Industrial Engineering Final Project

Viability and efficiency comparison of two energy generation systems based on solar panels, one with fixed direction and inclination and the other one with fixed direction but variable inclination

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GREETINGS

I would like to thank my parents, my brothers, and the rest of my family. I would like to thank my close friends, who along with my family, have been there not only in the good moments but also in the bad ones. I am also remembering the professors and other personal from the UPV.

RESUMEN

En este trabajo estudiaremos la viabilidad y eficiencia de dos instalaciones. Una con orientación e inclinación fija de 45º orientada al sur. La otra con una inclinación variable con la posición del sol y con la orientación, al igual que en el primer caso, fija hacia el sur. Lo que trataremos de hacer en este proyecto es determinar cuanta más electricidad es generada por la instalación con sistema de seguimiento al sol y la instalación fija y si merece la pena la inversión, teniendo en cuenta la ubicación y condiciones climáticas de este.

En nuestro caso será la ciudad polaca de Wroclaw, donde actualmente estoy cursando el programa Erasmus. Ubicaremos la instalación en la cubierta de un edificio de la Universidad Politécnica de Breslavia.

Se elaborará un estudio climatológico, considerando temperaturas, radiación y humedad entre otras.

Palabras clave: energías renovables; energía solar; instalación solar fotovoltaica; inclinación variable; automatización

ABSTRACT

In this project, we will study the viability and efficiency of two installations. One with a fixed direction and inclination, 45 degrees facing the south, while the other will be an installation with a fixed direction but a variable inclination, facing the south. The main objective of this project would be to determine how much electricity the tracking system installation produces in front of the fixed installation and if it is worth the investment, taking into account the geographical location and climate conditions of our installations.

In our case, it will be located in the Polish city of Wroclaw, where I am currently spending my Erasmus. The installation will be at the top of one building of the Politechnika Wroclawska.

A climatological study will be done, considering temperature, radiation, and humidity, among other parameters.

Keywords: renewable energy sources; solar energy source; photovoltaic installation; variable inclination; automation

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1. REPORT

1.1. Aim of the project and energy context

This project is born due to the necessity of Polish society, well, the world needs to find a profitable and efficient way to produce electricity/energy without harming the environment.

Since a long time ago, there have been regulations, global agreements, and laws that pursue limiting pollutant emissions and other things. Some of the regulations are going to be enumerated:

- The first global agreement, including 196 parties, is The Paris Agreement [1], a legally binding international treaty on climate change. It entered into force on 4 November 2016. This agreement looks for the global average temperature (which cannot increase to 1.5°C above pre-industrial levels). The Paris Agreement not only pushes the big and developed countries to invest money in environmentally friendly ways of producing energy but also to lend money to non-developed countries to improve their facilities to pursue the same goal. This agreement outlines the temperature brake by peaking the greenhouse gas emissions before 2025.
  The reason for the 1.5°C limitation is simple; beyond that, the climate would suffer severe changes such as more frequent and severe droughts, heatwaves, and rainfalls.

- More with mentioned before, the United Nations released in 2015 The 2030 Agenda for Sustainable Development [2]. The UN made the Agenda based in 17 Sustainable Development Goals, which, they say, are an urgent call for action by all countries. Among these 17 goals, the number 7 is really interesting for this project. The seventh goal is: "Ensure access to affordable, reliable, sustainable, and modern energy for all." So these goal wants to push the world to move partially to renewable energy sources. Should be underlined the subsequent:
  - Increase the share of renewable energy in. the global energy mix.
  - Enhance international cooperation to facilitate access to clean energy and promote investment in energy infrastructure and clean energy technology.

- The Renewable Energy Directive (RED II) from the European Union was adopted in 2018 [3]. The main goal of this directive is to reduce greenhouse gases by promoting the use of renewable energy sources. Another objective is to increase the share of renewable energy. So this directive pushes each country member to establish a national renewable energy target to contribute to the EU target. Also promotes the use of renewable electricity in transport.

These would give us an external image of how the world is behaving. Talking now about Poland, of course, they have to fit into the global and European regulations. But inside this regulation, talking about the European ones, each country member can apply their own measures and directives to achieve the European objective. So, some of the measures taken in Poland are:

- Poland Has developed a national energy efficiency plan, which is currently being applied to buildings, transport, and industry as well. The final objective of this measure is to use/waste less energy and to reduce greenhouse gas emissions.
- Poland has introduced subsidies for purchasing electric cars or low-emission vehicles, as well as infrastructure to charge them.

