the author.

We can appreciate how the green line is above the blue line, supporting the mentioned idea that 15° plate is the optimum for uses which require a better performance during summer, while the blue line is above the green one for the rest of the year, making 35° plates better if we want to maximize the annual generation. In addition to this, the 1-axis tracker produces much more energy than the others, specially between equinoxes; for the remainder of the year, the fixed 35° plate is better than the tracker.

If we have an installation of annual use, we obtain a production increase which can vary between 19% and 39% depending on each fixed inclination. The average increase of annual production of a 1-axis horizontal solar tracker is by 27%, but it is lower during winter and higher during summer. In terms performance rate between trackers and fixed installations, it is much higher in uses that require more energetic consumption during spring and summer months.

The research carried out by the energetics magazine FuturENERGY [11] (2018) worths to be mentioned, which talks about tracking architecture and reliability with a focus on Latin America, which drew from the report at that time published by Consultants TÜV Rheinland PTL (TÜV) about economic and risk analysis of both centralized and decentralized architectures of PV systems. The research evaluated principal challenges, some aspects about engineering, design and operation and financial implications.

With respect to challenges, they were considered in Mexico, Argentina and Chile.

"*In Mexico, which offers year-round solar irradiation, it exists the problem of high risk of hurricanes which are no extraordinary weather between June and November. The main characteristic of a hurricane is the extreme force of the wind, with steady speeds of over 200 km/h that can cause irreversible damage to PV arrays. Robust and durable tracker architectures are therefore required, specifically designed to mitigate the effects of high winds. Hurricanes also bring heavy precipitation which, in combination with the strong winds, can cause flooding in certain areas. Some delicate electronic equipment, such as CPUs and sensors are not usually designed to withstand submersion in salt water, or the corrosion caused by beach sand. In some zones, the arid climate is accompanied by periodic strong winds that whip up large amounts of fine sand particles that can penetrate delicate electronic components. In addition, the high temperatures in the region can adversely affect battery service life, increasing operation and maintenance (O&M) costs for tracker systems that require batteries*". [11]

"*In Argentina, the country's large size brings together a host of weather conditions and geographical properties that affect tracker performance. For this reason, the use of tracker systems is generally limited to the northern regions of the Chaco and the Northwest. The province of the Chaco is known for harsh temperature swings, to which the solar tracker is subjected. Temperatures during the summer can reach 49°C and severe frosts in the winter can drop to under -6°C. Such a wide temperature range requires robust tracker equipment in order to reduce the possibility of failure. With these extreme temperature differentials, batteries quickly degrade, requiring more frequent replacement and incurring much higher system lifetime costs. In the Northwest, high summer temperatures and winter frosts are accompanied by strong winds, particularly in the mountains, where the Zonda (a wind that originates in Antarctica) can reach gusts of up to 200 km/h*". [11]

"*In Chile, due to the high levels of solar irradiation in the Atacama Desert region, tracker installations are very common in this unique environment. In the desert, solar generation is not impeded by cloud* *cover or even by mild atmospheric humidity. Although these are beneficial factors, the extremely low temperatures due to the region's height above sea level mean that the equipment must withstand year-round frosts*". [11]

In terms of engineering, design and operation, "*the report delivered a range of favorable findings regarding individual components and the design of the centralized system, highlighting the following findings: the number of potential failure points in decentralized systems, in both electrical and mechanical components, is much greater than in centralized systems; when faced with high wind loads, the centralized tracker studied has a structurally robust load dispersal design and a high wind mitigation strategy, which reduces the risk to the tracking structure and to the PV modules; the centralized solar tracker does not require batteries, whose performance can suffer if subjected to high temperatures (over 40°C), and can be physically damaged when charged at temperatures below 0°C or above 50°C. The centralized system does not use batteries, therefore, there are zero replacement battery costs over the service life of the PV array*". [11]

As has already been mentioned, one of the most common metrics used by investors to assess the economic viability of investments in energy generation is the project's levelized cost of electricity (LCOE), what is going to be developed in the next chapter.

"*The economic analysis is based on a 100 MW system with a service life of 30 years at a discount rate of 10%. While the two tracker systems show similar performance and installation costs, the main difference lies in the expenditures for fixed and variable O&M. The centralized system assessed delivers significant cost advantages with lifetime savings of more than US$12.5m over the decentralized system. Both technologies have a proven viable business case and can be deployed profitably with positive net present values (NPV). However, the centralized architecture evaluated is preferable, delivering 6.7% lower LCOE and an NPV advantage of 4.5%.*

The operational cost advantage of centralized systems is mainly due to a more robust plant design and comparatively minimal maintenance requirements for the installed tracker components. Decentralized systems use a large number of components, which increases the risk of system failure. Consequently, the costs of inspecting and supplying these components clearly outweigh any potential benefits of decentralized systems. In the case of the extreme weather conditions that can occur throughout Latin America, such as very high or low temperatures or extreme wind loads, the vulnerability of decentralized systems increases, making the cost advantage of centralized systems even higher".

These problems associated with weather conditions will be considered in our project; taking into account cities as Nicosia (Cyprus), where the temperature oscillates between 6°C to 33°C, or Helsinki (Finland), with temperature variations from -9°C to 22°C.

As summary of the chapter, here below is presented a list with the main information about the articles which present comparative analyses of fixed and tracking technologies (one-axis or two-axis).

After that, some comments about comparisons of the different technologies are done, followed by a table with advantages and disadvantages of them.

Author(s)	Article	Countries studied	Year	Description
R. Eke & A. Senturk [9]	“Performance comparison of a double-axis sun tracking versus fixed PV system.”	Turkey	2009	Comparison of two identical PV systems, one in a fixed position and the other tracking the sun in two-axis. After one year of operation, it was calculated that 30.79% more electricity was obtained in the double-axis sun-tracking system when compared to the latitude tilt fixed PV system.
P.J. Axaopoulos & E.D. Fylladitakis [8]	“Energy and economic comparative study of a tracking vs. a fixed photovoltaic system in the northern hemisphere.”	Greece Germany United Kingdom	2014	Comparison of the performance of a two-axis tracking system and an identical fixed for three locations across Europe: Athens (Greece), Stuttgart (Germany) and Aberdeen (UK); variations on irradiation and monthly energy generation depending on latitude. Economic analysis based on current economic data and local legislation to evaluate any future changes of the feed-in tariff rates and capital cost.
A. Toribio [10]	“Viabilidad de la instalación de Seguidores Solares de 1 Eje respecto de instalaciones fijas, en aplicaciones de riego, bombeo solar y autoconsumo.”	Spain	2016	Comparative analysis about the use of a one-axis horizontal solar tracker (moving around N-S axis) against some fixed installations with different inclination angles (35°, 15°, 0°).
FuturENERGY [11]	“Tracking Architecture and Reliability with a focus on Latin America.”	Mexico Argentina Chile	2018	Economic and risk analysis of both centralized and decentralized architectures of PV systems in Latin America, evaluating principal challenges, some aspects about engineering, design and operation and financial implications.

Table 1: Background researches comparing fixed and tracking technologies

- When comparing general tracking vs fixed systems, we can see that a tracking system gives much more energy generation, specially in summer months, but in the remainders of the year, it depends highly on the latitude, making that the energy generation decreases with increasing latitude. If we have a fixed system, the inclination angle is a quite important factor that we should consider, as we have seen in the DEGERiberica research [10], in which we have studied fixed 0°, 15° and 35°; we have concluded that it exists an angle which optimizes the performance of our installation during summer time, being different from that which optimizes the total annual energy production, which is less effective during summer.

- When comparing specifically two-axis trackers vs fixed systems, we could see in the research carried out in Mugla Sıtkı Kocman University, Turkey [9] that 30.79% more electricity was obtained in the double-axis sun-tracking system when compared to the latitude tilt fixed PV system. In the study by TEI [8], in which three locations were studied, in Athens, the utilization of a two-axis tracker improved the annual energy generation of a PV system by 34.8%, in Stuttgart by 28.7% and in Aberdeen by 30.4% and in terms of Performance Ratio (PR) the increases were by 0.8% in Athens, by 1.1% in Stuttgart and by 1.3% in Aberdeen. However, if we look at economics, the constant reductions of the feed in tariff rates turned land-based energy generation photovoltaic systems into an unappealing business investment in Germany and unprofitable in Scotland, making necessary the introduction of considerable government subsidies to become viable economic investments once again, making clear that investing on grid connected photovoltaic systems critically depends not only on the climatic conditions of the area but also on the national legislation and regional energy prices.

- When comparing specifically one-axis trackers vs fixed systems, as in the commented DEGERiberica research [10], one-axis tracking systems increase so much the production of energy, mainly between equinoxes, although in the remainders of the year it gives almost as much production as the fixed system with the optimum angle in terms of average annual generation.

- When comparing one-axis vs two-axis trackers, if we look at the aforementioned HISPANOTRACKER research [6], one-axis trackers are simpler and, therefore, their cost is less than the two-axis plates; however, one-axis systems undertake an inaccurate solar tracking, causing a lower production of energy.

Technology	Advantages	Disadvantages
Fixed	Easy and cheap to design, fabricate and maintain. Good performance for most of the year.	Bad performance between equinoxes The optimization of inclination angle is essential.
One-axis tracker	Better tracking of sun than fixed plates. Good performance, especially in summer months.	More difficult design, fabrication and maintenance than fixed plates. Inaccurate solar tracking, causing a lower production of energy than the two-axis trackers.
Two-axis tracker	Very accurate tracking of sun. Better performance than the other technologies, specially in summer months.	Difficult and expensive design, fabrication and maintenance. Not advisable for high latitudes.

Table 2: Advantages and disadvantages of different PV technologies

3 METHOD

In this chapter, we will explain the instruments that are going to be used in the project, including the web page to produce calculations of solar radiation and photovoltaic system energy production as well as the mathematical tool to evaluate the costs of producing energy by means of PV cells.

3.1 Calculation of the Energy Production

In order to perform all the calculations of electricity produced in each European country, we will use a web application called "Photovoltaic Geographical Information System (PVGIS)", powered by the European Commission Joint Research Centre (JRC), with the purpose of researching "in solar resource assessment, photovoltaic (PV) performance studies and the dissemination of knowledge and data about solar radiation and PV performance". The application allows the user to get data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world. [12]

3.1.1 Selection of geographical location

First of all, we have to select the geographical location for which to make the calculation; it can be done by clicking on the map, by entering an address or by entering the latitude and longitude of the location. In our case, considering that the twenty locations have been chosen directly on a map by using Google Earth, we will select the locations by entering latitudes and longitudes.

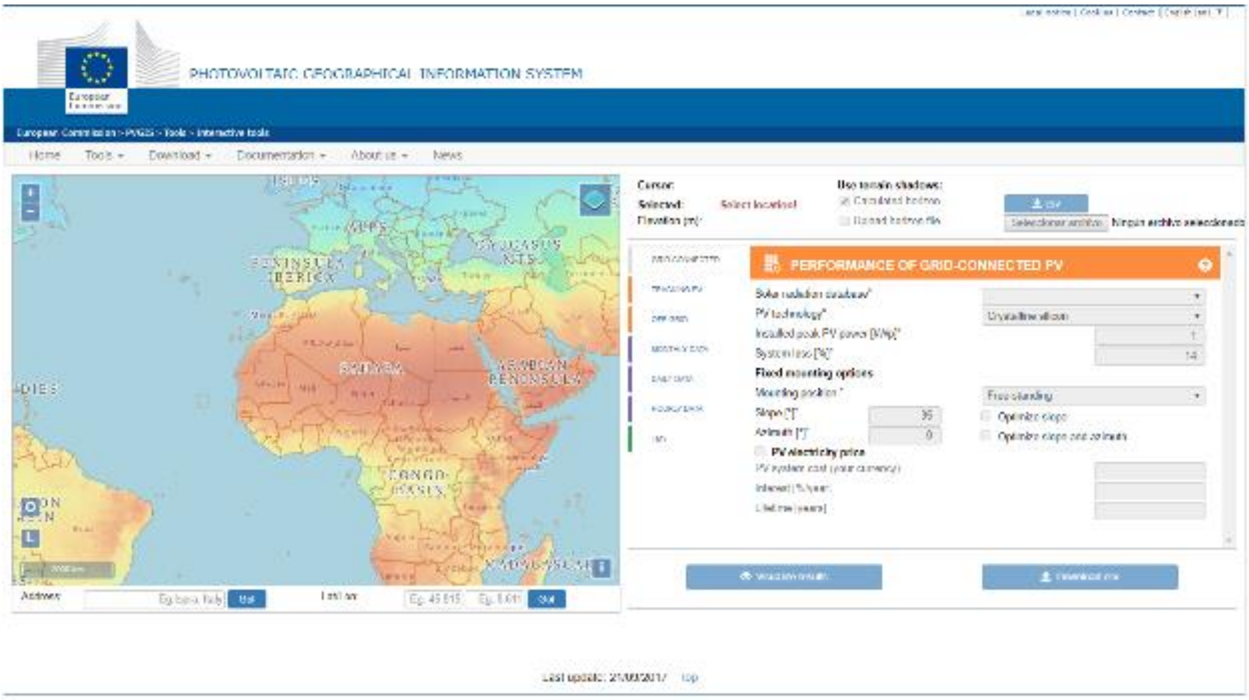


Fig. 10: Selecting a location by latitude and longitude in PVGIS

Source: [13]

Furthermore, the tool allows us to use information about the local horizon to estimate the effects of shadows from nearby hills and mountains. However, our locations have been selected to be virtually free from any obstacle that could make as significant shadows as to change the results of the calculation; consequently, we will deselect the “calculated horizon” box in “Use of terrain shadows”.

3.1.2 Solar radiation database

In terms of solar radiation data used by PVGIS for Europe, most have been calculated from satellite images (PVGIS-CMSAF and PVGIS-SARAH), but areas which are not covered by the satellite data (especially the case for high-latitude areas), use two additional solar radiation databases, including northern latitudes (PVGIS-ERA5 and PVGIS-COSMO).

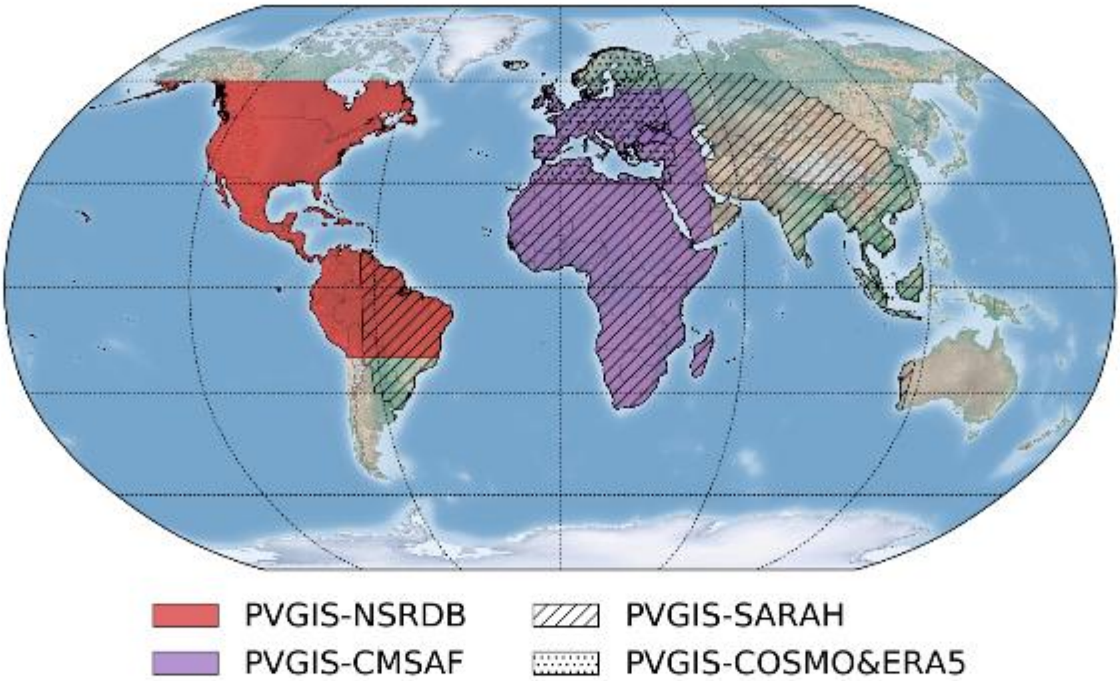


Fig. 11: Geographical extent of the solar radiation databases

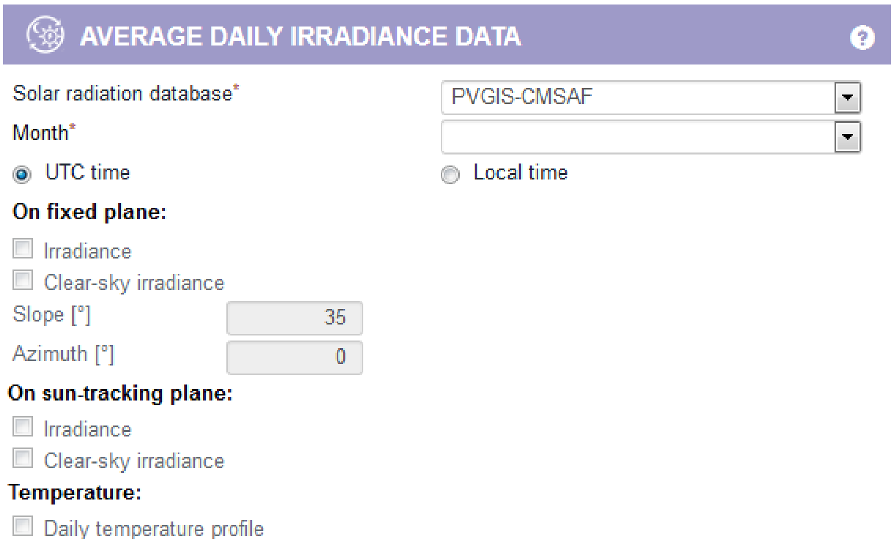
Source: https://re.jrc.ec.europa.eu/pvg_static/en/manual.html#

For each calculation option in the web interface, PVGIS present the user with a choice of the databases that cover the location chosen. Nevertheless, when a location is set in the system, it adjusts which database is the most adequate to that location and gets the most accurate results.

For that reason, we will not stop for explaining more details apart from the covering zones exposed in the figure above. [Fig. 11]

3.1.3 Daily radiation profile data

This tool lets us see the average daily profile of solar radiation for a given month. For our study, we will only obtain the Irradiance on a fixed plane; "*with this option you get the global, direct, and diffuse irradiance profiles for solar radiation on a fixed plane, with slope and azimuth chosen by the user*" [13].



AVERAGE DAILY IRRADIANCE DATA

Solar radiation database* PVGIS-CMSAF
Month*
● UTC time ○ Local time

On fixed plane:
☐ Irradiance
☐ Clear-sky irradiance
Slope [°] 35
Azimuth [°] 0

On sun-tracking plane:
☐ Irradiance
☐ Clear-sky irradiance

Temperature:
☐ Daily temperature profile

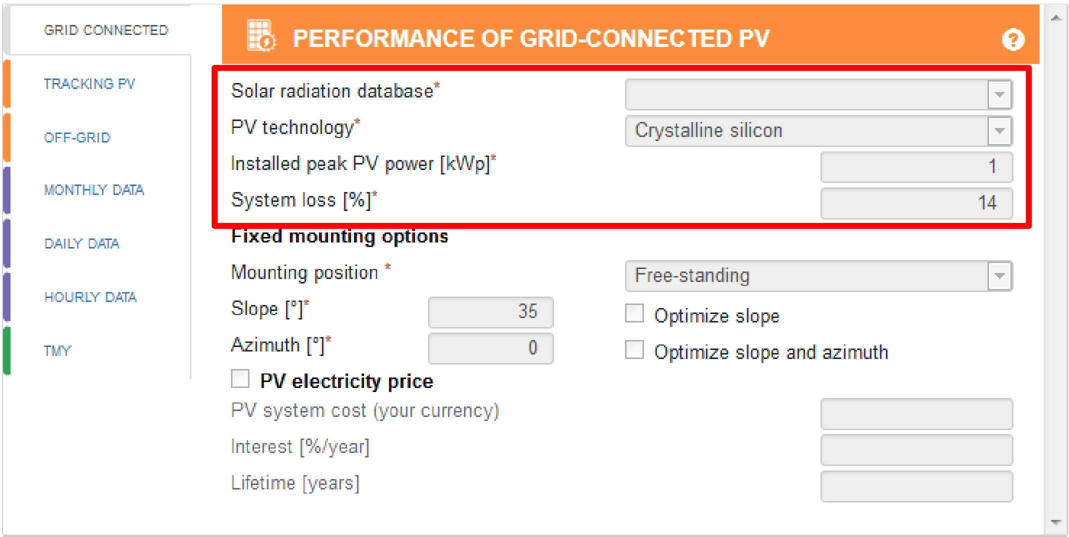
Fig. 12: Average Daily Irradiance Data menu

Source: [13]

3.1.4 Grid-connected PV system performance

As explained in previous chapters, photovoltaic systems convert the energy of sunlight into electric energy; however, PV modules produce direct current (DC) electricity, while the regular consumption of electricity is alternate current (AC), making necessary that modules are connected to an inverter which converts the electricity from DC to AC, and then it can be used locally or sent to the electricity grid. This type of system is grid-connected PV. The calculation of the energy production assumes that all the energy that is not used locally can be sent to the grid.

3.1.4.1 Inputs for the PV system calculations



PERFORMANCE OF GRID-CONNECTED PV

Solar radiation database*
PV technology* Crystalline silicon
Installed peak PV power [kWp]* 1
System loss [%]* 14

Fixed mounting options
Mounting position * Free-standing
Slope [°]* 35 ☐ Optimize slope
Azimuth [°]* 0 ☐ Optimize slope and azimuth

☐ **PV electricity price**
PV system cost (your currency)
Interest [%/year]
Lifetime [years]

Fig. 13: Inputs for the PV system calculations
Source: [13]

- **Solar radiation database**: As mentioned, PVGIS offers several databases to the calculations, but when we set the location, the system suggests us the best option in accordance with the accurate for the selected geographical location.

- **PV technology**: The performance of PV modules depends on the temperature and on the solar irradiance, which also depends on the type of the PV modules. PVGIS can estimate losses due to temperature and irradiance effects for different types of modules: crystalline silicon cells, thin film modules made from CIS or CIGS and thin film modules made form Cadmium Telluride (CdTe).

- **Installed peak PV power $[kWp]$**: This is the power that the manufacturer declares that the PV array can produce under Standard Test Conditions (STC) [13], being: irradiance of 1000 W/m^2, a module temperature at 25 $°C$ and a solar spectrum of AM 1.5. This is a standardized test which enables comparison between different technologies and brands. [14]

  AM stands for Air Mass, which is "the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust.

  The Air Mass is defined as:

$$AM = \frac{1}{cos(\theta)} \tag{1}$$

Where θ is the angle from the vertical (zenit angle). When the sun is directly overhead, the Air Mass is 1". [15]

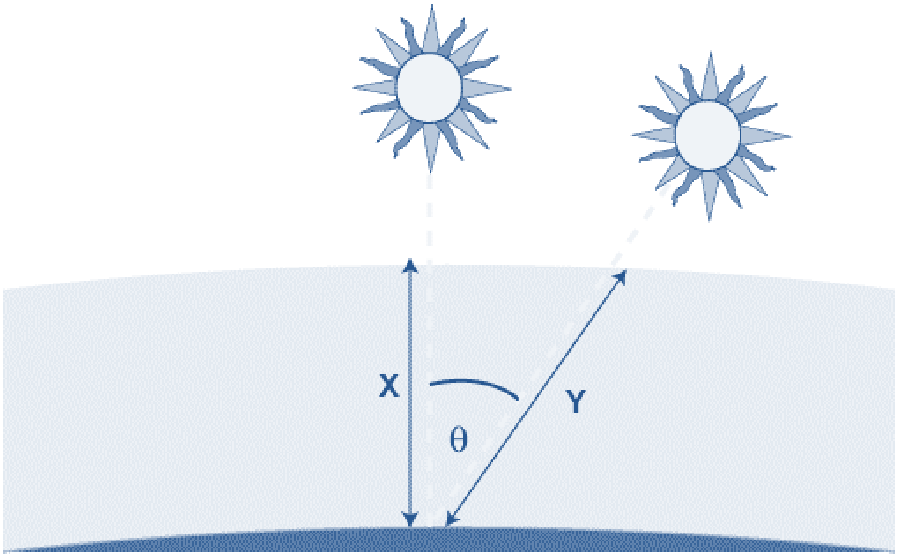


Fig. 14: Air Mass definition

Source: https://www.pveducation.org/pvcdrom/properties-of-sunlight/air-mass

In the figure, the air mass represents the proportion of atmosphere that the light must pass through before striking the Earth relative to its overhead path length, and is equal to Y/X.

- **System loss**: The estimated system losses are all the losses in the system, which cause the power delivered to the electricity grid to be lower than the power produced by the PV modules. Several causes of losses could appear, such as losses in cables, power inverters, dirt (sometimes snow) on the modules and so on. Moreover, the modules tend to lose a bit of their power over the years, so the electricity production over the lifetime of the system will be a few lower than the production in the first years.

  In PVGIS, a default value of 14% is given for the overall losses, but it permits the user to change the value (for example if we have a high-efficiency inverter, we may reduce this value a little).

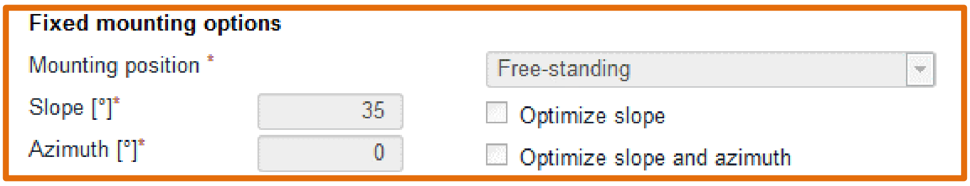
  This type of system, the grid-connected PV system is the one that we will use for our calculations, with independence on the type of tracking technology (fixed, 1-axis tracking or 2-axis tracking), thus, in the next subsections we will explain the PVGIS tabs corresponding to "Fixed mounting options" and "Tracking mounting options".

3.1.4.2 Fixed photovoltaic modules

Previously, it was said that one of the objectives of this project is to compare electricity production by means of photovoltaic plates and its costs depending on geographical location and the used tracking technology.

PVGIS permits to make the distinction in calculations between fixed and tracking PV plates. In this subsection, we will present all the inputs and outputs that PVGIS offers from the fixed-plates point of view.

3.1.4.2.1 Inputs for fixed mounting PV modules



Fixed mounting options

Mounting position * Free-standing

Slope [°]* 35 ☐ Optimize slope

Azimuth [°]* 0 ☐ Optimize slope and azimuth

Fig. 15: Fixed mounting options

Source: [13]

- **Mounting position**: For fixed systems, the way the modules are mounted is a very important aspect to bear in mind, because it has an influence on the temperature of the module and, as consequence, on the efficiency. "In PVGIS there are two possibilities: *free-standing*, meaning that the modules are mounted on a rack with air flowing freely behind the modules; and *building-integrated*, which means that the modules are completely built into the structure of the wall or roof of a building, with no air movement behind the modules." [13]

  For our studies, we have free-standing mounting, with racks installed on the floor, far from any building.

- **Slope of PV modules**: Slope, elevation angle or inclination angle (defined in subsection 2.1.2) is the angle of the PV modules from the horizontal plane, for a fixed mounting.

- **Azimuth of PV modules**: Azimuth or orientation angle (defined in subsection 2.1.2) is the angle of the PV modules relative to the direction due South. -90° is East, 0° is South and 90° is West.

PVGIS can calculate for our selected locations the optimal values for slope and azimuth (assuming fixed angles for the entire year).

For our calculations, we are going to fix azimuth to 0° (oriented to South) for all locations and will calculate from PVGIS the optimal inclination angle, supposing that, in every location, plates are mounted with the corresponding optimal inclination angle.

In the results section, we will prove the validity of our assumption, that fixing azimuth to 0° does not affect significantly the yearly PV energy production.

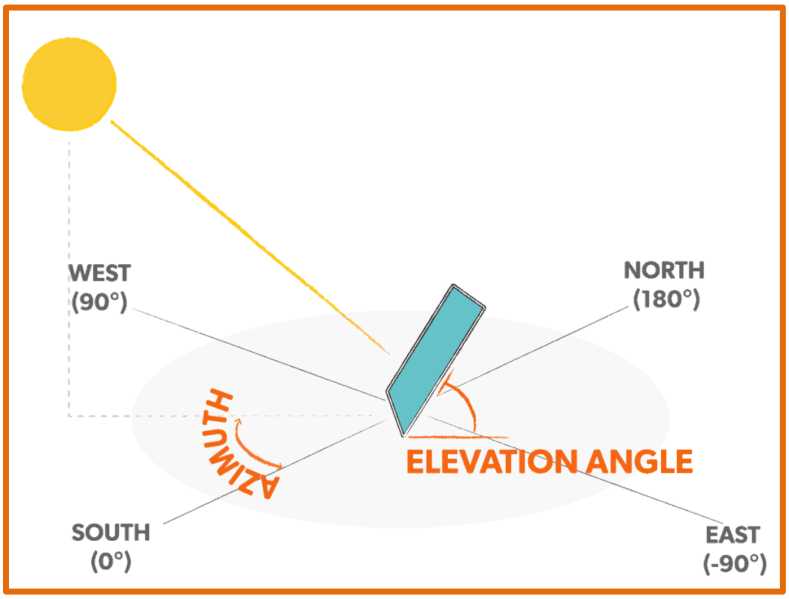


Fig. 16: Azimuth and elevation angles

Source: https://www.wholesalesolar.com/blog/azimuth-angle-diagram/

- **PV electricity price**: The last update of PVGIS, the version 5, includes the method that is described in the next section, as tool to calculate the cost of electricity generated by the PV system. the next information is needed:
  - Total cost of buying and installing the PV system. With out notation, it is equivalent to Investment costs in year t (I_t). It is important to remind that we will obtain annual average values of energy production in a generic taken year.

$$PV\ system\ cost = I_t \quad [€] \tag{2}$$

As expected, the cost is directly related with the installed peak PV power (the bigger the system, the higher the costs).

- Interest rate, in % per year, assumed to be constant throughout the lifetime of the PV system. It is the inverse value of the aforementioned r (discount rate).

$$Interest\ rate = \frac{1}{r} \quad [\%\ \text{year}] \tag{3}$$

- Expected lifetime of the PV system, in years. It is the aforementioned n.

The calculation assumes that there will be a fixed cost per year for maintenance of the PV system (such as replacement of components that break down), equal to 2% of the original cost of the system. It is equivalent to the aforementioned M_t (Maintenance costs in year t).

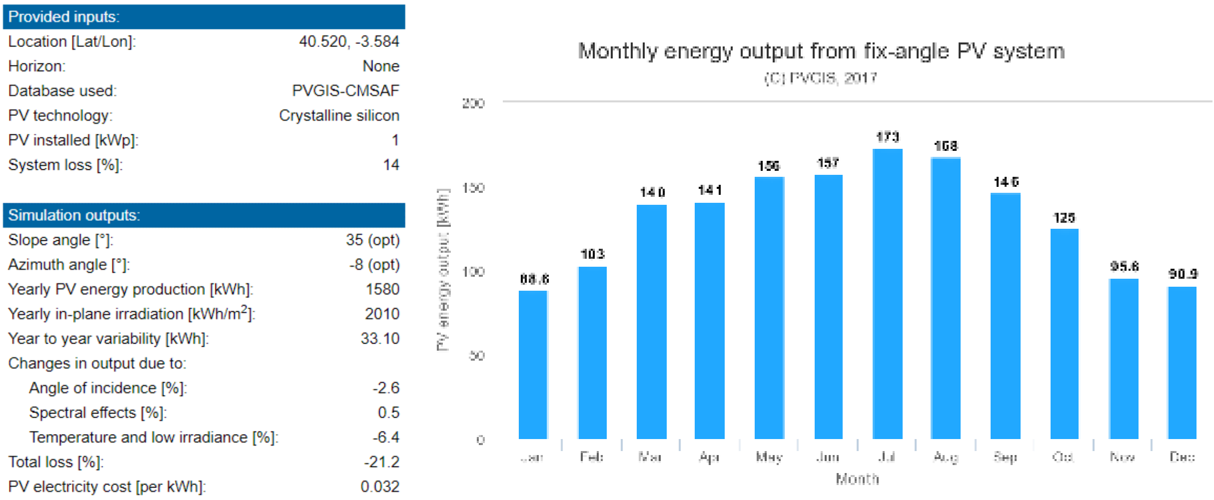
3.1.4.2.2 Outputs for fixed mounting PV modules

“The outputs of the PVGIS calculation consist of annual values of energy production and in-plane solar irradiation, as well as graphs of the monthly values”. [13]

These outputs are: slope and azimuth angles (previously fixed by us or calculated as optimal if we have selected the option), Yearly PV energy production [kWh], Yearly in-plane irradiation [kWh/m^2], Year to year variability [kWh], percentages from causes of losses in the PV output, such as Angle of incidence and Spectral effects, and Total loss (in %).

“Year to year variability in the PV output is the standard deviation of the yearly values over the period with solar radiation data in the chosen solar radiation database”. [13]

The main graph that we will obtain for our project is the monthly PV energy output.



Provided inputs:	
Location [Lat/Lon]:	40.520, -3.584
Horizon:	None
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	35 (opt)
Azimuth angle [°]:	-8 (opt)
Yearly PV energy production [kWh]:	1580
Yearly in-plane irradiation [kWh/m^2]:	2010
Year to year variability [kWh]:	33.10
Changes in output due to:	
Angle of incidence [%]:	-2.6
Spectral effects [%]:	0.5
Temperature and low irradiance [%]:	-6.4
Total loss [%]:	-21.2
PV electricity cost [per kWh]:	0.032

Fig. 17: Example of outputs table and monthly energy output graph for a fixed PV system

Source: Own elaboration

3.1.4.3 Sun-tracking photovoltaic modules

In this subsection, as done for fixed PV modules, we will differentiate between inputs and outputs.

3.1.4.3.1 Inputs for tracking mounting PV modules

As it was previously mentioned, PVGIS lets the user make calculations of the energy production from fixed and sun-tracking PV systems. PVGIS includes three different types of sun-tracking PV modules of the four that were described in section *2.2 Fixed or tracking technology*.

- **Vertical axis tracking**: The movement that follows the daily path of the sun is done around a vertical axis, maintaining the slope angle constant and varying the azimuth angle, facing east in the morning, gradually moving towards west in the evening.

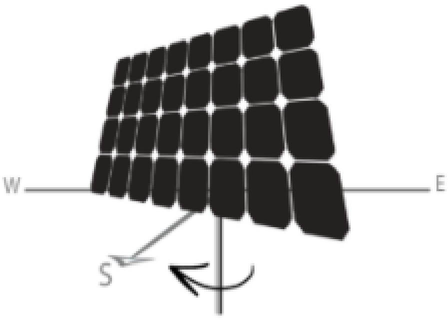


Fig. 18: Vertical axis tracking PV plate

Source: [13]

PVGIS also includes the option of calculating an optimal slope angle, being the slope of the modules (which remain fixed).

- **Inclined axis tracking**: The movement that follows the daily path of the sun is done around an inclined axis. "*In the morning the modules are nearly vertical facing east, at noon they face upwards at an angle equal to the axis slope and then gradually turn towards west, again being nearly vertical in the evening. The azimuth of the inclined axis is due south (because all the locations of our study are in the northern hemisphere)*". [13]

  The option of optimizing the slope angle is also included, being in this case the slope of the axis around which the modules are rotated.

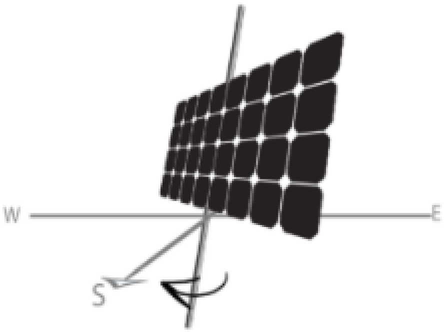


Fig. 19: Inclined axis tracking PV plate

Source: [13]

- **Two-axis tracking**: In these systems the modules can be moved following the path of the sun, always facing directly towards the sun, obtaining a much higher energy performance; however, the tracking system is generally more complicated and more expensive than the single-axis tracking systems (more complex engineering affects design, operation, parts involved, maintenance tasks).

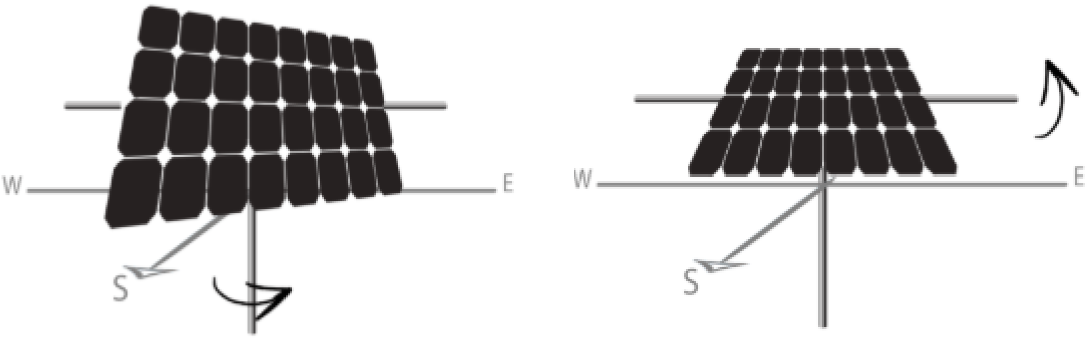


Fig. 20: Two-axis tracking PV plate

Source: [13]

There is another common type of one-axis tracking system, but PVGIS does not include it in its calculations. It was shown in the Fig. 3 left:

- **Horizontal axis tracking**: The movement that follows the daily path of the sun is done around a horizontal axis, maintaining the azimuth angle fixed (due south) and varying the slope angle. In this way, PV modules face east in the morning, being horizontal at noon and then gradually turn towards west.

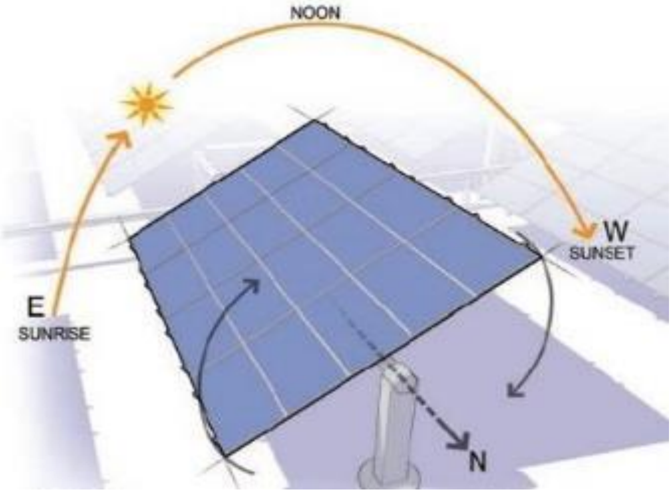


Fig. 21: Horizontal axis tracking PV plate

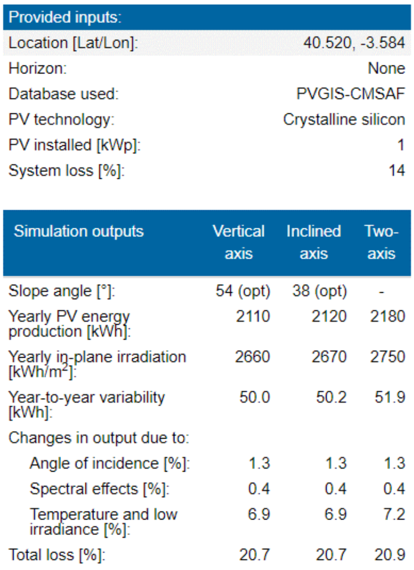
Source: https://www.solsystems.com/blog/2017/11/20/tracking-the-sun-the-increasing-popularity-of-trackers/

3.1.4.3.2 Outputs for tracking mounting PV modules

The output calculations of the tracking PV system are essentially the same as the outputs for fixed-mounted grid-connected. The main difference is that we may now obtain results for up to the three different mounting types that we presented in the previous subsection.

A table with three columns is obtained (vertical axis, inclined axis and two-axis), with rows for the different output parameters: slope angle (defined as is explained at subsection 3.1.4.3.1), Yearly PV energy production [kWh], Yearly in-plane irradiation [kWh/m^2], Year to year variability [kWh], percentages from causes of losses in the PV output, such as Angle of incidence and Spectral effects, and Total loss (in %).

With regard to the graphs, the same as fixed plates, the monthly PV energy output, but including three bars for each month (one for every type of tracking technology).



Provided inputs:	
Location [Lat/Lon]:	40.520, -3.584
Horizon:	None
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs	Vertical axis	Inclined axis	Two-axis
Slope angle [°]:	54 (opt)	38 (opt)	-
Yearly PV energy production [kWh]:	2110	2120	2180
Yearly in-plane irradiation [kWh/m²]:	2660	2670	2750
Year-to-year variability [kWh]:	50.0	50.2	51.9
Changes in output due to:			
Angle of incidence [%]:	1.3	1.3	1.3
Spectral effects [%]:	0.4	0.4	0.4
Temperature and low irradiance [%]:	6.9	6.9	7.2
Total loss [%]:	20.7	20.7	20.9

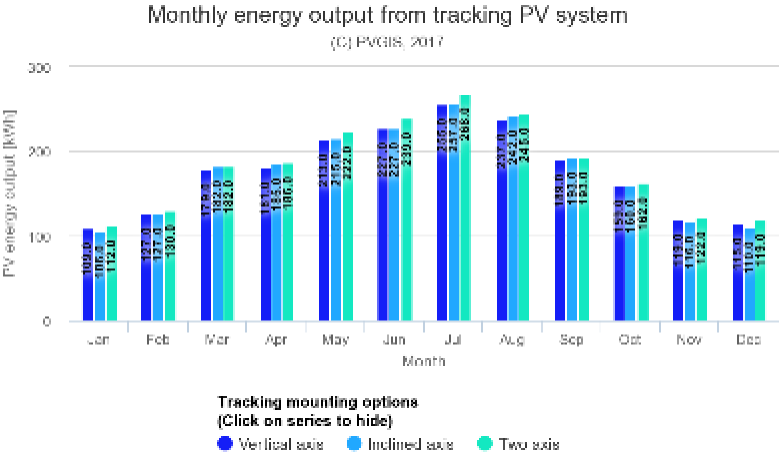


Fig. 22: Example of outputs table and monthly energy output graph for a tracking PV system

Source: Own elaboration

3.1.5 Off-grid PV system performance

In the previous section, we explained the performance of an on-grid PV system, in which the produced electricity in form direct current (DC), was converted to alternate current (AC) by means of an inverter, and then this AC electricity could be used locally or sent to the electricity grid. However, there are some systems that are not connected to the electricity grid but instead rely on battery storage to supply energy when the sun is not shining.

PVGIS includes the performance of this off-grid PV system, but we will not explain it in detail because it is not the object of our project (we will do all the calculations for on-grid PV systems). "*The calculation uses information about the daily variation in electricity consumption for the system to simulate the flow of energy to the users in and out of the battery*". [13]

3.1.5.1 Inputs for the off-grid PV calculations

The inputs for the off-grid calculations are essentially the same as the inputs for the on-grid calculations but including some parameters such as the Battery capacity [Wh], the percentage of Discharge cut of limit and the Consumption per day. Furthermore, it is not possible to choose the PV technology, instead the calculation assumes a constant loss of 32%, including also the losses that occur when charging and discharging the batteries.

3.1.5.2 Outputs for the off-grid PV calculations

As the other PV calculation tools in PVGIS, the outputs for the off-grid system consist of annual statistical values and graphs of monthly parameters.

Appart from the previous outputs, there are three different monthly graphs: [13]

- A graph showing the monthly average of the daily energy output as well as the daily average of the energy not captured because the battery became full.
- A graph of monthly statistics on how often battery became full or empty during the day.
- A histogram of the battery charge state.

3.1.6 Other functions in PVGIS

PVGIS has some more functions, which are going to be described briefly because they are not directly used in the project, such as: [13]

- ***Monthly average solar radiation data***: This tab allows the user to visualize and download monthly average data for solar radiation and temperature over a multiyear period.

- ***Hourly solar radiation and PV energy data***: This tool gives the user access to the full contents of solar radiation database. In addition, the user can also request a calculation of PV energy output for each hour during the chosen period.

- ***Typical Meteorological Year (TMY) data***: This option allows the user to download a data set containing a Typical Meteorological Year (TMY) of data. The data set contains hourly data of the following variables:

  - Date and time
  - Global horizontal irradiance
  - Direct normal irradiance
  - Diffuse horizontal irradiance
  - Air pressure
  - Dry bulb temperature (2m temperature)
  - Wind speed
  - Wind direction (degrees clockwise from north)
  - Relative humidity
  - Long-wave downwelling infrared radiation

3.2 Costs of Energy Production

In this chapter, we will define the mathematical method that we will follow in order to calculate the costs of energy production for each type of PV system. We will use the Levelized Cost of Energy.

The "Levelized Cost of Energy" (LCOE), as defined in the research *Cost Map for Unsubsidised Photovoltaic Electricity,* published by the Joint Research Centre of European Commission [16] (2014), "*is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital.*"

In accordance with the article carried out by Abadie and Chamorro (2019) [17], we could have two different methods to approach to LCOE. "*The first one considers a yearly timeframe, so it yields a yearly estimate of the LCOE. The second one, instead, keeps the whole lifetime of the facility when computing its LCOE; it thus results in a life-cycle estimate. This said, they share some features, for example, their reliance on the net-present-value methodology and the scant use of market prices. Unfortunately, they also stumble on some common issues, such as the proper way to account for risk".*

3.2.1 Single-period plant-level LCOE

It is the most used in the electrical industry and is defined by the US National Renewable Energy Laboratory (NREL) as 'simple LCOE (sLCOE)*'which is measured in $/kWh and allows the comparison of the combination of capital costs, operations and maintenance, performance, and fuel costs."*

It can be calculated in the following formula:

$$sLCOE = \frac{overnight\ capital\ cost * CRF + FOM}{8760 * capacity\ factor} + fuel\ cost * heat\ rate + VOM \quad (4)$$

Where:

- Overnight Capital Cost is measured in dollars per installed kilowatt ($/kW)
- CRF is the capital recovery factor (measures the ratio of a constant annuity to the present value of receiving that annuity for a given length of time).

$$CRF = \frac{1}{\frac{1}{i} - \frac{1}{i(1+i)^t}} = \frac{i(1+i)^t}{(1+i)^t - 1} \quad (5)$$

i = interest rate; t = next years of production

- Fixed Operation and Maintenance (FOM) costs are in dollars per kilowatt-year ($/kW-yr).
- Variable Operation and Maintenance (VOM) costs are in dollars per kilowatt-hour ($/kWh)
- In the denominator, 8760 = 365 × 24 is the number of hours in a year.
- The Capacity Factor is the portion of a year that the power plant is generating ($0 \leq CF \leq 1$).

3.2.2 Multi-period plant-level LCOE

There are different definitions of this type of LCOE, but in our study we will use the given by the UK Department for Business, Energy and Industrial Strategy, which defines the LCOE as the "*the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh".*

$$LCOE = \frac{PV(total\ costs)}{PV(electricity\ generation)} \tag{6}$$

"Total costs are the sum of 'Capex costs' and 'Opex costs'. Capital expenditure costs comprise: predevelopment costs, construction costs and infrastructure cost. Operation exprenditure costs comprise: fixed opex, variable opex, insurance, connection costs, carbon transport and storage costs, decommissioning fund costs, heat revenues, fuel prices and carbon costs". [17]

Internal rate of return (IRR) on an investment project is the discount rate that makes it Net Present Value (NPV) equal to zero:

$$NPV = PV(revenues) - PV(costs) = 0 \rightarrow PV(costs) = PV(revenues) \tag{7}$$

Therefore, when $r = IRR$, LCOE can be equivalently defined as:

$$LCOE = \frac{PV(revenues)}{PV(energy)} = \frac{PV(energy \times price)}{PV(energy)} \tag{8}$$

"*The LCOE can naturally be interpreted as the electricity price required for the project to have a zero NPV, or, in other words, for the revenues from the project to provide a return (IRR) that exactly matches the discount rate (r)*".

$$LCOE \times \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{9}$$

In our case of study, this formula can be expressed as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{10}$$

I_t = Investment expenditures in year t

M_t = Operations and maintenance expenditures in year t

F_t = fuel expenditures in year t (zero for photovoltaic electricity)

E_t = Electricity generation in the year t

r = discount rate

n = investment period (in years)

If we do not make any investment every year, but we make an initial investment, we can write the previous expression in the form:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{11}$$

I_0 = Initial investment expenditure

4 RESULTS

4.1 Studied locations

In this chapter, we will provide a list of the selected locations for each state of European Union, including typical parameters such as latitude, longitude, minimum and maximum average yearly temperature [18], as well as satellite pictures. [19]

The capital cities of each European Union country have been selected, with the exception of those countries which have less than 65000 km^2 of extent and choosing one country for those little such as Belgium, Luxembourg and Netherlands, Latvia, Lithuania and Estonia, Croatia and Slovenia, Denmark and Sweden, Slovakia and Hungary or Italy and Malta. Cyprus, because of being far for other EU countries, is also selected.

Fig. 23: EU Countries and chosen locations

Source: Google Earth

At the end, in the Annex 1, maps of the 20 chosen locations are available, including information about their geographic coordinates and minimum and maximum average temperatures. A summary of this information is also presented in the next table:

4.1.1 Summary table of locations

#	Location	Latitude	Longitude	Minimum Temperature	Maximum Temperature
1	Vienna	48° 6'54.06"N	16°32'32.36"E	-3°C	26°C
2	Brussels	50°53'29.46"N	4°30'10.84"E	1°C	23°C
3	Sofia	42°41'5.97"N	23°25'37.43"E	-5°C	29°C
4	Zagreb	45°44'32.08"N	16° 3'27.32"E	-3°C	28°C
5	Nicosia	35°11'39.06"N	33°22'49.16"E	6°C	33°C
6	Prague	50° 7'9.98"N	14°14'11.72"E	-4°C	24°C
7	Helsinki	60°19'21.22"N	24°56'22.68"E	-9°C	22°C
8	Paris	48°43'32.10"N	2°23'24.32"E	1°C	26°C
9	Berlin	52°33'40.60"N	13°17'21.33"E	-2°C	25°C
10	Athens	37°56'35.93"N	23°56'1.79"E	5°C	32°C
11	Budapest	47°27'9.59"N	19°16'42.08"E	-4°C	28°C
12	Dublin	53°25'50.98"N	6°17'0.88"W	3°C	19°C
13	Rome	41°51'54.57"N	12°15'22.79"E	4°C	29°C
14	Riga	56°56'18.85"N	23°59'15.64"E	-6°C	22°C
15	Warsaw	52°16'28.32"N	20°54'1.63"E	-5°C	24°C
16	Lisbon	38°45'48.21"N	9° 8'42.09"W	8°C	29°C
17	Bucharest	44°35'28.67"N	26° 6'35.72"E	-5°C	30°C
18	Madrid	40°31'13.25"N	3°35'1.06"W	1°C	33°C
19	Stockholm	59°20'12.74"N	18° 6'39.14"E	-6°C	22°C
20	London	51°29'32.35"N	0°28'16.80"W	2°C	23°C

Table 3: List of locations with coordinates and average yearly temperatures

4.2 Energy production

In this chapter we will present the PVGIS results of energy production for each location and each PV technology, giving the graphs of monthly energy output and average daily irradiance and tables with output parameters, having the yearly PV energy production as the most important parameter, with the input of installed peak PV power 1 kWp.

For each location, a graph with the PV technologies and their production will be also included.

In the Annex 2 we can consult the graphs and tables of yearly production of energy depending on the tracking technology and also a graph with the daily irradiance in both best and worst months of production for each location with a fixed PV system.

The results for Vienna are presented here below as an example:

Daily data

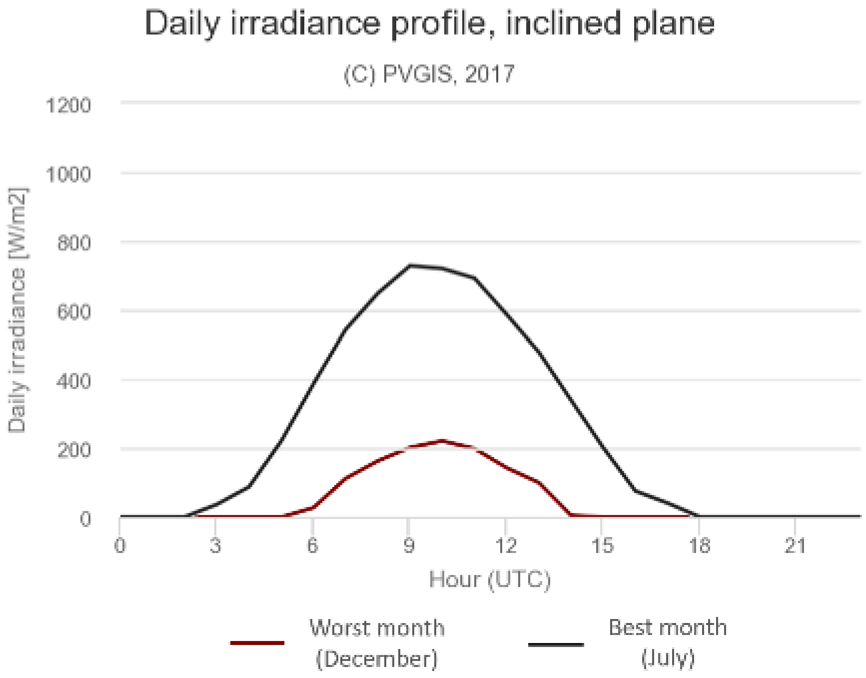


Fig. 24: Example of daily irradiance in both best and worst months - Vienna

This graph shows the irradiance in a typical day in both worst and best months in terms of irradiance (December and July). The fact that days are longer in July and shorter in December is clearly appreciable, having for this example around 16 hours of irradiance, while in January we have only around 10 hours.

In terms of irradiance, the differences are also remarkable, with a maximum daily irradiance around 750 W/m^2 in July, whereas the maximum in December is just around 250 W/m^2.

For the rest of the locations, this trend would be approximately the same, but the best and worst months could probably change.

Monthly data

Fixed plate

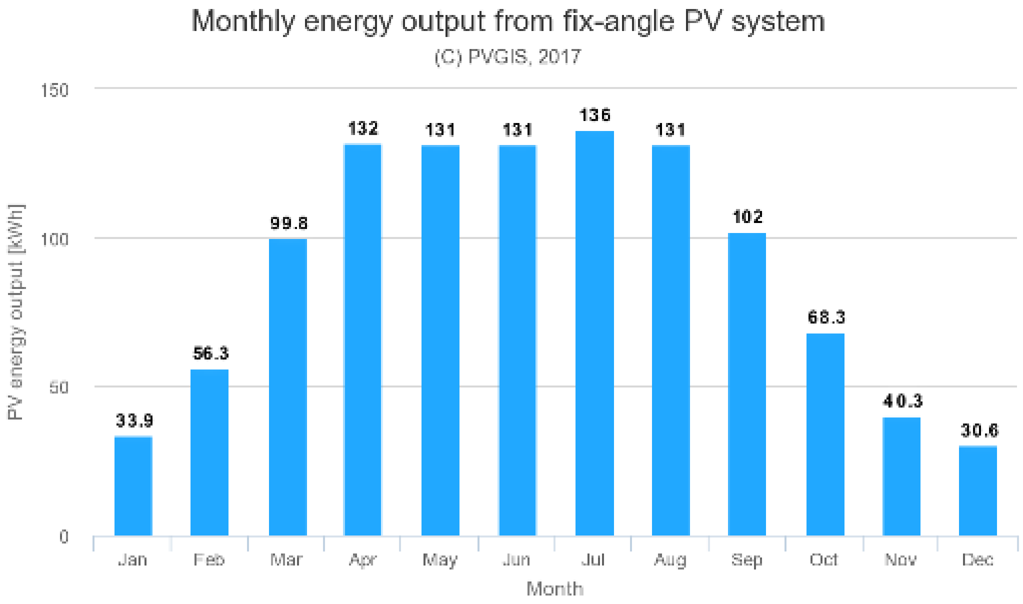


Fig. 25: Example of monthly energy output from fix-angle PV system - Vienna

In this figure, we can see the monthly energy production, which reaches the highest values between April and August, while in the rest of the year has a very low values, varying from the 136 kWh produced in July, to the 30.6 kWh produced in December (22.5% of July´s production).

This behaviour will probably be very similar for the rest the locations, as shown in Annex 2, with little variations. In some locations the differences in production between worst and best months can be reduced, as in the case of Spain, where the production in January is 51.21% of the production in July.

Output parameter	Value
Slope angle [°]	36 (opt)
Azimuth angle [°]	-4 (opt)
Yearly in-plane irradiation [kWh/m^2]	1370
Year to year variability [kWh]	47.70
Yearly PV energy production [kWh]	**1090**

Table 4: Example of output parameters from fix-angle PV system - Vienna

The table above shows the optimal angles, the yearly in-plane irradiation, the year to year variability and the most important variable for our study, the yearly PV energy production.

Tracking plates (Vertical axis, Inclined axis and Two-axis)

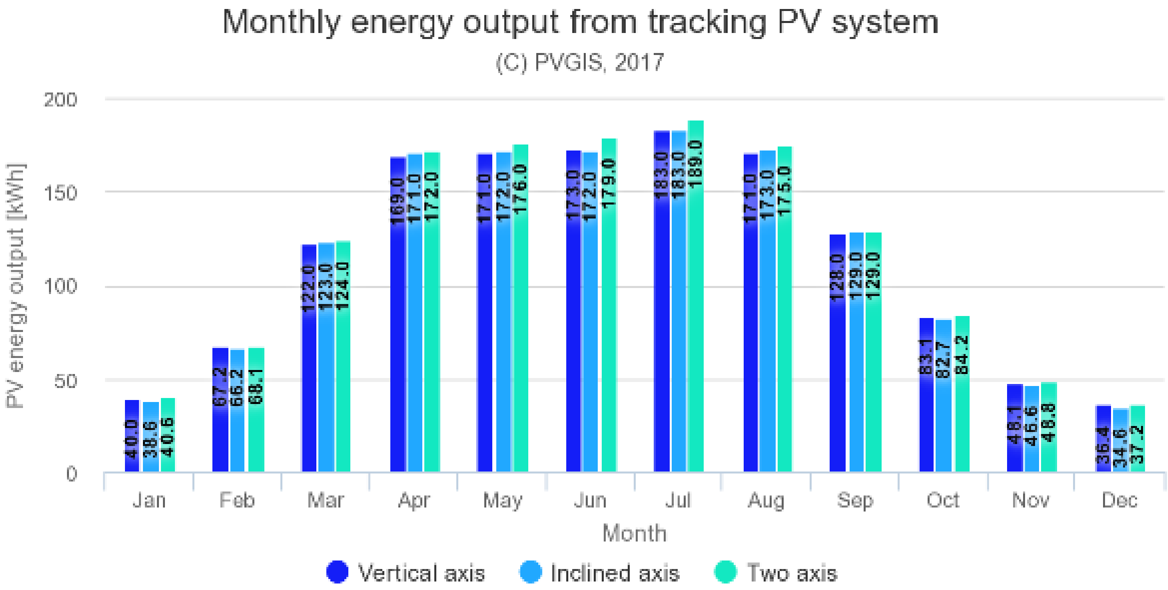


Fig. 26: Example of monthly energy output from tracking PV systems - Vienna

Similar to the Fig. 26, this graph shows the monthly energy production, but from tracking PV systems, Vertical axis, Inclined axis and Two-axis. We can clearly see that 1 axis bars (vertical and inclined) are very similar, while the two-axis bar is lightly higher, mainly in summer months.

Furthermore, here we have again big differences between summer and winter months, differences which could be less appreciable for other locations.

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	38 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1730	1730	1760
Year to year variability [kWh]	67.1	66.7	68.8
Yearly PV energy production [kWh]	**1390**	**1390**	**1420**

Table 5: Example of output parameters from tracking PV systems - Vienna

This table represents essentially the same as the previous table but considering the three tracking PV technologies.

PV technologies comparison

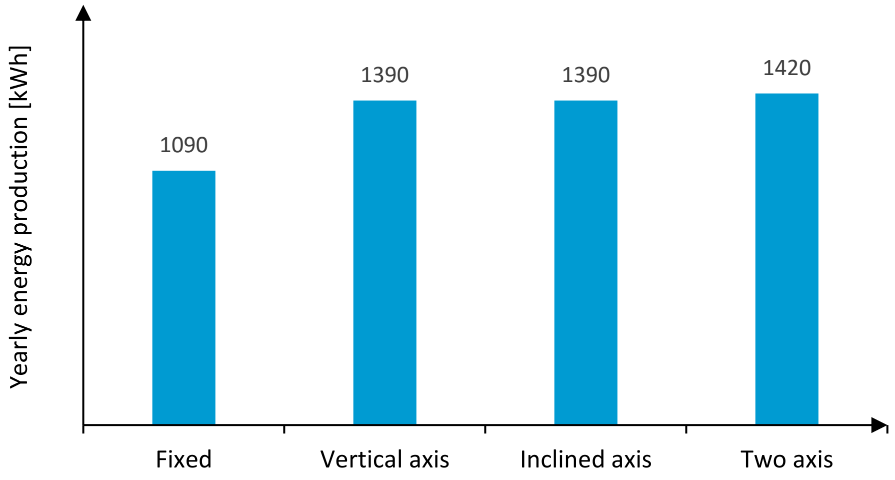


Fig. 27: PV technologies comparison - Vienna

The value of the energy production, considering that our installed peak power is 1 kWp, coincides with the Equivalent Hours (H_{eq}), defined as the measure of hours insolation in a year, expressed as:

$$H_{eq}[h] = \frac{E[kWh]}{P[kW]} \tag{12}$$

In the next page, we present a summary table with the energy production for each location and each PV technology. It is important to have these values together because, as we have mentioned, they also represent the Equivalent Hours, which will play an important role in the Sensitivity Analysis chapter.

We can observe big differences in terms of energy production between countries, from the highest values as 2450 kWh in Portugal, 2420 kWh in Cyprus, 2200 kWh in Greece and 2180 kWh in Spain to the lowest values as 1230 kWh in Ireland, 1240 kWh in Finland, 1270 kWh in Czech Republic and 1310 kWh in Sweden.

#	Country	H_{eq} Fixed [h]	H_{eq} Vertical axis [h]	H_{eq} Inclined axis [h]	H_{eq} Two-axis [h]
1	**Austria**	1090	1390	1390	1420
2	**Belgium**	1010	1290	1280	1320
3	**Bulgaria**	1310	1690	1700	1740
4	**Croatia**	1200	1550	1560	1590
5	**Cyprus**	1720	2330	2350	2420
6	**Czech Republic**	989	1240	1240	1270
7	**Finland**	912	1220	1210	1240
8	**France**	1110	1430	1430	1470
9	**Germany**	1020	1320	1320	1350
10	**Greece**	1600	2120	2130	2200
11	**Hungary**	1210	1560	1560	1600
12	**Ireland**	945	1200	1200	1230
13	**Italy**	1540	2040	2040	2100
14	**Latvia**	1010	1340	1330	1360
15	**Poland**	1040	1360	1360	1380
16	**Portugal**	1710	2360	2380	2450
17	**Romania**	1280	1660	1660	1700
18	**Spain**	1580	2110	2120	2180
19	**Sweden**	950	1280	1270	1310
20	**United Kingdom**	997	1280	1270	1310

Table 6: Summary table of Equivalent Hours (H_{eq})

4.3 Cost of Energy - LCOE

4.3.1 Investment and Operation Expenditures

As mentioned before, we are going to perform an analysis of cosr of the energy production in the twenty locations selected, for each PV technology.

For the calculations, we will consider the following investment (I_0) and operation or maintenance (M_t) costs. It is important to notice that the investment costs are not equal for each country, and we also can divide them in three important categories: Installation (I), Soft Costs (SC) and Hardware (H), basing on a study carried out by the IRENA. [20]

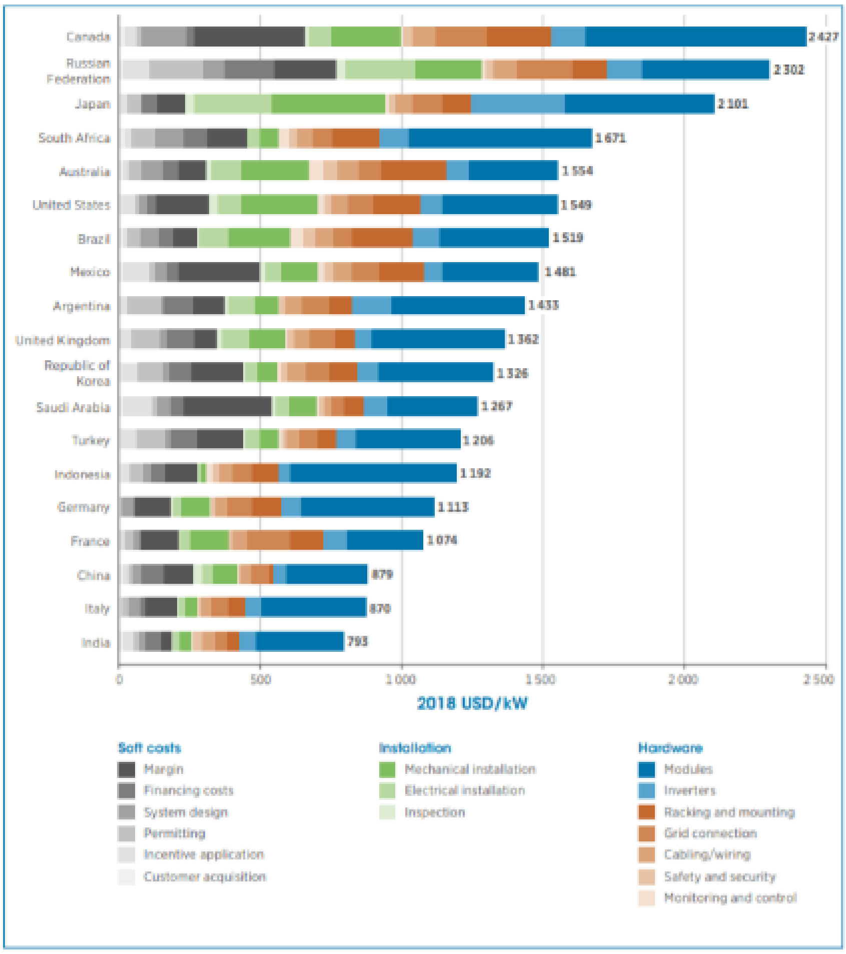


Fig. 28: Breakdown of utility-scale solar PV total installed costs in G20 countries, 2018

Source: IRENA

Installation costs are the expenditures related with the setup of the PV system, including mechanic and electrical as well. Soft costs include not only the cost of all relevant permits, but also all overhead costs including the marketing, sales and administrative costs associated with the system [21]. Hardware costs include all the materials needed to construct the system: module, inverter, racking and electrical wiring.

In accordance with the graph presented below, taken from the study carried out by the IRENA, and, we can consider that, in the European Union, hardware costs represent around a 50% (according to [22]) and can be regarded as a constant value for the same PV system (accepting that in the European Union exists an Common Market), while soft and installation costs can be combined and defined as dependent on wage ($\overline{w}$). Therefore, total investment costs can be expressed by the following equation:

$$I_0 = H + SC + I = H + R \cdot \phi \tag{13}$$

Where: H= hardware costs, R is not any variable, it is only a constant value that only have sense with the ϕ and its value is equal to H, ϕ is a variable defined as $\overline{\phi} = 1$ and expresses the dependence on the wage of each country. In this way, the country which its $\overline{w}$ is the average of all the wages will have a value of $\phi = 1$, the countries with a w below average of the European Union will have a value of $\phi < 1$ and countries with a w above average of EU will have a $\phi > 1$.

Having consulted the data of wages, we have adjusted the values of ϕ, presented in the following table.

Country	w[€]	ϕ
Bulgaria	7105	0.25
Romania	9312	0.33
Latvia	11881	0.42
Poland	12716	0.45
Croatia	12776	0.45
Hungary	12978	0.46
Czech Republic	14945	0.53
Portugal	18343	0.65
Greece	21214	0.75
Cyprus	23052	0.81
Spain	26923	0.95
Italy	31292	1.10
France	39436	1.39
Finland	43984	1.55
Sweden	44212	1.56
United Kingdom	44453	1.57
Ireland	46774	1.65
Austria	47120	1.66
Belgium	48455	1.71
Germany	50546	1.78
Average ($\overline{w}$)	**28375,85**	**1**

Table 7: Wages and ϕ

Source Wages <datosmacro.com>

In addition, we can consider the following hardware and maintenance costs values:

PV technology	H [€]	M_t [€]
Fixed plate	250 = F	1% I_0
Vertical axis	F + 10% F	2% I_0
Inclined axis	F + 10% F	2% I_0
Two-axis	F + 25% F	5% I_0

Table 8: Hardware and Maintenance costs for each PV technology

With the previous two tables and the defined formula of I_0, we can create a table with the investment and maintenance expenditures for each country and each PV technology. Then, with these values, we could calculate the cost of energy production in an easy way.

Country	PV technology	Investment costs			Maintenance costs
		H [€]	SC + I [€]	I0 [€]	Mt [€]
Austria	Fixed	250	415,00	665,00	6,65
	1 axis (V & I)	275	456,50	731,50	14,63
	2 axis	312,5	518,75	831,25	41,56
Belgium	Fixed	250	427,50	677,50	6,78
	1 axis (V & I)	275	470,25	745,25	14,91
	2 axis	312,5	534,38	846,88	42,34
Bulgaria	Fixed	250	62,50	312,50	3,13
	1 axis (V & I)	275	68,75	343,75	6,88
	2 axis	312,5	78,13	390,63	19,53
Croatia	Fixed	250	112,50	362,50	3,63
	1 axis (V & I)	275	123,75	398,75	7,98
	2 axis	312,5	140,63	453,13	22,66
Cyprus	Fixed	250	202,50	452,50	4,53
	1 axis (V & I)	275	222,75	497,75	9,96
	2 axis	312,5	253,13	565,63	28,28
Czech Republic	Fixed	250	132,50	382,50	3,83
	1 axis (V & I)	275	145,75	420,75	8,42
	2 axis	312,5	165,63	478,13	23,91
Finland	Fixed	250	387,50	637,50	6,38
	1 axis (V & I)	275	426,25	701,25	14,03
	2 axis	312,5	484,38	796,88	39,84

France	Fixed	250	347,50	597,50	5,98
	1 axis (V & I)	275	382,25	657,25	13,15
	2 axis	312,5	434,38	746,88	37,34
Germany	Fixed	250	445,00	695,00	6,95
	1 axis (V & I)	275	489,50	764,50	15,29
	2 axis	312,5	556,25	868,75	43,44
Greece	Fixed	250	187,50	437,50	4,38
	1 axis (V & I)	275	206,25	481,25	9,63
	2 axis	312,5	234,38	546,88	27,34
Hungary	Fixed	250	115,00	365,00	3,65
	1 axis (V & I)	275	126,50	401,50	8,03
	2 axis	312,5	143,75	456,25	22,81
Ireland	Fixed	250	412,50	662,50	6,63
	1 axis (V & I)	275	453,75	728,75	14,58
	2 axis	312,5	515,63	828,13	41,41
Italy	Fixed	250	275,00	525,00	5,25
	1 axis (V & I)	275	302,50	577,50	11,55
	2 axis	312,5	343,75	656,25	32,81
Latvia	Fixed	250	105,00	355,00	3,55
	1 axis (V & I)	275	115,50	390,50	7,81
	2 axis	312,5	131,25	443,75	22,19
Poland	Fixed	250	112,50	362,50	3,63
	1 axis (V & I)	275	123,75	398,75	7,98
	2 axis	312,5	140,63	453,13	22,66
Portugal	Fixed	250	162,50	412,50	4,13
	1 axis (V & I)	275	178,75	453,75	9,08
	2 axis	312,5	203,13	515,63	25,78

Romania	Fixed	250	82,50	332,50	3,33
	1 axis (V & I)	275	90,75	365,75	7,32
	2 axis	312,5	103,13	415,63	20,78
Spain	Fixed	250	237,50	487,50	4,88
	1 axis (V & I)	275	261,25	536,25	10,73
	2 axis	312,5	296,88	609,38	30,47
Sweden	Fixed	250	390,00	640,00	6,40
	1 axis (V & I)	275	429,00	704,00	14,08
	2 axis	312,5	487,50	800,00	40,00
United Kingdom	Fixed	250	392,50	642,50	6,43
	1 axis (V & I)	275	431,75	706,75	14,14
	2 axis	312,5	490,63	803,13	40,16

Table 9: Investment and maintenance cost for each country and PV system

This calculations have been carried out by Matlab, whose code can be consulted below.

4.3.2 LCOE calculations

In order to make our calculations by an easier way, we have created a Matlab script in order to calculate the LCOE for each of 20 locations and the 4 PV technologies. For it, we have taken the data of electricity production and investment and maintenance expenditures from the previous chapter, creating the matrixes E_t , I_0 and M_t. The Matlab code is the attached:

```
%%%LCOE calculation for each of the 20 locations and the 4 PV
technologies
clc, clear all

phi=[1.66 1.71 0.25 0.45 0.81 0.53 1.55 1.39 1.78 0.75 0.46 1.65 1.10
0.42 0.45 0.65 0.33 0.95 1.56 1.57];
F=250*[1 1.1 1.1 1.25];
H=repmat(F,20,1);
Rphi=phi'*F;
I_0=H+Rphi;
b=[0.01 0.02 0.02 0.05];
B=repmat(b,20,1);
M_t=I_0.*B;

E_t=[1090 1390 1390 1420;
    1010 1290 1280 1320;
    1310 1690 1700 1740;
```

```
    1200 1550 1560 1590;
    1720 2330 2350 2420;
    989 1240 1240 1270;
    912 1220 1210 1240;
    1110 1430 1430 1470;
    1020 1320 1320 1350;
    1600 2120 2130 2200;
    1210 1560 1560 1600;
    945 1200 1200 1230;
    1540 2040 2040 2100;
    1010 1340 1330 1360;
    1040 1360 1360 1380;
    1710 2360 2380 2450;
    1280 1660 1660 1700;
    1580 2110 2120 2180;
    950 1280 1270 1310;
    997 1280 1270 1310]; %Matrix of electricity production rows: cities, columns: PV technology

r=6.5/100; %Discount rate
n=25; %Lifetime

for i=1:20
    for j=1:4
        for t=1:n
            A(t)=M_t(i,j)/((1+r)^t);
            den(t)=(E_t(i,j))/((1+r)^t);
        end

        numerador(i,j)=I_0(i,j) + sum(A);
        denominador(i,j)=sum(den);
        cost(i,j)=numerador(i,j)/denominador(i,j);
    end
end
cost=cost*1000 %We will express LCOE in €/MWh
```

Obtaining the following matrix as a result:

```
cost =


   56.1171   53.6687   53.6687   77.3219
   61.7054   58.9199   59.3802   84.6731
   21.9460   20.7462   20.6242   29.6290
   27.7902   26.2388   26.0706   37.6153
   24.2015   21.7881   21.6027   30.8476
   35.5793   34.6078   34.6078   49.6912
   64.3017   58.6226   59.1070   84.8140
   49.5171   46.8758   46.8758   67.0546
   62.6737   59.0643   59.0643   84.9344
```

```
25.1543   23.1526   23.0439   32.8064
27.7465   26.2472   26.2472   37.6338
64.4897   61.9367   61.9367   88.8629
31.3573   28.8698   28.8698   41.2430
32.3301   29.7192   29.9427   43.0656
32.0657   29.9045   29.9045   43.3393
22.1914   19.6098   19.4450   27.7764
23.8975   22.4727   22.4727   32.2670
28.3835   25.9206   25.7984   36.8935
61.9665   56.0898   56.5315   80.5994
59.2809   56.3128   56.7562   80.9174
```

#	Country	Fixed [€/MWh]	Vertical axis [€/MWh] (#/fixed %)	Inclined axis [€/MWh] (#/fixed %)	Two-axis [€/MWh] (#/fixed %)
1	**Austria**	56.12	53.67 (95.63)	53.67 (95.63)	77.32 (137.78)
2	**Belgium**	61.71	58.92 (95.48)	59.38 (96.22)	84.67 (137.21)
3	**Bulgaria**	21.95	20.75 (94.53)	20.62 (93.94)	29.63 (134.99)
4	**Croatia**	27.80	26.24 (94.39)	26.07 (93.78)	37.62 (135.42)
5	**Cyprus**	24.20	21.79 (90.04)	21.60 (89.26)	30.85 (127.48)
6	**Czech Republic**	35.58	34.61 (97.27)	34.61 (97.27)	49.69 (139.66)
7	**Finland**	64.30	58.63 (91.18)	59.11 (91.93)	84.81 (131.90)
8	**France**	49.52	46.88 (94.67)	46.88 (94.67)	67.05 (135.40)
9	**Germany**	62.67	59.06 (94.24)	59.06 (94.24)	84.93 (135.52)
10	**Greece**	25.15	23.15 (92.05)	23.04 (91.61)	32.81 (130.45)
11	**Hungary**	27.75	26.25 (94.60)	26.25 (94.60)	37.64 (135.64)
12	**Ireland**	64.49	61.94 (96.05)	61.94 (96.05)	88.86 (137.79)
13	**Italy**	31.36	28.87 (92.06)	28.87 (92.06)	41.24 (131.51)
14	**Latvia**	32.33	29.72 (91.93)	29.94 (92.61)	43.07 (133.22)
15	**Poland**	32.07	29.90 (93.23)	29.90 (93.23)	43.34 (135.14)
16	**Portugal**	22.19	19.61 (88.37)	19.45 (87.65)	27.78 (125.19)
17	**Romania**	23.90	22.47 (94.02)	22.47 (94.02)	32.27 (135.02)
18	**Spain**	28.38	25.92 (91.33)	25.80 (90.91)	36.89 (129.99)
19	**Sweden**	61.97	56.09 (90.51)	56.53 (91.22)	80.60 (130.06)
20	**United Kingdom**	59.28	56.31 (94.99)	56.76 (95.75)	80.92 (136.50)

Table 10: LCOE results depending on location and PV technology

In the previous table, we can see not only the LCOE, but also a comparison between LCOE of all tracking technologies against the LCOE of fixed plates:

$$\#/fixed\,\% = \frac{LCOE(Tracking)}{LCOE(Fixed)} \cdot 100 \tag{14}$$

Furthermore, for each location, the best option in terms of cost have been highlighted in green, while the worst option has been highlighted in red. We can see that, for the given investment and maintenance costs, the best option in the majority of the cases is the Inclined axis tracking system, which combines a good sun tracking and a simple and, therefore, a cheap technology in terms of investment and maintenance. In addition to this, the worst option is always the Two-axis tracking system, probably due to the high values of Investment (I_0) and Maintenance (M_t) costs, which signify an important weight to drive up the LCOE of this system, without being compensated the fact of being the technology which produces a greater amount of PV energy.

However, in the next section, we will perform a sensitivity analysis, changing some parameters which affect the results of LCOE, such as I_0 or M_t.

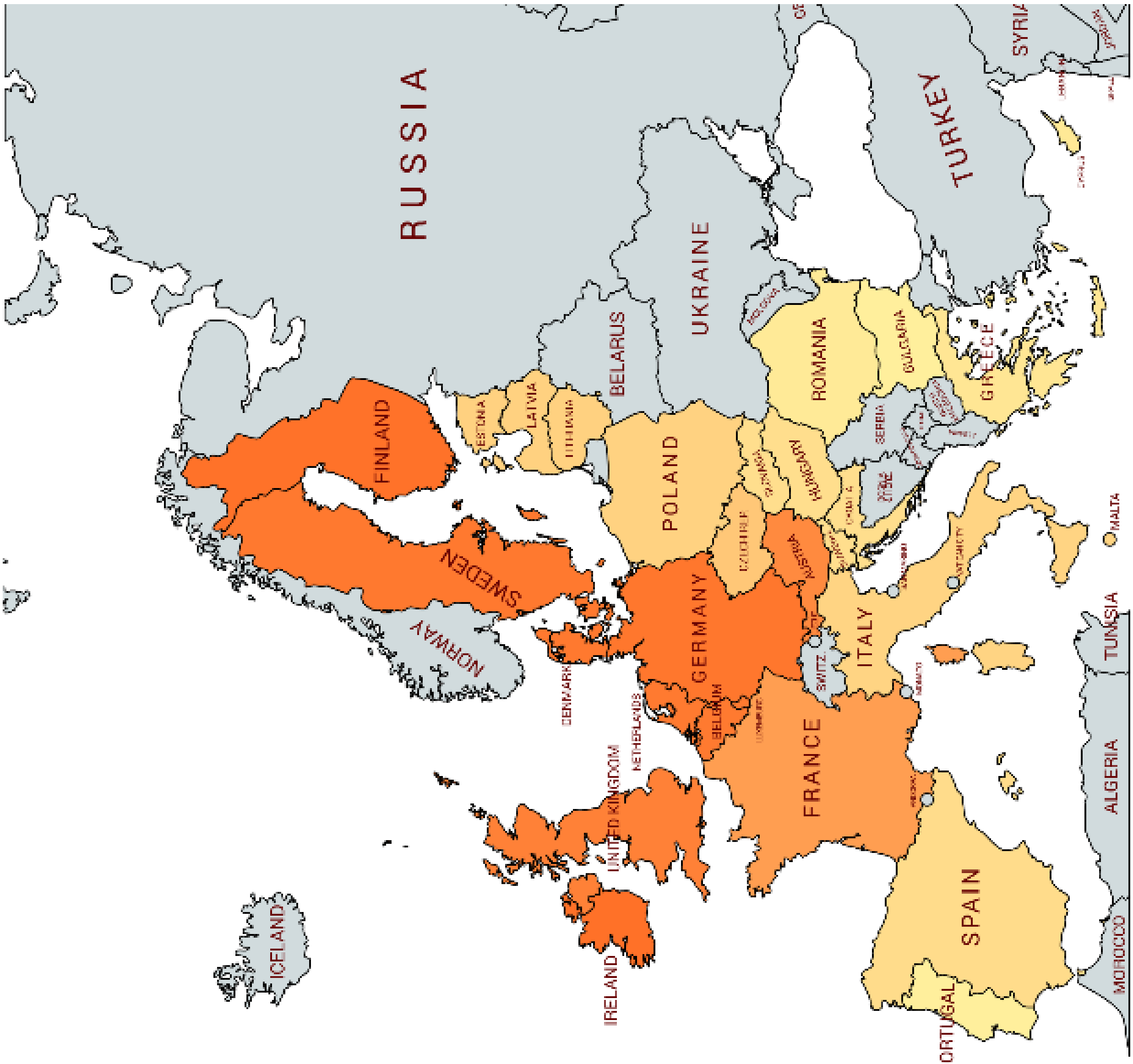
Now, five maps of EU will be created, one for each type of PV tracking system and finally one with the values of optimum LCOE.

4.3.3 LCOE results from fixed plates

In order to create the map, the LCOE column has been sorted from highest to lowest and a conditional scale format has been assigned from darkest to lightest.

Ireland	64.49
Finland	64.30
Germany	62.67
Sweden	61.97
Belgium	61.71
United Kingdom	59.28
Austria	56.12
France	49.52
Czech Republic	35.58
Latvia	32.33
Poland	32.07
Italy	31.36
Spain	28.38
Croatia	27.80
Hungary	27.75
Greece	25.15
Cyprus	24.20
Romania	23.90
Portugal	22.19
Bulgaria	21.95

Table 11: Colour scale for LCOE from fixed plates



Created with mapchart.net©

Fig. 29: EU map of LCOE from fixed plates

If we take a look on the map, we could clearly identify that, for fixed plates, the higher the latitude of the country, the more expensive the production of electricity is. The wages have also influenced strongly, making that Bulgaria, the country with the lowest wage, has the lowest value of LCOE; Germany, with the highest wage, is the country with the third of the highest values of LCOE, despite having good values of energy production. We can observe that the cheapest countries are Bulgaria, Portugal, Romania, Cyprus and Greece, while the more expensive are Sweden, Germany, Finland and Ireland.

This big difference in terms of LCOE between Ireland, the more expensive country (64.49 €/MWh) and Bulgaria, the cheapest (21.95 €/MWh) is not only caused by the difference in solar irradiation, which is 1150 kWh/m^2 for Ireland and 1660 kWh/m^2 for Bulgaria and consequently the yearly PV energy production of 945 kWh in Ireland, while in Bulgaria is 1310 kWh, but also the wages play an important role (46774 € for Ireland and 7105 € for Bulgaria).

However, despite having the lowest investment and maintenance expenditures, the LCOE for fixed plates is not the optimum for any country, because the solar tracking systems produces such a great amount of energy to counteract their higher investment and maintenance expenditures.

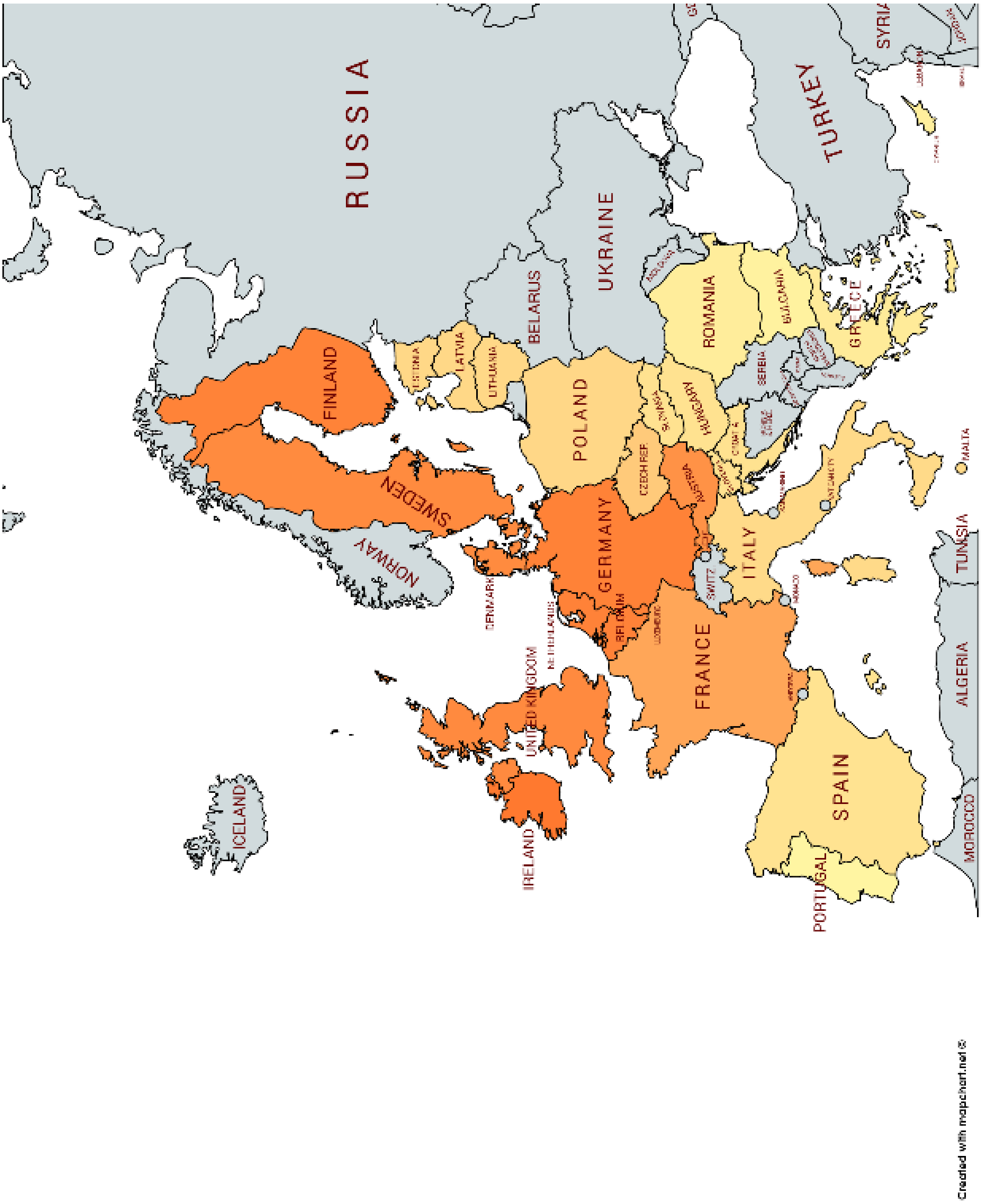
4.3.4 LCOE results from vertical axis tracking systems

For the creation of the map we have taken a similar way to the previous one but maintaining the colour scale of the values from the previous section in order to make, at the end, a map with the scaled colours of the optimum values of LCOE for each location.

Ireland	61.94
Germany	59.06
Belgium	58.92
Finland	58.63
United Kingdom	56.31
Sweden	56.09
Austria	53.67
France	46.88
Czech Republic	34.61
Poland	29.90

Latvia	29.72
Italy	28.87
Hungary	26.25
Croatia	26.24
Spain	25.92
Greece	23.15
Romania	22.47
Cyprus	21.79
Bulgaria	20.75
Portugal	19.61

Table 12: Colour scale for LCOE from vertical axis tracking systems



Created with mapchart.net ©

Fig. 30: EU map of LCOE from vertical axis tracking systems

This map of LCOE results from vertical axis tracking systems shows some interesting differences with the previous map from fixed plates. We have to remark that Belgium has become the third country with highest value of LCOE, mainly caused by the high wage, expressed as high values of investment and maintenance expenditures, combined with a not so high energy production.

Another important fact can be appreciated in the bottom of the table, with the case of Portugal, which was the second cheapest country in terms of LCOE for fixed systems, which is the cheapest country for vertical axis tracking systems, this is because the energy production is very good for this technology.

Even so, we can see that in this map the colours are lighter than in the other one, this is because the vertical axis tracking systems permit a better performance in terms of energy production and its relationship with investment and maintenance expenditures.

The mentioned difference between vertical axis tracking systems and fixed plates is clearly evidenced with the LCOE values in Portugal: 22.19 €/MWh for fixed plates vs 19.61 €/MWh for vertical axis.