- Poland has introduced the forestry program. This program plans to increase the forest areas so the carbon dioxide can be removed faster and in bigger quantities. With this measure, climate change is mitigated.

- Poland has also established a coal phase-out, which means that Poland has the objective of not depending on coal for electricity production by 2049.

As is known worldwide, Poland is very reliant on their coal-based energy system. Poland has been criticized because of it. In order to change public opinion, to adapt to European regulation, and to fix the future problems of energy scarcity this country would have to survive, they are migrating to a, for the moment, mixed system. This mixed system right now is based on coal and renewable energy sources.

[4] Poland has committed to having a 21% of their energy production based on renewable energy sources by 2030; right now, they have a 15.6% of renewable energy production.

1.1.1. Spain and renewables

As a Spanish student in the Erasmus program, I would like to make a brief introduction to the Spanish energy system and how my country is managing the actual energy problem.

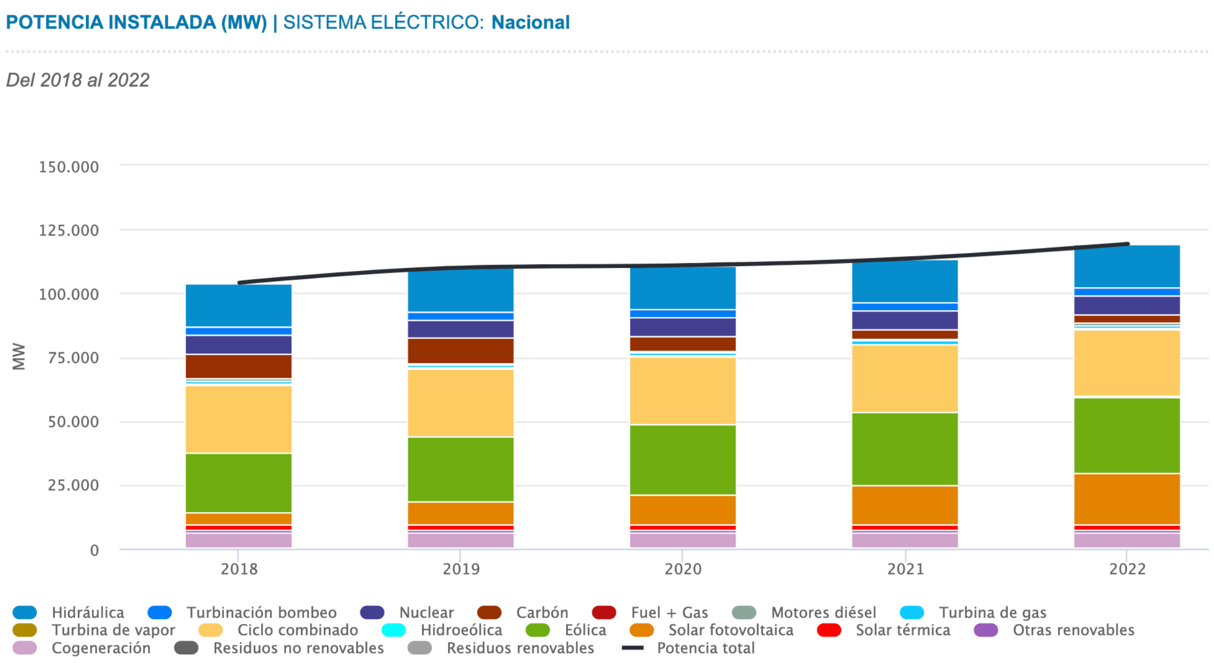


Figure 1. Comparison of the Installed power in Spain distinguishing between the different energy sources. Source: Red Eléctrica Española [5]

In the graph above, can be seen how the energy installed has been growing little by little through the last few years. What can be clearly seen is the growth in renewable energy sources, for example, the solar photovoltaic has grown considerably, and the eolic also. On the other hand, the use of coal has been significantly reduced in this period of time.

So, at first glance, it seems that Spain is moving to a more renewable energy system, however, having a look at this other chart, in the last five years (from 2018 to 2022), renewable energy sources have grown, but in the year 2022 these sources had decreased a bit.