4.3.5 LCOE results from inclined axis tracking systems

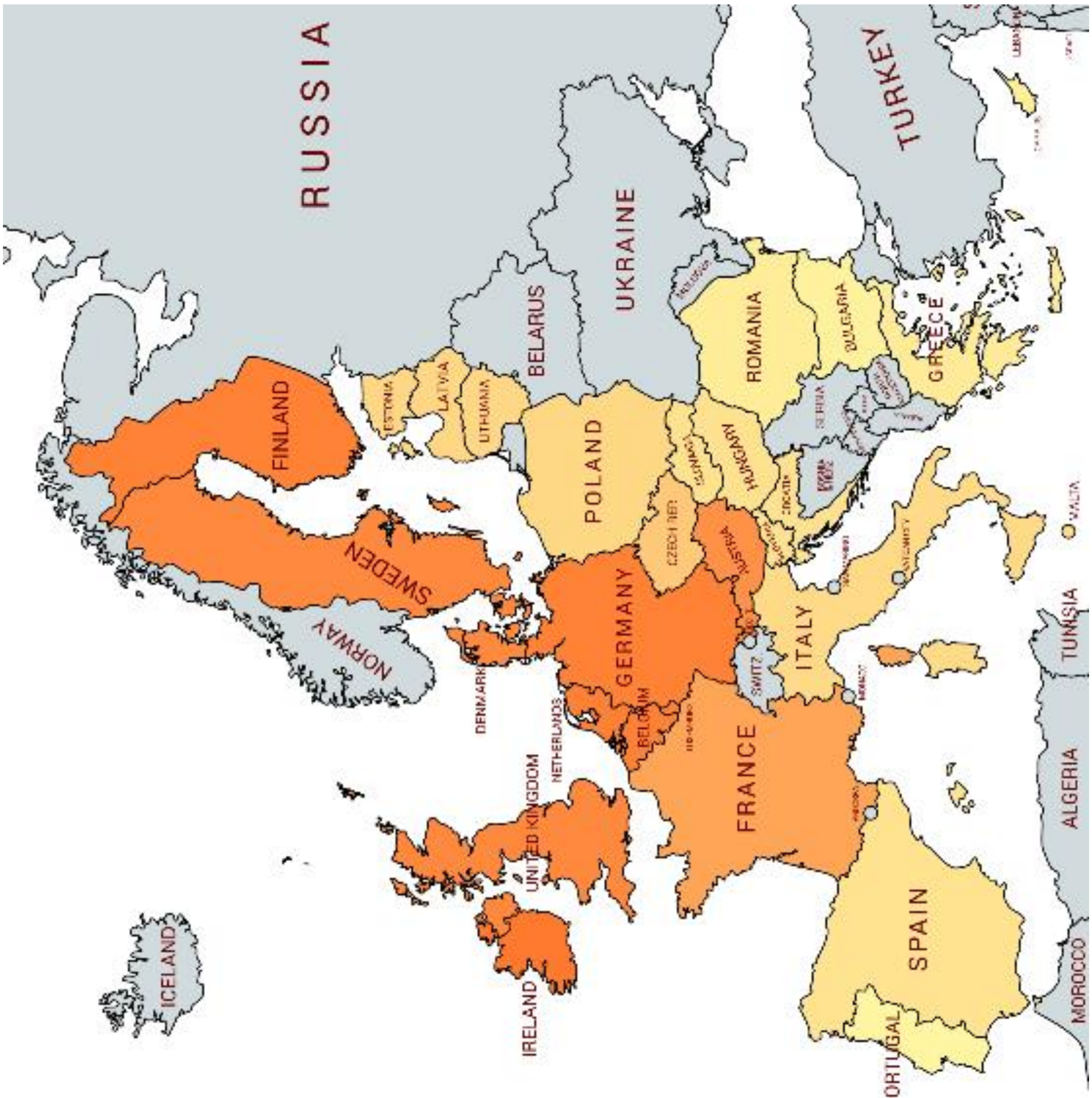
Maintaining the same colour scale, we have repeated the previous process for the creation of the map with LCOE results from inclined axis tracking systems.

We will see that values are very similar to the obtained from vertical axis tracking systems or, in some cases, the LCOE is slightly reduced.

Ireland	61.94
Belgium	59.38
Finland	59.11
Germany	59.06
United Kingdom	56.76
Sweden	56.53
Austria	53.67
France	46.88
Czech Republic	34.61
Latvia	29.94

Poland	29.90
Italy	28.87
Hungary	26.25
Croatia	26.07
Spain	25.80
Greece	23.04
Romania	22.47
Cyprus	21.60
Bulgaria	20.62
Portugal	19.45

Table 13: Colour scale for LCOE from inclined axis tracking systems



Created with mapchart.net ©

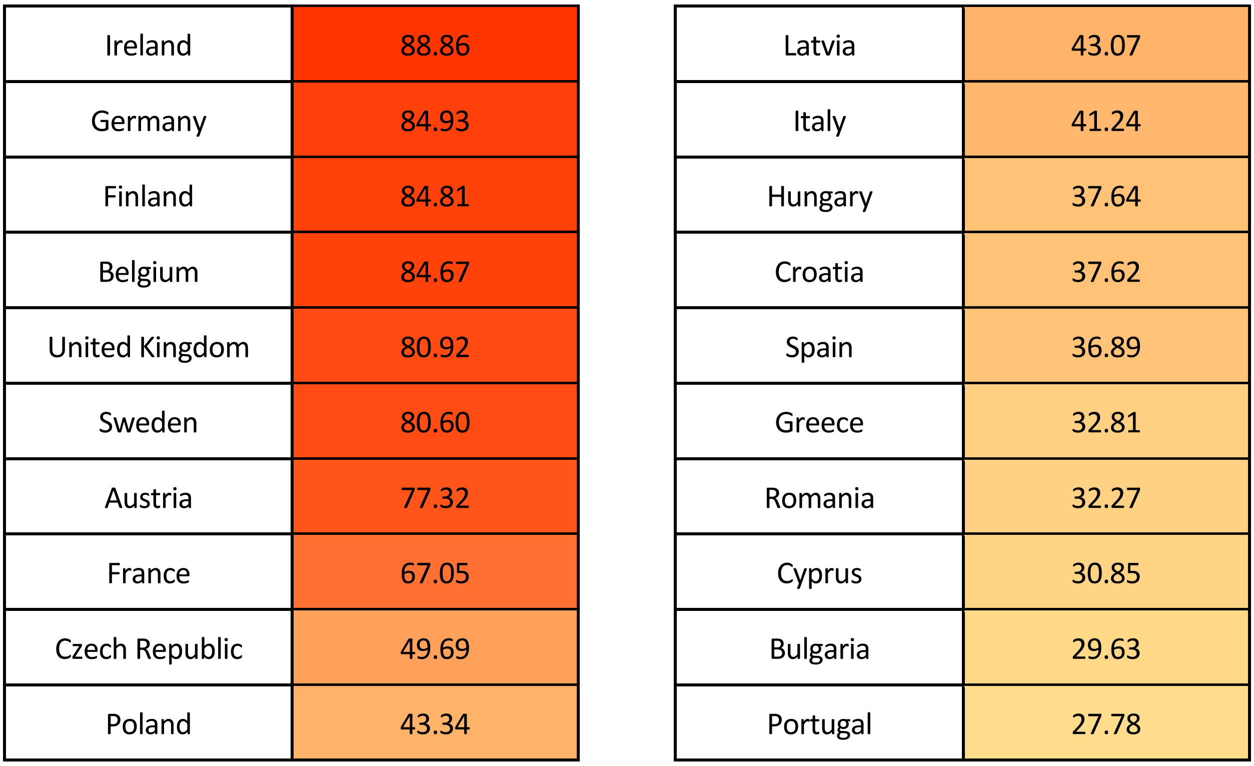
Fig. 31: EU map of LCOE from inclined axis tracking systems

As mentioned before, this map shown is very similar to the previous other, with very little differences. Even so, we can appreciate that Belgium is now the second most expensive country, above Germany (this did not happen for vertical axis tracking systems); not only due to its high wage, but also caused by the fact that the inclined axis tracking system yearly energy production is less than the one produced by the vertical axis tracking system.

The values of LCOE are exactly the same for many countries: Ireland (61.94 €/MWh), France (46.88 €/MWh), Hungary (26.25€/kWh), etc. Furthermore, in many cases, these coincident values of LCOE are the optimum, while for the rest of the locations. the optimal values are distributed among vertical and inclined axis systems.

4.3.6 LCOE results from two-axis tracking systems

In this section we will see the results of LCOE calculations from the more expensive system in terms of investment and maintenance expenditures, the two-axis tracking system, which is also the technology which produces a larger amount of yearly energy.



Ireland	88.86
Germany	84.93
Finland	84.81
Belgium	84.67
United Kingdom	80.92
Sweden	80.60
Austria	77.32
France	67.05
Czech Republic	49.69
Poland	43.34

Latvia	43.07
Italy	41.24
Hungary	37.64
Croatia	37.62
Spain	36.89
Greece	32.81
Romania	32.27
Cyprus	30.85
Bulgaria	29.63
Portugal	27.78

Table 14: Colour scale for LCOE from two-axis tracking systems

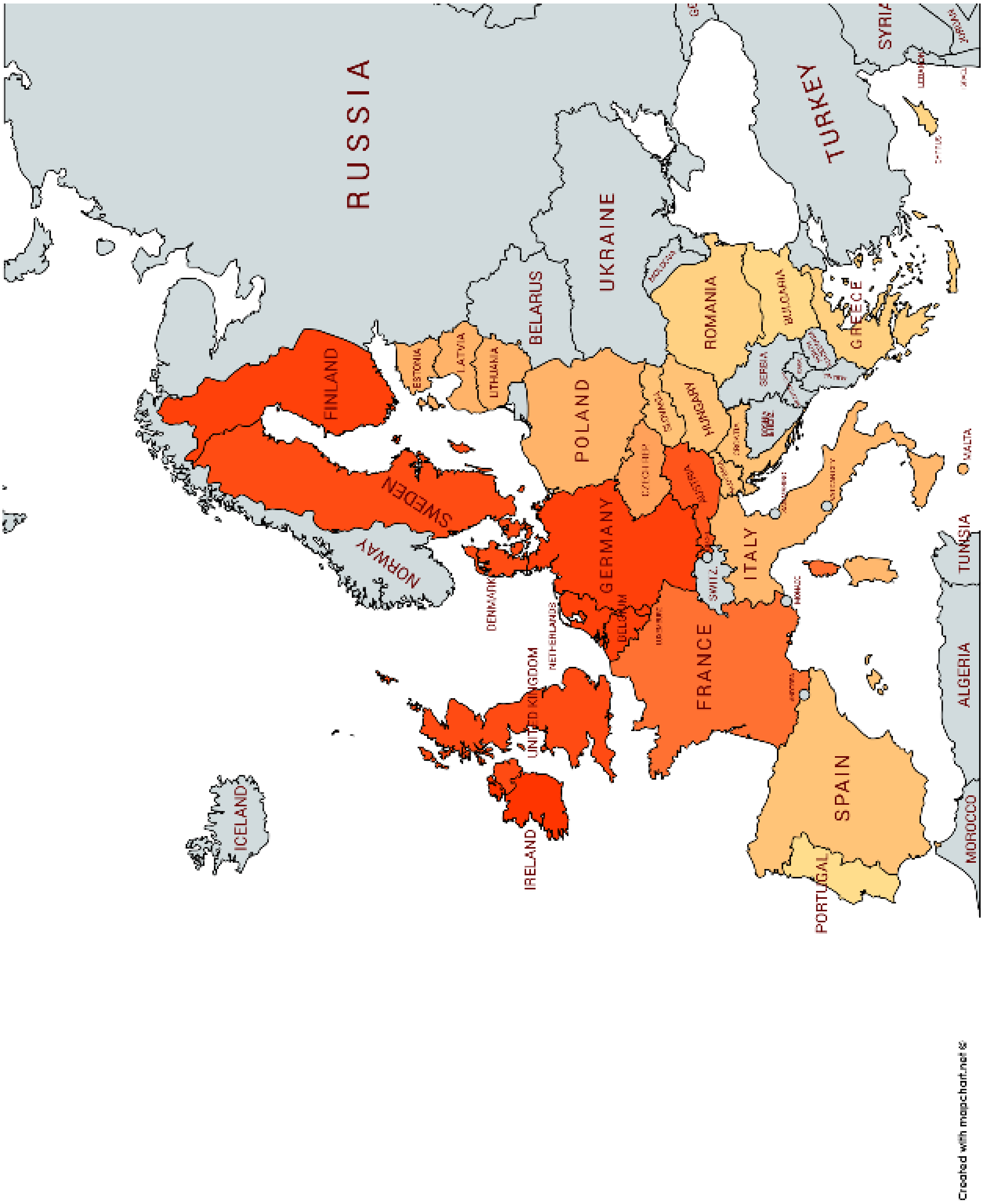


Fig. 32: EU map of LCOE from two-axis tracking systems

Looking at the map. the first thing we appreciate is that its colours are much darker than the ones on previous maps, because the LCOE from two-axis tracking systems is much higher than the LCOE from previous technologies. Despite being the system that produces the larger amount of yearly production of energy, two-axis tracking is the less advisable in terms of LCOE, due to its high investment and maintenance expenditures. We observe big difference in terms of cost, as shown in the Table 10 in the last column, in which LCOE from two-axis systems is around 30% higher than the LCOE from fixed plates.

It is also appreciable that two-axis tracking systems are less advisable for countries with high latitudes, for example, for Finland: LCOE for inclined axis tracking system is 59.11 €/MWh, and 84.81 €/MWh for two-axis system, making a difference of 25.7 €/MWh. However, for Portugal: LCOE from inclined axis plates is 19.45 €/MWh and 27.78 €/MWh from two-axis plates, making a difference of 8.33 €/MWh, the third part of the difference in Finland, what means that in the southern countries, the sun tracking from two-axis systems is much more advisable than in the northern countries. Even so, the wages affect greatly, causing that countries as Latvia, Estonia and Lithuania, whose wage is not so high

Even so, in the next chapter, we will perform a sensivity analysis, in which we could observe that, if we reduce the investment and maintenance expenditures, two-axis would become more profitable.

4.3.7 Optimal values of LCOE

In this section, we take the optimal values calculated previously the highlighted in green in Table 10, considering all the technologies, sorting them with the same colour scale and creating a optimums map.

Ireland	61.94	Latvia	29.72
Germany	59.06	Italy	28.87
Belgium	58.92	Hungary	26.25
Finland	58.63	Croatia	26.07
United Kingdom	56.31	Spain	25.80
Sweden	56.09	Greece	23.04
Austria	53.67	Romania	22.47
France	46.88	Cyprus	21.60
Czech Republic	34.61	Bulgaria	20.62
Poland	29.90	Portugal	19.45

Table 15: Colour scale for optimal values of LCOE

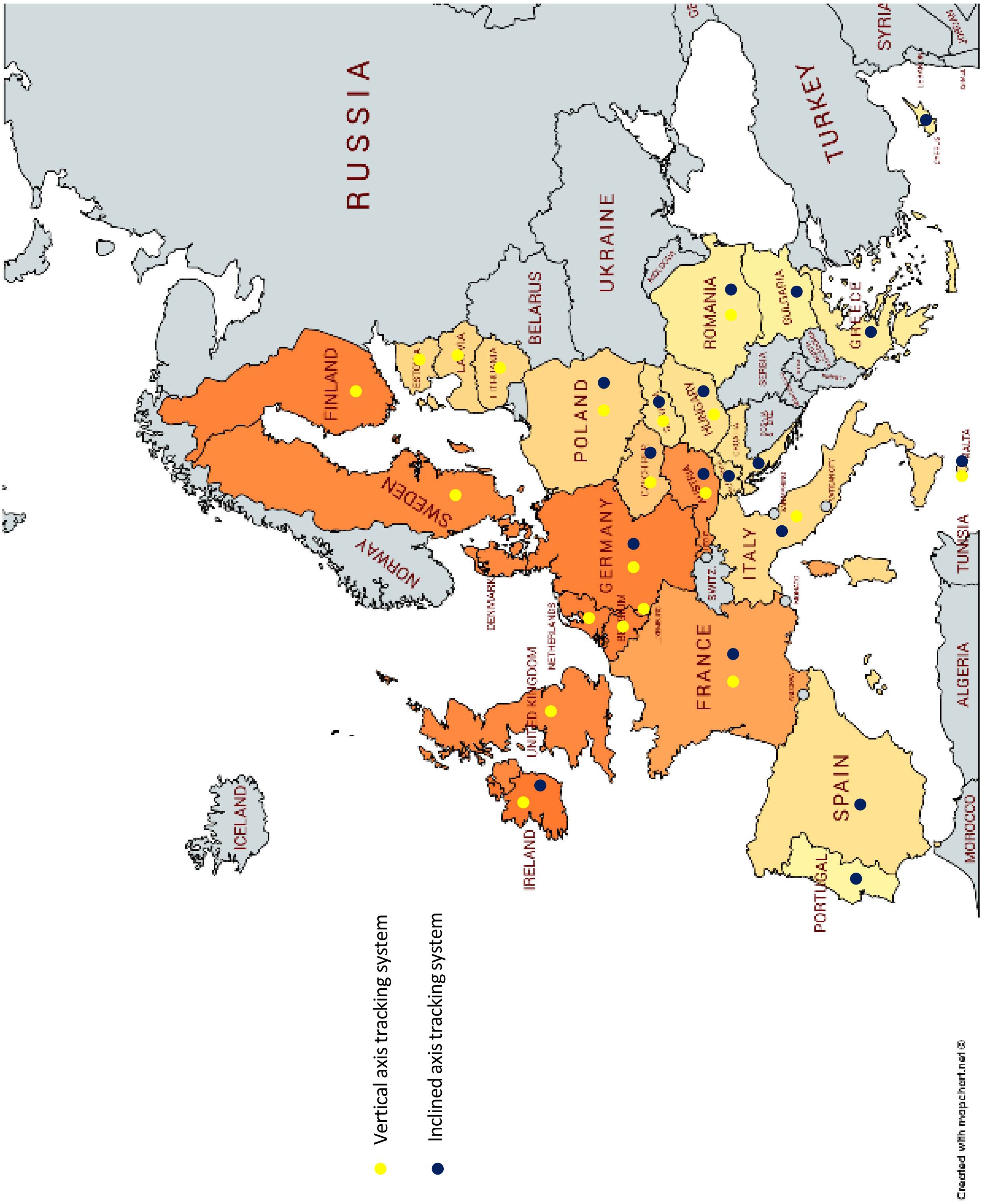


Fig. 33: EU map of optimal values of LCOE for each country

As we said previously, the optimal values of LCOE are almost equally distributed among vertical and inclined axis tracking systems. Therefore, the map presented in Fig. 32 is very similar to the maps in Fig. 29 and Fig. 30, with values from 19.45 €/MWh in Portugal to 61.94 €/MWh in Ireland.

The general trend is that LCOE is lower in southern countries such as Portugal, Spain, Italy, Greece and Cyprus, while it is higher in northern countries: Ireland, Sweden, Denmark and Finland. The wages also affect greatly, making that those countries with lower wages have lower values of LCOE.

It is important to remember that all the calculations, for each country, have been made in the capital, therefore, if we had chosen Seville for Spain instead of Madrid and Oporto for Portugal instead of Lisbon, LCOE results may probably have changed resulting LCOE higher in Portugal than in Spain.

Another reminder is that the calculations have not been carried out in all countries of EU due to the reduced extension, having taken the calculations in a neighbour country. These countries do not appear in the tables but do appear in the maps (Belgium also includes Netherlands and Luxembourg; Sweden includes Denmark; Latvia includes Lithuania and Estonia; Croatia includes Slovenia; Hungary includes Slovakia and Italy includes Malta).

Considering our results, we have to aclare that if we change some parameters such as investment and maintenance cost, LCOE could vary enormously, as we will see in the sensitivity analysis in the next chapter.

4.4 Sensitivity analysis

As we had commented in previous chapters, the results of our calculations depend strongly on parameters such as yearly PV energy production, investment and maintenance expenditures, interest rate. However, among these parameters, there are some that are given as a constant, such as the energy production, or have the same value for each PV technology, such as the interest rate.

Therefore, in our sensitivity analysis, which is essentially an approximation to how would our results change if we vary the input parameters, we will evaluate the variation of LCOE when we modify the wages of the countries (which affect both investment and maintenance costs) and also the energy production.

We will carry out our analysis for fixed PV system; for the other technologies, the study would be the same, but we only need to perform it with one technology to extract a trend.

4.4.1 Variation with wage (w)

The aim of this subsection is to evaluate the relationship among wages of the countries and their values of LCOE and creating an elasticity of LCOE against wage.

The LCOE elasticity against wage is defined as:

$$\epsilon_{LCOE-w} = \frac{\frac{dLCOE}{LCOE}}{\frac{dw}{w}} = \frac{\Delta\%LCOE}{\Delta\%w} \qquad (15)$$

We will increase the *w* a 10%, which is also a 10% of increase in ϕ

Country	$w[€]$	$w \times 1.1[€]$	ϕ
Bulgaria	7105	7816	0.275
Romania	9312	10243	0.363
Latvia	11881	13069	0.462
Poland	12716	13988	0.495
Croatia	12776	14054	0.495
Hungary	12978	14276	0.506
Czech Republic	14945	16440	0.583
Portugal	18343	20177	0.715
Greece	21214	23335	0.825
Cyprus	23052	25357	0.891
Spain	26923	29615	1.045
Italy	31292	34421	1.210
France	39436	43380	1.529
Finland	43984	48382	1.705
Sweden	44212	48633	1.716
United Kingdom	44453	48898	1.727
Ireland	46774	51451	1.815
Austria	47120	51832	1.826
Belgium	48455	53301	1.881
Germany	50546	55601	1.958

Table 16: Wages and ϕ - Sensitivity Analysis

#	Country	$LCOE(w)$ [€]	$LCOE$ $(w \times 1.10)$ [€]	ϵ_{LCOE-w}
1	**Austria**	56.12	59.62	0.6241
2	**Belgium**	61.71	65.59	0.6310
3	**Bulgaria**	21.95	22.38	0.2000
4	**Croatia**	27.80	28.65	0.3103
5	**Cyprus**	24.20	25.28	0.4475
6	**Czech Republic**	35.58	36.81	0.3464
7	**Finland**	64.30	68.20	0.6078
8	**France**	49.52	52.39	0.5816
9	**Germany**	62.67	66.69	0.6403
10	**Greece**	25.15	26.23	0.4286
11	**Hungary**	27.75	28.62	0.3151
12	**Ireland**	64.49	68.50	0.6226
13	**Italy**	31.36	33.00	0.5238
14	**Latvia**	32.33	33.29	0.2958
15	**Poland**	32.07	33.06	0.3103
16	**Portugal**	22.19	23.06	0.3939
17	**Romania**	23.90	24.49	0.2481
18	**Spain**	28.38	29.76	0.4872
19	**Sweden**	61.97	65.74	0.6094
20	**United Kingdom**	59.28	62.90	0.6109

Table 17: LCOE and elasticity for wage - Sensitivity Analysis

We can see a big disparity between elasticities, with values from 0.2000 in the case of Bulgaria, to 0.6409 in the case of Germany; but all cities share the fact that their elasticity is between 0 and 1, which means that for all countries, the increase of LCOE is lower than the increase of wage (w). A growth in the wage produces a growth in the LCOE, but it is very slight.

4.4.2 Variation with equivalent hours (H_{eq})

The equivalent hours, commented in previous chapters, and coincide in value with the yearly energy production (Eq. 12), considering that our installed peak power is 1 kW.

The aim of this subsection is to evaluate how does the LCOE change when we change the equivalent hours and creating an elasticity of LCOE against H_{eq}.

The LCOE against elasticity is defined as:

$$\epsilon_{LCOE-H_{eq}} = \frac{\frac{dLCOE}{LCOE}}{\frac{dH_{eq}}{H_{eq}}} = \frac{\Delta\%LCOE}{\Delta\%Heq} \qquad (16)$$

We will increase the Heq a 10%

#	Country	H_{eq} [h]	$H_{eq} \times 1.1$ [h]
1	**Austria**	1090	1199
2	**Belgium**	1010	1111
3	**Bulgaria**	1310	1441
4	**Croatia**	1200	1320
5	**Cyprus**	1720	1892
6	**Czech Republic**	989	1088
7	**Finland**	912	1003
8	**France**	1110	1221
9	**Germany**	1020	1122
10	**Greece**	1600	1760
11	**Hungary**	1210	1331
12	**Ireland**	945	1039
13	**Italy**	1540	1694
14	**Latvia**	1010	1111
15	**Poland**	1040	1144
16	**Portugal**	1710	1881
17	**Romania**	1280	1408
18	**Spain**	1580	1738
19	**Sweden**	950	1045
20	**United Kingdom**	997	1097

Table 18: H_{eq} - Sensitivity Analysis

#	Country	$LCOE(H_{eq})$ [€]	$LCOE$ $(\mathrm{H_{eq}} \times 1.10)$ [€]	$\epsilon_{LCOE-Heq}$
1	**Austria**	56.12	51.02	-0.9090
2	**Belgium**	61.71	56.09	-0.9107
3	**Bulgaria**	21.95	19.95	-0.9112
4	**Croatia**	27.80	25.26	-0.9137
5	**Cyprus**	24.20	22.00	-0.9091
6	**Czech Republic**	35.58	32.34	-0.9106
7	**Finland**	64.30	58.45	-0.9098
8	**France**	49.52	45.01	-0.9107
9	**Germany**	62.67	56.98	-0.9079
10	**Greece**	25.15	22.86	-0.9105
11	**Hungary**	27.75	25.22	-0.9117
12	**Ireland**	64.49	58.62	-0.9102
13	**Italy**	31.36	28.51	-0.9088
14	**Latvia**	32.33	29.39	-0.9094
15	**Poland**	32.07	29.14	-0.9136
16	**Portugal**	22.19	20.17	-0.9103
17	**Romania**	23.90	21.72	-0.9121
18	**Spain**	28.38	25.80	-0.9117
19	**Sweden**	61.97	56.33	-0.9101
20	**United Kingdom**	59.28	53.89	-0.9092

Table 19: LCOE and elasticity for H_{eq} - Sensitivity Analysis

The results of elasticity are all similar (around 0.91), but this is not surprising, because if we take the LCOE formula (Eq. 11):

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{17}$$

The numerator remains constant and E_t is the same for every year, because it is the average yearly production and can be extracted from the summatory. The term $(1+r)^t$ remains also constant, therefore, LCOE formula can be expressed as:

$$LCOE(E_t) = \frac{C}{E_t} \tag{18}$$

Where C is a constant value.

If we increase E_t (which coincides in value with H_{eq}, not in units) a 10%.

$$\left(\frac{1}{1.1} = 0.9091\right) \rightarrow; H_{eq} \uparrow 10\%;\ LCOE \downarrow 0.9091$$

Therefore, the variable LCOE is almost elastic in relation with the variable H_{eq}. We have to observe that our elasticities are negative, which means that an increase in H_{eq} produces a decrease in LCOE, something very reasonable if we consider that in the equation of LCOE, LCOE and E_t are inversely proportional variables.

5 CONCLUSIONS

Taking into consideration all the background, method, and results of this study, it is necessary to make a section as a conclusion of all the information presented in the previous pages.

Solar energy is becoming one of the most used renewal sources, resulting in two main different ways of collection: solar thermal and photovoltaic, being the second one the object of our calculations. PV energy is becoming so important that in some countries, new buildings must by law, have PV plates installed. Technological advances and researchs not only have permitted the optimization of PV systems, increasing their production and reducing their costs as consequence, but also have opened a promising way with the creation of PV systems that imitate the motion of the sun, acting like a sunflower, facing sun throughout the day.

Considering this broad range of PV technologies, some research about performance, costs and profitability is needed, and that has been the purpose of this work: to perform an economic analysis of the photovoltaic energy production in the European Union.

In our study, first of all, we defined a background, a state of the art, including theoretical concepts such as how does a PV system work, geographical and geometrical notions and then the studies that have inspired our research, with comparisons between fixed and tracking technologies.

Then, in the method chapter, we explained the informatic tool we have used, the PVGIS, basing our indications in its manual, followed by our economic tool, by which we have calculated the costs of energy production, the Levelized Cost of Energy (LCOE).

After that and before getting into calculations, the list of selected locations is presented, with 20 locations of 28 EU countries (some little countries were joined in order to simplify); followed by the calculations of Energy Production and the corresponding costs of this production, including maps with colour scales for each PV technology, and also one map with the optimal system in every country. Finally, a sensitivity analysis was carried out, expressing the dependence of LCOE with wage and equivalent hours.

If we analyze the energy production, or the equivalent hours (coincident in value because the peak installed power is 1 KW), presented in Table 6, we normally obtain less energy in those countries which have higher latitudes, and more energy in southern countries. In terms of costs of energy production, for the assumed investment and maintenance costs, the best option, with lower values of LCOE, are the one-axis tracking systems (vertical and inclined axis), while the worst options are always the two-axis tracking systems.

We also detected that, the higher the latitude of the country, the more expensive the production of electricity is. The wages often influence strongly, making that, for fixed plates, Bulgaria, the country with the lowest wage, has the lowest value of LCOE while Germany, with the highest wage, is the country with the third of the highest values of LCOE, despite having good values of energy production.

Furthermore, when we analyzed the LCOE of tracking systems, detected that the wage becomes a more important aspect, making that in the case of Belgium, a country with a high value of wage, is the second country in highest value of LCOE for vertical axis tracking systems.

In relation with the sensitivity analysis, we have detected that an increase in wage produces an increase in LCOE, but very slight, with values of elasticity against wage from 0.2 to 0.6. For the case of the equivalent hours, we obtained that LCOE is a variable almost elastic, with values of elasticity against equivalent hours around -0.91, which means that an increase of H_{eq} produces an almost equal decrease in LCOE.

Considering the appreciations of this chapter, and also the presented previously but not commented here, it is evident that two-axis systems are not worthy, despite being the technology which produces most. The most profitable are the one-axis tracking systems and, if we want to obtain more energy and use the two-axis trackers, we should improve the performance and reduce the costs of manufacturing, installation and maintenance.

Finally, we should end our work recognizing the importance of PV energy as the most promising but at the same time so needed of research source of energy, not only in our times, but also in the future, applicable to buildings and surely to unimaginable fields such as aviation, seamanship and automotive sectors (to propel airplanes, ships, cars, bicycles or scooters), solar-powered toilets (promoted by Bill Gates foundation) or electronic devices sector (with solar rechargeable batteries), etc.

"Perhaps human cannot go to the Sun, but, for sure, he can bring it to Earth".

6 ANNEXES

Annex 1: Geographical locations

1) Vienna, Austria

Fig. 34: Location in Austria

Fig. 35: Location in Vienna

Latitude: 48° 6'54.06"N **Longitude**: 16°32'32.36"E

Minimum Temperature: -3°C **Maximum Temperature**: 26°C

2) Brussels, Belgium

Fig. 36: Location in Belgium

Fig. 37: Location in Brussels

Latitude: 50°53'29.46"N	**Longitude**: 4°30'10.84"E
Minimum Temperature: 1°C	**Maximum Temperature**: 23°C

This location covers our calculations not only in Belgium, but also in other countries of European Union such as Netherlands and Luxembourg.

3) Sofia, Bulgaria

Fig. 38: Location in Bulgaria

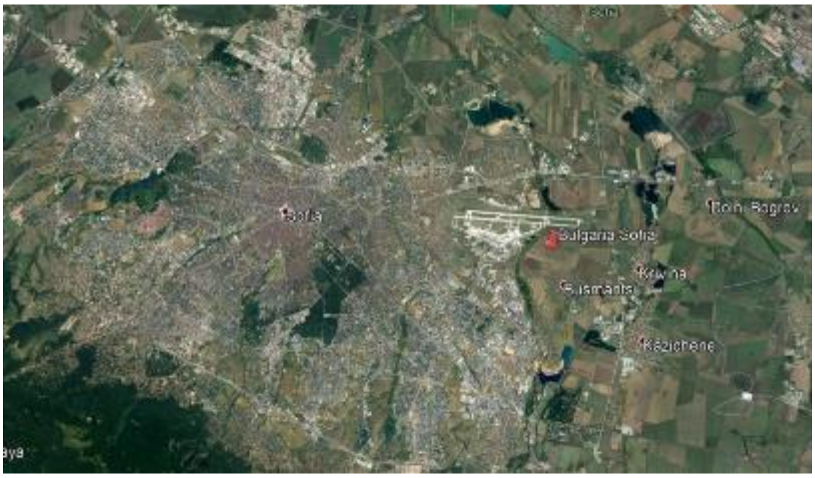


Fig. 39: Location in Sofia

Latitude: 42°41'5.97"N **Longitude**: 23°25'37.43"E

Minimum Temperature: -5°C **Maximum Temperature**: 29°C

4) Zagreb, Croatia

Fig. 40: Location in Croatia

Fig. 41: Location in Zagreb

Latitude: 45°44'32.08"N **Longitude**: 16° 3'27.32"E

Minimum Temperature: -3°C **Maximum Temperature**: 28°C

This location covers our calculations not only in Croatia, but also in Slovenia, considering its 20.273 km^2 of extent.

5) Nicosia, Cyprus

Fig. 42: Location in Cyprus

Fig. 43: Location in Nicosia

Latitude: 35°11'39.06"N **Longitude**: 33°22'49.16"E

Minimum Temperature: 6°C **Maximum Temperature**: 33°C

As mentioned, this location has been maintained because of being far from other EU countries, despite its small extension.

6) Prague, Czech Republic

Fig. 44: Location in Czech Republic

Fig. 45: Location in Prague

Latitude: 50° 7'9.98"N

Longitude: 14°14'11.72"E

Minimum Temperature: -4°C

Maximum Temperature: 24°C

7) Helsinki, Finland

Fig. 46: Location in Finland

Fig. 47: Location in Helsinki

Latitude: 60°19'21.22"N **Longitude**: 24°56'22.68"E

Minimum Temperature: -9°C **Maximum Temperature**: 22°C

8) Paris, France

Fig. 48: Location in France

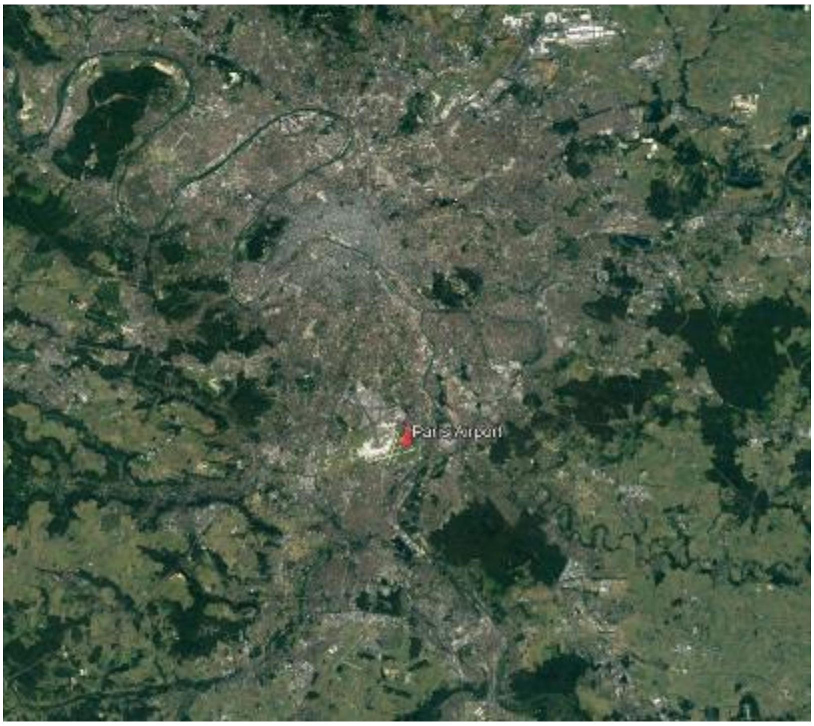


Fig. 49: Location in Paris

Latitude: 48°43'32.10"N **Longitude**: 2°23'24.32"E

Minimum Temperature: 1°C **Maximum Temperature**: 26°C

9) Berlin, Germany

Fig. 50: Location in Germany

Fig. 51: Location in Berlin

Latitude: 52°33'40.60"N **Longitude**: 13°17'21.33"E

Minimum Temperature: -2°C **Maximum Temperature**: 25°C

10) Athens, Greece

Fig. 52: Location in Greece

Fig. 53: Location in Athens

Latitude: 37°56'35.93"N **Longitude**: 23°56'1.79"E

Minimum Temperature: 5°C **Maximum Temperature**: 32°C

11) Budapest, Hungary

Fig. 54: Location in Hungary

Fig. 55: Location in Budapest

Latitude: 47°27'9.59"N **Longitude**: 19°16'42.08"E

Minimum Temperature: -4°C **Maximum Temperature**: 28°C

This location covers our calculations not only in Hungary, but also in Slovakia, considering its 48.845 km^2 of extent.

12) Dublin, Ireland

Fig. 56: Location in Ireland

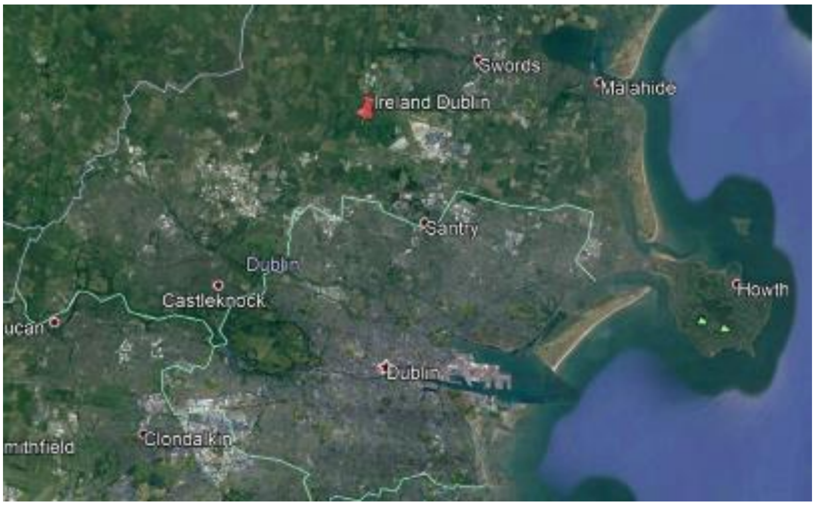


Fig. 57: Location in Dublin

Latitude: 53°25'50.98"N

Longitude: 6°17'0.88"W

Minimum Temperature: 3°C

Maximum Temperature: 19°C

13) Rome, Italy

Fig. 58: Location in Italy

Fig. 59: Location in Rome

Latitude: 41°51'54.57"N **Longitude**: 12°15'22.79"E

Minimum Temperature: 4°C **Maximum Temperature**: 29°C

This location covers our calculations not only in Italy, but also in Malta, considering its 316 km^2 of extent.

14) Riga, Latvia

Fig. 60: Location in Latvia

Fig. 61: Location in Riga

Latitude: 56°56'18.85"N **Longitude**: 23°59'15.64"E

Minimum Temperature: -6°C **Maximum Temperature**: 22°C

This location covers our calculations not only in Latvia, but also in other countries of European Union such as Estonia and Lithuania.

15) Warsaw, Poland

Fig. 62: Location in Poland

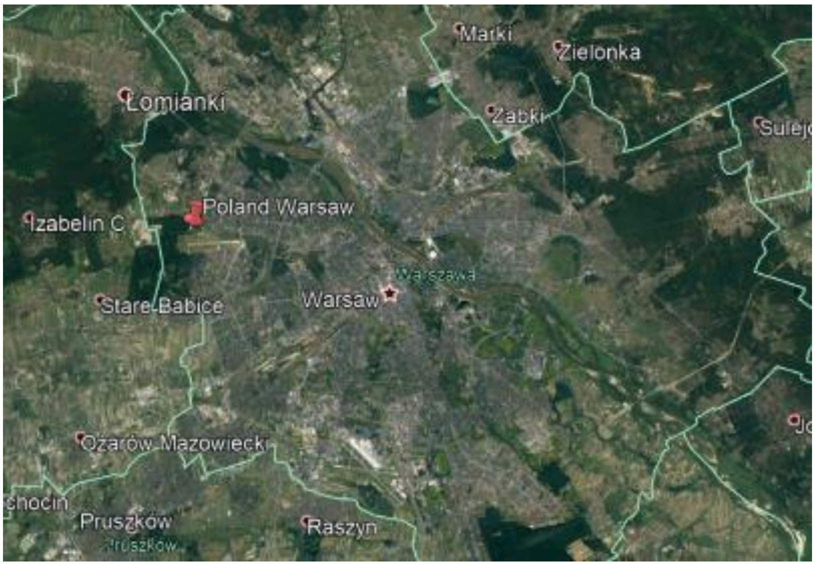


Fig. 63: Location in Warsaw

Latitude: 52°16'28.32"N	**Longitude**: 20°54'1.63"E
Minimum Temperature: -5°C	**Maximum Temperature**: 24°C

16) Lisbon, Portugal

Fig. 64: Location in Portugal

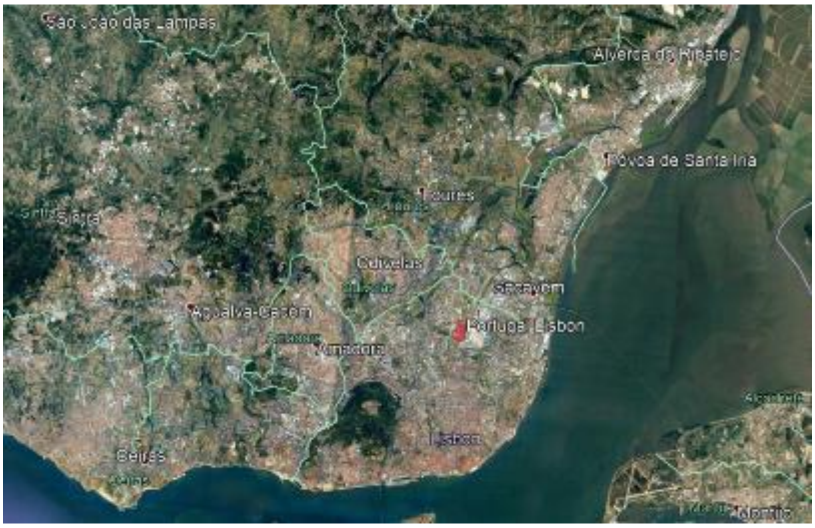


Fig. 65: Location in Lisbon

Latitude: 38°45'48.21"N **Longitude**: 9° 8'42.09"W

Minimum Temperature: 8°C **Maximum Temperature**: 29°C

17) Bucharest, Romania

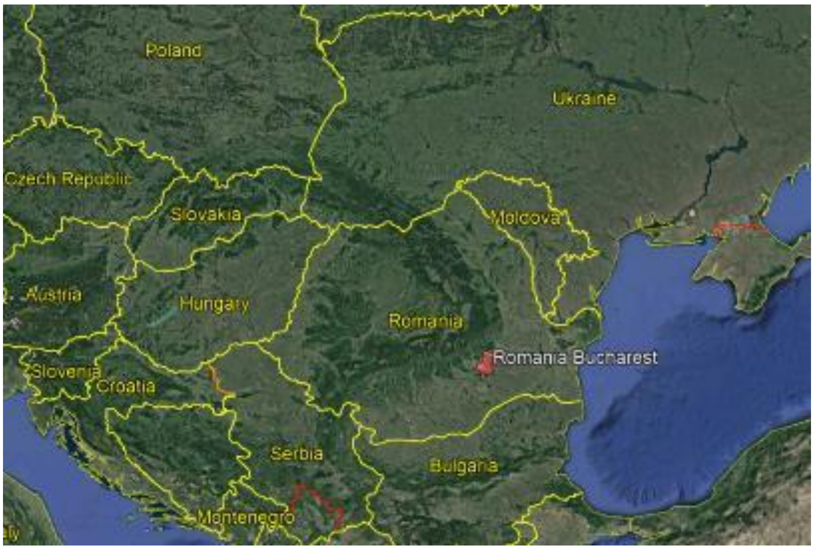


Fig. 66: Location in Romania

Fig. 67: Location in Bucharest

Latitude: 44°35'28.67"N **Longitude**: 26° 6'35.72"E

Minimum Temperature: -5°C **Maximum Temperature**: 30°C

18) Madrid, Spain

Fig. 68: Location in Spain

Fig. 69: Location in Madrid

Latitude: 40°31'13.25"N **Longitude**: 3°35'1.06"W

Minimum Temperature: 1°C **Maximum Temperature**: 33°C

19) Stockholm, Sweden

Fig. 70: Location in Sweden

Fig. 71: Location in Stockholm

Latitude: 59°20'12.74"N	**Longitude**: 18° 6'39.14"E
Minimum Temperature: -6°C	**Maximum Temperature**: 22°C

This location covers our calculations not only in Sweden, but also in Denmark, considering its 43.094 km^2 of extent.

20) London, United Kingdom

Fig. 72: Location in United Kingdom

Fig. 73: Location in London

Latitude: 51°29'32.35"N **Longitude**: 0°28'16.80"W

Minimum Temperature: 2°C **Maximum Temperature**: 23°C

Note: Temperatures taken from [18].