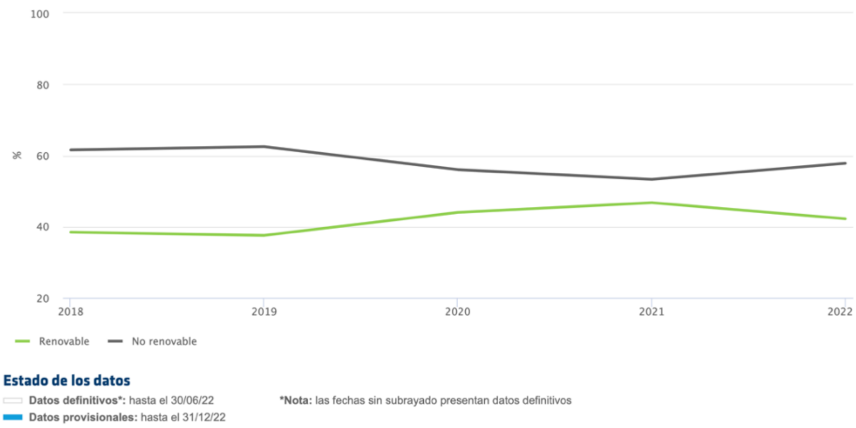


Figure 2. Evolution of the renewable and non-renewable energy sources in Spain (in percentage). Source: Red Eléctrica Española. [6]

The renewables have decreased the production of energy in the year 2022 due to technical restrictions. Spain has a distribution system that, at the moment, is not capable of holding all the energy generated that is not consumed instantaneously, which is why producing energy with renewable energy sources has become more expensive this last year. The government is trying to protect the electricity distribution system by including fees for the energy produced that is not required. This system requires an update or the Spanish transition to renewable energy sources would be stopped.

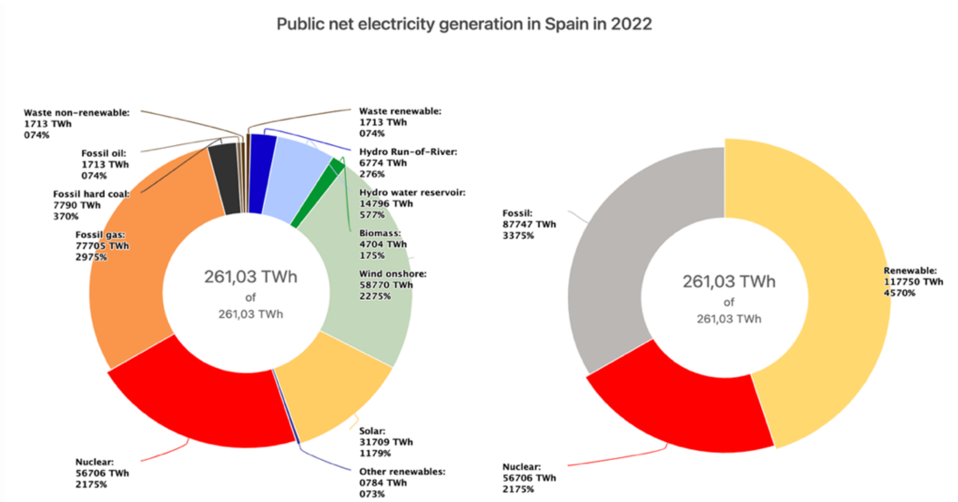
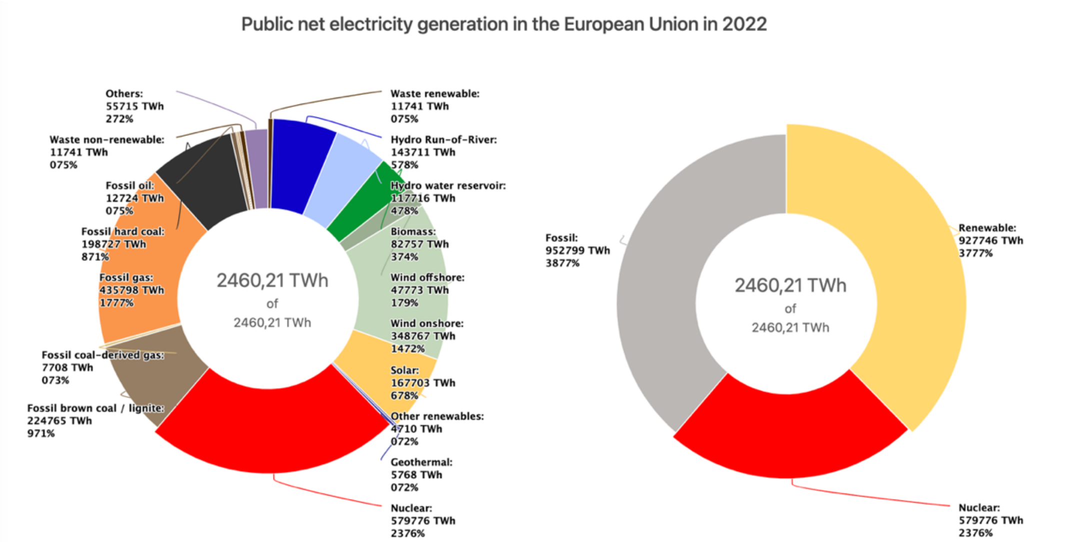