Annex 2: Detailed energy production

1) Vienna, Austria

Daily data

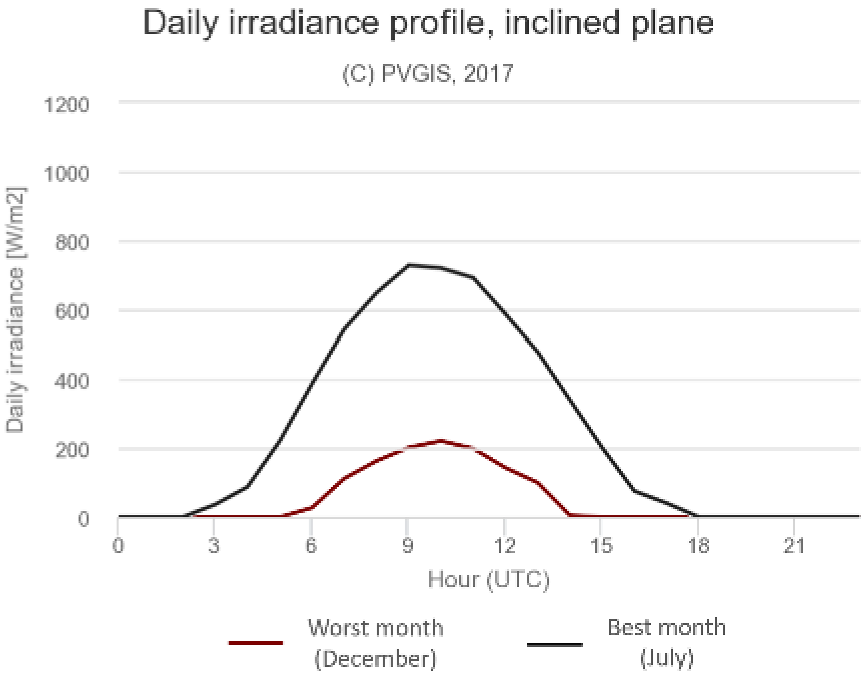


Fig. 74: Vienna - Daily irradiance

Monthly data

Fixed plate

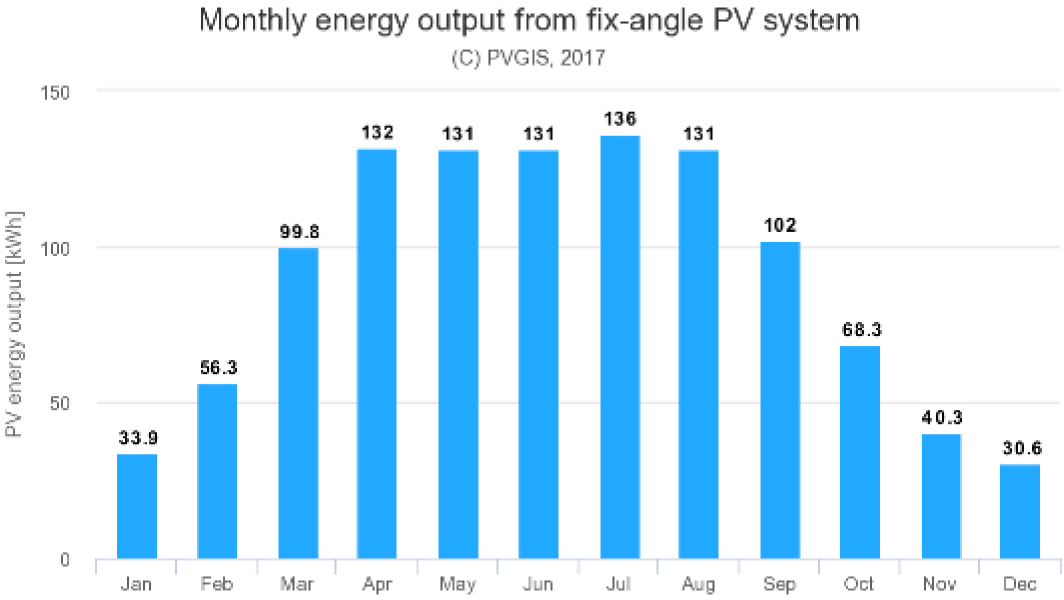


Fig. 75: Vienna - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	36 (opt)
Azimuth angle [°]	-4 (opt)
Yearly in-plane irradiation [kWh/m²]	1370
Year to year variability [kWh]	47.70
Yearly PV energy production [kWh]	**1090**

Table 20: Vienna - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

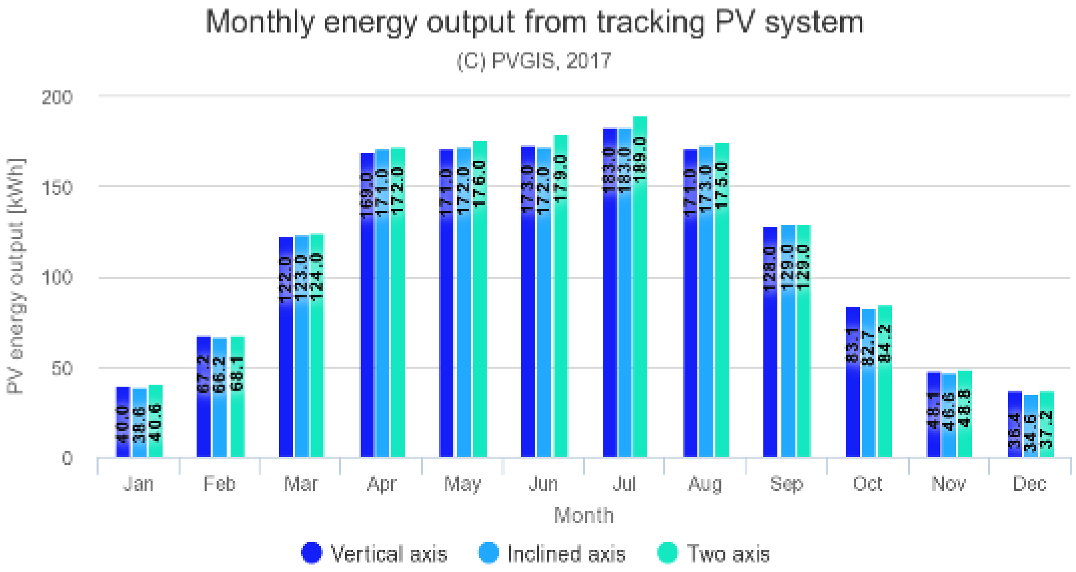


Fig. 76: Vienna - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	38 (opt)	-
Yearly in-plane irradiation [kWh/m²]	1730	1730	1760
Year to year variability [kWh]	67.1	66.7	68.8
Yearly PV energy production [kWh]	**1390**	**1390**	**1420**

Table 21: Vienna - Output parameters from tracking PV systems

PV technologies comparison

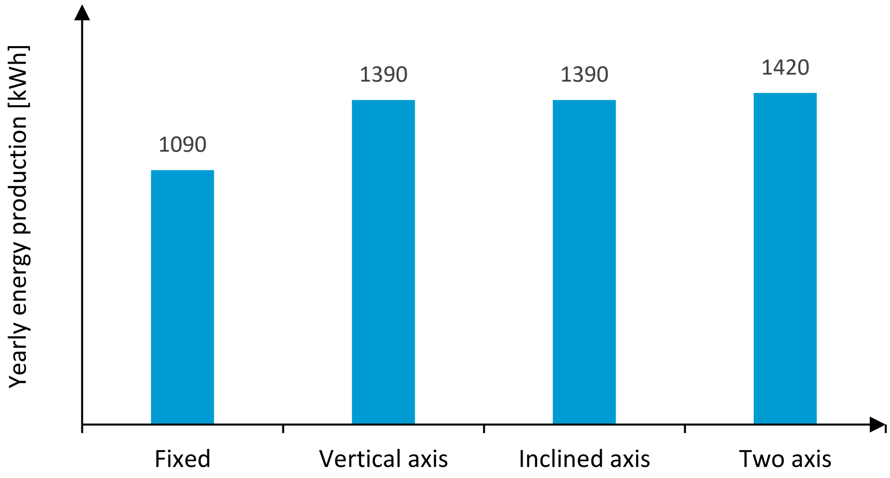


Fig. 77: Vienna - PV technologies comparison

2) Brussels, Belgium

Daily data

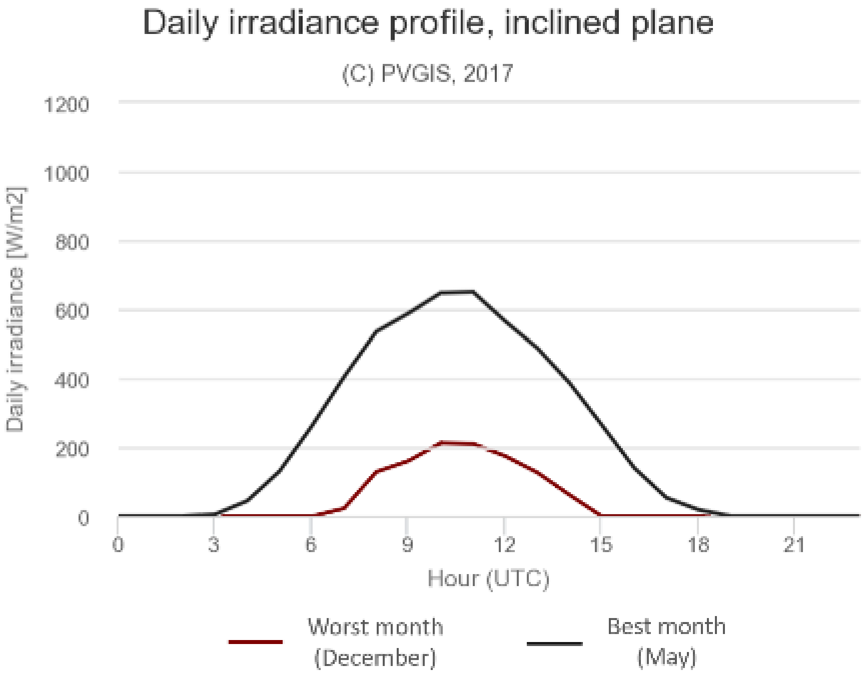


Fig. 78: Brussels - Daily Irradiance

Monthly data

Fixed plate

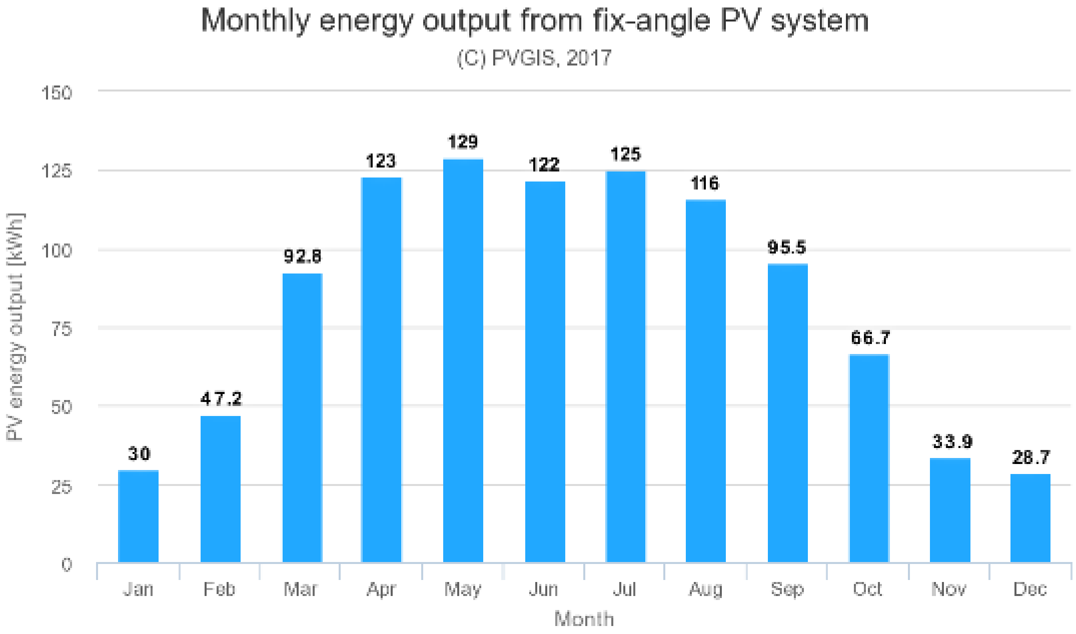


Fig. 79: Brussels - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	37 (opt)
Azimuth angle [°]	-7 (opt)
Yearly in-plane irradiation [kWh/m^2]	1250
Year to year variability [kWh]	34.30
Yearly PV energy production [kWh]	**1010**

Table 22: Brussels - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

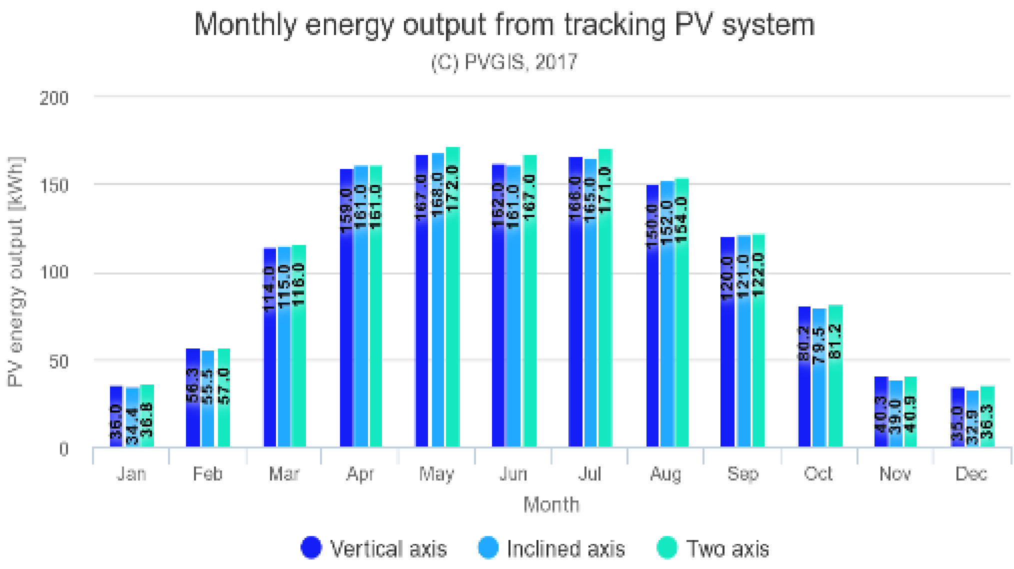


Fig. 80: Brussels - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	54 (opt)	39 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1570	1570	1600
Year to year variability [kWh]	46.5	45.6	47.9
Yearly PV energy production [kWh]	**1290**	**1280**	**1320**

Table 23: Brussels - Output parameters from tracking PV systems

PV technologies comparison

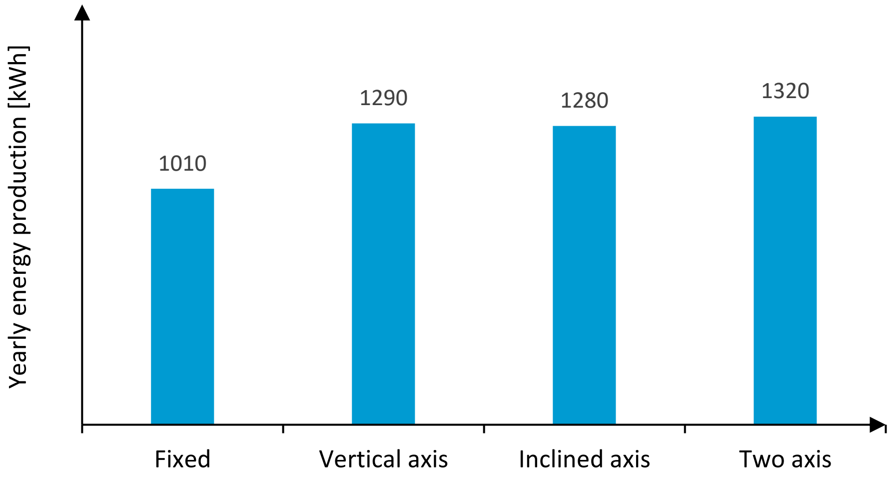


Fig. 81: Brussels - PV technologies comparison

3) Sofia, Bulgaria

Daily data

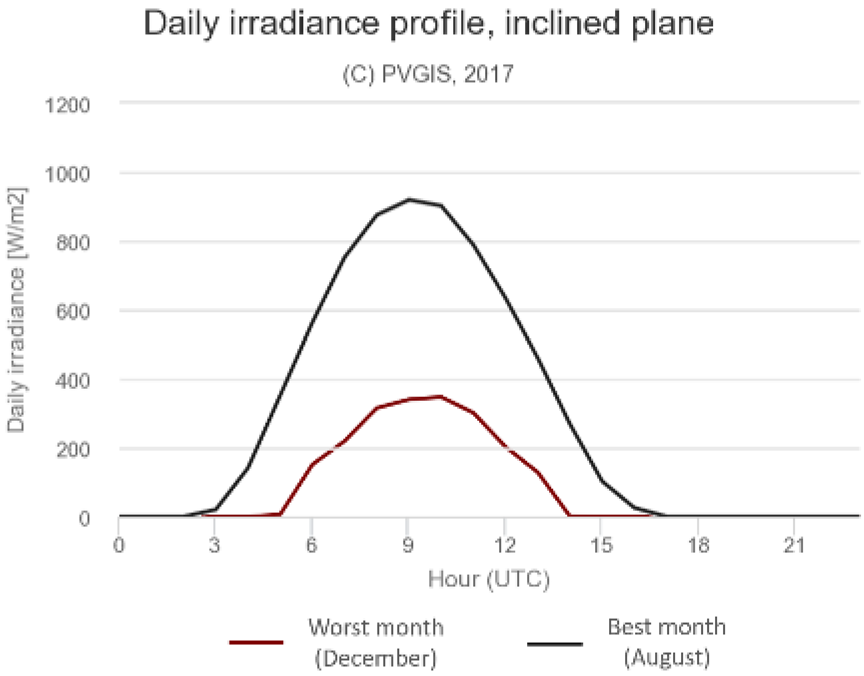


Fig. 82: Sofia - Daily Irradiance

Monthly data

Fixed plate

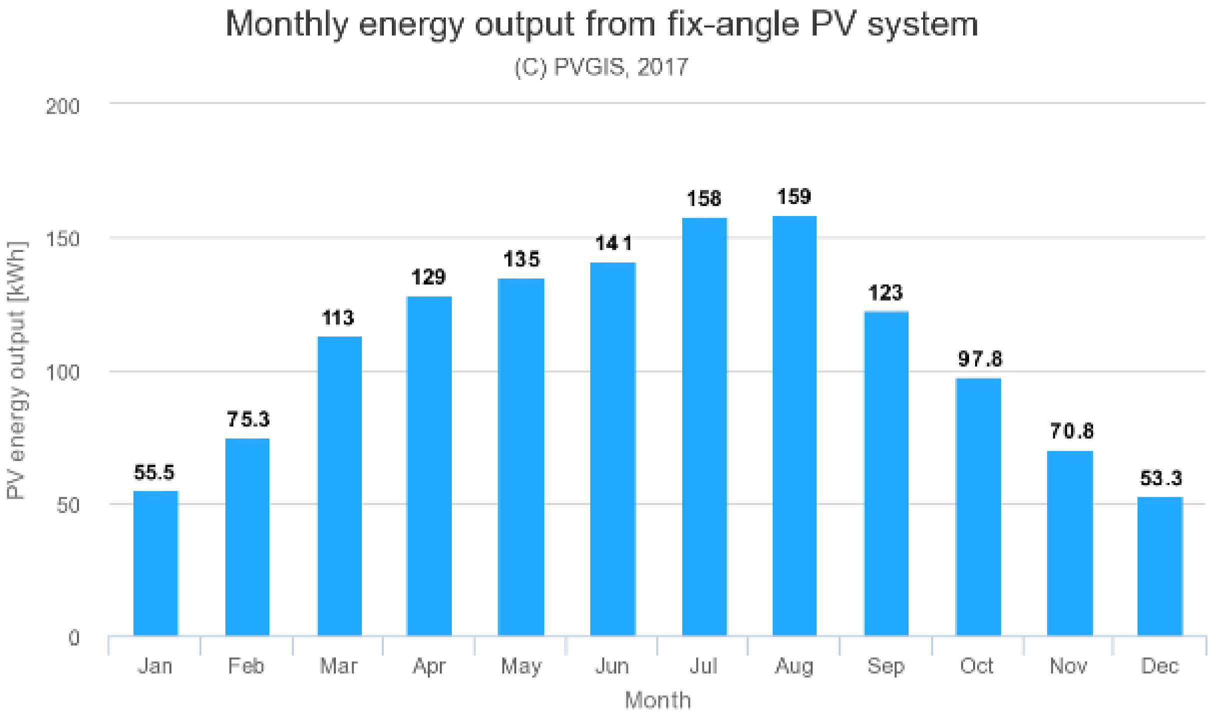


Fig. 83: Sofia - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	34 (opt)
Azimuth angle [°]	-8 (opt)
Yearly in-plane irradiation [kWh/m²]	1660
Year to year variability [kWh]	57.20
Yearly PV energy production [kWh]	**1310**

Table 24: Sofia - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

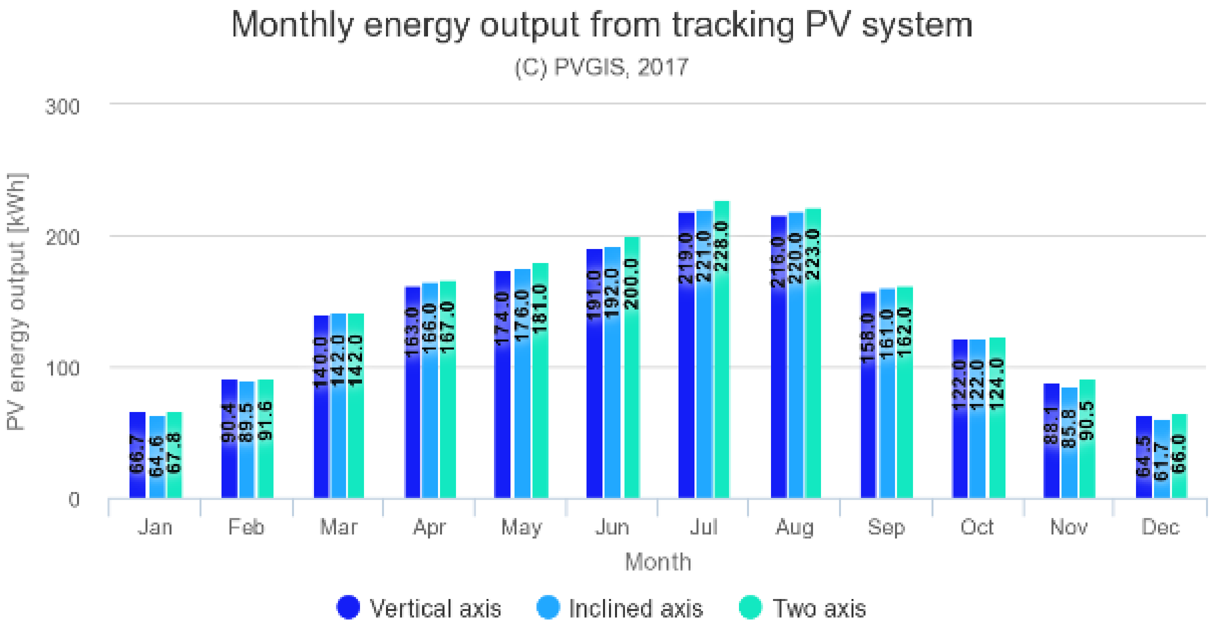


Fig. 84: Sofia - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	36 (opt)	-
Yearly in-plane irradiation [kWh/m²]	2130	2140	2190
Year to year variability [kWh]	90.3	90.8	93.5
Yearly PV energy production [kWh]	**1690**	**1700**	**1740**

Table 25: Sofia - Output parameters from tracking PV systems

PV technologies comparison

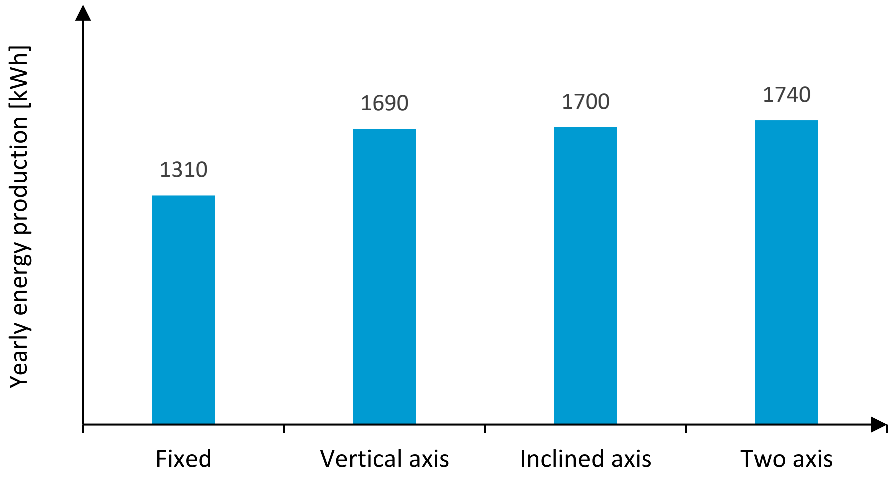


Fig. 85: Sofia - PV technologies comparison

4) Zagreb, Croatia

Daily data

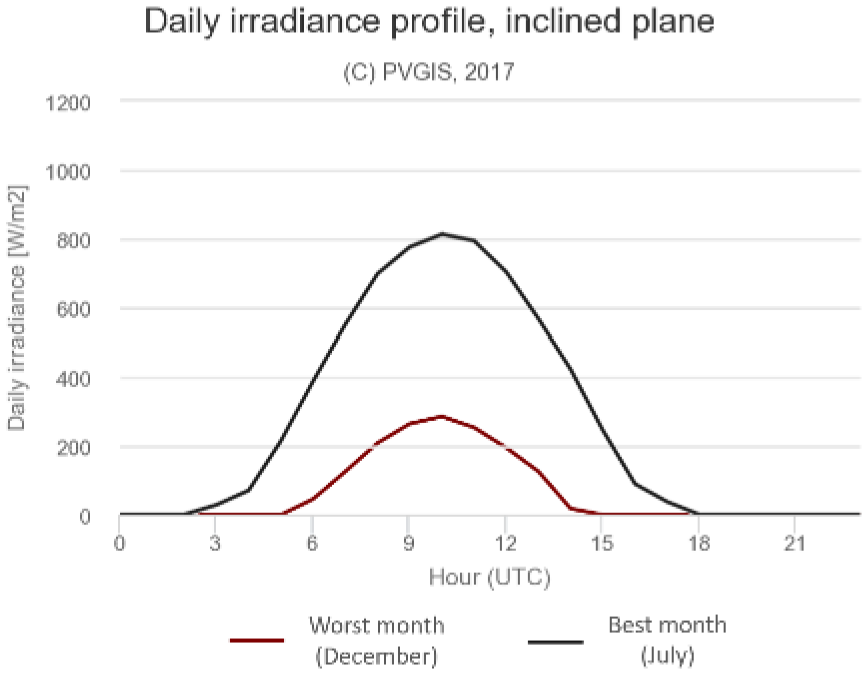


Fig. 86: Zagreb - Daily Irradiance

Monthly data

Fixed plate

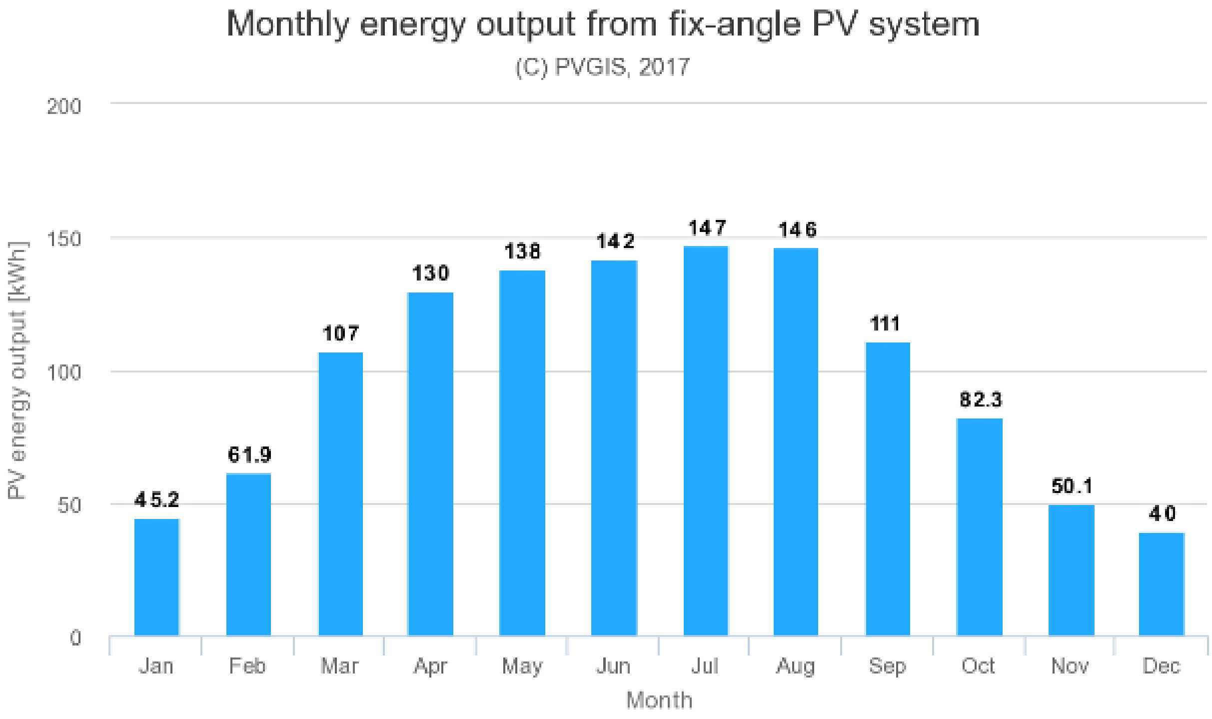


Fig. 87: Zagreb - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	34 (opt)
Azimuth angle [°]	0 (opt)
Yearly in-plane irradiation [kWh/m²]	1530
Year to year variability [kWh]	70.30
Yearly PV energy production [kWh]	**1200**

Table 26: Zagreb - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

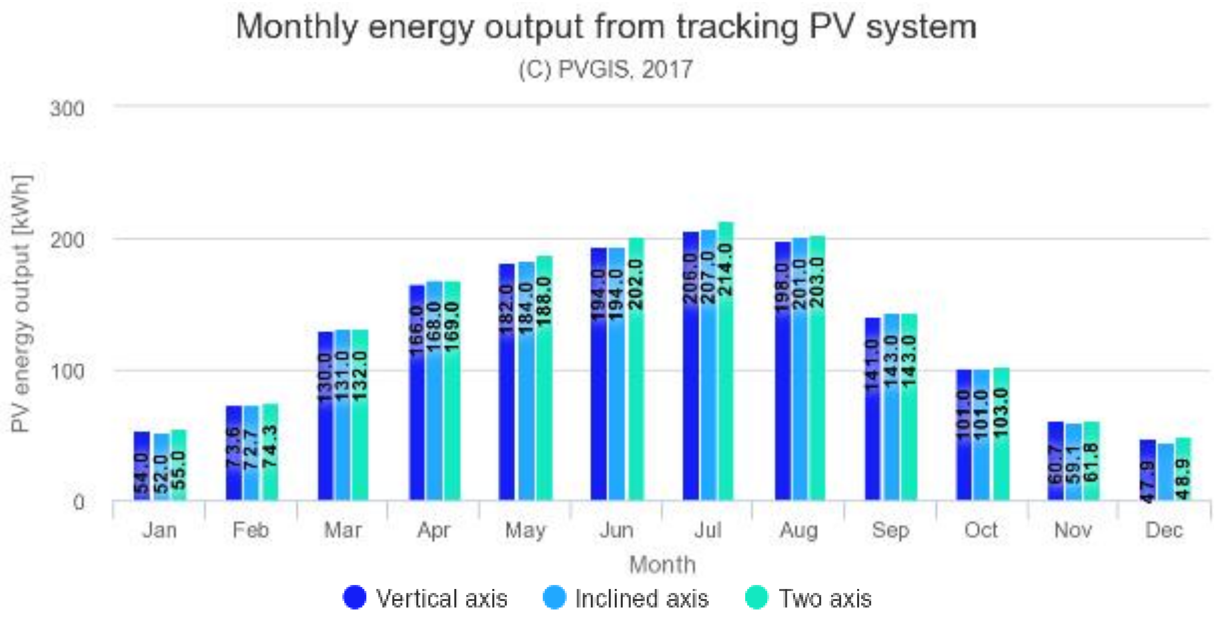


Fig. 88: Zagreb - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	37 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1960	1960	2010
Year to year variability [kWh]	103.0	103.0	106.0
Yearly PV energy production [kWh]	**1550**	**1560**	**1590**

Table 27: Zagreb - Output parameters from tracking PV systems

PV technologies comparison

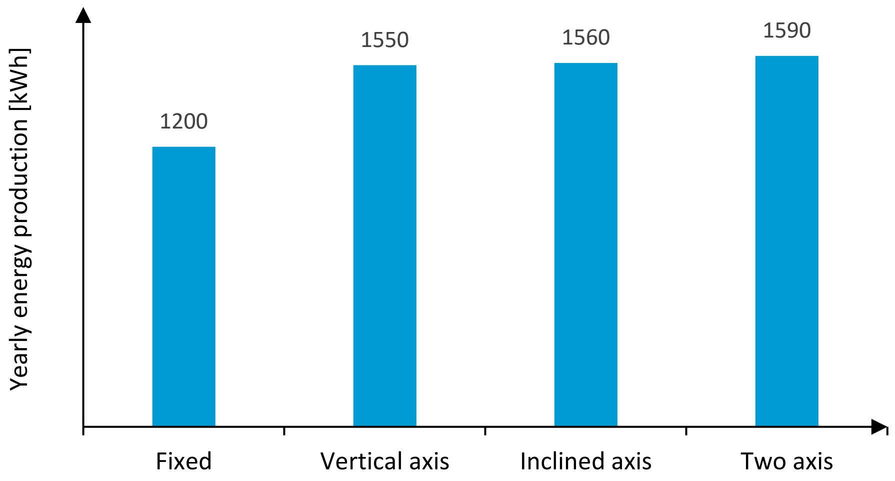


Fig. 89: Zagreb - PV technologies comparison

5) Nicosia, Cyprus

Daily data

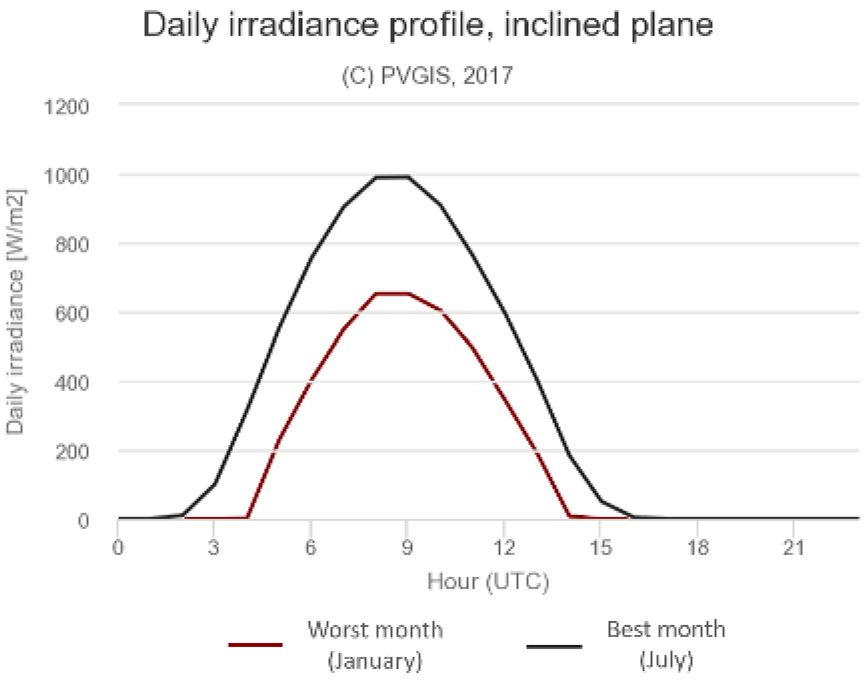


Fig. 90: Nicosia - Daily Irradiance

Monthly data

Fixed plate

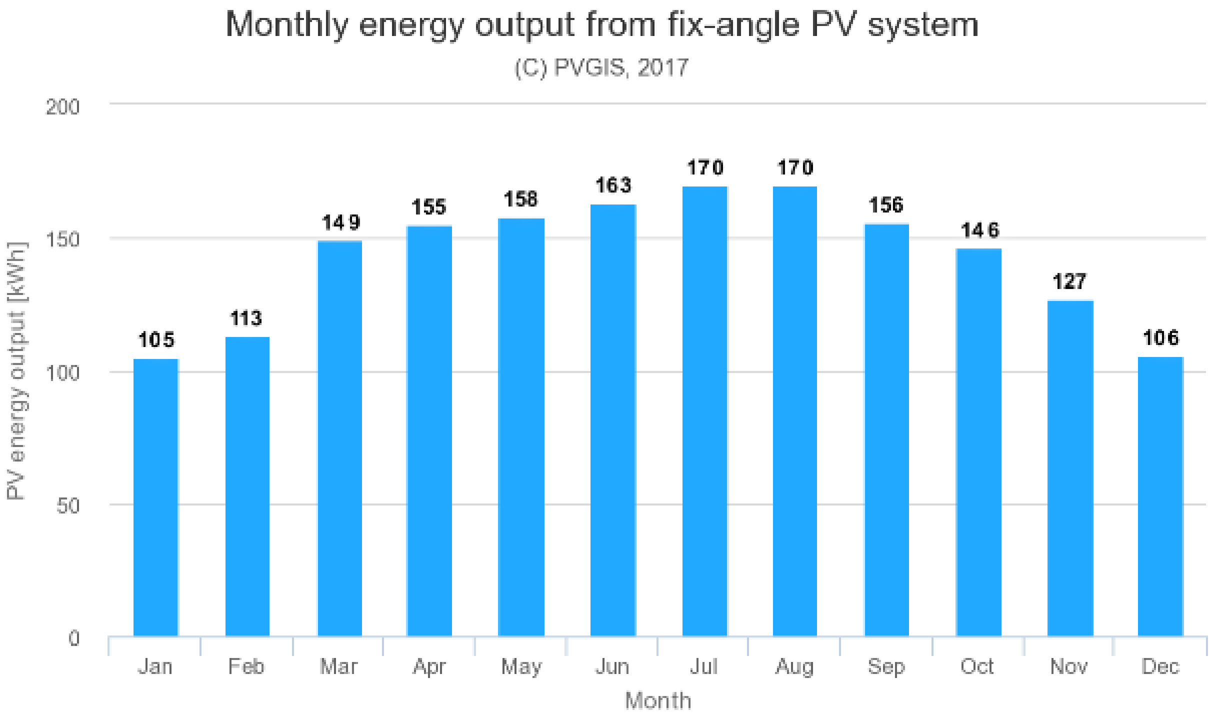


Fig. 91: Nicosia - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	32 (opt)
Azimuth angle [°]	-9 (opt)
Yearly in-plane irradiation [kWh/m^2]	2240
Year to year variability [kWh]	44.20
Yearly PV energy production [kWh]	**1720**

Table 28: Nicosia - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

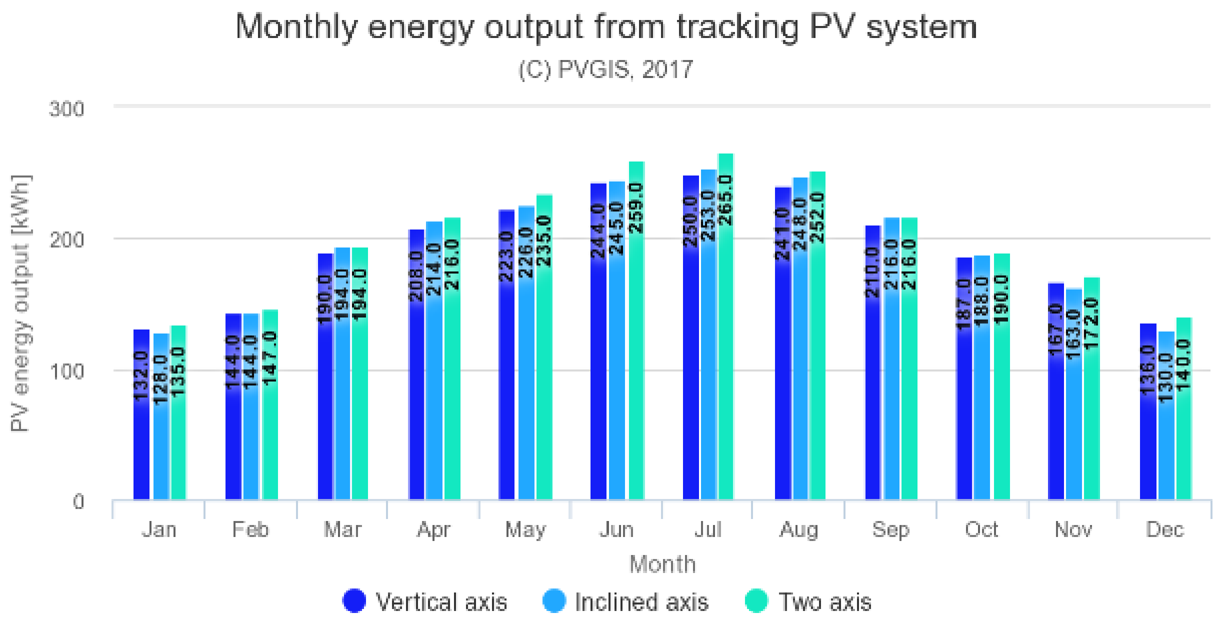


Fig. 92: Nicosia - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	34 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	3020	3040	3140
Year to year variability [kWh]	68.3	68.4	71.5
Yearly PV energy production [kWh]	**2330**	**2350**	**2420**

Table 29: Nicosia - Output parameters from tracking PV systems

PV technologies comparison

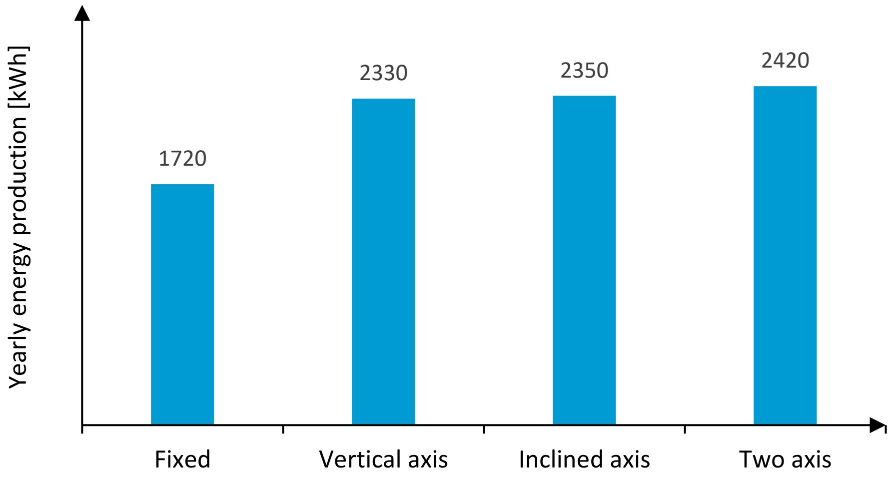


Fig. 93: Nicosia - PV technologies comparison

6) Prague, Czech Republic

Daily data

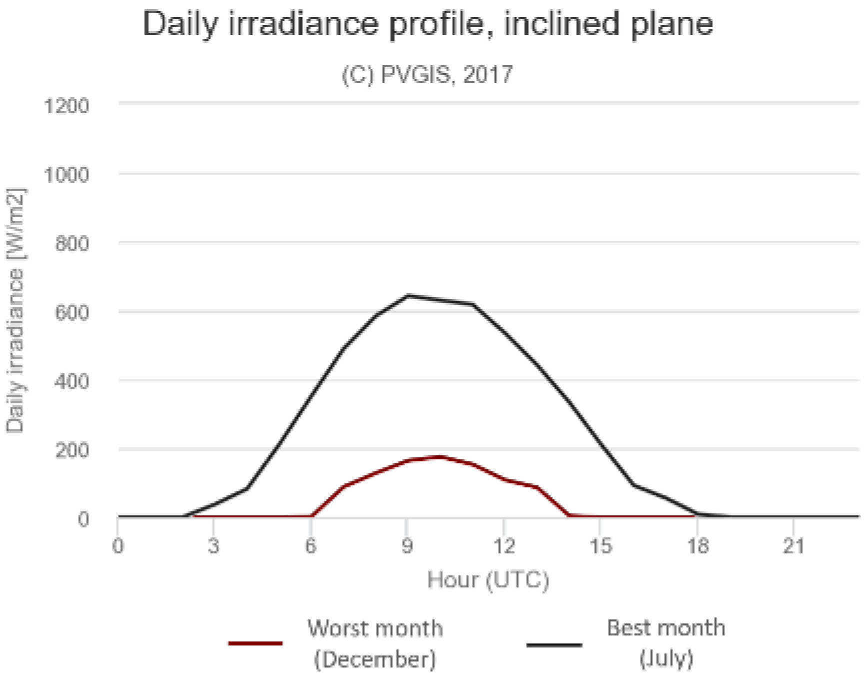


Fig. 94: Prague - Daily Irradiance

Monthly data

Fixed plate

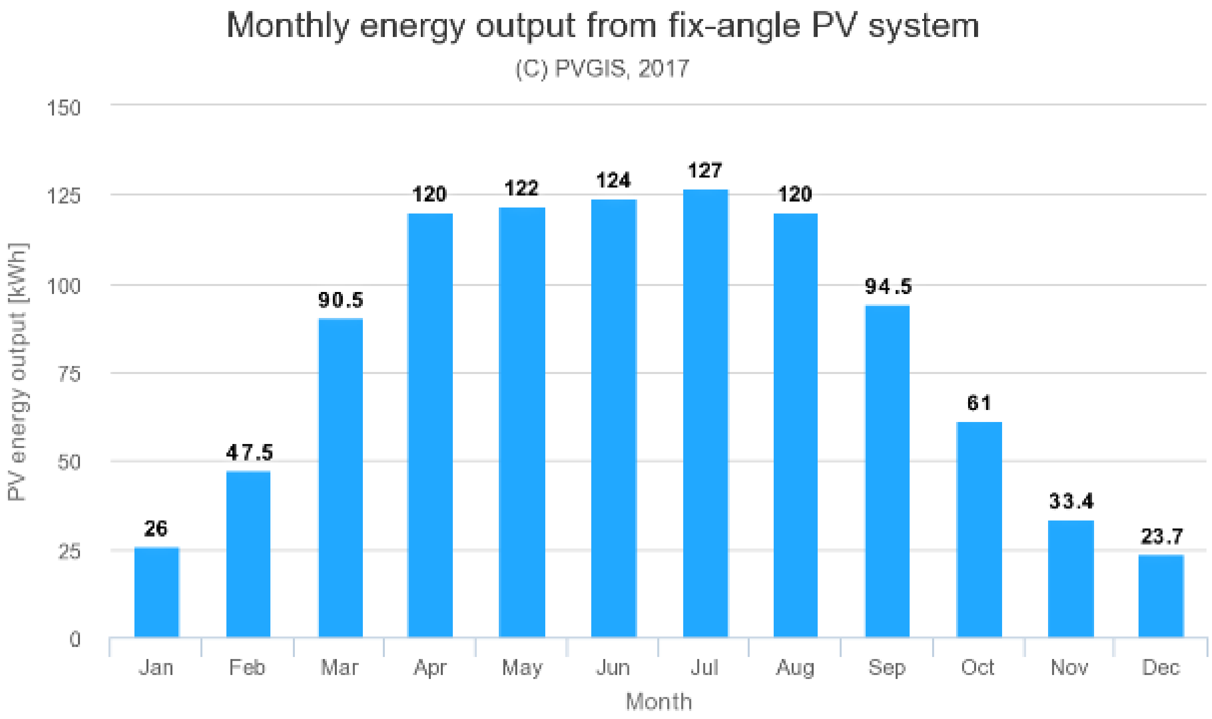


Fig. 95: Prague - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	36 (opt)
Azimuth angle [°]	-7 (opt)
Yearly in-plane irradiation [kWh/m^2]	1230
Year to year variability [kWh]	47.70
Yearly PV energy production [kWh]	**989**