Figure 3. Public net electricity generation in Spain in 2022. Source: Energy-Charts.[7]

Comparing the energy infrastructure of Spain with the rest of Europe, It is clear that Spain has a bigger renewable energy percentage of the energy infrastructure (45.7 %) than the European Community (37.77 %), but on the contrary, Spain has a lower percentage for nuclear energy (21.75 %) compared with Europe (23.76 %), and this difference will continue growing because Spain has a plan to destroy some of their active nuclear plants, arguing that nuclear energy is not a renewable energy source.

Figure 4. Public net electricity generation in the European Union in 2022. Source: Energy-Charts.[8]



1.1.2. Poland and renewables

Not only for the reasons above, which are directives and laws that Poland needed to follow, but to win energy independence and security envisages. For this to occur, Poland requires a big investment in renewable energy sources. So the reasons are simple [4]:

- Gain independence from imported raw materials and complete the transition to domestic resources.
- Build a strong and modern industrial sector
- Being prepared for the upcoming economic crisis caused by the energy crisis. The less you depend on the rest of the countries, the more independent you will be.
- Accelerate the energy transition, as the EU indicates, to reach a zero-carbon economy.

It is worth mentioning that the investment is not only required in building new installations, but it is also necessary to invest in the current infrastructure, which is old and needs to be more to hold all the upcoming production. This means that the existing lines, apart from the old, would be overloaded due to the connection of the new installations, so Poland requires new production and infrastructure.

The main renewable energy sources in Poland are solid biofuels, wind, biogas, Solar and Hydropower.

As can be seen on Figure 5, solid biofuels are the most important renewable energy source right now, with 71.6% of renewable energy production, followed by the wind energy source with 10.9% [9].

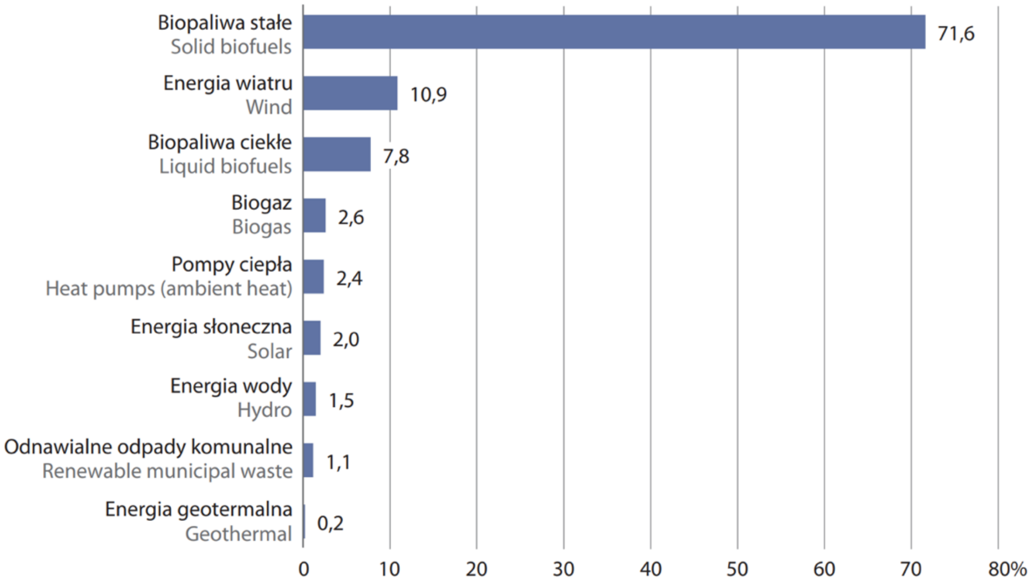


Figure 5. Distribution of the energy infrastructure in Poland. Source: Statistics Poland.