Table 30: Prague - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

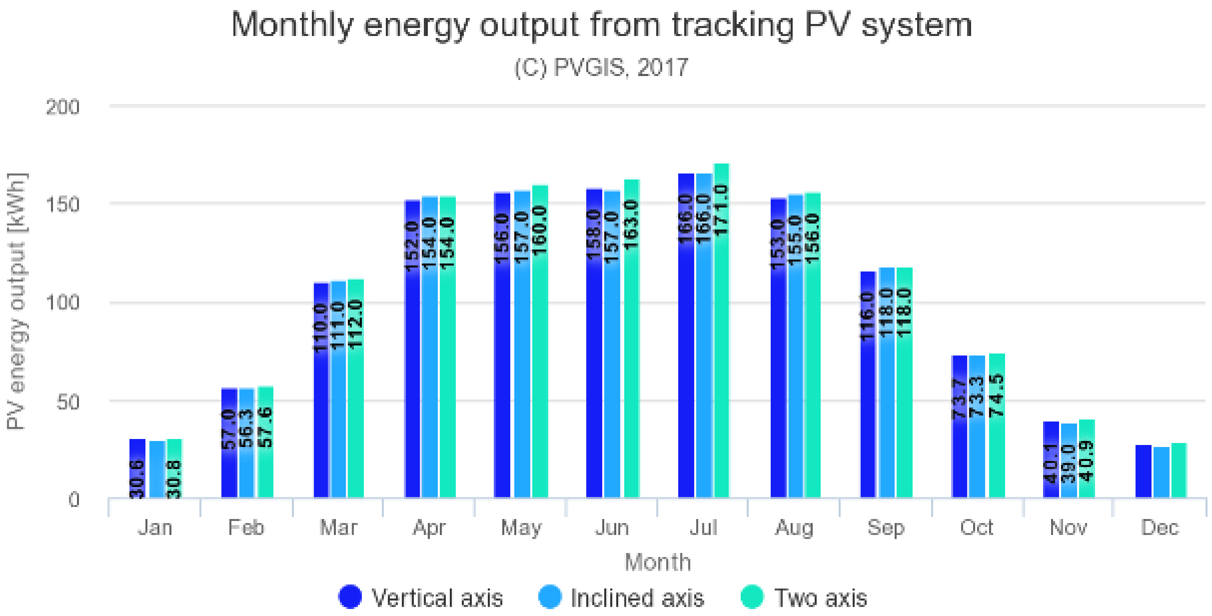


Fig. 96: Prague - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	37 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1530	1530	1560
Year to year variability [kWh]	65.3	64.8	66.9
Yearly PV energy production [kWh]	**1240**	**1240**	**1270**

Table 31: Prague - Output parameters from tracking PV systems

PV technologies comparison

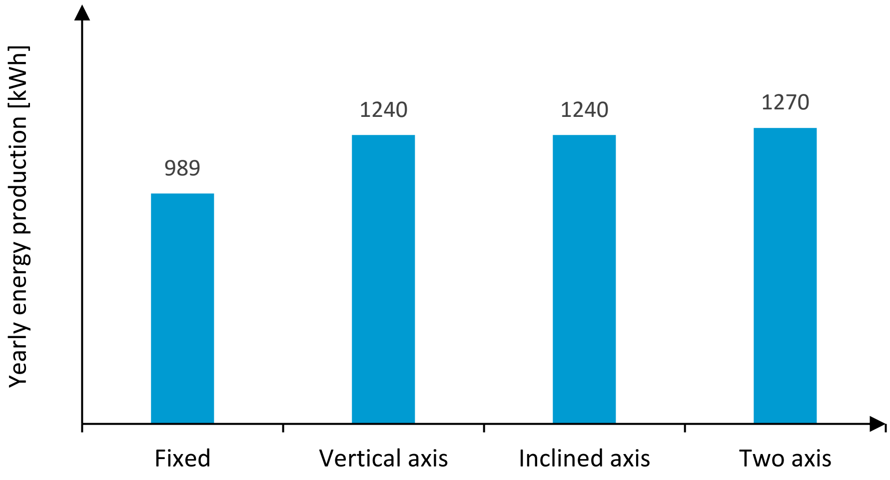


Fig. 97: Prague - PV technologies comparison

7) Helsinki, Finland

Daily data

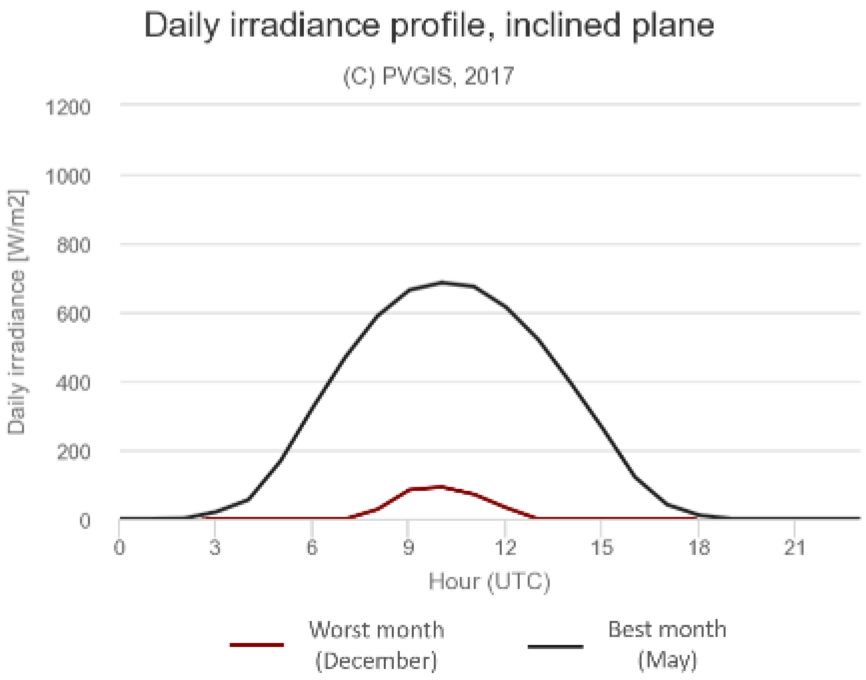


Fig. 98: Helsinki - Daily Irradiance

Monthly data

<u>Fixed plate</u>

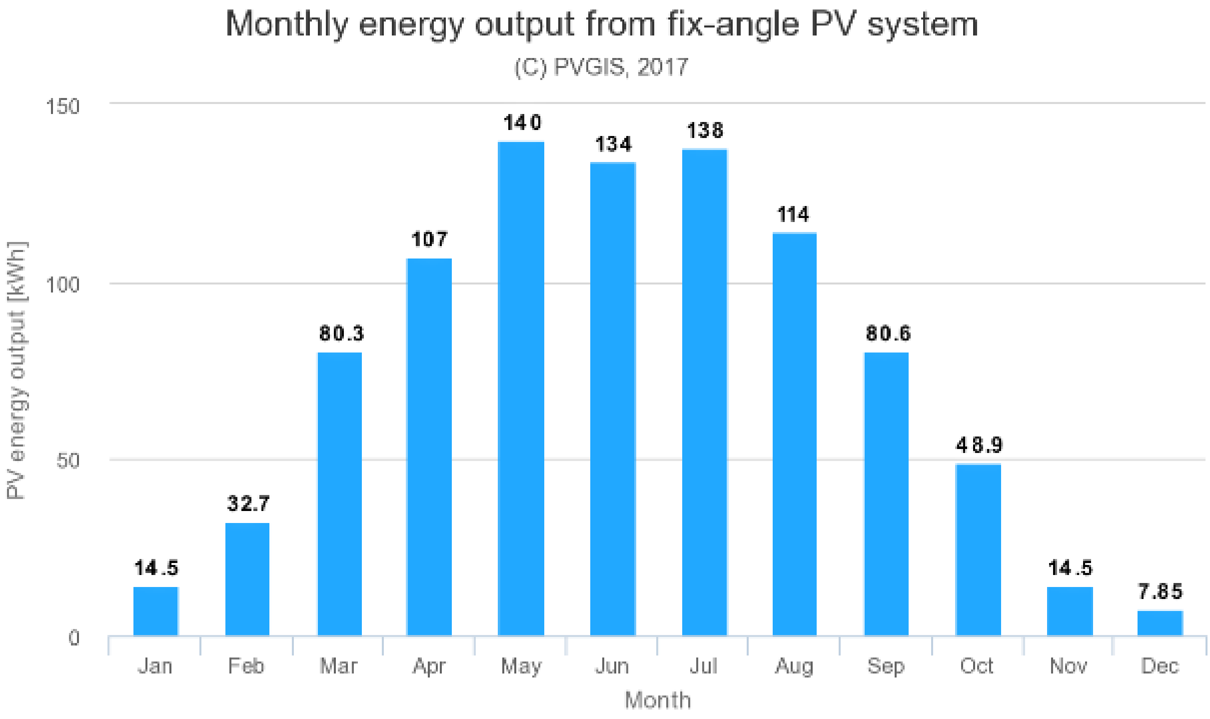


Fig. 99: Helsinki - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	43 (opt)
Azimuth angle [°]	3 (opt)
Yearly in-plane irradiation [kWh/m^2]	1130
Year to year variability [kWh]	55.30
Yearly PV energy production [kWh]	**912**

Table 32: Helsinki - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

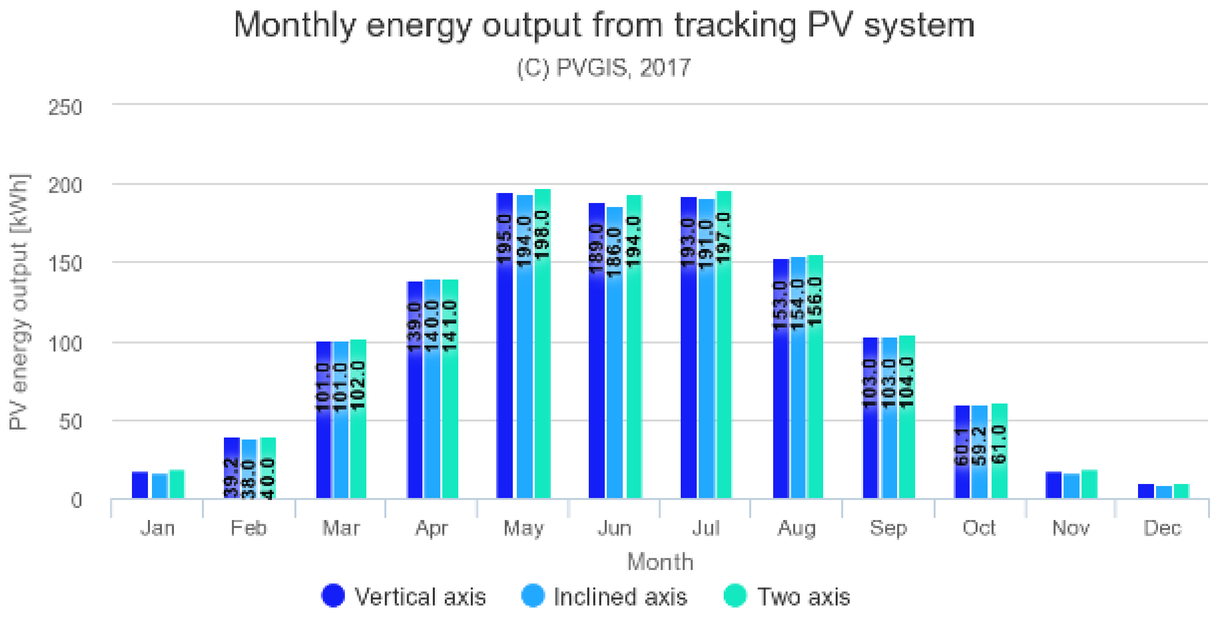


Fig. 100: Helsinki - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	59 (opt)	46 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1490	1480	1520
Year to year variability [kWh]	72.7	72.0	73.5
Yearly PV energy production [kWh]	**1220**	**1210**	**1240**

Table 33: Helsinki - Output parameters from tracking PV systems

PV technologies comparison

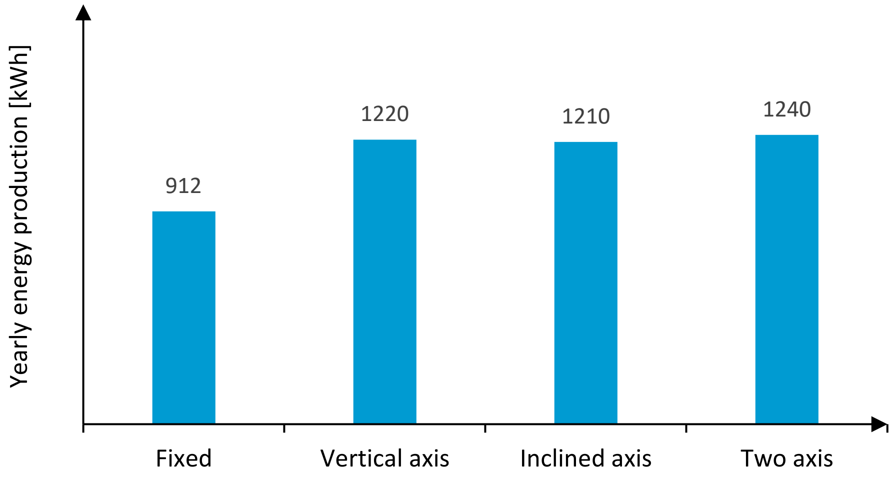


Fig. 101: Helsinki - PV technologies comparison

8) Paris, France

Daily data

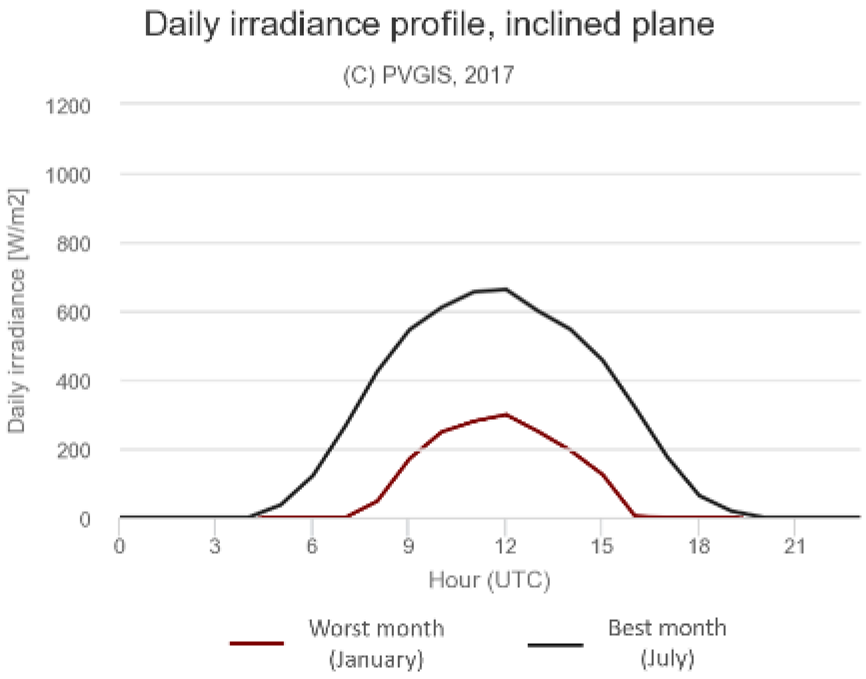


Fig. 102: Paris - Daily Irradiance

Monthly data

Fixed plate

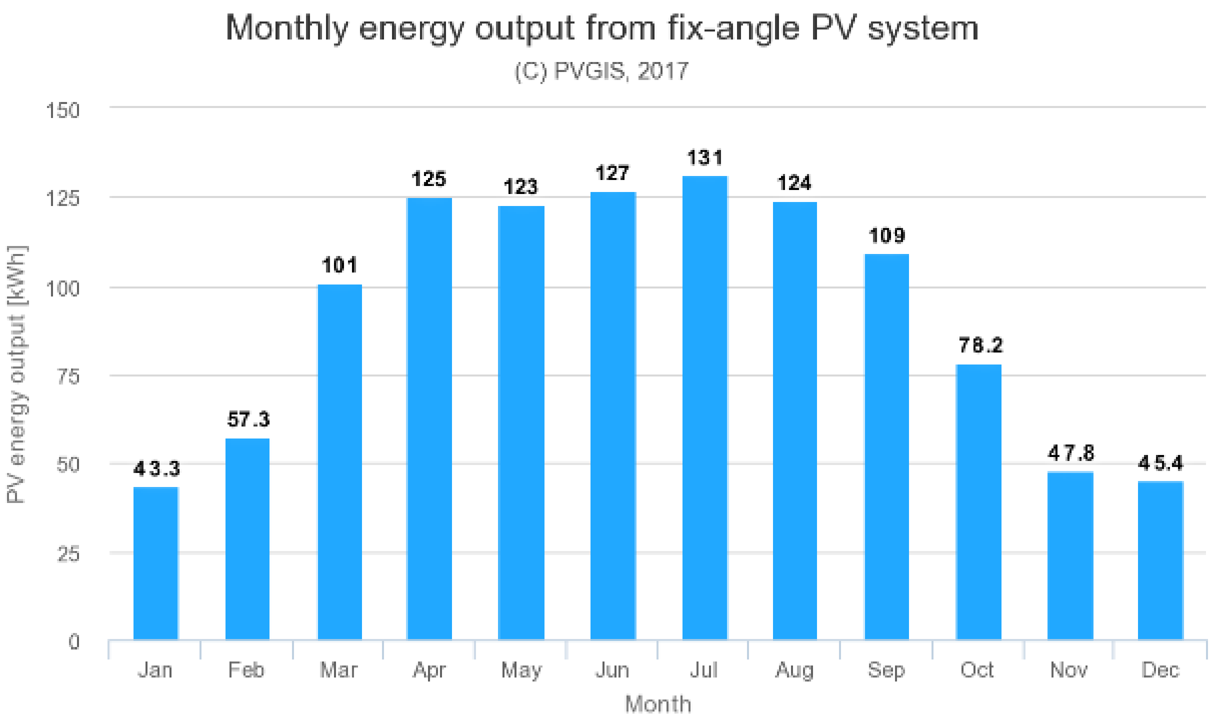


Fig. 103: Paris - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	38 (opt)
Azimuth angle [°]	-3 (opt)
Yearly in-plane irradiation [kWh/m^2]	1380
Year to year variability [kWh]	45.80
Yearly PV energy production [kWh]	**1110**

Table 34: Paris - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

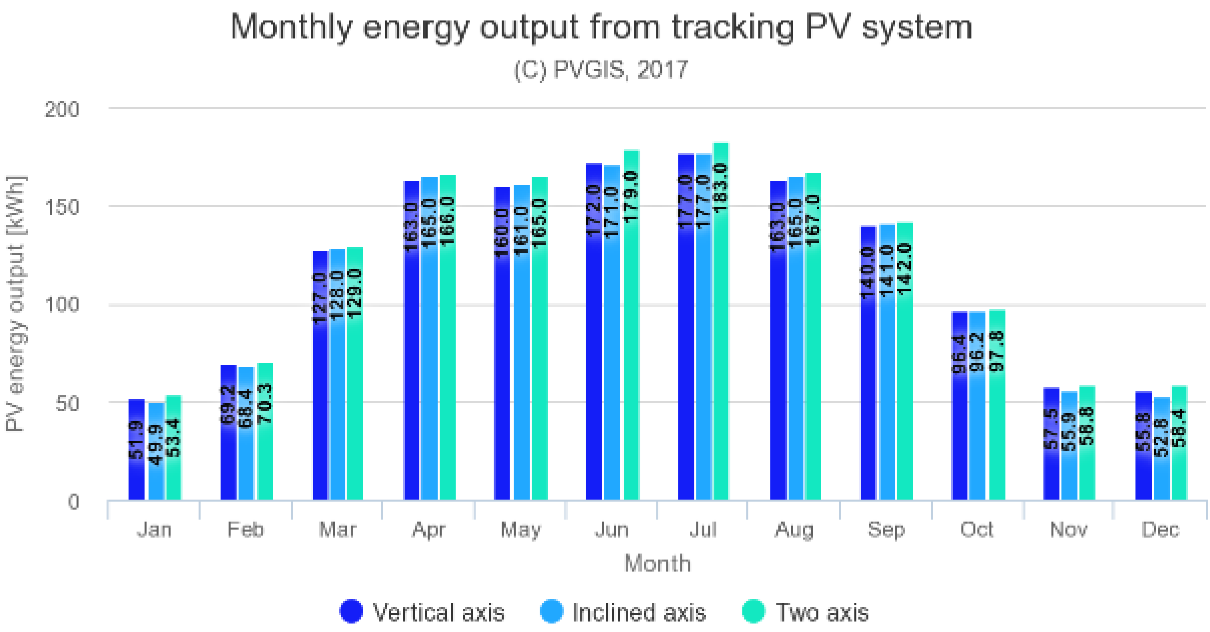


Fig. 104: Paris - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	40 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1760	1760	1810
Year to year variability [kWh]	67.5	68.1	69.3
Yearly PV energy production [kWh]	**1430**	**1430**	**1470**

Table 35: Paris - Output parameters from tracking PV systems

PV technologies comparison

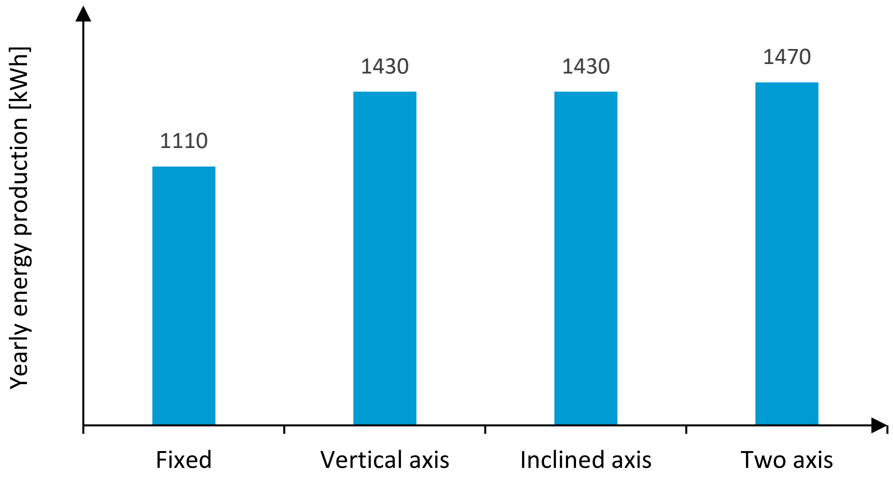


Fig. 105: Paris - PV technologies comparison

9) Berlin, Germany

Daily data

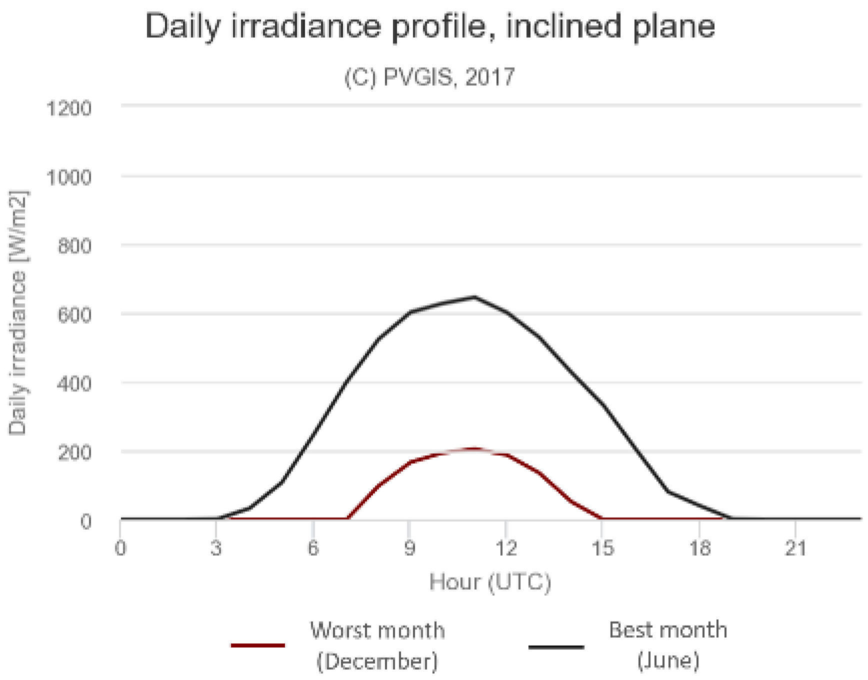


Fig. 106: Berlin - Daily Irradiance

Monthly data

Fixed plate

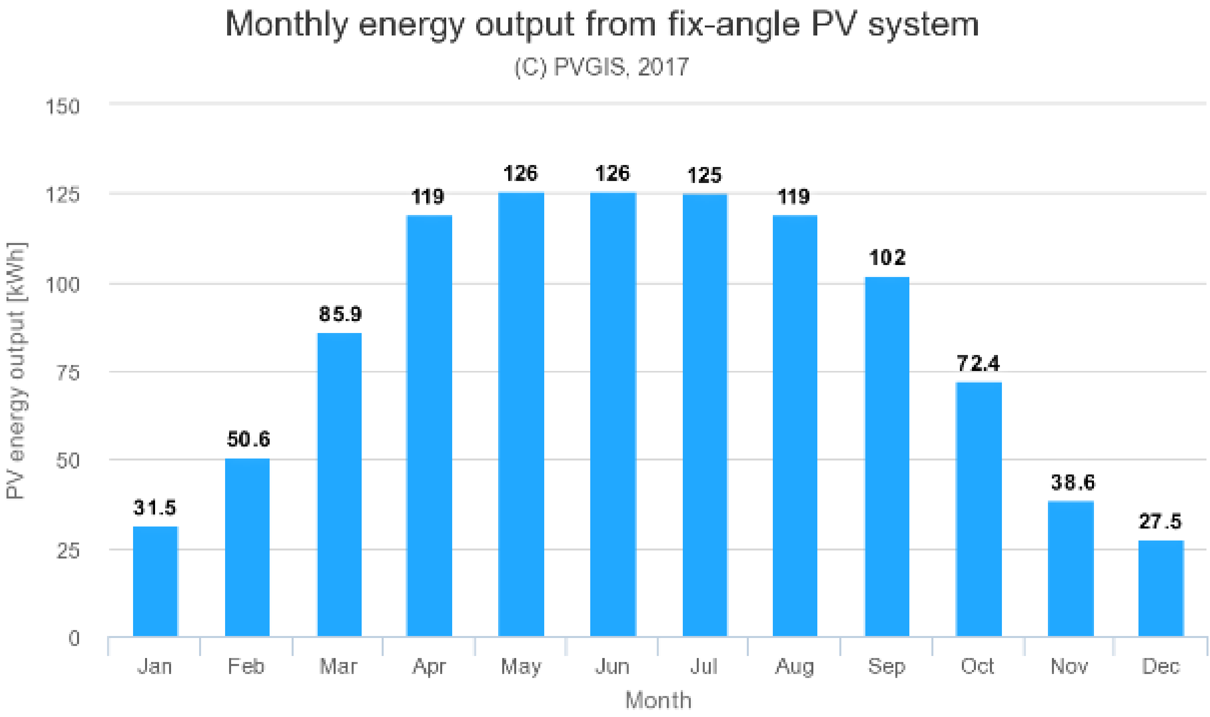


Fig. 107: Berlin - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	40 (opt)
Azimuth angle [°]	-5 (opt)
Yearly in-plane irradiation [kWh/m^2]	1270
Year to year variability [kWh]	54.90
Yearly PV energy production [kWh]	**1020**

Table 36: Berlin - Output parameters from fix-angle PV system

racking plates (Vertical axis, Inclined axis and Two-axis)

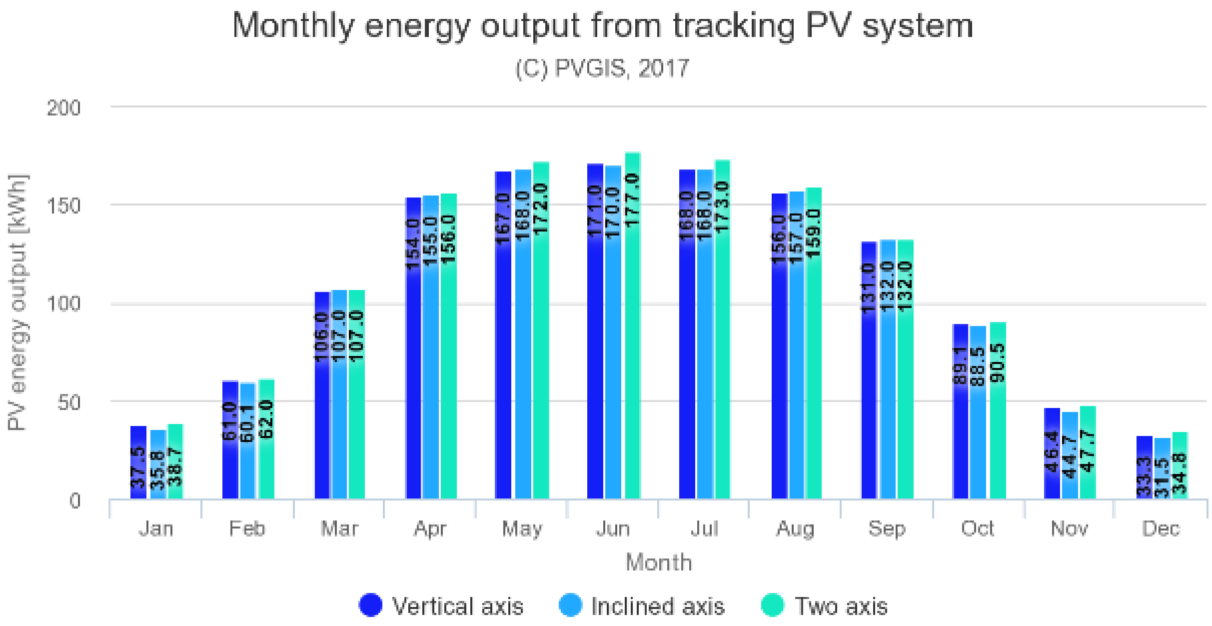


Fig. 108: Berlin - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	56 (opt)	42 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1620	1610	1660
Year to year variability [kWh]	75.2	74.5	78.1
Yearly PV energy production [kWh]	**1320**	**1320**	**1350**

Table 37: Berlin - Output parameters from tracking PV systems

PV technologies comparison

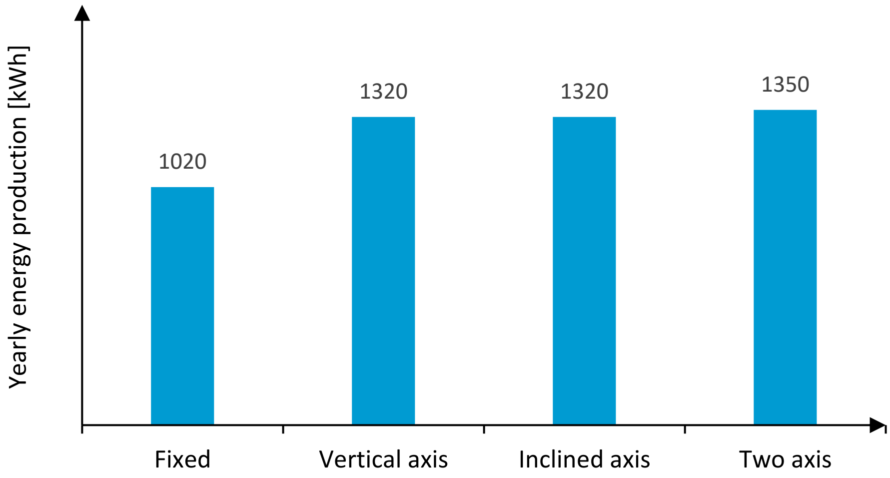


Fig. 109: Berlin - PV technologies comparison

10) Athens, Greece

Daily data

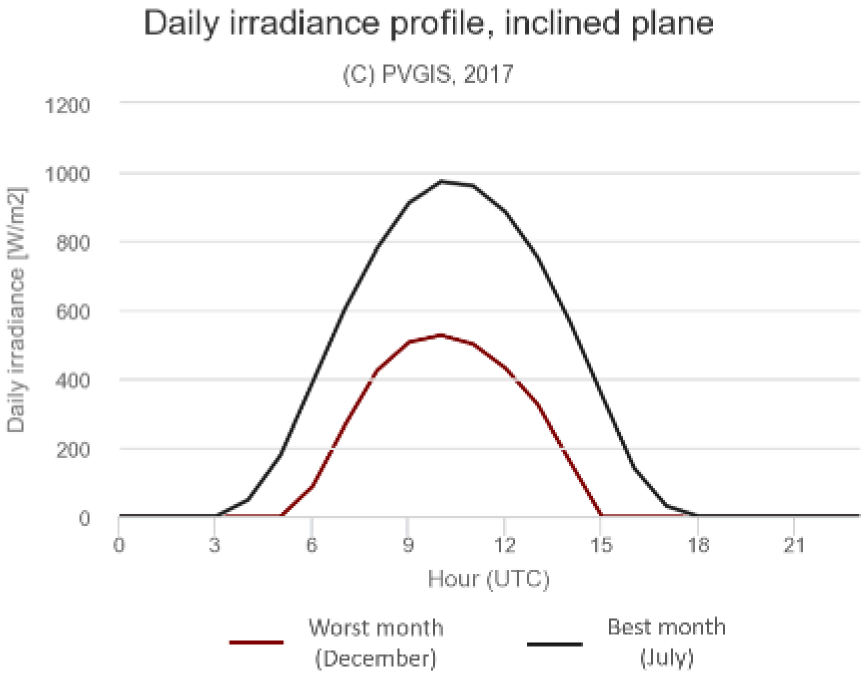


Fig. 110: Athens - Daily Irradiance

Monthly data

Fixed plate

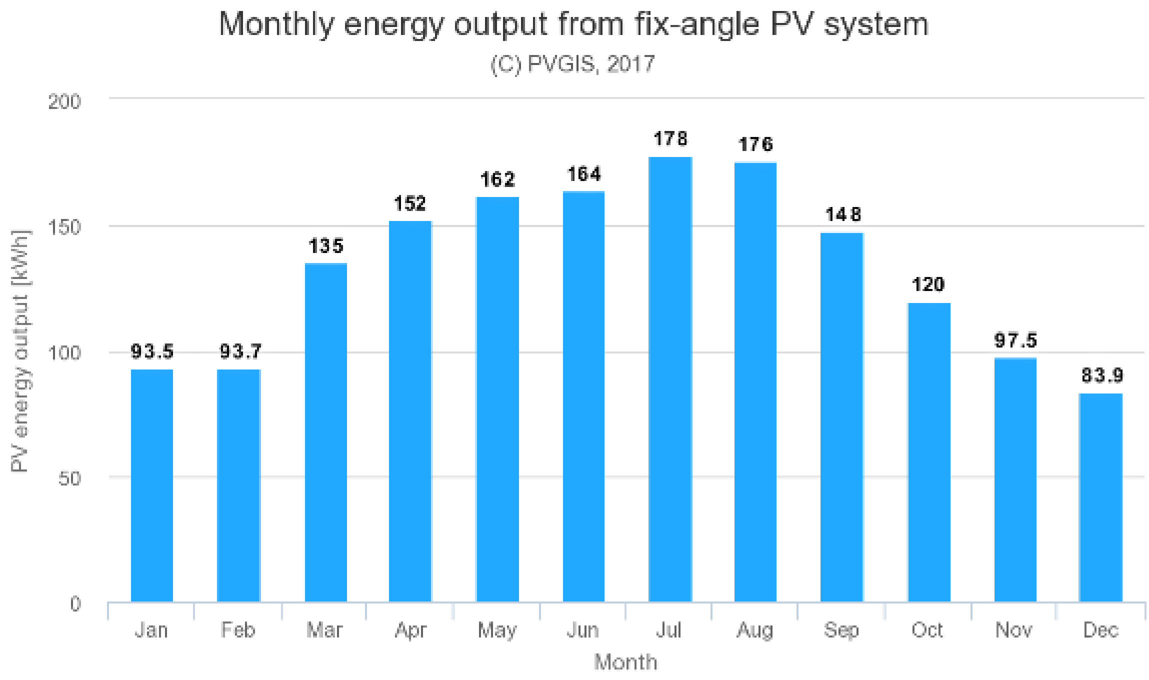


Fig. 111: Athens - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	32 (opt)
Azimuth angle [°]	2 (opt)
Yearly in-plane irradiation [kWh/m^2]	2030
Year to year variability [kWh]	57.50
Yearly PV energy production [kWh]	**1600**

Table 38: Athens - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

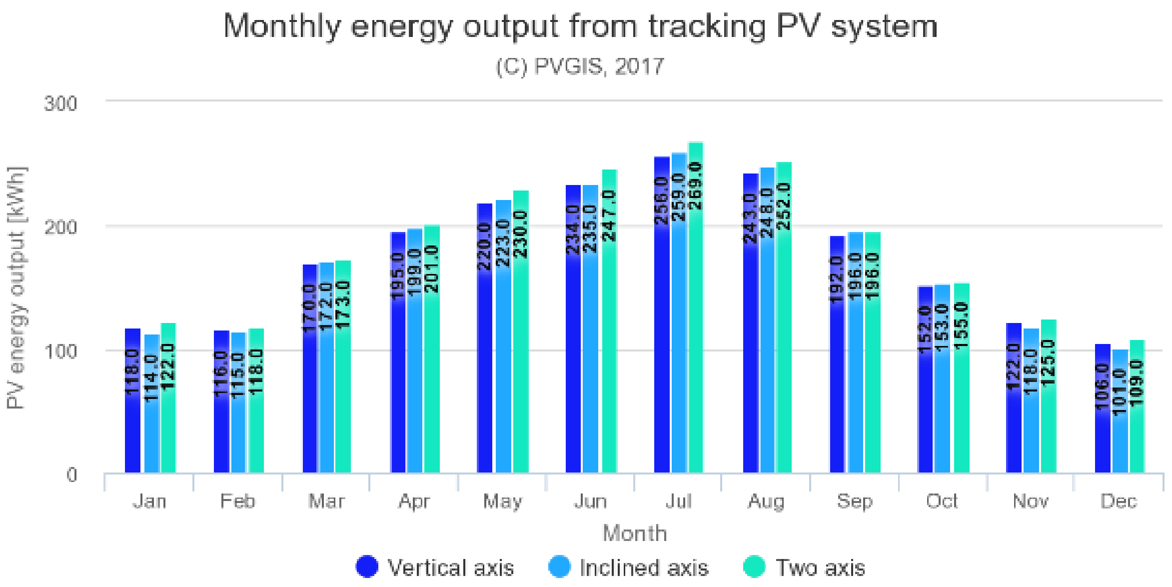


Fig. 112: Athens - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	34 (opt)	-
Yearly in-plane irradiation [kWh/m²]	2660	2670	2760
Year to year variability [kWh]	81.8	80.8	84.5
Yearly PV energy production [kWh]	**2120**	**2130**	**2200**

Table 39: Athens - Output parameters from tracking PV systems

PV technologies comparison

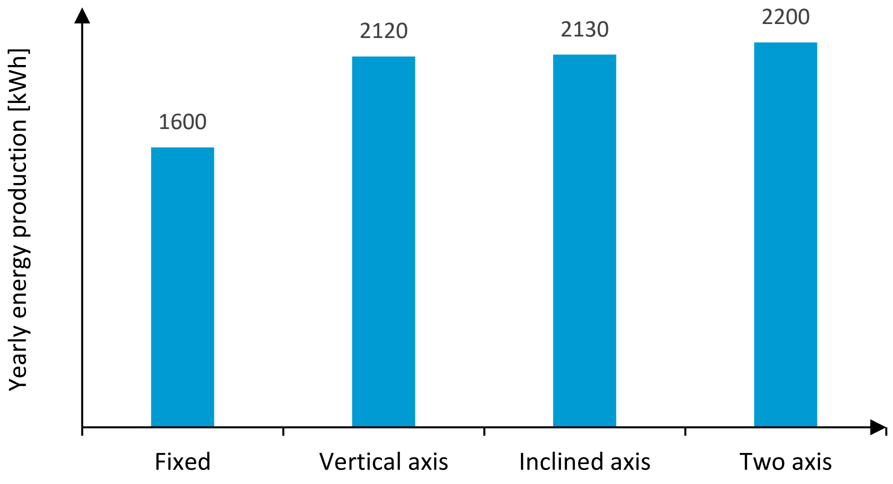


Fig. 113: Athens - PV technologies comparison

11) Budapest, Hungary

Daily data

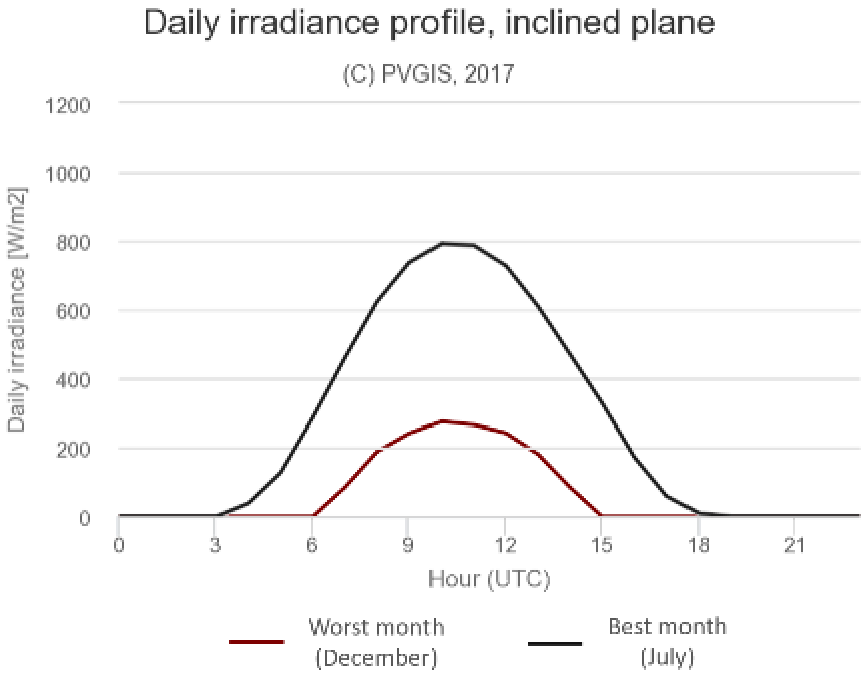


Fig. 114: Budapest - Daily Irradiance

Monthly data

Fixed plate

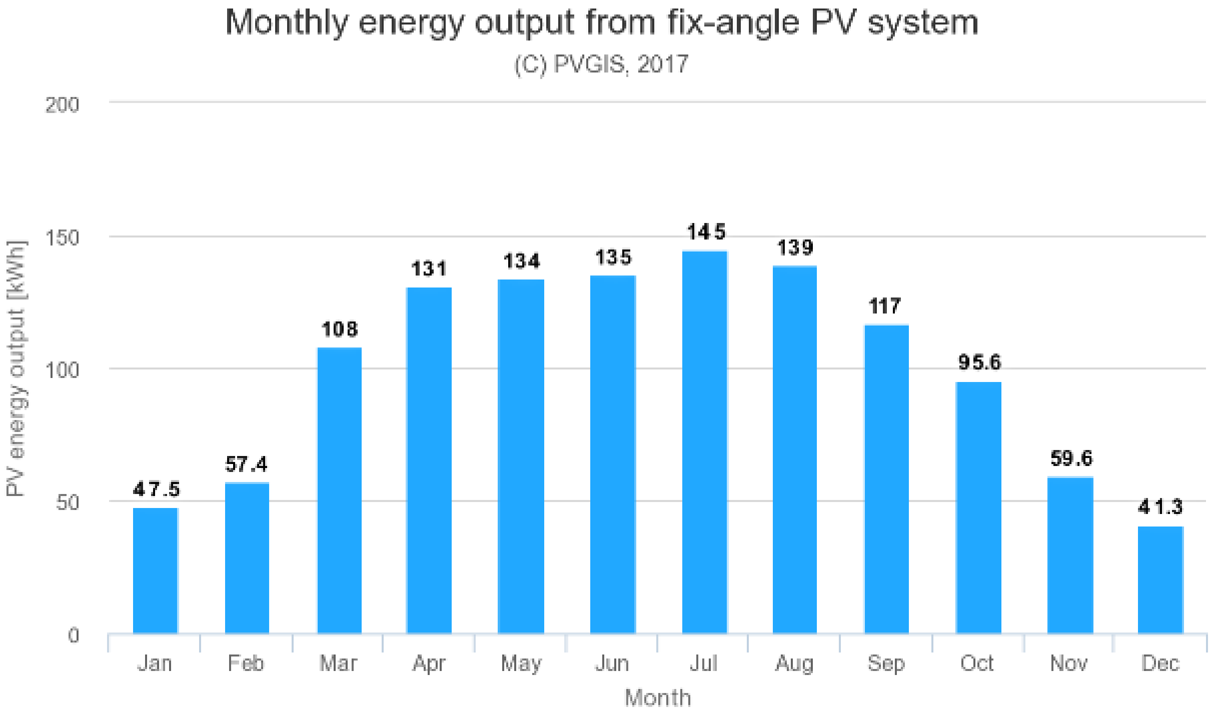


Fig. 115: Budapest - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	38 (opt)
Azimuth angle [°]	-1 (opt)
Yearly in-plane irradiation [kWh/m²]	1530
Year to year variability [kWh]	66.10
Yearly PV energy production [kWh]	**1210**

Table 40: Budapest - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

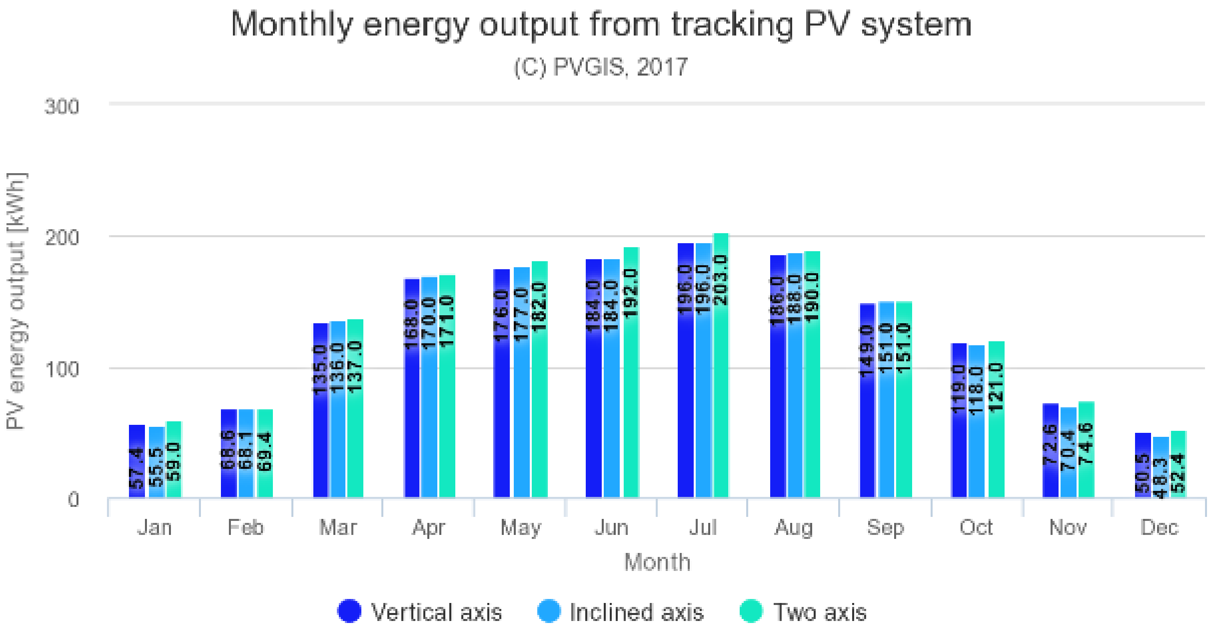


Fig. 116: Budapest - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	40 (opt)	-
Yearly in-plane irradiation [kWh/m²]	1950	1950	2000
Year to year variability [kWh]	94.1	93.7	96.8
Yearly PV energy production [kWh]	**1560**	**1560**	**1600**

Table 41: Budapest - Output parameters from tracking PV systems

PV technologies comparison

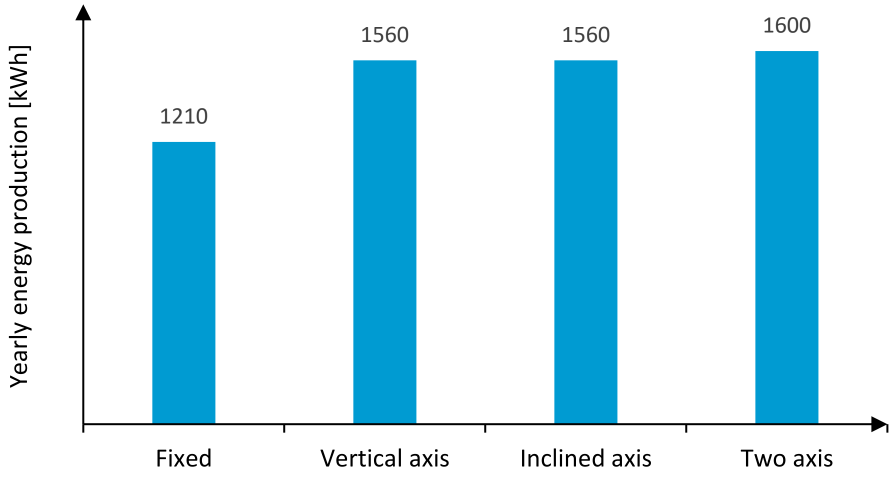


Fig. 117: Budapest - PV technologies comparison

12) Dublin, Ireland

Daily data

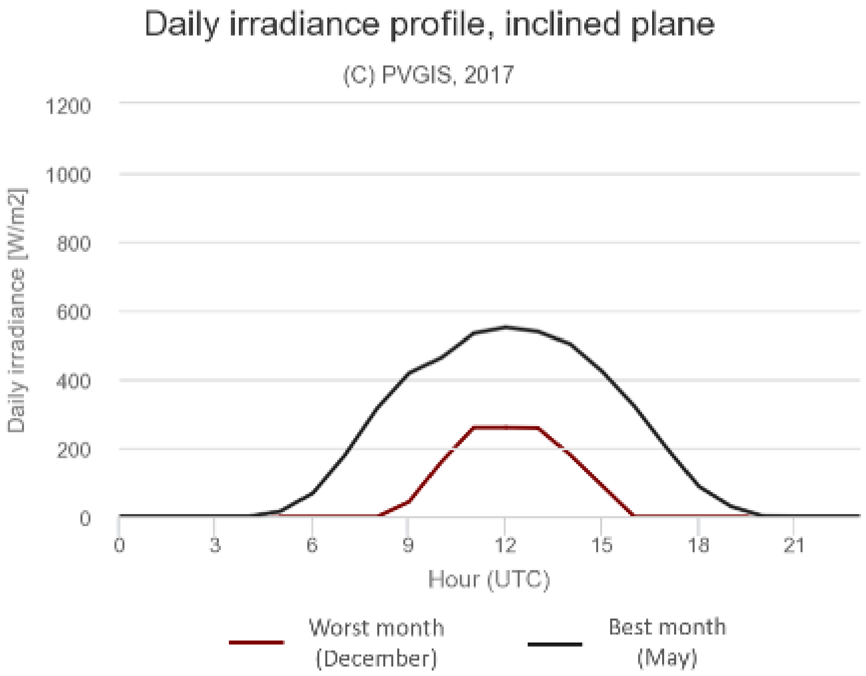


Fig. 118: Dublin - Daily Irradiance

Monthly data

Fixed plate

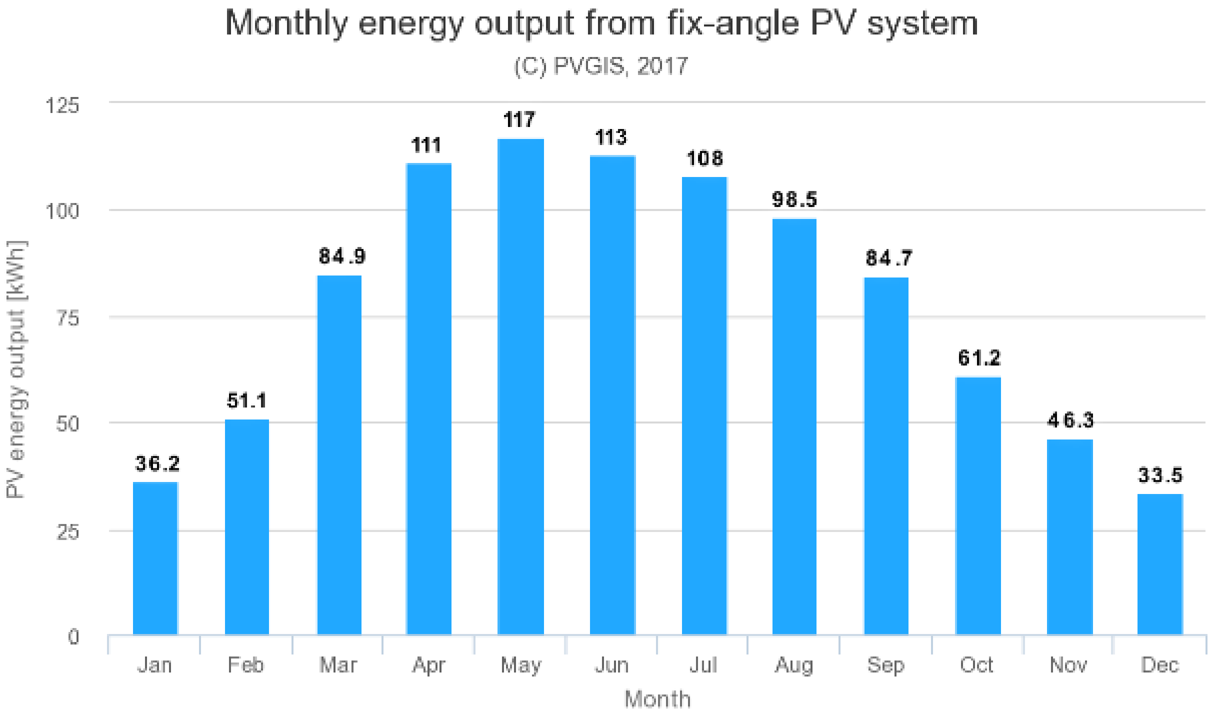


Fig. 119: Dublin - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	41 (opt)
Azimuth angle [°]	-3 (opt)
Yearly in-plane irradiation [kWh/m^2]	1150
Year to year variability [kWh]	50.00
Yearly PV energy production [kWh]	**945**

Table 42: Dublin - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

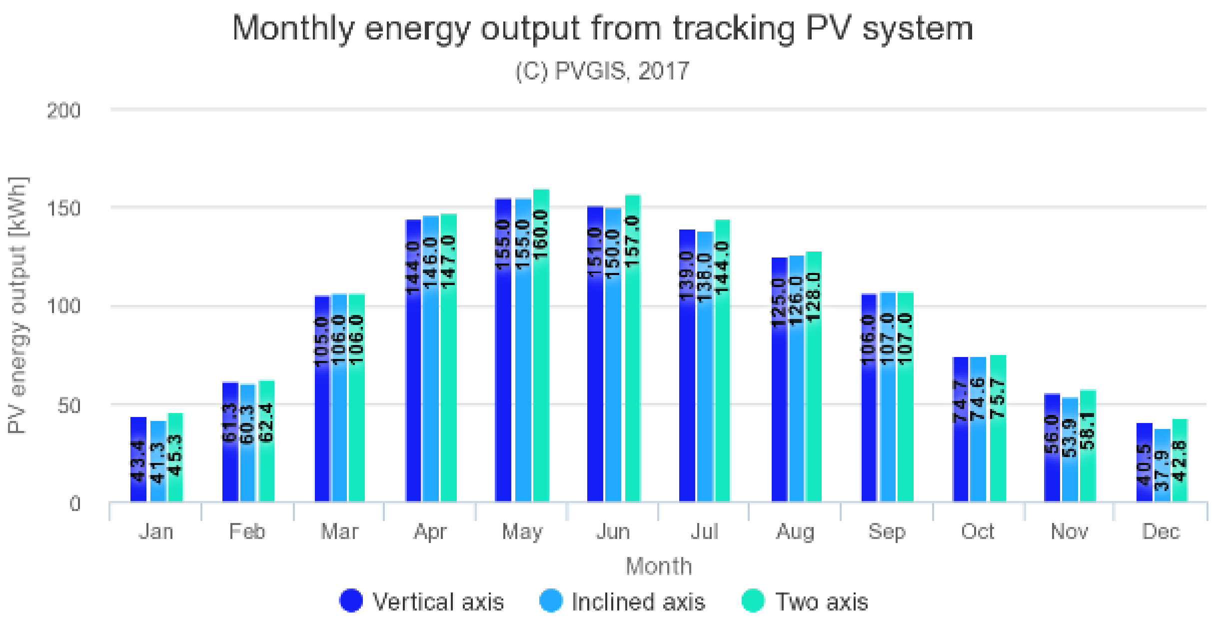


Fig. 120: Dublin - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	56 (opt)	43 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1440	1430	1470
Year to year variability [kWh]	66.4	66.3	68.0
Yearly PV energy production [kWh]	**1200**	**1200**	**1230**

Table 43: Dublin - Output parameters from tracking PV systems

PV technologies comparison

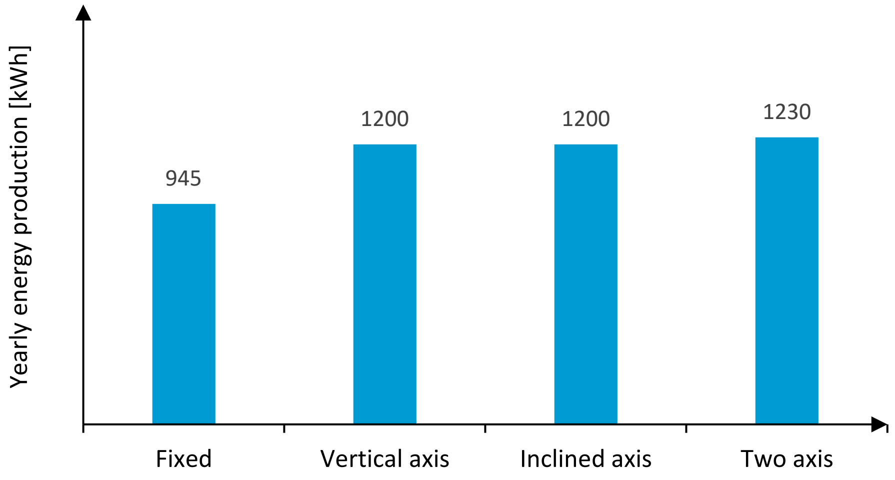


Fig. 121: Dublin - PV technologies comparison

13) Rome, Italy

Daily data

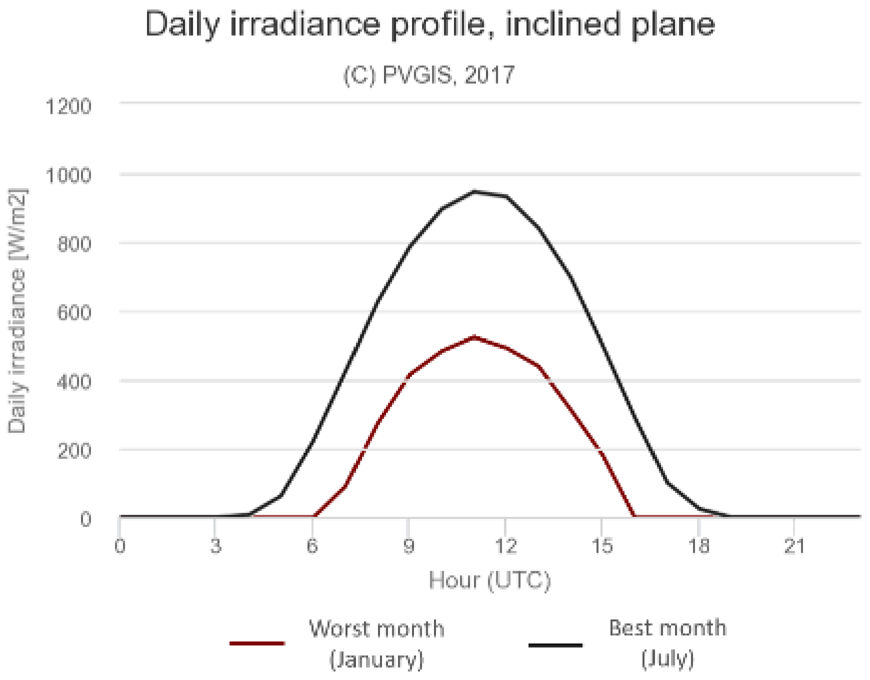


Fig. 122: Rome - Daily Irradiance

Monthly data

Fixed plate

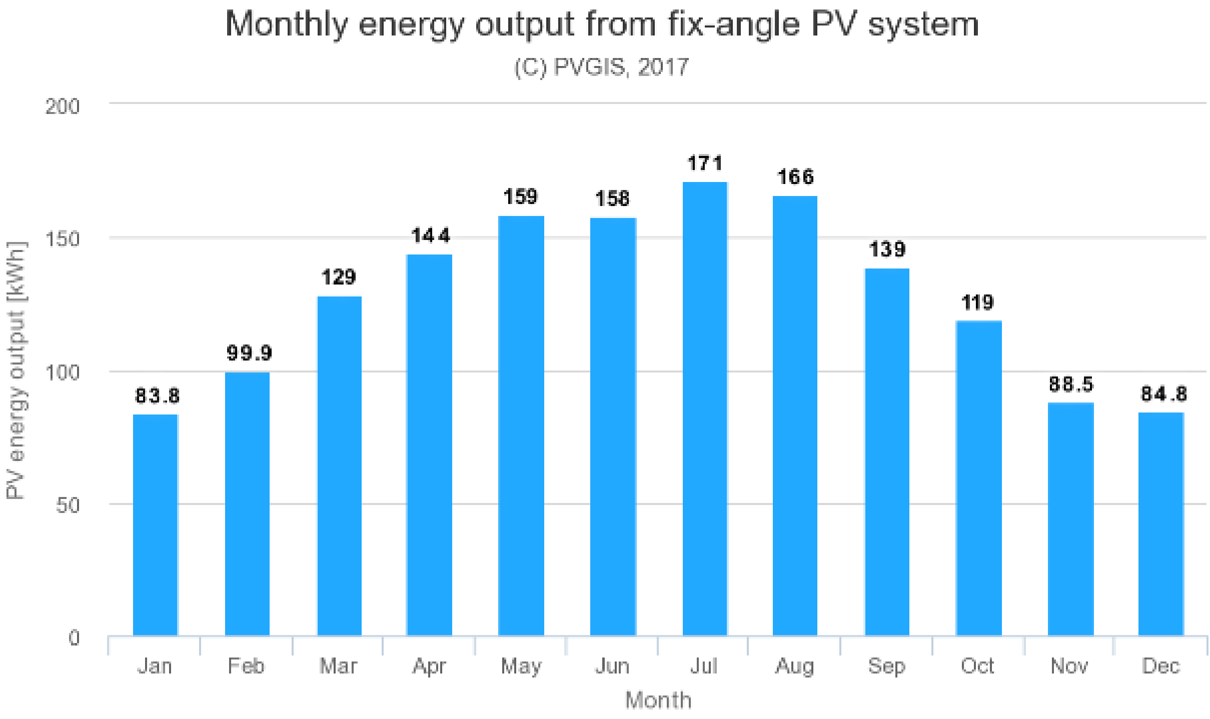


Fig. 123: Rome - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	36 (opt)
Azimuth angle [°]	2 (opt)
Yearly in-plane irradiation [kWh/m^2]	1960
Year to year variability [kWh]	49.40
Yearly PV energy production [kWh]	**1540**

Table 44: Rome - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

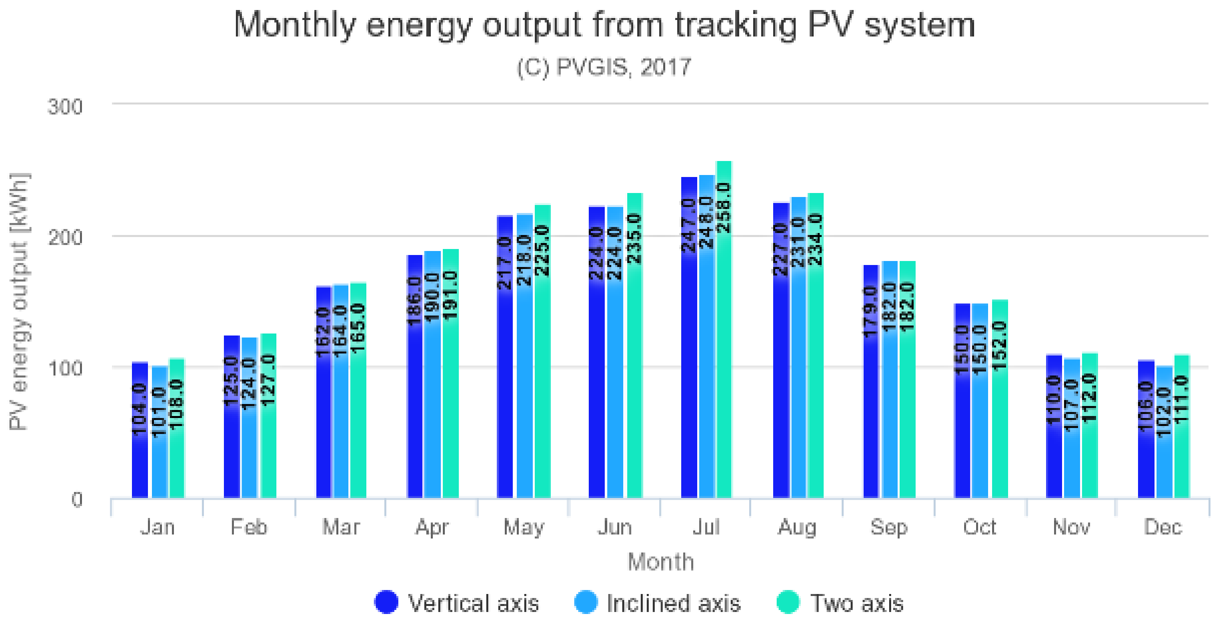


Fig. 124: Rome - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	39 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	2570	2570	2650
Year to year variability [kWh]	72.3	71.7	75.2
Yearly PV energy production [kWh]	**2040**	**2040**	**2100**

Table 45: Rome - Output parameters from tracking PV systems

PV technologies comparison

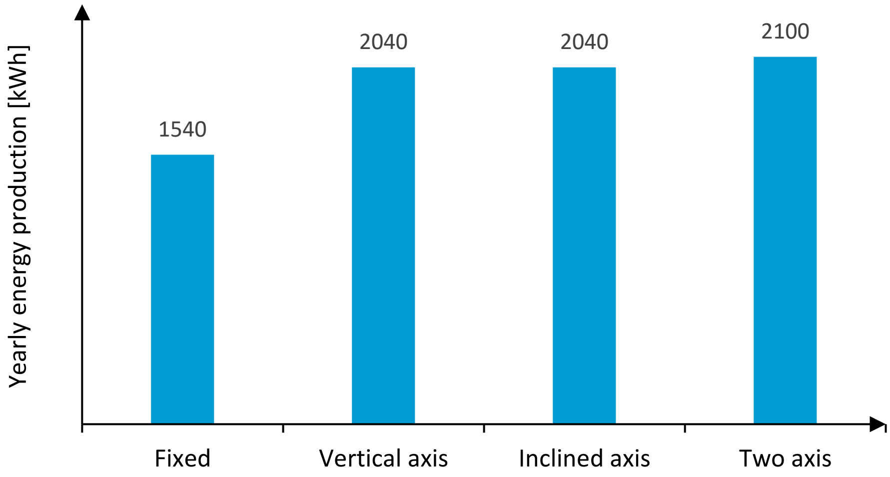


Fig. 125: Rome - PV technologies comparison

14) Riga, Latvia

Daily data

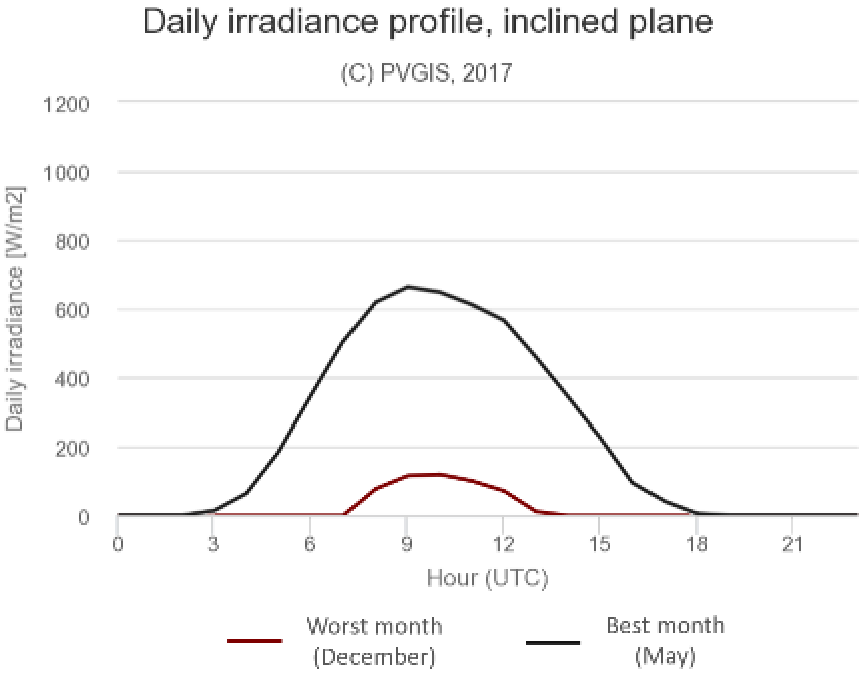


Fig. 126: Riga - Daily Irradiance

Monthly data

Fixed plate

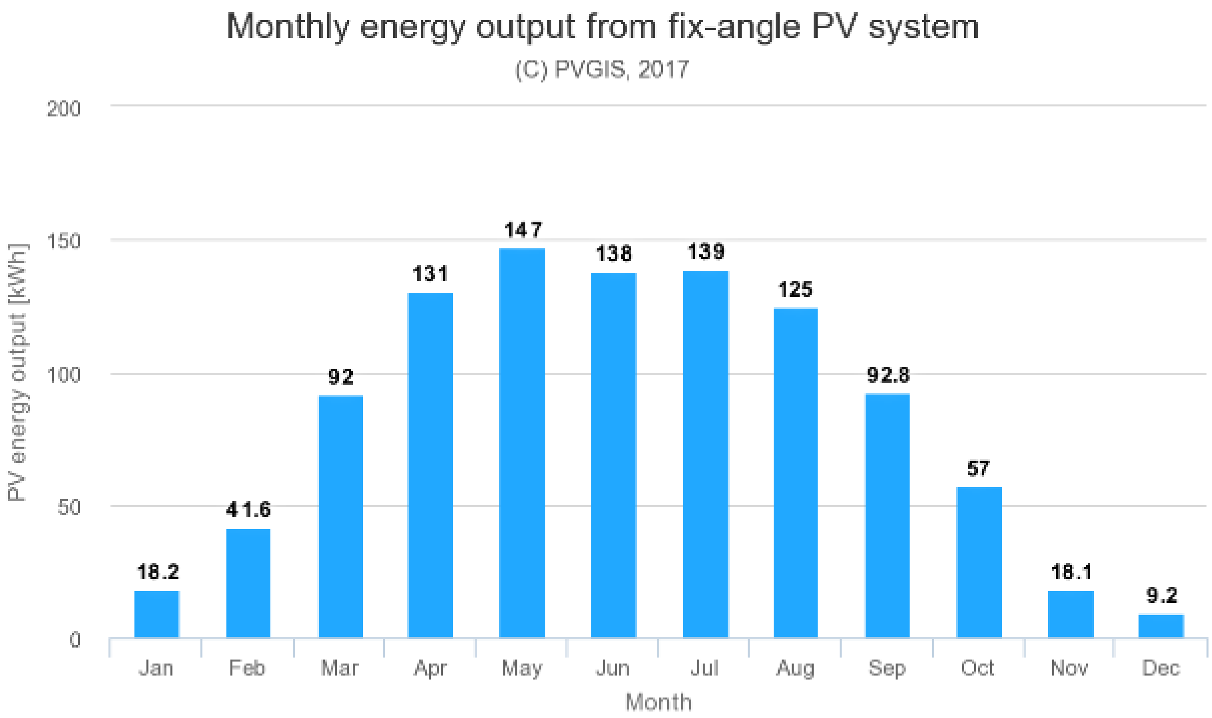


Fig. 127: Riga - Monthly energy output from fix-angle PV system

Output parameter	**Value**
Slope angle [°]	41 (opt)
Azimuth angle [°]	-5 (opt)
Yearly in-plane irradiation [kWh/m^2]	1240
Year to year variability [kWh]	62.70
Yearly PV energy production [kWh]	**1010**

Table 46: Riga - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

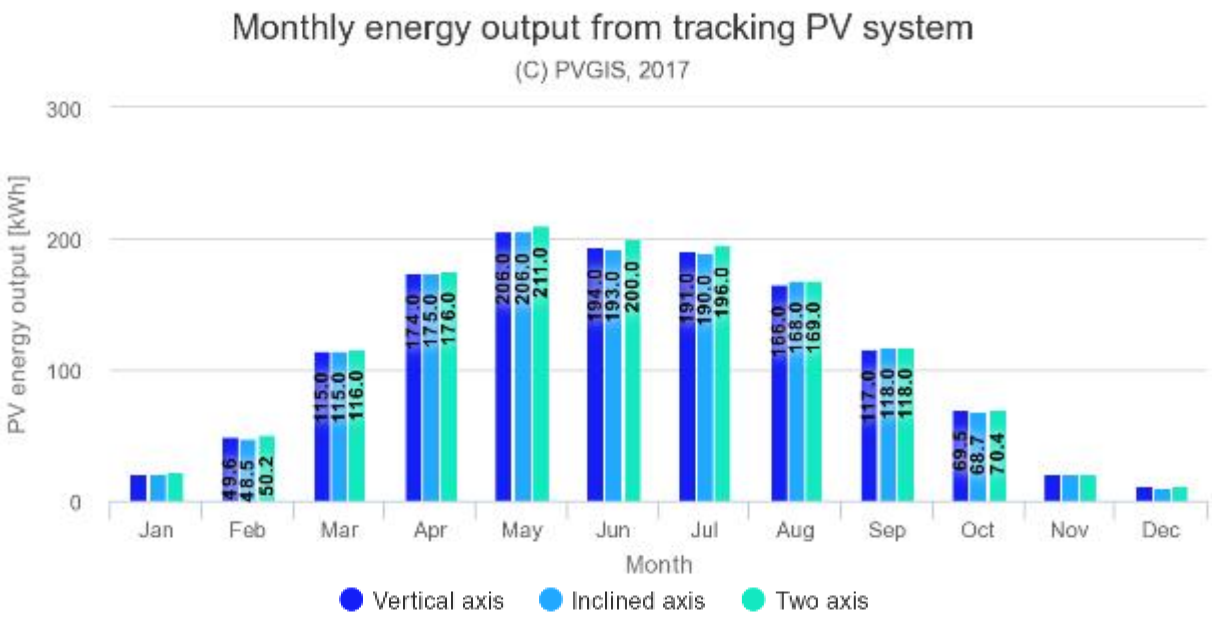


Fig. 128: Riga - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	58 (opt)	44 (opt)	-
Yearly in-plane irradiation [kWh/m²]	1620	1620	1650
Year to year variability [kWh]	102.0	100.0	107.0
Yearly PV energy production [kWh]	**1340**	**1330**	**1360**

Table 47: Riga - Output parameters from tracking PV systems

PV technologies comparison

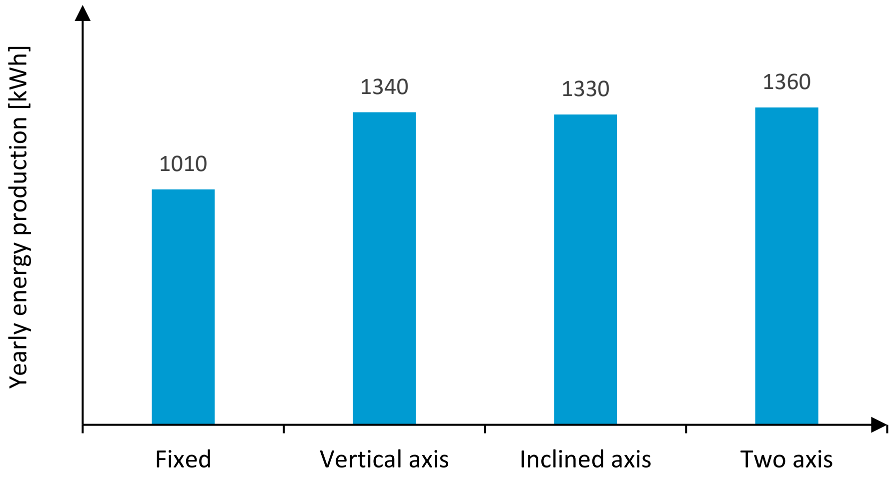


Fig. 129: Riga - PV technologies comparison

15) Warsaw, Poland

Daily data

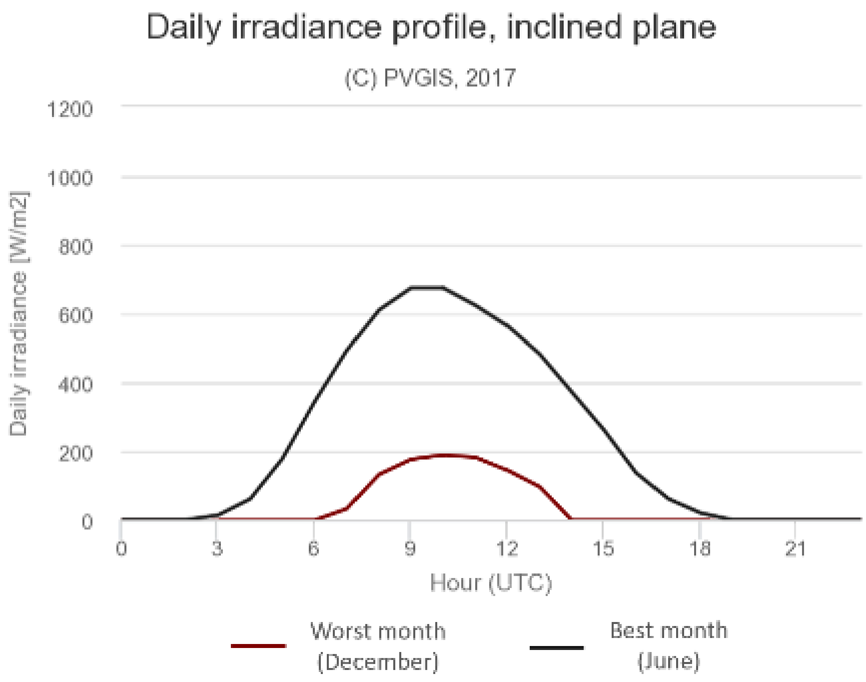


Fig. 130: Warsaw - Daily Irradiance

Monthly data

<u>Fixed plate</u>

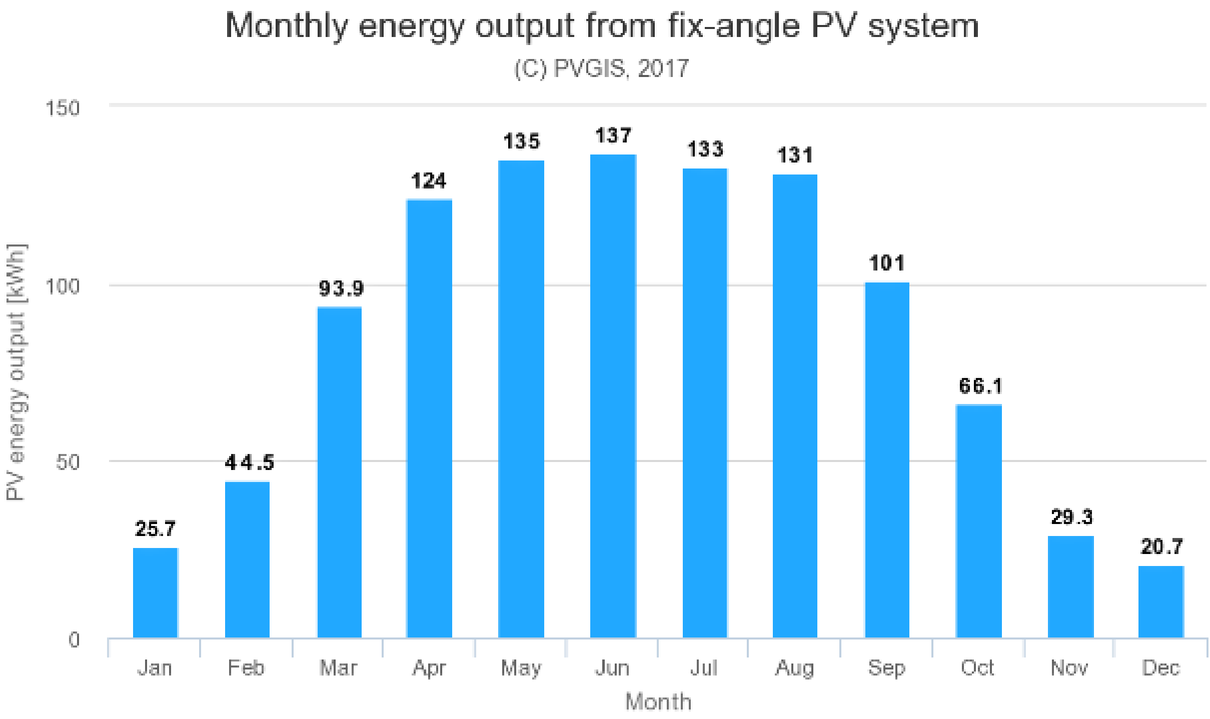


Fig. 131: Warsaw - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	37 (opt)
Azimuth angle [°]	-7 (opt)
Yearly in-plane irradiation [kWh/m^2]	1290
Year to year variability [kWh]	47.50
Yearly PV energy production [kWh]	**1040**

Table 48: Warsaw - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

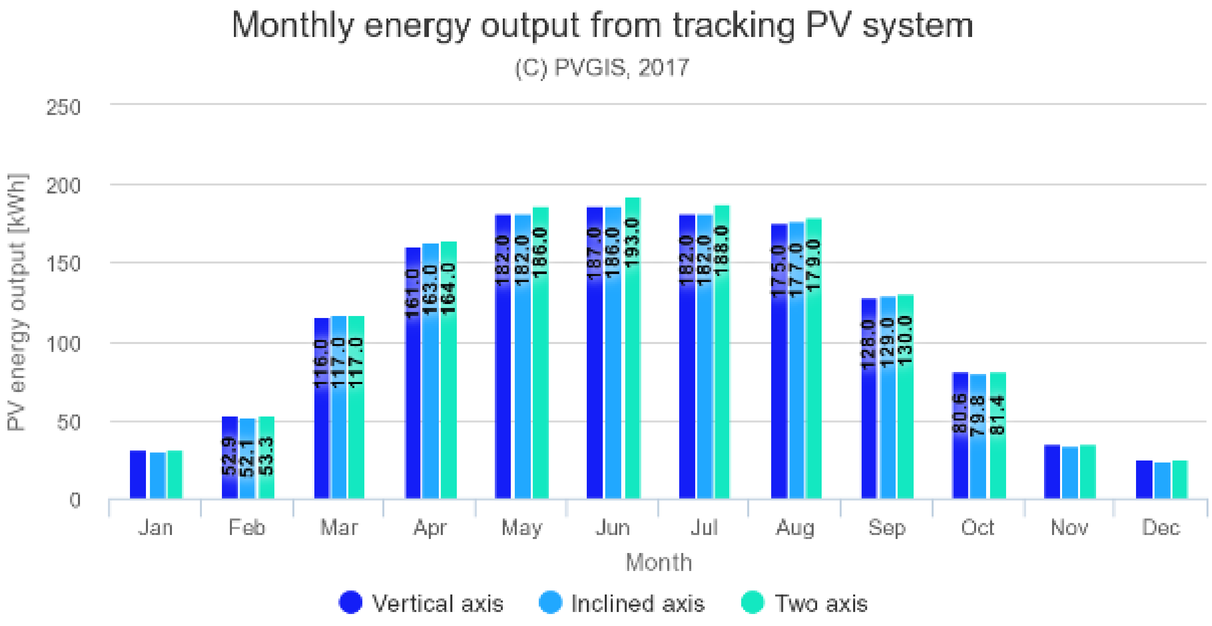


Fig. 132: Warsaw - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	40 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1660	1660	1690
Year to year variability [kWh]	63.2	62.4	64.6
Yearly PV energy production [kWh]	**1360**	**1360**	**1380**

Table 49: Warsaw - Output parameters from tracking PV systems

PV technologies comparison

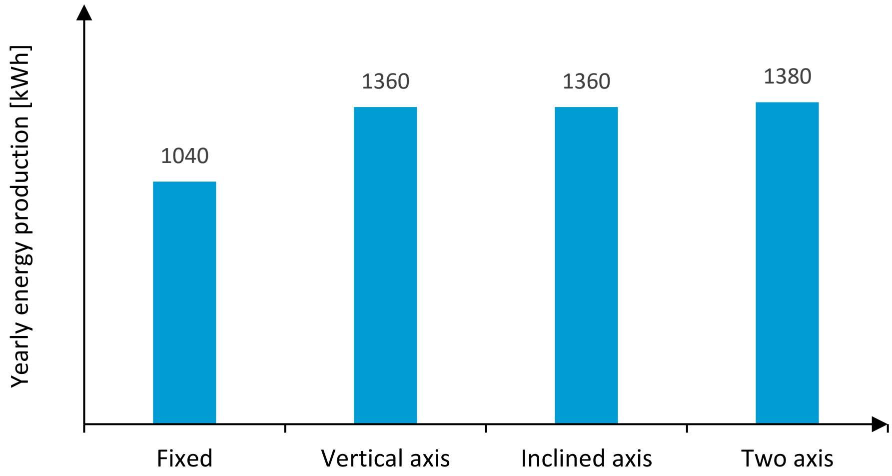


Fig. 133: Warsaw - PV technologies comparison

16) Lisbon, Portugal

Daily data

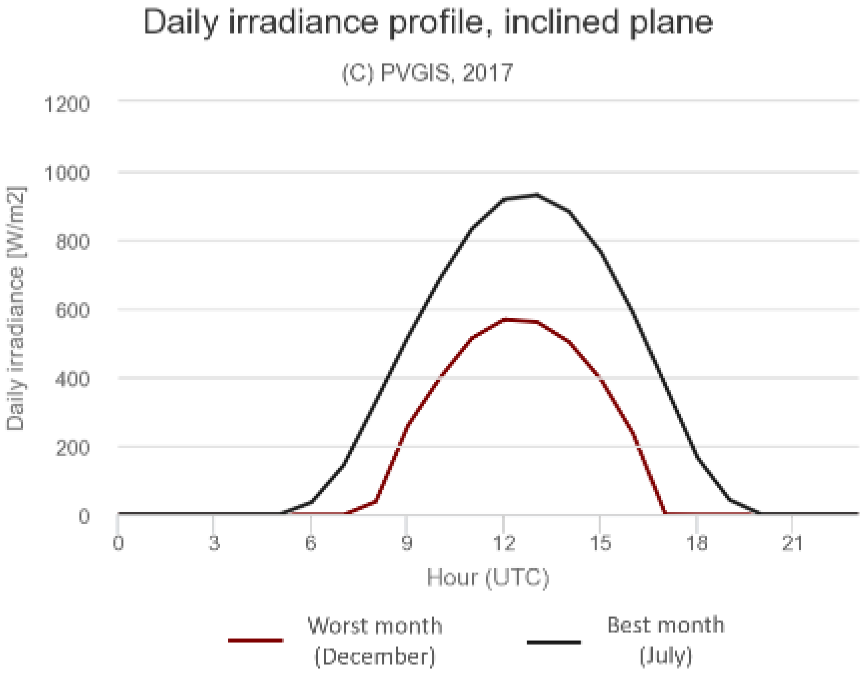


Fig. 134: Lisbon - Daily Irradiance

Monthly data

Fixed plate

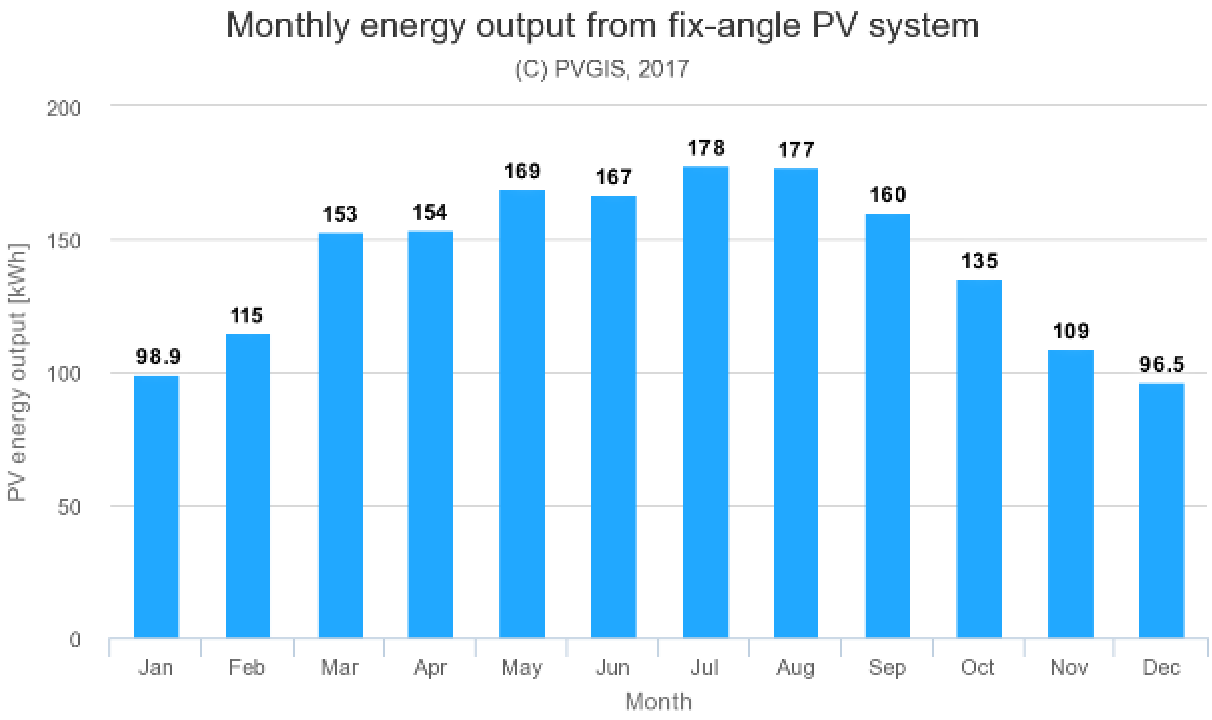


Fig. 135: Lisbon - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	33 (opt)
Azimuth angle [°]	0 (opt)
Yearly in-plane irradiation [kWh/m^2]	2170
Year to year variability [kWh]	58.90
Yearly PV energy production [kWh]	**1710**

Table 50: Lisbon - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

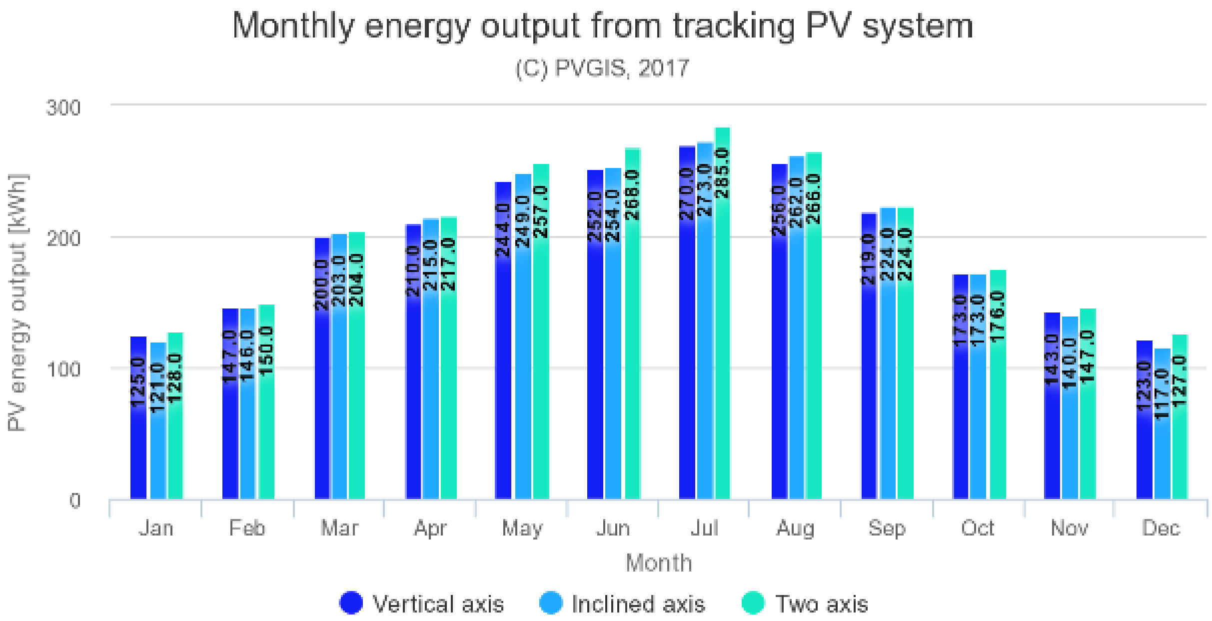


Fig. 136: Lisbon - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	36 (opt)	-
Yearly in-plane irradiation [kWh/m²]	2950	2980	3070
Year to year variability [kWh]	83.0	81.0	86.6
Yearly PV energy production [kWh]	**2360**	**2380**	**2450**

Table 51: Lisbon - Output parameters from tracking PV systems

PV technologies comparison

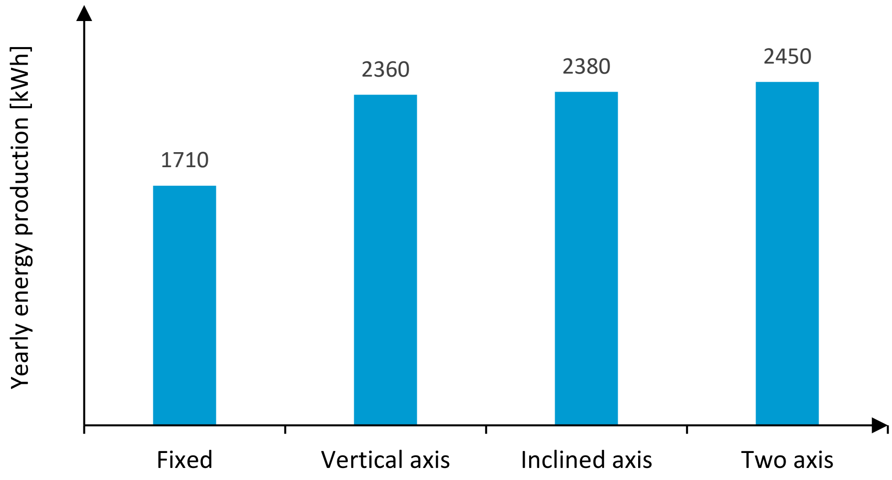


Fig. 137: Lisbon - PV technologies comparison

17) Bucharest, Romania

Daily data

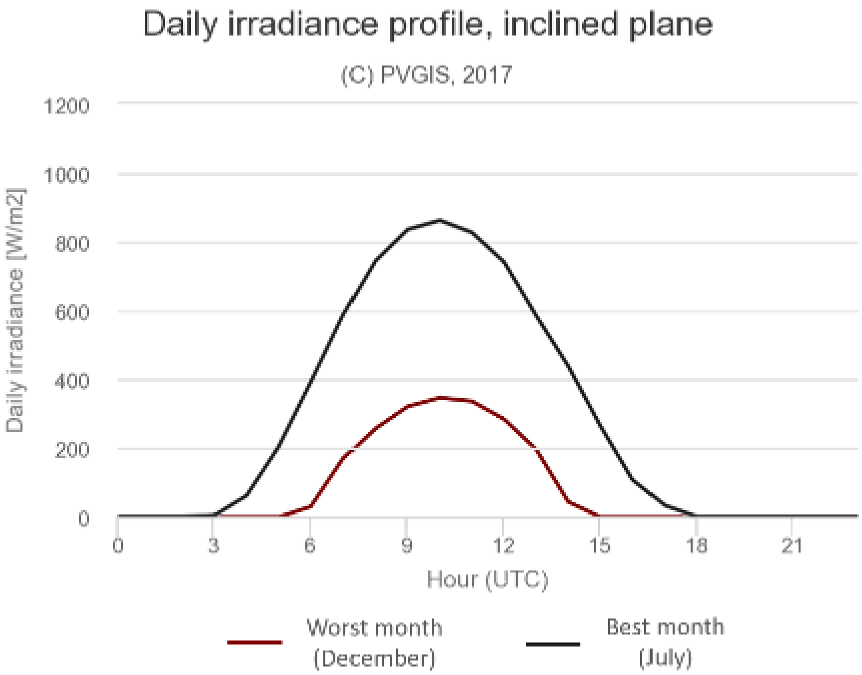


Fig. 138: Bucharest - Daily Irradiance

Monthly data

Fixed plate

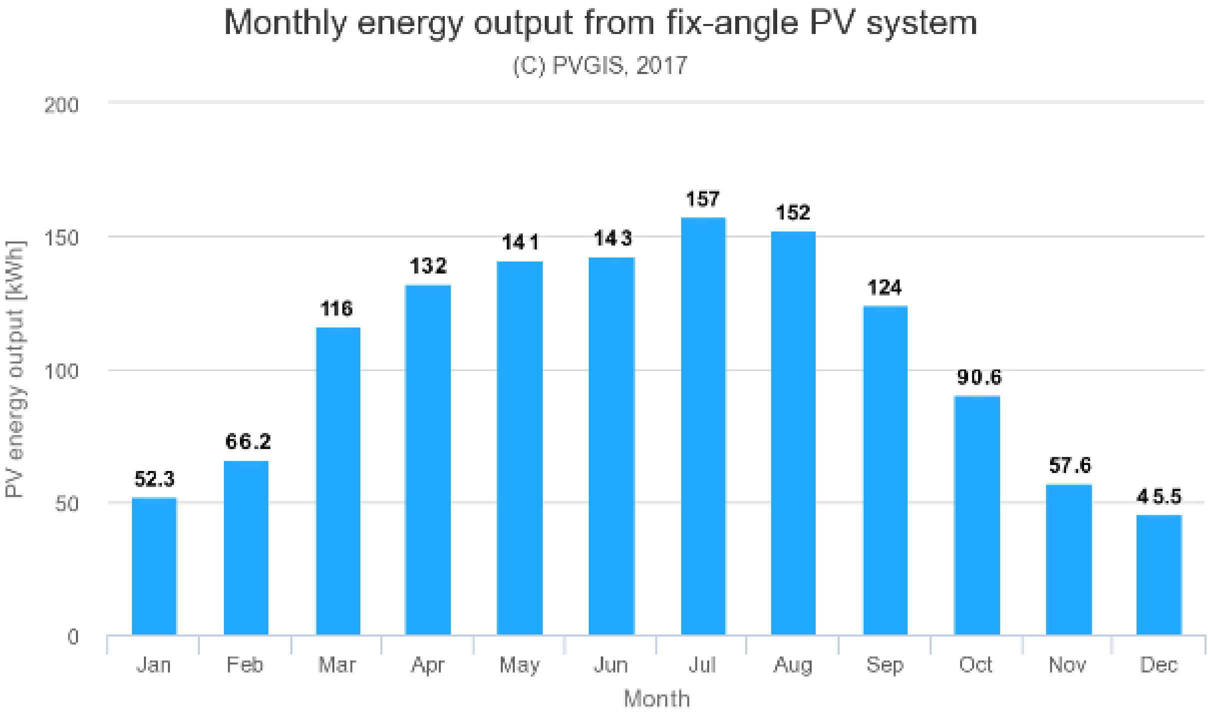


Fig. 139: Bucharest - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	35 (opt)
Azimuth angle [°]	-1 (opt)
Yearly in-plane irradiation [kWh/m^2]	1620
Year to year variability [kWh]	62.50
Yearly PV energy production [kWh]	**1280**

Table 52: Bucharest - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

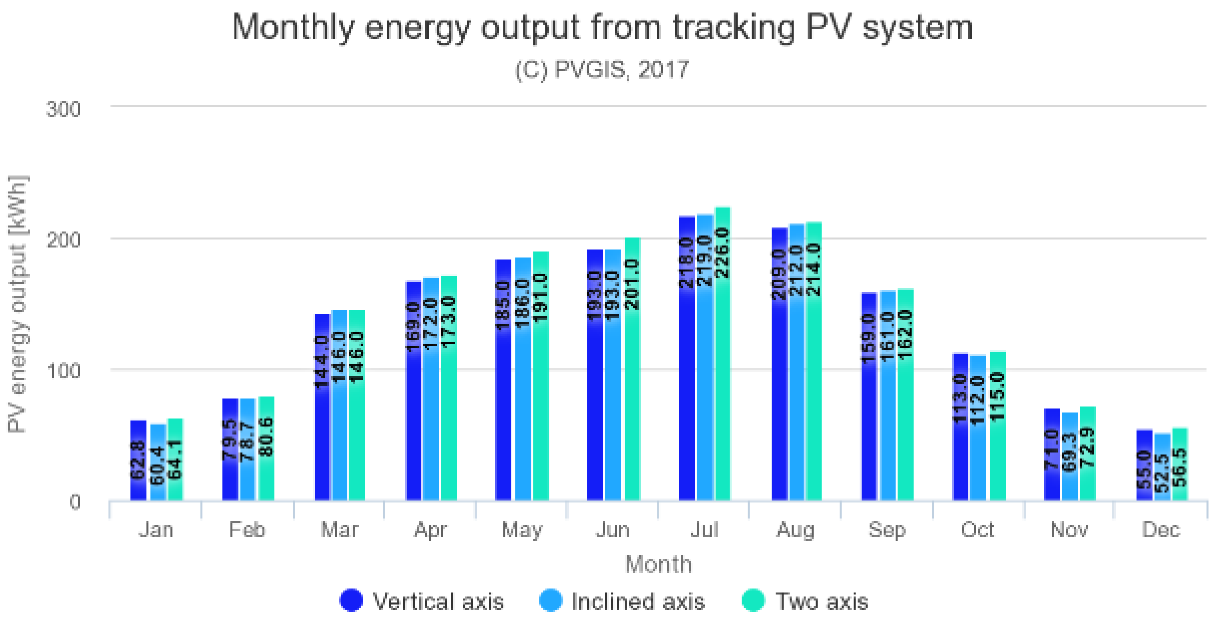


Fig. 140: Bucharest - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	37 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	2090	2090	2140
Year to year variability [kWh]	90.0	89.4	93.0
Yearly PV energy production [kWh]	**1660**	**1660**	**1700**

Table 53: Bucharest - Output parameters from tracking PV systems

PV technologies comparison

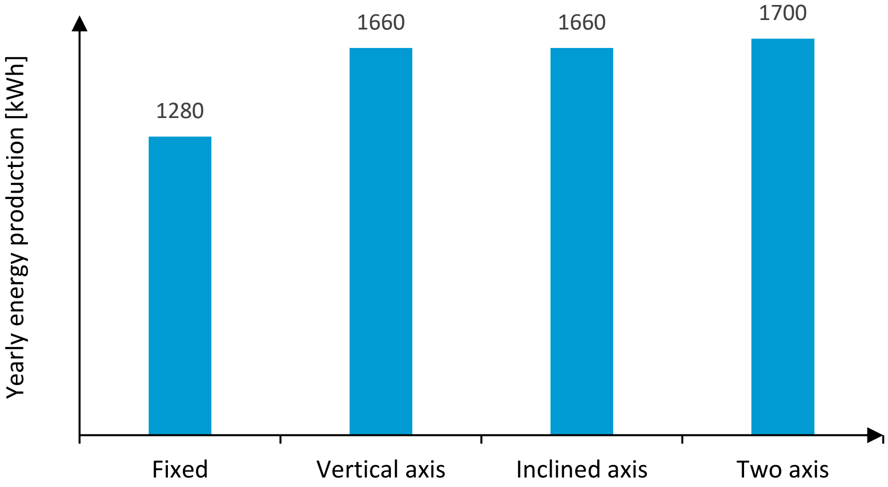


Fig. 141: Bucharest - PV technologies comparison

18) Madrid, Spain

Daily data

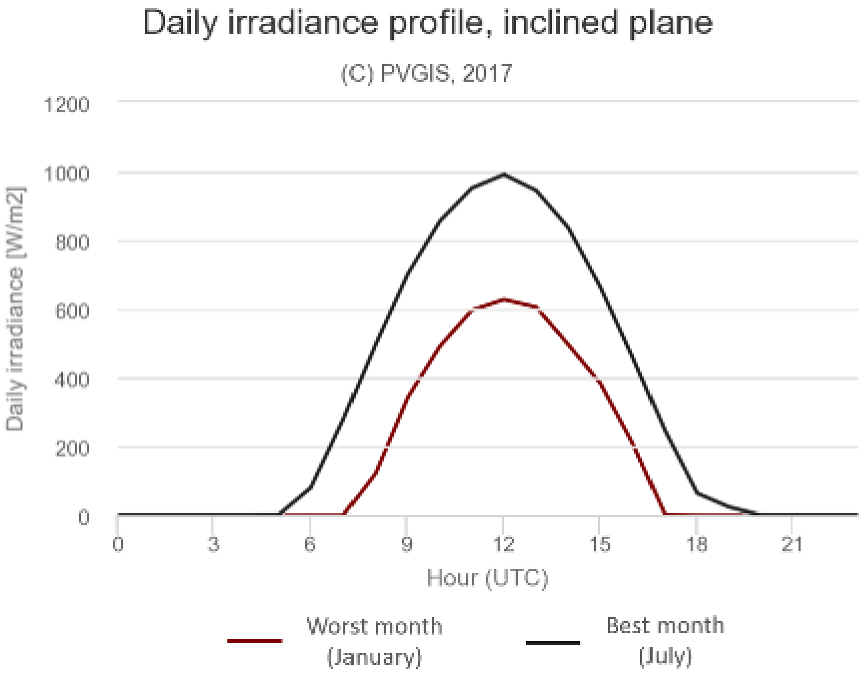


Fig. 142: Madrid - Daily Irradiance

Monthly data

Fixed plate

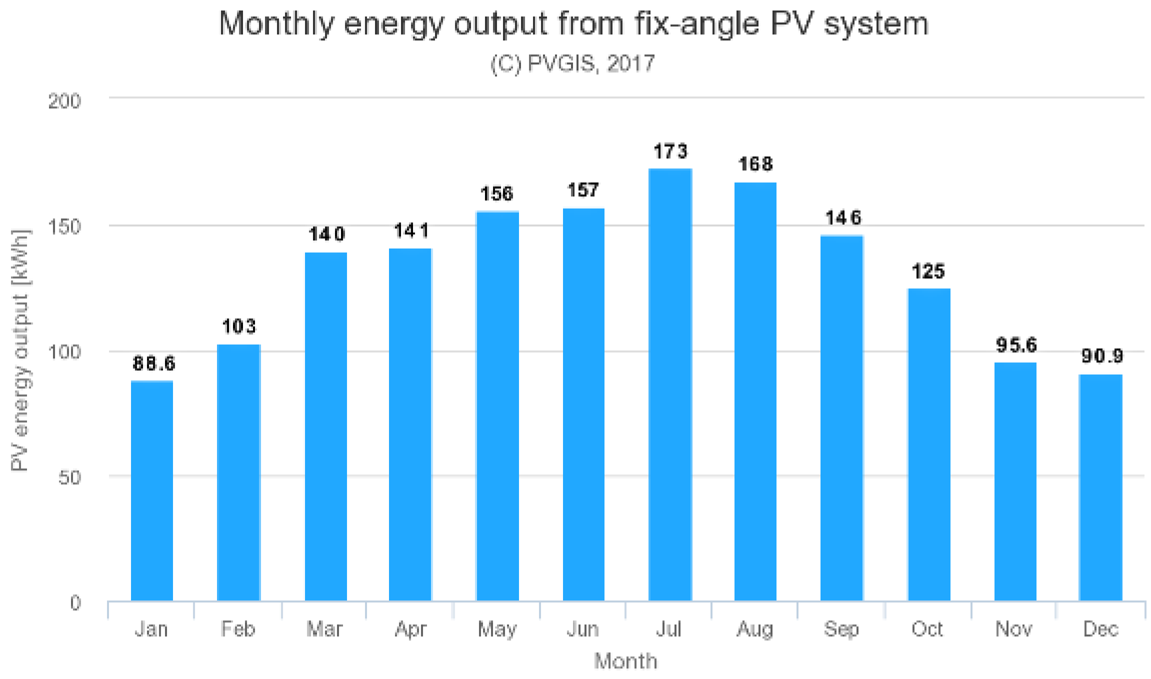


Fig. 143: Madrid - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	35 (opt)
Azimuth angle [°]	-8 (opt)
Yearly in-plane irradiation [kWh/m^2]	2010
Year to year variability [kWh]	33.10
Yearly PV energy production [kWh]	**1580**

Table 54: Madrid - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

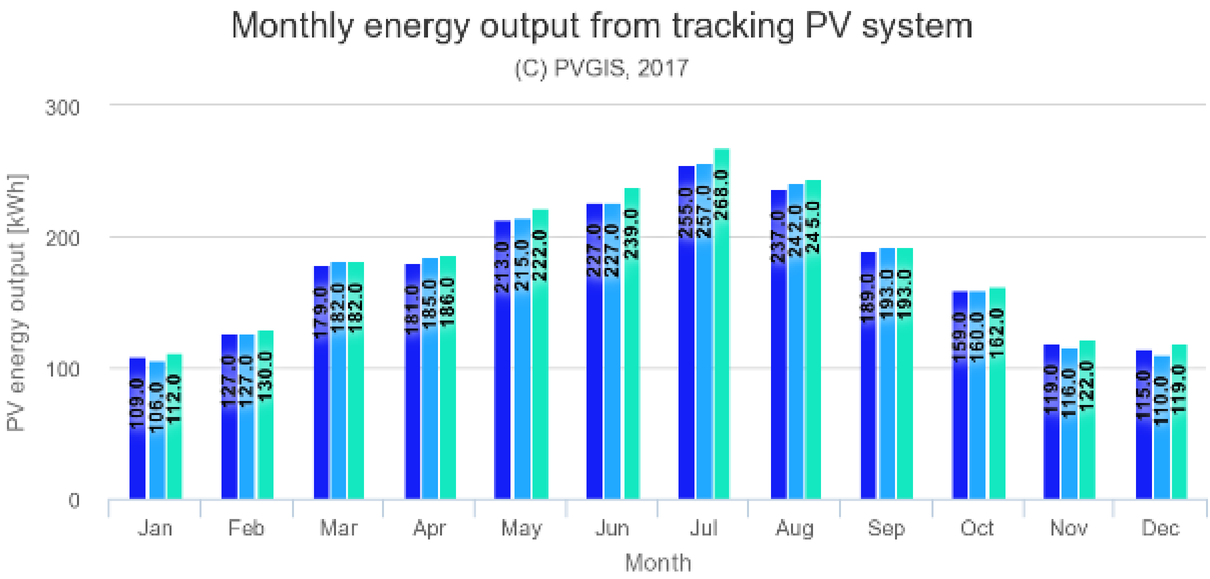


Fig. 144: Madrid - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	54 (opt)	38 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	2660	2670	2750
Year to year variability [kWh]	50.0	50.2	51.9
Yearly PV energy production [kWh]	**2110**	**2120**	**2180**

Table 55: Madrid - Output parameters from tracking PV systems

PV technologies comparison

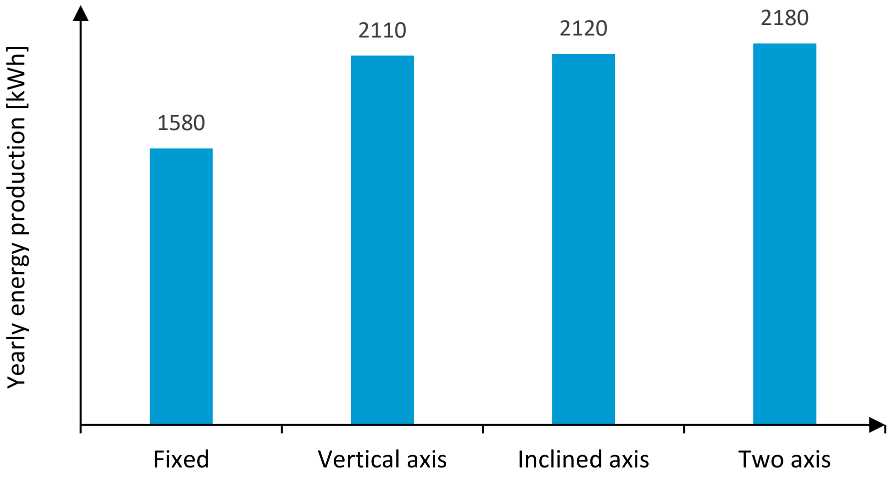


Fig. 145: Madrid - PV technologies comparison

19) Stockholm, Sweden

Daily data

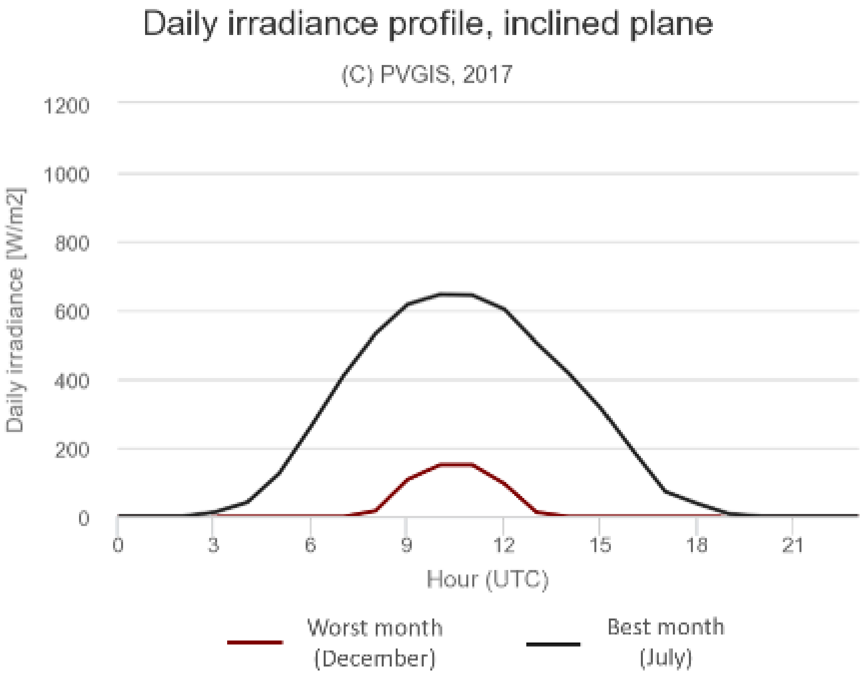


Fig. 146: Stockholm - Daily Irradiance

Monthly data

Fixed plate

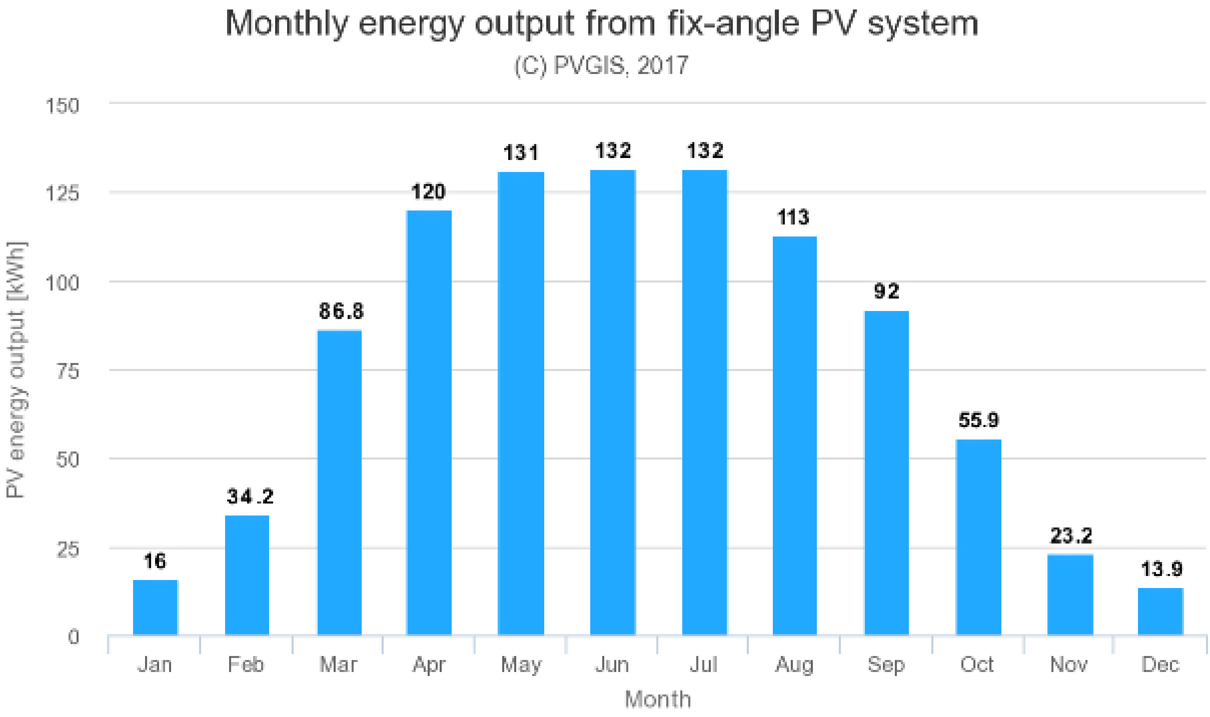


Fig. 147: Stockholm - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	44 (opt)
Azimuth angle [°]	-1 (opt)
Yearly in-plane irradiation [kWh/m^2]	1170
Year to year variability [kWh]	32.40
Yearly PV energy production [kWh]	**950**

Table 56: Stockholm - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

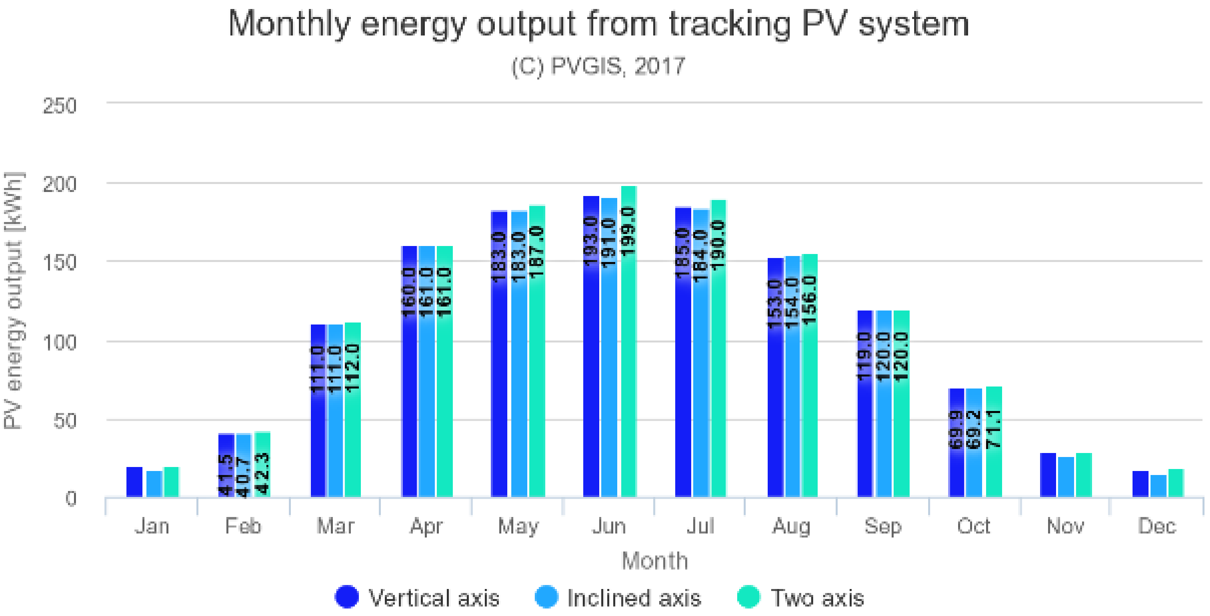


Fig. 148: Stockholm - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	59 (opt)	47 (opt)	-
Yearly in-plane irradiation [kWh/m^2]	1550	1540	1580
Year to year variability [kWh]	49.3	48.8	50.8
Yearly PV energy production [kWh]	**1280**	**1270**	**1310**

Table 57: Stockholm - Output parameters from tracking PV systems

PV technologies comparison

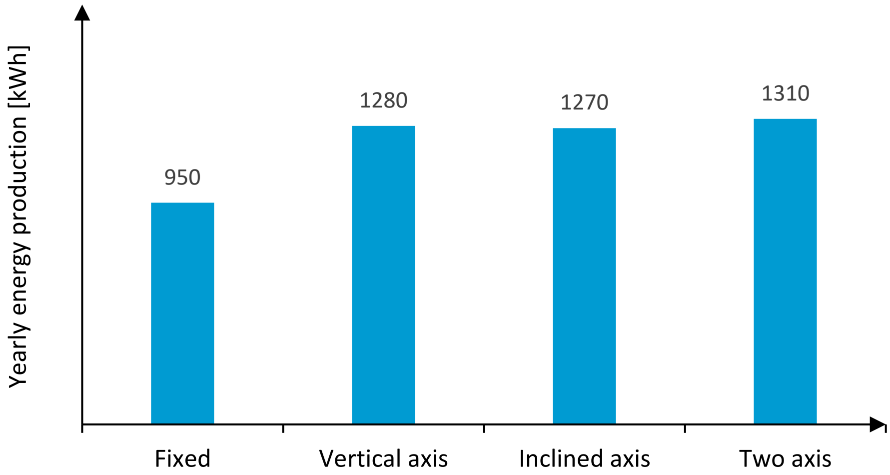


Fig. 149: Stockholm - PV technologies comparison

20) London, United Kingdom

Daily data

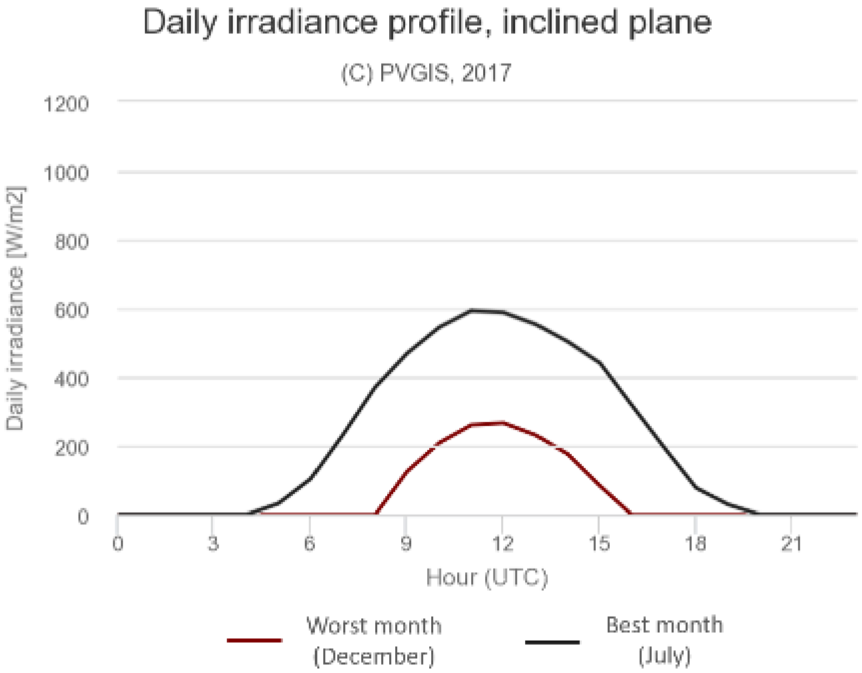


Fig. 150: London - Daily Irradiance

Monthly data

Fixed plate

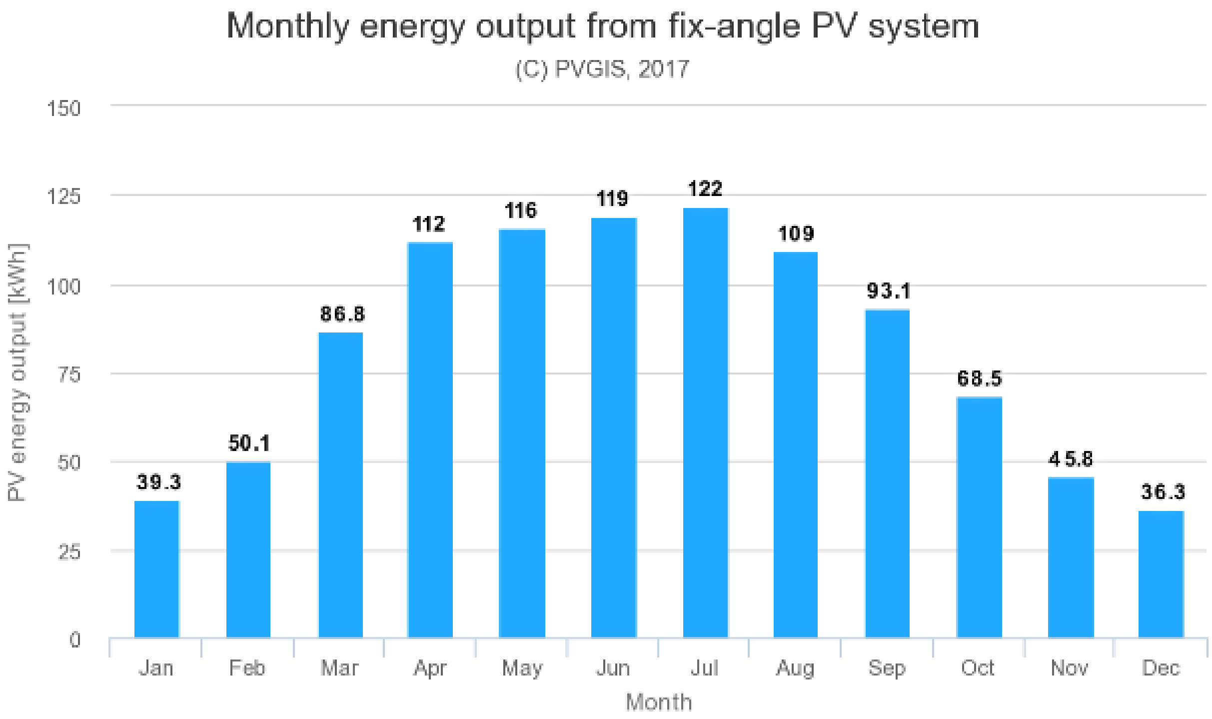


Fig. 151: London - Monthly energy output from fix-angle PV system

Output parameter	Value
Slope angle [°]	39 (opt)
Azimuth angle [°]	-3 (opt)
Yearly in-plane irradiation [kWh/m^2]	1230
Year to year variability [kWh]	38.90
Yearly PV energy production [kWh]	**997**

Table 58: London - Output parameters from fix-angle PV system

Tracking plates (Vertical axis, Inclined axis and Two-axis)

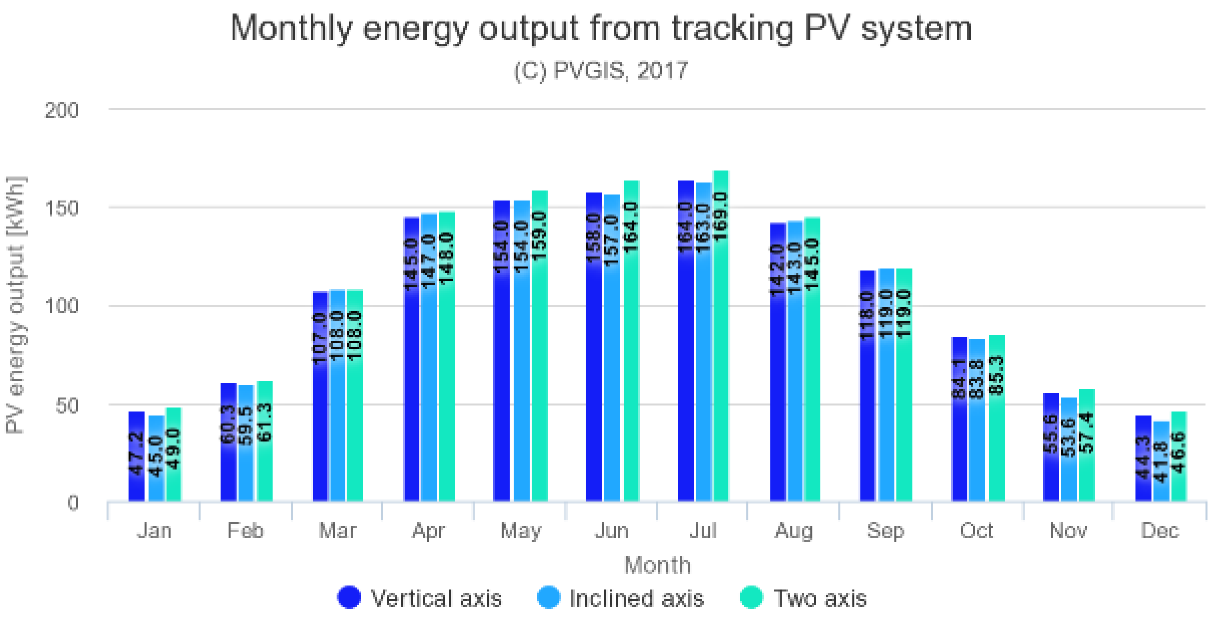


Fig. 152: London - Monthly energy output from tracking PV systems

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	55 (opt)	42 (opt)	-
Yearly in-plane irradiation [kWh/m²]	1550	1550	1590
Year to year variability [kWh]	49.9	49.8	51.0
Yearly PV energy production [kWh]	**1280**	**1270**	**1310**

Table 59: London - Output parameters from tracking PV systems

PV technologies comparison

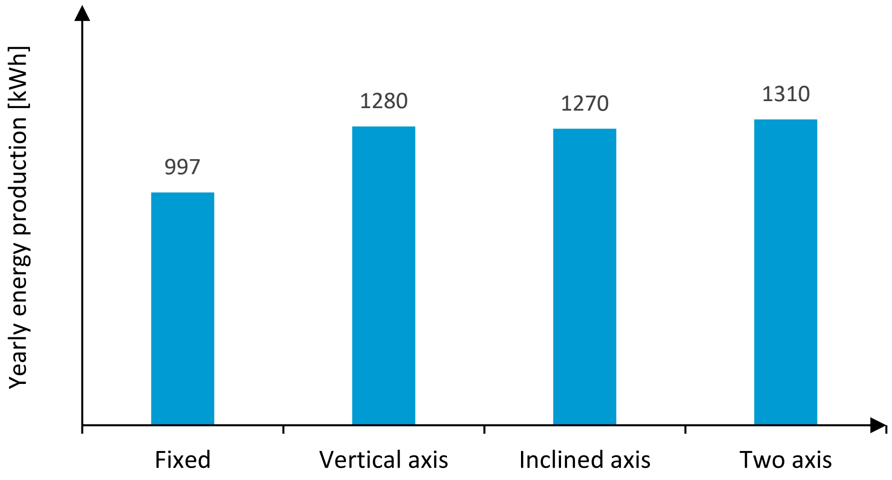


Fig. 153: London - PV technologies comparison

7 RESUMEN

7.1 INTRODUCCIÓN

Actualmente, parece innegable el hecho de que el sol se ha convertido en una de las fuentes de energía renovable más importantes en todo el mundo, proporcionando recursos enormes para generar electricidad limpia y sostenible sin emitir partículas contaminantes a la atmósfera. La solar es una energía inagotable que puede ser capturada fácilmente y ser convertida en potencia eléctrica con la única ayuda de un panel fotovoltaico. Algunas de las primeras aplicaciones de la tecnología solar fueron llevadas a cabo en el espacio exterior, donde la energía solar se utilizaba para proveer de potencia eléctrica a satélites, y después de esto, fue desarrollándose no solo para uso residencial, sino también, por ejemplo, para aviones solares como el "Sunrise II", una aeronave de control remoto diseñada por Robert J. Boucher, que supuso el primer vuelo propulsado por el sol. [1]

Los avances tecnológicos produjeron una caída de los costes de fabricación y operación, teniendo como consecuencia que desde 2009 el coste de la electricidad solar fotovoltaica (PV) cayera en torno a un 80%, según afirma el reporte realizado por la Agencia Internacional de Energía Renovable. [2]

En este proyecto llevaremos a cabo un análisis económico de la producción de electricidad por medio de sistemas fotovoltaicos alrededor de los países de la Unión Europea en función de aspectos geográficos como la latitud, longitud y la tecnología de las placas PV: ángulos de inclinación y azimut, placas fijas o con seguimiento (de uno y dos ejes).

Antes de meternos en el cuerpo de la investigación, debemos comentar brevemente las secciones que serán desarrolladas: incluyendo un estado del arte, con investigaciones previas relacionadas con el tema, una base teórica (incluyendo terminología geográfica, una introducción a la tecnología de seguimiento solar y algunas nociones básicas acerca de la producción y el funcionamiento de la electricidad por medio de placas PV), así como la comparativa entre diferentes tecnologías, con dos tablas a modo de sumario.

En el siguiente capítulo, se explica el método usado para el proyecto: en primer lugar, relativo al cálculo de la producción de energía en cada país de la UE, el "Photovoltaic Geographical Information System (PVGIS)", una herramienta informática impulsada por el Joint Research Centre (JRC), que es el servicio de ciencia y conocimiento de la Comisión Europea; este sistema presenta mapas interactivos y estimaciones de la producción eléctrica y de la irradiación global. A continuación, se presenta la herramienta matemática que se aplica para realizar el análisis de costes de energía producida y su principal indicador: el Coste Nivelado de Energía (LCOE, por sus siglas en inglés).

Finalmente, en el último capítulo, se muestran algunas conclusiones que han sido extraídas tras la realización del estudio.

En la memoria, en el capítulo anterior, se adjuntaban dos anexos: el primero con información sobre la localización geográfica exacta de los lugares donde se han llevado a cabo los cálculos, incluyendo capturas de Google Earth e información no sólo acerca de las coordenadas geográficas, sino también con las temperaturas mínima y máxima promedio.

En el segundo anexo se pueden consultar los datos detallados y gráficos que se han obtenido como resultado del PVGIS en cada localización: tablas para tecnologías fijas y con seguimiento, producción de energía mensual e irradiación diaria en los meses más favorables y más desfavorables.

7.2 ESTADO DEL ARTE

Como podemos imaginar, al tratarse este capítulo de un resumen, no nos detendremos en tanto detalle como en el propio proyecto. A pesar de ello, antes de entrar en la parte correspondiente al estudio propiamente dicho, debemos hacer referencia a los documentos que han servido de preludio para todo el trabajo posterior.

7.2.1 Conceptos previos

7.2.1.1 Funcionamiento de una placa fotovoltaica

Las placas PV están formadas por módulos, y éstos por células fotovoltaicas, compuestas por diferentes capas y láminas. La luz solar incide en las células PV, creando un campo eléctrico entre las capas, generando un circuito eléctrico. La corriente producida es continua y a menudo transformada en corriente alterna por medio de inversores, haciéndola adecuada para la distribución y el consumo. [3]

7.2.1.2 Parámetros geográficos y geométricos

- *Latitud:* distancia desde un punto de la superficie terrestre al ecuador, contada en grados de meridiano. [23]
- *Longitud:* distancia angular medida en grados sobre el ecuador entre el meridiano de un punto y otro de referencia, actualmente el que pasa por Greenwich. [23]

Según la posición de la placa PV, se definen dos parámetros:

- *Ángulo de inclinación:* pendiente de la célula PV comparada con la célula PV horizontal. [5]
- *Ángulo de orientación (o azimut):* describe la orientación con respecto a la dirección sur. [5]

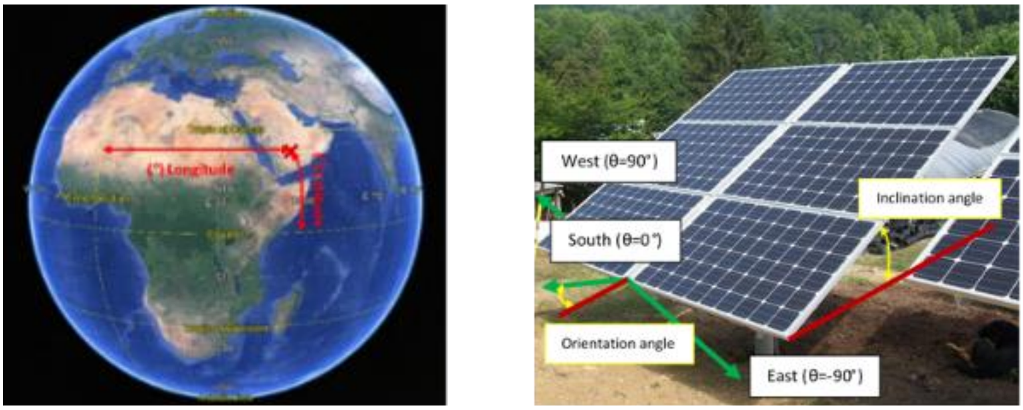


Fig. 154: Resumen: Parámetros geográficos y geométricos

Fuente: Google Earth y alibaba.com. Líneas y etiquetas de elaboración propia.

7.2.2 Tecnología fija o de seguimiento

Como se mencionó anteriormente, algunas evoluciones tecnológicas relativas a las placas fotovoltaicas se han enfocado en mejorar la irradiación solar recibida. Actualmente, podemos encontrar instalaciones móviles, en las cuales los paneles fotovoltaicos imitan el movimiento del sol, bien sea moviéndose alrededor de un eje o de dos ejes.

Una instalación PV fija es aquella en la que sus paneles no cambian su posición a lo largo del tiempo [6], situados con un ángulo fijado que normalmente es la inclinación óptima.

Para obtener eficiencias mayores, los paneles solares deben apuntar en la dirección que capture la mayor cantidad de luz solar posible, algo que se consigue mucho mejor por medio de seguidores solares. Un seguidor solar es una máquina con una parte fija y otra móvil que se coloca lo más perpendicular posible al sol a lo largo del día dentro de su rango de movimiento. Podemos identificar dos tipos;

- Seguidor de un eje: tiene solamente un grado de libertad y hay varios tipos (fijado en azimut y orientable en inclinación o fijado en inclinación y orientable en azimut alrededor de un eje vertical o inclinado).
- Seguidor de dos ejes: con dos grados de libertad, permitiendo una mayor precisión en seguimiento solar.

Fig. 155: Resumen: Seguidor de un eje (izquierda) y de dos ejes (derecha)

Fuente: solarbay.com.au y mecasolar.com. Flechas de elaboración propia

A continuación, debemos comentar algunos estudios que han investigado acerca de sistemas de seguimiento y comparativas entre tecnologías fijas, seguidores de un eje y seguidores de dos ejes y su producción. Como no vamos a entrar en tanto detalle como en la memoria completa, nos limitaremos en este resumen a ofrecer las tablas resumen, una de todos los informes y artículos, y otro con los distintos tipos de placas fotovoltaicas y sus ventajas e inconvenientes.

Autor(es)	Artículo	Países estudiados	Año	Descripción
R. Eke & A. Senturk [7]	“Performance comparison of a double-axis sun tracking versus fixed PV system.”	Turquía	2009	Comparación de dos sistemas PV idénticos, uno en posición fija y otro siguiendo al sol alrededor de dos ejes. Después de un año de operación se calculó que se obtenía un 30.79% más de energía por medio del seguidor de dos ejes frente al sistema fijo.
P.J. Axaopoulos & E.D. Fylladitakis [8]	“Energy and economic comparative study of a tracking vs. a fixed photovoltaic system in the northern hemisphere.”	Grecia Alemania Reino Unido	2014	Comparación del rendimiento de un sistema seguidor de dos ejes y uno idéntico fijo para tres localizaciones en Europa: Atenas (Grecia), Stuttgart (Alemania) y Aberdeen (Reino Unido); variaciones en irradiación y generación de energía mensual dependiendo de la latitud. Análisis económico basado en datos económicos actuales y legislación local para evaluar cualquier cambio futuro en feed-in-tariff y coste del capital.
A. Toribio [9]	“Viabilidad de la instalación de Seguidores Solares de 1 Eje respecto de instalaciones fijas, en aplicaciones de riego, bombeo solar y autoconsumo.”	España	2016	Análisis comparative sobre el uso de un seguidor de un eje horizontal (moviéndose alrededor del eje N-S) frente a algunas instalaciones fijas con diferentes ángulos de inclinación (35°, 15°, 0°)
FuturENERGY [10]	“Tracking Architecture and Reliability with a focus on Latin America.”	México Argentina Chile	2018	Análisis económico y de riesgos de arquitecturas centralizadas y descentralizadas de sistemas PV en Latinoamérica, evaluando los principales retos, algunos aspectos sobre ingeniería, diseño y operación e implicaciones financieras.

Table 60: Resumen: Estudios antecendentes comparando tecnologías fijas y de seguimiento

Tecnología	Ventajas	Desventajas
Fija	Fácil y barata de diseñar, fabricar y mantener. Buen rendimiento la mayor parte del año.	Mal rendimiento entre los equinoccios. La optimización del ángulo de inclinación es esencial.
Seguidor de un eje	Mejor seguimiento del sol que las placas fijas. Buen rendimiento, especialmente en los meses de verano.	Más difícil de diseñar, fabricar y mantener que las placas fijas. Seguimiento solar imprecise, causando una menor producción de energía que los seguidores de dos ejes.
Seguidor de dos ejes	Seguimiento del sol muy preciso. Mejor rendimiento que las otras tecnologías, especialmente en los meses de verano.	Difícil y caro de diseñar, fabricar y mantener. No recomendable para grandes latitudes.

Table 61: Ventajas y desventajas de las diferentes tecnologías PV

7.3 MÉTODO

En este capítulo se explican los instrumentos usados para el proyecto, incluyendo tanto la página web que realiza los cálculos de radiación solar y la producción energética del sistema fotovoltaico como la herramienta matemática para evaluar los costes de producir electricidad por medio de células fotovoltaicas.

7.3.1 Cálculo de la Producción de Energía

Para llevar a cabo todos los cálculos de electricidad producida en cada país europeo, usamos la aplicación web llamada “Photovoltaic Geographical Information System (PVGIS)”, impulsada por el Joint Research Centre (JRC) de la Comisión Europea, la cual permite obtener datos de radiación solar y producción de energía solar fotovoltaica en cualquier lugar del mundo. [11]

7.3.1.1 Selección de la localización geográfica

Se puede realizar clicando en el mapa, introduciendo una dirección o introduciendo la latitud y la longitud de la localización. En nuestro caso, considerando que las veinte localizaciones han sido escogidas directamente en un mapa usando Google Earth, seleccionaremos en PVGIS los lugares introduciendo latitudes y longitudes.

Además, la herramienta permite usar información sobre horizonte local para estimar efectos de sombras de colinas y montañas cercanas. Sin embargo, nuestras localizaciones se han seleccionado para estar prácticamente libres de cualquier obstáculo que pudiera crear una sobra tan importante como para cambiar los resultados de los cálculos; consecuentemente, deseleccionaremos la opción de “horizonte calculado” en “Uso de sombras de terreno”.

7.3.1.2 Base de datos de radiación solar

En términos de datos de radiación solar usados por PVGIS para Europa, la mayoría han sido calculados con imágenes satélite (PVGIS-CMSAF y PVGIS-SARAH), pero ciertas áreas que no están cubiertas por datos satélite (especialmente para grandes latitudes), usan dos bases de datos adicionales (PVGIS-ERA5 y PVGIS-COSMO).

Para cada opción de cálculo, PVGIS presenta al usuario la posibilidad de escoger base de datos, aunque ajusta automáticamente la base de datos más adecuada para obtener resultados más precisos.

7.3.1.3 Datos del perfil de radiación diaria

Esta herramienta nos permite ver el perfil de radiación diaria para un mes dado. Para nuestro estudio, únicamente obtendremos la Irradiación en un plano fijo.

7.3.1.4 Rendimiento de un Sistema PV conectado a la red

Como se explicó anteriormente, los sistemas fotovoltaicos convierten la energía de la luz solar en electricidad; sin embargo, los módulos PV producen corrience continua (CC), mientras que el consumo habitual de electricidad es corriente alterna (CA), haciendo necesario que los módulos estén conectados a un inversor que pase la electricidad de CC a CA, y ésta pueda ser utilizada localmente o enviada a la red eléctrica. Este tipo de sistema recibe el nombre de PV conectado a la red; en el caso de PVGIS, para el cálculo de producción de energía, se asume que toda la energía que no se usa localmente puede enviarse a la red.

7.3.1.4.1 Entradas para el cálculo del sistema PV

Las entradas del PVGIS son fundamentalmente, la base de datos de radiación ya mencionada, el material de los módulos PV, la potencia pico instalada (que para nuestros cálculos se ha fijado en 1 kWp) y las pérdidas del sistema (que PVGIS fija por defecto en 14%, como pérdidas generales).

7.3.1.4.2 Módulos fotovoltaicos fijos

PVGIS permite hacer distinción en los cálculos entre sistemas fijos o con seguimiento. En este apartado se presentan las entradas y salidas que PVGIS ofrece desde el punto de vista de las placas fijas.

7.3.1.4.2.1 Entradas para los módulos PV fijos

Entre las entradas cabe destacar la posición de montaje (posición libre o integrado en el edificio) y ángulos de inclinación y azimut de los módulos PV.

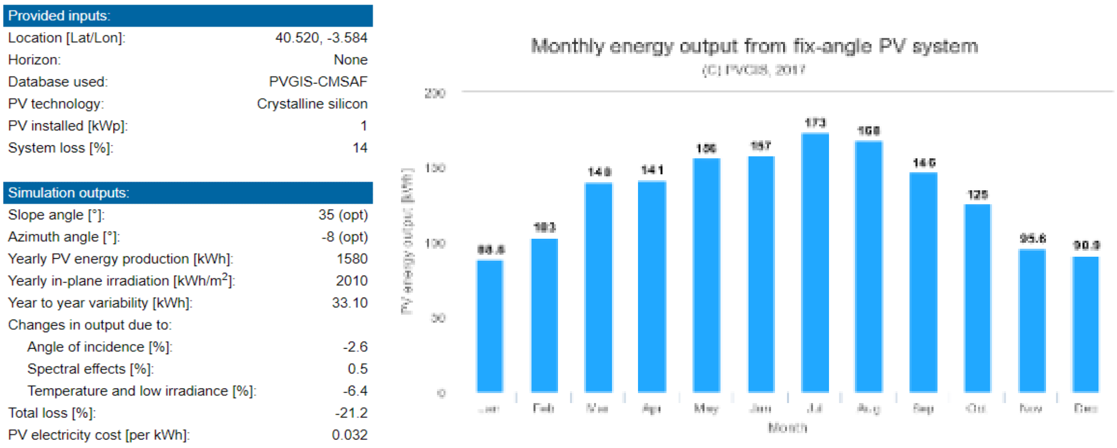
Además, debemos considerar que la última versión de PVGIS incluye la opción de calcular el coste de la electricidad generada por medio de sistemas PV, para lo que se necesitan el coste del sistema PV (equivalente a lo que en nuestra notación recibe el nombre de costes de inversión en el año t, I_t), la tasa de interés r y la vida útil esperada del sistema PV, en años (n).

7.3.1.4.2.2 Salidas para los módulos PV fijos

Las salidas de los cálculos de PVGIS consisten en valores anuales, mensuales o diarios de producción de energía, irradiación solar en un plano, así como gráficos de distintas variables mensuales o diarias.

Aquellas salidas en los que nos hemos centrado son los ángulos de inclinación y azimut (previamente fijados por nosotros o bien calculados sus valores óptimos si se ha seleccionado la opción), Producción anual PV [kWh], Irradiación anual [kWh/m^2], Variación interanual [kWh], porcentajes de causas de pérdidas en la salida PV, como el Ángulo de incidencia y los Efectos espectrales, y las Pérdidas totales.

El principal gráfico que obtendremos para nuestro proyecto es la producción mensual de energía PV.



Provided inputs:	
Location [Lat/Lon]:	40.520, -3.584
Horizon:	None
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	35 (opt)
Azimuth angle [°]:	-8 (opt)
Yearly PV energy production [kWh]:	1580
Yearly in-plane irradiation [kWh/m^2]:	2010
Year to year variability [kWh]:	33.10
Changes in output due to:	
Angle of incidence [%]:	-2.6
Spectral effects [%]:	0.5
Temperature and low irradiance [%]:	-6.4
Total loss [%]:	-21.2
PV electricity cost [per kWh]:	0.032

Fig. 156: Resumen: Ejemplo de tabla y gráfico de salida de energía mensual producida para un sistema PV fijo

Fuente: Elaboración propia

7.3.1.4.3 Módulos fotovoltaicos de seguimiento

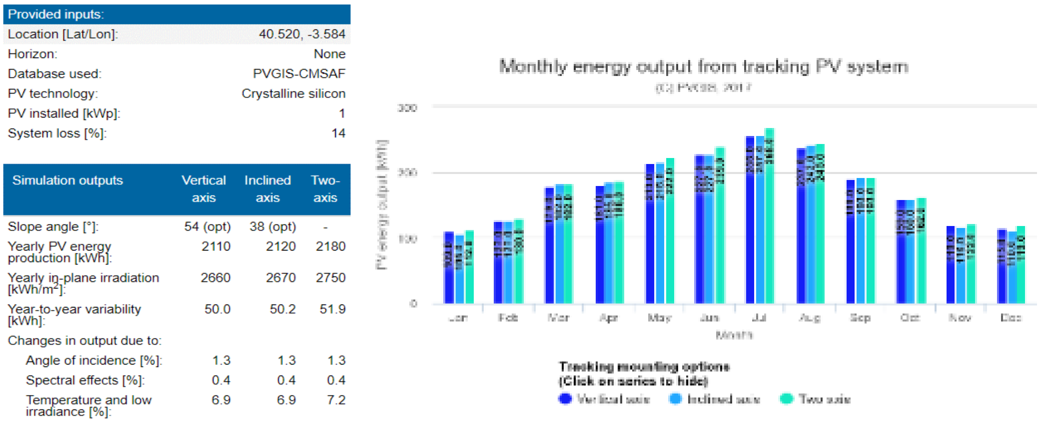
7.3.1.4.3.1 Entradas para módulos PV con seguimiento

Las entradas más importantes son, principalmente las presentadas para módulos fijos, así como el tipo de sistema de seguimiento, pudiendo escoger entre eje vertical (ángulo de inclinación se mantiene constante y movimiento alrededor de un eje vertical, variando el ángulo de azimut, apuntando al este por la mañana y al oeste por la tarde), eje inclinado (por la mañana los módulos están casi verticales apuntados al este, al mediodía apuntando hacia arriba a un ángulo igual al del eje inclinado y después gira gradualmente hacia el oeste, situándose de nuevo casi vertical por la tarde, el azimut apunta prácticamente al sur, ya que todas nuestras localizaciones están en el hermisferio norte) y dos ejes.

7.3.1.4.3.2 Salidas para módulos PV con seguimiento

Los cálculos de salida de los sistemas PV con seguimiento son esencialmente los mismos que los de los de montaje fijo: ángulo de inclinación, Producción anual PV [kWh], Irradiación anual [kWh/m^2], Variación interanual [kWh] y porcentajes de causas de pérdidas, así como Pérdidas totales (en %).

En cuanto a los gráficos, al igual que para placas fijas, obtenemos la salida de energía PV mensual, pero incluyendo tres barras para cada mes (una para cada tecnología de seguimiento solar).



Provided inputs:	
Location [Lat/Lon]:	40.520, -3.584
Horizon:	None
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs	Vertical axis	Inclined axis	Two-axis
Slope angle [°]:	54 (opt)	38 (opt)	-
Yearly PV energy production [kWh]:	2110	2120	2180
Yearly in-plane irradiation [kWh/m^2]:	2660	2670	2750
Year-to-year variability [kWh]:	50.0	50.2	51.9
Changes in output due to:			
Angle of incidence [%]:	1.3	1.3	1.3
Spectral effects [%]:	0.4	0.4	0.4
Temperature and low irradiance [%]:	6.9	6.9	7.2

Fig. 157: Resumen Ejemplo de tabla y gráfico de salida de energía mensual producida para un sistema PV con seguimiento

7.3.1.5 Rendimiento de un sistema PV desconectado de la red

Como este tipo de sistemas no se ha contemplado en nuestro estudio, no nos vamos a detener en su desarrollo, simplemente comentamos que, al no estar conectados a la red, necesitan de baterías para poder almacenar la energía y tomarla de ahí en los días en los que no brille el sol.

7.3.1.6 Otras funciones de PVGIS

Además de las funciones ya comentadas, PVGIS permite otros cálculos y funciones como los datos de radiación solar media mensual, los datos de radiación solar y energía PV horaria y datos del Año Meteorológico Típico (TMY, de Typical Monthly Year).

7.3.2 Costes de Producción de Energía

En este apartado se describe la herramienta matemática con la cual se calculan los costes de producción de energía solar para cada tipo de sistema fotovoltaico. Usaremos el Coste Nivelado de Energía (LCOE).

El LCOE (Levelized Cost of Energy), definido en el estudio "*Cost Map for Unsubsidised Photovoltaic Electricity*", publicado por el Joint Research Centre de la Comisión Europea [12] (2004), "es el precio al cual la electricidad debe generarse desde una fuente específica para cubrir los gastos durante la vida útil del proyecto. Es una evaluación económica del coste del sistema de generación de energía incluyendo todos los costes a lo largo de la vida útil: inversión inicial, operación y mantenimiento, coste de combustible y costes de capital".

De acuerdo con el artículo de Abadie y Chamorro (2019) [13], existen dos métodos de calcular el LCOE: *"el primero considera un marco de tiempo anual, lo que nos deja estimar anualmente el LCOE. El segundo, en cambio, mantiene el tiempo de vida completo de la instalación cuando calcula su LCOE; resulta así en una estimación del ciclo de vida. Dicho esto, comparten algunas características, por ejemplo, su dependencia de la metodología del valor actual neto y el escaso uso de los precios de mercado. Desafortunadamente, también tropiezan con algunos problemas comunes, como la forma adecuada de dar cuenta del riesgo".*

En este resumen nos vamos a centrar únicamente en la forma de multi-período, ya que es la que hemos utilizado para el trabajo. Usamos la definición dada por el Department for Business, Energy and Industrial Strategy de Reino Unido, que define el LCOE como "*el costo de propiedad descontado de por vida y el uso de un activo de generación, convertido en una unidad equivalente de costo de generación en £ / MWh".*

$$LCOE = \frac{PV(total\ costs)}{PV(electricity\ generation)} \tag{19}$$

Que, tras considerar todos los gastos del sistema fotovoltaico y despreciando aquellos que son nulos y agrupando algunos términos, podría quedar escrito de la siguiente forma:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{20}$$

Donde:

I_0 = Inversión inicial

M_t = Gastos de operación y mantenimiento en el año t

r = Tasa de descuento

E_t = Generación de energía en el año t

n = Duración de la inversión (en años)

7.4 RESULTADOS

7.4.1 Localizaciones estudiadas

Para el estudio se escogieron lugares para cada país de la Unión Europea, aunque aquellos países con menos de 65000 km^2 fueron agrupados, de forma que en Bruselas se agrupan Bélgica, Luxemburgo y Países Bajos; en Riga, Letonia, Estonia y Lituania; en Zagreb, Croacia y Eslovenia; en Estocolmo, Suecia y Dinamarca; en Budapest, Eslovaquia y Hungría; en Roma, Italia y Malta. Chipre, a pesar de que es un país muy pequeño, al estar bastante alejado del resto de países, se ha decidido mantener.

En este capítulo, en la memoria en inglés, se provee, aparte de la lista de localizaciones escogidas con los países y capitales y las coordenadas, valores de temperaturas máximas y mínimas medias. Los países son (los mantenemos en inglés porque se han ordenado alfabéticamente en inglés): Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Poland, Portugal, Romania, Spain, Sweden, United Kingdom.

7.4.2 Producción de Energía

En este capítulo se presentan los resultados de PVGIS de producción de energía para cada localización y cada tecnología PV, proporcionando gráficos de energía mensual e irradiación media, así como tablas con los parámetros de salida, teniendo como parámetro más importante la Producción anual de energía PV, para una entrada de potencia pico instalada de 1 kWp.

A modo de ejemplo, proporcionamos los resultados de los cálculos en Viena (Austria):

Datos diarios

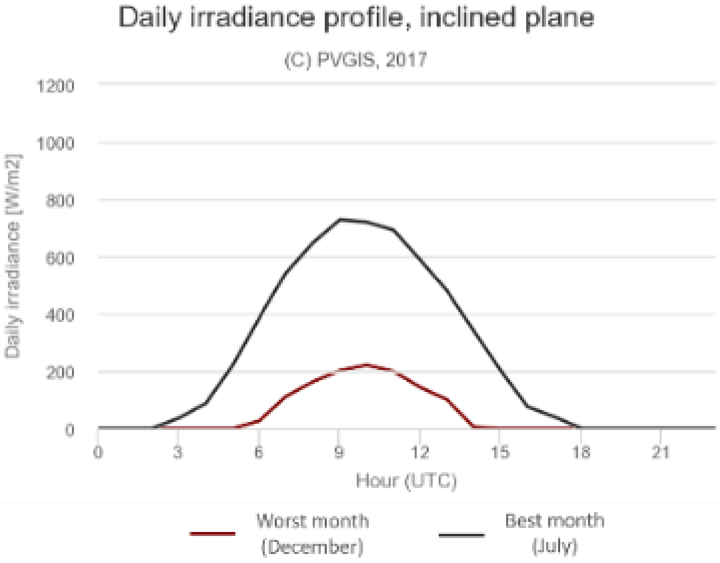


Fig. 158: Resumen: Ejemplo de irradiación diaria para el mejor y el peor mes - Viena

El gráfico muestra la irradiación en un día típico para el peor y el mejor mes en términos de irradiación (para este caso diciembre y julio). Se aprecia el hecho de que los días son más largos en julio y más cortos en diciembre, además de que la irradiación es mucho mayor en julio (750 W/m^2) frente a los 250 W/m^2 en diciembre. Un comportamiento parecido sucede para el resto de localizaciones.

Datos mensuales

Sistemas fijos

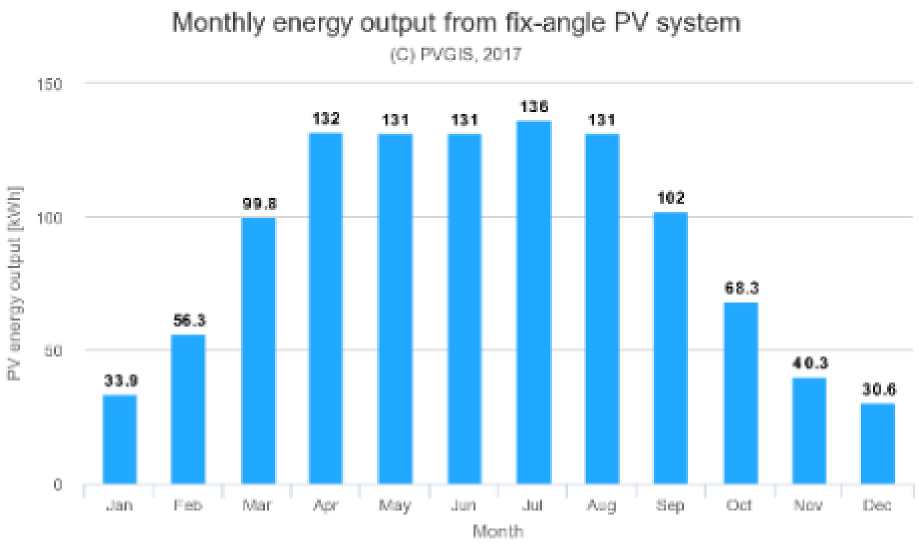


Fig. 159: Resumen: Ejemplo de producción mensual para sistemas fijos - Viena

Se aprecia claramente que los valores mayores se producen entre abril y agosto, mientras que se hacen bastante bajos para el resto del año. Para comentarios más extendidos, se remite a la memoria original.

Output parameter	Value
Slope angle [°]	36 (opt)
Azimuth angle [°]	-4 (opt)
Yearly in-plane irradiation [kWh/m^2]	1370
Year to year variability [kWh]	47.70
Yearly PV energy production [kWh]	**1090**

Table 62: Ejemplo de parámetros de salida para sistemas fijos - Viena

La tabla superior muestra los ángulos óptimos, la irradiación anual, la variabilidad interanual y la producción anual de energía PV.

Sistemas de seguimiento (eje vertical, eje inclinado y dos ejes)

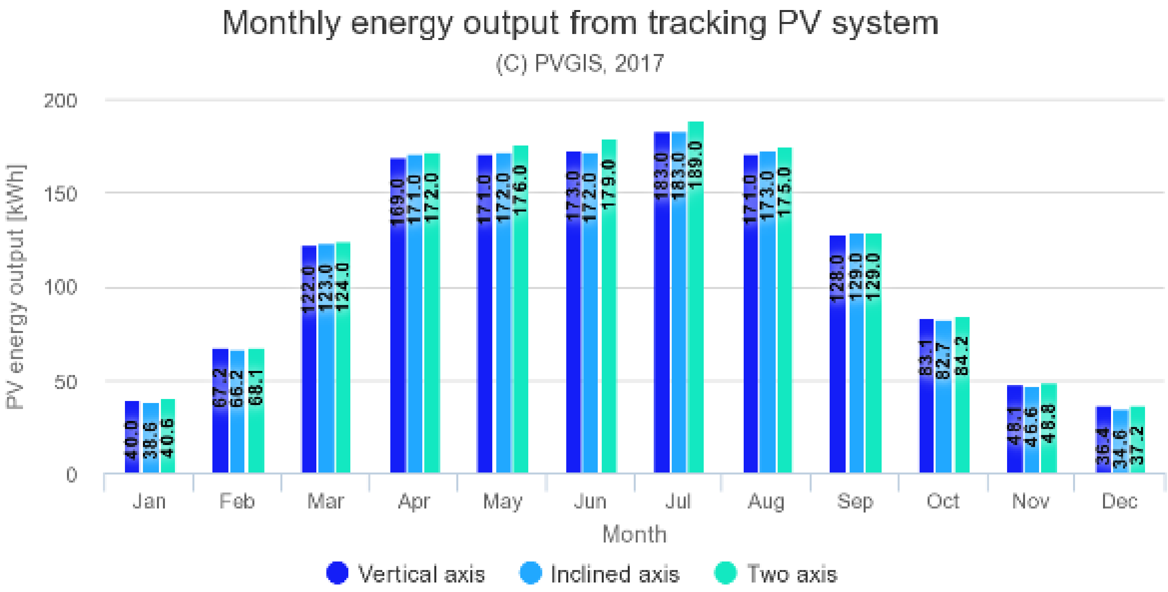


Fig. 160: Resumen: Ejemplo de producción mensual para sistemas de seguimiento - Viena

Output parameter	Vertical axis	Inclined axis	Two-axis
Slope angle [°]	53 (opt)	38 (opt)	-
Yearly in-plane irradiation [kWh/m²]	1730	1730	1760
Year to year variability [kWh]	67.1	66.7	68.8
Yearly PV energy production [kWh]	**1390**	**1390**	**1420**

Table 63: Resumen: Ejemplo de parámetros de salida para sistemas de seguimiento - Viena

Comparación entre tecnologías PV

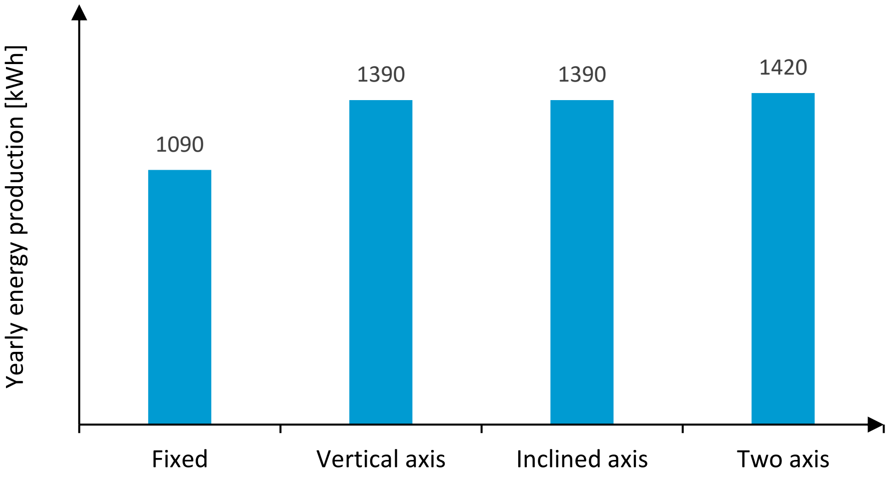


Fig. 161: Resumen: Ejemplo de comparación entre tecnologías PV - Viena

#	Country	H_{eq} Fixed [h]	H_{eq} Vertical axis [h]	H_{eq} Inclined axis [h]	H_{eq} Two-axis [h]
1	**Austria**	1090	1390	1390	1420
2	**Belgium**	1010	1290	1280	1320
3	**Bulgaria**	1310	1690	1700	1740
4	**Croatia**	1200	1550	1560	1590
5	**Cyprus**	1720	2330	2350	2420
6	**Czech Republic**	989	1240	1240	1270
7	**Finland**	912	1220	1210	1240
8	**France**	1110	1430	1430	1470
9	**Germany**	1020	1320	1320	1350
10	**Greece**	1600	2120	2130	2200
11	**Hungary**	1210	1560	1560	1600
12	**Ireland**	945	1200	1200	1230
13	**Italy**	1540	2040	2040	2100
14	**Latvia**	1010	1340	1330	1360
15	**Poland**	1040	1360	1360	1380
16	**Portugal**	1710	2360	2380	2450
17	**Romania**	1280	1660	1660	1700
18	**Spain**	1580	2110	2120	2180
19	**Sweden**	950	1280	1270	1310
20	**United Kingdom**	997	1280	1270	1310

Table 64: Reusmen: Tabla resumen de las Horas Equivalentes (H_{eq})

El valor de la energía producida, considerando que la potencia pico instalada es de 1 kWp, coincide en valor (no en unidades) con las Horas Equivalentes (H_{eq}), definidas como la medida de horas de sol en un año, expresado como:

$$H_{eq}[h] = \frac{E[kWh]}{P[kW]} \tag{21}$$

7.4.3 Coste de Energía - LCOE

7.4.3.1 Gastos de Inversión y Operación

Como mencionamos anteriormente, para los cálculos de costes de energía producida tenemos en cuenta los gastos de inversión inicial (I_0) y operación y mantenimiento (M_t). Es importante destacar que los costes de inversión no son iguales en cada país y que pueden dividirse, basándonos en un estudio de IRENA [14], en costes de Instalación (I), Soft Costs (SC) y costes de Hardware (H).

$$I_0 = H + SC + I = H + R \cdot \phi \tag{22}$$

Se considera, según el estudio de IRENA y [15], que los valores de H representan el 50% y son constantes para el mismo sistema PV, mientras que SC e I pueden combinarse y dependen del salario ($\overline{w}$). Para modelar las variables que dependen del salario se ha creado una nueva variable ϕ de tal forma que aquel país cuyo salario sea igual que la media de los salarios de la UE, tendrá un valor de $\phi = 1$, los países cuyo salario sea inferior al de la media tendrán $\phi < 1$ y los que tengan salario por encima de la media tendrán una $\phi > 1$. No nos vamos a detener a detallar aquí los valores de dicha variable ni los valores H, SC + I, I_0 y M_t, que pueden ser consultados para cada localización y cada sistema PV en la tabla 9..

7.4.4 Cálculos de LCOE

Para facilitar los cálculos de gastos y LCOE, se ha creado una función de Matlab que se puede consultar en la sección equivalente a esta de la memoria original.

En la página siguiente se muestran los valores de LCOE para cada país y tecnología, resaltando los valores óptimos en verde y los peores en rojo, además de incluir una columna con la comparación de cada valor de LCOE frente al LCOE del sistema fijo, definida como:

$$\#/fixed\,\% = \frac{LCOE(Tracking)}{LCOE(Fixed)} \cdot 100 \tag{23}$$

A la vista de la tabla, podemos apreciar cómo, para los valores dados de gastos de inversión y mantenimiento, la mejor opción en la mayoría de los casos es el sistema de seguimiento de un eje, que combina un buen seguimiento del movimiento del sol, con una tecnología más o menos simple y barata en términos de inversión y mantenimiento. Además, la peor opción siempre es la tecnología de seguimiento de dos ejes, probablemente debido a que sus altos valores de gastos de I_0 y M_t, que suponen un peso importante en el LCOE de este sistema, no se compensan con el hecho de que esta tecnología es la que produce una mayor cantidad de energía PV.

No obstante, en la siguiente sección se llevará a cabo un análisis de sensibilidad, cambiando algunos parámetros que afectan a los resultados del LCOE.

#	Country	Fixed [€/MWh]	Vertical axis [€/MWh] (#/fixed %)	Inclined axis [€/MWh] (#/fixed %)	Two-axis [€/MWh] (#/fixed %)
1	**Austria**	56.12	53.67 (95.63)	53.67 (95.63)	77.32 (137.78)
2	**Belgium**	61.71	58.92 (95.48)	59.38 (96.22)	84.67 (137.21)
3	**Bulgaria**	21.95	20.75 (94.53)	20.62 (93.94)	29.63 (134.99)
4	**Croatia**	27.80	26.24 (94.39)	26.07 (93.78)	37.62 (135.42)
5	**Cyprus**	24.20	21.79 (90.04)	21.60 (89.26)	30.85 (127.48)
6	**Czech Republic**	35.58	34.61 (97.27)	34.61 (97.27)	49.69 (139.66)
7	**Finland**	64.30	58.63 (91.18)	59.11 (91.93)	84.81 (131.90)
8	**France**	49.52	46.88 (94.67)	46.88 (94.67)	67.05 (135.40)
9	**Germany**	62.67	59.06 (94.24)	59.06 (94.24)	84.93 (135.52)
10	**Greece**	25.15	23.15 (92.05)	23.04 (91.61)	32.81 (130.45)
11	**Hungary**	27.75	26.25 (94.60)	26.25 (94.60)	37.64 (135.64)
12	**Ireland**	64.49	61.94 (96.05)	61.94 (96.05)	88.86 (137.79)
13	**Italy**	31.36	28.87 (92.06)	28.87 (92.06)	41.24 (131.51)
14	**Latvia**	32.33	29.72 (91.93)	29.94 (92.61)	43.07 (133.22)
15	**Poland**	32.07	29.90 (93.23)	29.90 (93.23)	43.34 (135.14)
16	**Portugal**	22.19	19.61 (88.37)	19.45 (87.65)	27.78 (125.19)
17	**Romania**	23.90	22.47 (94.02)	22.47 (94.02)	32.27 (135.02)
18	**Spain**	28.38	25.92 (91.33)	25.80 (90.91)	36.89 (129.99)
19	**Sweden**	61.97	56.09 (90.51)	56.53 (91.22)	80.60 (130.06)
20	**United Kingdom**	59.28	56.31 (94.99)	56.76 (95.75)	80.92 (136.50)

Table 65: Resumen: Resultados de LCOE en función de la localización y la tecnología PV

7.4.4.1 Resultados de LCOE para sistemas fijos, con seguimiento y valores óptimos

En este punto del documento que aquí se resume, hay cinco subsecciones acerca de los resultados de LCOE para cada tecnología PV (fija, seguidor de eje vertical, seguidor de eje inclinado y seguidor de dos ejes), así como la correspondiente a los valores óptimos para cada país.

Con intención de no repetir, describiremos el proceso seguido para los valores óptimos, que es equivalente en el resto de subsecciones.

Tomando los valores de LCOE presentados en la Tabla 4, se han ordenado de mayor a menor (recordemos que las unidades de LCOE son €/MWh) y se ha asignado una escala de color, de tal forma que aquellos valores más altos de LCOE tienen asignado un tono más oscuro de naranja, mientras que los valores más pequeños tienen asignado un tono más claro.

Ireland	61.94
Germany	59.06
Belgium	58.92
Finland	58.63
United Kingdom	56.31
Sweden	56.09
Austria	53.67

France	46.88
Czech Republic	34.61
Poland	29.90
Latvia	29.72
Italy	28.87
Hungary	26.25
Croatia	26.07

Spain	25.80
Greece	23.04
Romania	22.47
Cyprus	21.60
Bulgaria	20.62
Portugal	19.45

Table 66: Resumen: Escala de colores para valores óptimos de LCOE

:

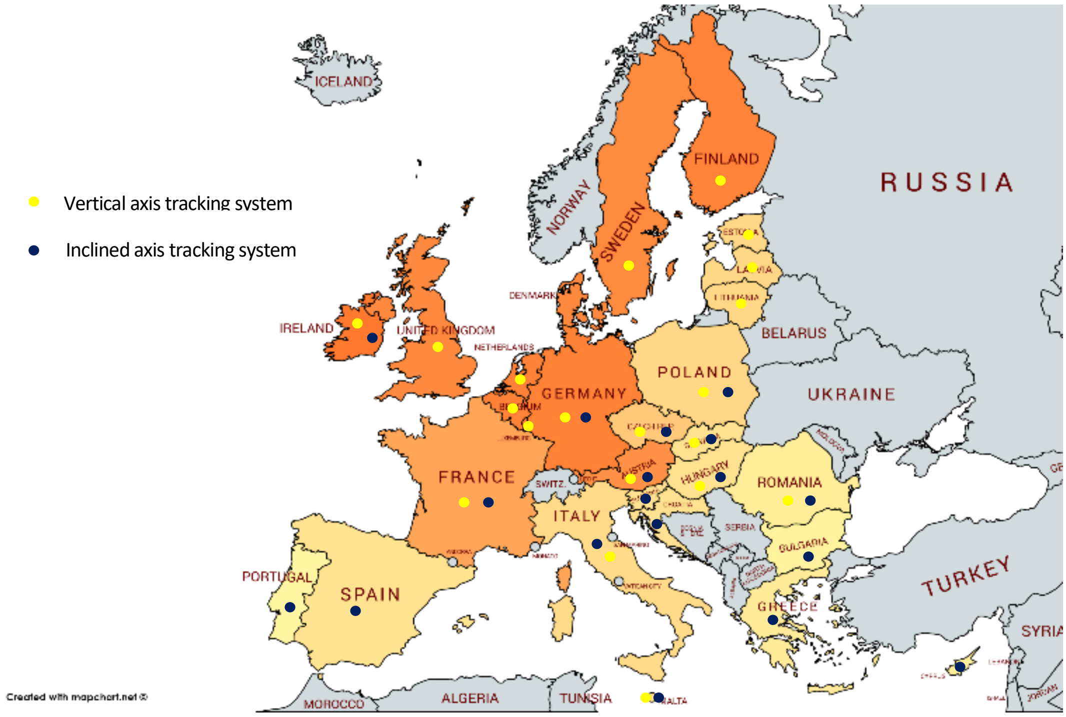


Fig. 162: Resumen: Mapa de la UE con valores óptimos de LCOE para cada país

7.4.5 Análisis de sensibilidad

Como se ha comentado, los resultados de los cálculos dependen fuertemente de parámetros como la producción de energía PV anual, los gastos de inversión y mantenimiento, tasa de interés, etc. Sin embargo, entre estos parámetros, hay algunos que vienen dados como constantes, como la producción de energía, o tienen el mismo valor para todas las tecnologías PV, como la tasa de interés.

Por tanto, en nuestro análisis de sensibilidad, que no es más que ver cómo cambiarían los resultados si variamos ciertos parámetros de entrada, veremos cómo afectan cambios en los salarios y en las horas equivalentes.

Se lleva a cabo el análisis para sistemas fijos, ya que para el resto de tecnologías el resultado sería equivalente y solamente con realizar el análisis de una tecnología podemos extraer perfectamente una tendencia.

7.4.5.1 Variación con el salario (w)

En esta subsección se evalúa la relación entre los salarios de los países y sus valores de LCOE, además de crear una elasticidad de LCOE frente a salario, incrementando w en un 10%:

$$\epsilon_{LCOE-w} = \frac{\frac{dLCOE}{LCOE}}{\frac{dw}{w}} = \frac{\Delta\%LCOE}{\Delta\%w} \qquad (24)$$

Los valores de LCOE para w y de LCOE para $(w \times 1.10)$ están disponibles en la tabla 17 del documento original y presentan unos valores de elasticidades (ϵ) muy dispares, aunque para todos los países se tienen elasticidades entre 0 y 1, lo que indica que, para todos los países, el incremento de LCOE es menor que el incremento del salario. Un crecimiento de salario produce un incremento de LCOE, pero bastante ligero.

7.4.5.2 Variación con las Horas equivalentes (H_{eq})

Las horas equivalentes, como ya se comentó, coinciden en valor (que no en unidades) con la energía anual producida, ya que la potencia pico instalada es de 1 kW.

El objetivo de este apartado, análogamente al anterior, es evaluar cómo cambia el LCOE cuando cambiamos las horas equivalentes, creando una elasticidad de LCOE frente a H_{eq}, incrementando H_{eq} un 10%:

$$\epsilon_{LCOE-H_{eq}} = \frac{\frac{dLCOE}{LCOE}}{\frac{dH_{eq}}{H_{eq}}} = \frac{\Delta\%LCOE}{\Delta\%Heq} \qquad (25)$$

Los valores de LCOE para H_{eq} y de LCOE para $\left(H_{eq} \times 1.10\right)$ están disponibles en la tabla 19 del documento y presentan unos valores de elasticidades (ϵ) muy similares (alrededor de -0.91), algo que no nos sorprende ya que, si partimos de la fórmula de LCOE:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{26}$$

Vemos que el numerador permanece constante y E_t es el mismo cada año y puede extraerse del sumatorio. El término $(1+r)^t$ también permanece constante, quedando:

$$LCOE(E_t) = \frac{C}{E_t} \tag{27}$$

Donde C es un valor constante.

Si aumentamos E_t (que coincide en valor con H_{eq}, no en unidades) un 10%:

$$\left(\frac{1}{1.1} = 0.9091\right) \rightarrow; H_{eq} \uparrow 10\%;\ LCOE \downarrow 0.9091$$

Por tanto, la variable LCOE es casi elástica en relación con la variable H_{eq}. Tenemos que observar que nuestras elasticidades son negativas, lo que significa que un incremento de H_{eq} produce un decremento de LCOE, algo muy razonable si tenemos en cuenta que en la ecuación de LCOE, LCOE y E_t son variables inversamente proporcionales.

Nota: Para la numeración de ecuaciones se ha seguido el orden del resto del documento, aunque pueda haber ecuaciones iguales repetidas con diferentes numeraciones.

7.5 CONCLUSIONES

Considerando todos los antecendentes, método y resultados de este estudio, se hace necesario hacer una sección como conclusión de toda la información presentada en las páginas anteriores.

La energía solar se está convirtiendo en una de las fuentes de renovación más utilizadas, dando como resultado dos formas diferentes de recolección: solar térmica y fotovoltaica, siendo la segunda el objeto de nuestros cálculos. La energía fotovoltaica se está volviendo tan importante que, en algunos países, por ley, los nuevos edificios deben tener placas fotovoltaicas instaladas. Los avances e investigaciones tecnológicas no solo han permitido la optimización de los sistemas fotovoltaicos, aumentando su producción y reduciendo sus costos como consecuencia, sino que también han abierto un camino prometedor con la creación de sistemas fotovoltaicos que imitan el movimiento del sol, actuando como un girasol, apuntando al sol durante todo el día.

Teniendo en cuenta esta amplia gama de tecnologías fotovoltaicas, se necesita una investigación sobre el rendimiento, los costos y la rentabilidad, y ese ha sido el propósito de este trabajo: realizar un análisis económico de la producción de energía fotovoltaica en la Unión Europea.

En nuestro estudio, en primer lugar, definimos un estado del arte, que incluye conceptos teóricos como por ejemplo cómo funciona un sistema PV, nociones geográficas y geométricas y luego los estudios que han inspirado nuestra investigación, con comparaciones entre tecnologías fijas y de seguimiento.

A continuación, en el capítulo del método, se explicaba la herramienta informática que hemos utilizado, el PVGIS, basando nuestras indicaciones en su manual, seguido de nuestra herramienta económica, mediante la cual hemos calculado los costos de producción de energía, el Coste Nivelado de Energía (LCOE).

Después de eso y antes de entrar en cálculos, se presenta la lista de ubicaciones seleccionadas, con 20 ubicaciones de 28 países de la UE (algunos países pequeños se unieron para simplificar); seguido de los cálculos de producción de energía y los costes correspondientes de esta producción, incluyendo mapas con escalas de colores para cada tecnología fotovoltaica, y también un mapa con el sistema óptimo en cada país. Finalmente, se realizó un análisis de sensibilidad, expresando la dependencia de LCOE con salario y horas equivalentes.

Finalmente, deberíamos terminar nuestro trabajo reconociendo la importancia de la energía fotovoltaica como la fuente de energía más prometedora pero al mismo tiempo tan necesaria para la investigación, no solo en nuestros tiempos, sino también en el futuro, aplicable a edificios y seguramente a campos inimaginables como los sectores de aviación, marinería y automoción (para propulsar aviones, barcos, automóviles, bicicletas o scooters), inodoros con energía solar (promovido por la fundación Bill Gates) o sector de dispositivos electrónicos (con baterías recargables solares), etc.

"Quizás el humano no pueda ir al Sol, pero seguro que lo que sí puede es traerlo a la Tierra".

LIST OF TABLES

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