1.1.2.1. Wind energy

Poland this last year invested much money in the wind energy source, installing up to 1.5 GW of onshore (directly in their ground, and not in the sea) wind. That turned Poland into one of the biggest investors in the wind from last year [10].

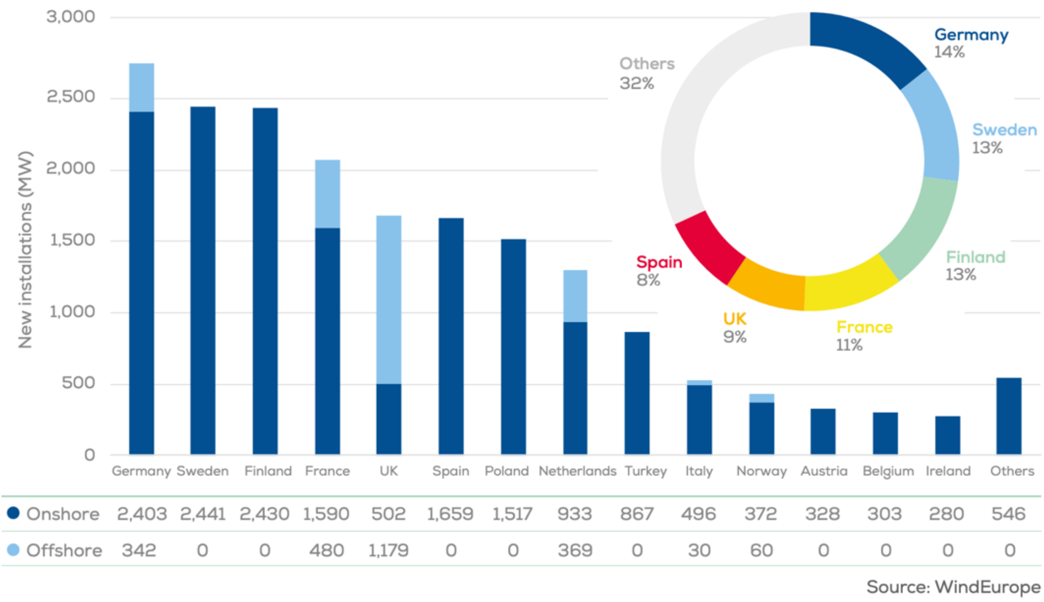


Figure 6. Comparison between the wind energy infrastructure in the different European countries. Source: WindEurope.

The following graph shows how much of the electricity demand is covered by wind energy production [10]:

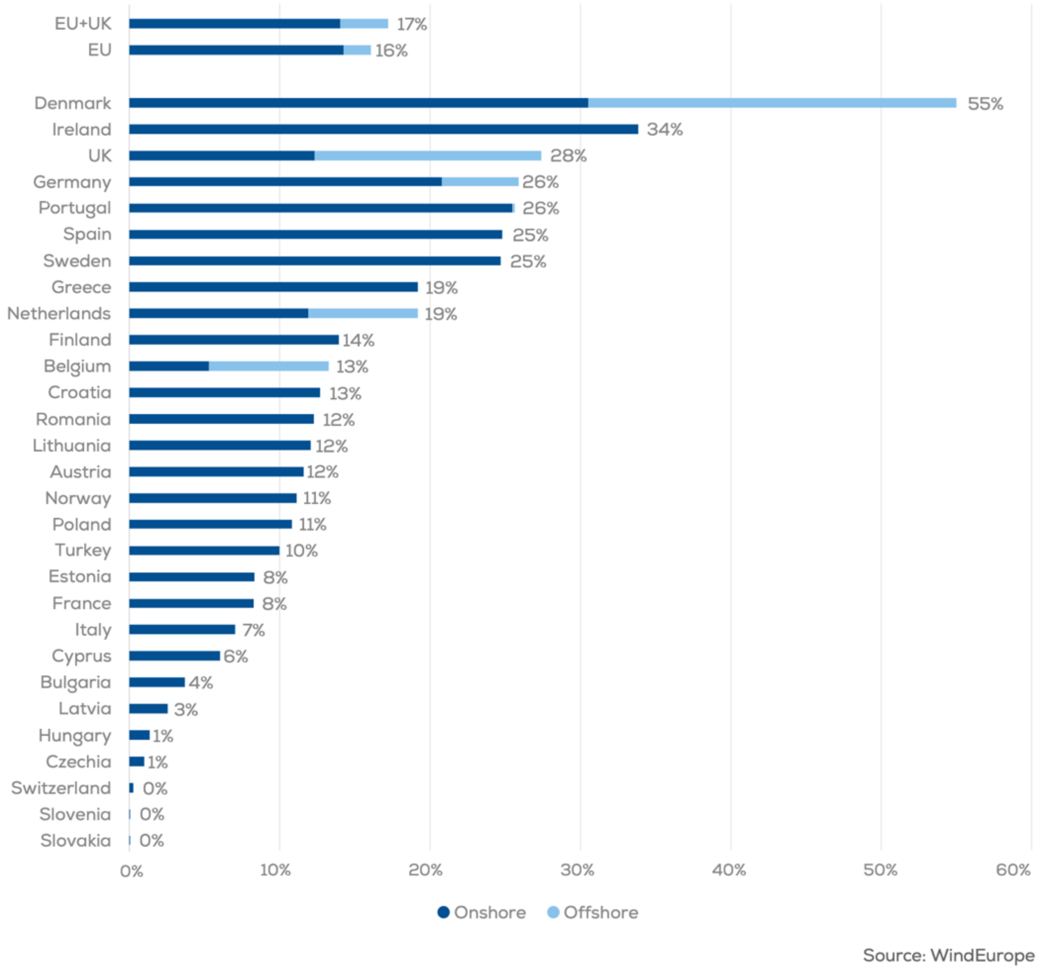


Figure 7. Electricity demand satisfied by the wind energy source distinguished by countries. Source: WindEurope.

So, for the moment, the capacity of production of wind energy that Poland currently has, can satisfy 11% of the electricity demand. Even though Poland is investing a lot in wind energy, with 8 GW of installed capacity, they are not even close to the top wind energy holders in Europe, which are Germany with 66 GW of installed capacity, Spain with 30 GW, the UK with 29 GW, France with 21 GW and then Sweden with 15 GW.

1.1.2.2. Solar Energy

Solar energy is represented with a small amount of only 2% in renewable energy sources, but this will change shortly. Recently, on 18 May 2022, Europe decided to end reliance on imported Russian fossil fuels. This included the first EU Solar Strategy, known as RePowerEU package [11]. Basically, Europe agreed to accelerate the process of installing solar energy plants. This new strategy has raised the EU's objectives for the installed solar energy to 320 GWac in 2025 and 600 GWac in 2030. The strategy includes three "phases":

1. Facilitate deployment of solar PV
2. Access to sustainable solar products
3. Strengthening of international cooperation in the field of solar energy

The biggest measures are the following. The first big measure is the European Solar Rooftop Initiative. This measure wants solar rooftop installations in all the new public buildings with more than 250 m² by 2026, on all existing public and commercial buildings (with more than 250 m²) by 2027 and in all the new residential buildings by 2029.

The second big measure of this plan is: each municipality with more than 10,000 people in the population will need at least one renewable energy community.

The third big measure will be: a new EU Solar PV Industry Alliance, this will basically connect the energy producers with the off-takers and establish an objective of 20 GW of solar PV production by 2025.

The last big measure of this program will be a new EU Solar Skills Partnership, which will be a formation program, for entrepreneurs.

Following the different directives from the European Union and United Nations, Poland is making steps forward. Making an overview of the Polish Solar Market this last year, 2022, 20 GW of solar energy was installed (11 GW came from solar PV installations). Taking into account that last year, installed solar energy was only 6 GW, and in 2020 just 2.9 GW, and this shows the commitment Poland has to the energy production transformation.

If this data is not enough, can be confirmed now that Poland could satisfy 10% of the final demand just with solar PV production (in 2020, they were capable of covering less than 1% of the demand). But, surprisingly, this massive change in the energy production of the country is not only due to big industrial installations but, in part, thanks to the popularity of home prosumer installations. Poland has more than 1,000,000 micro-installations under 50 KW, this big interest from the Polish population in having their own installation was born not long ago when they were, apart from saving money in bills, capable of selling the excess production without paying for using the distribution fee of the public grid. In the following graph, a trend can be seen in solar energy production (which means investment In solar energy):

Having a look at the graph, a clear change in tendency in May 2022 can be seen, the reason is simple, the Poland administration decided to replace the net-metering system with a net-billing system [12].

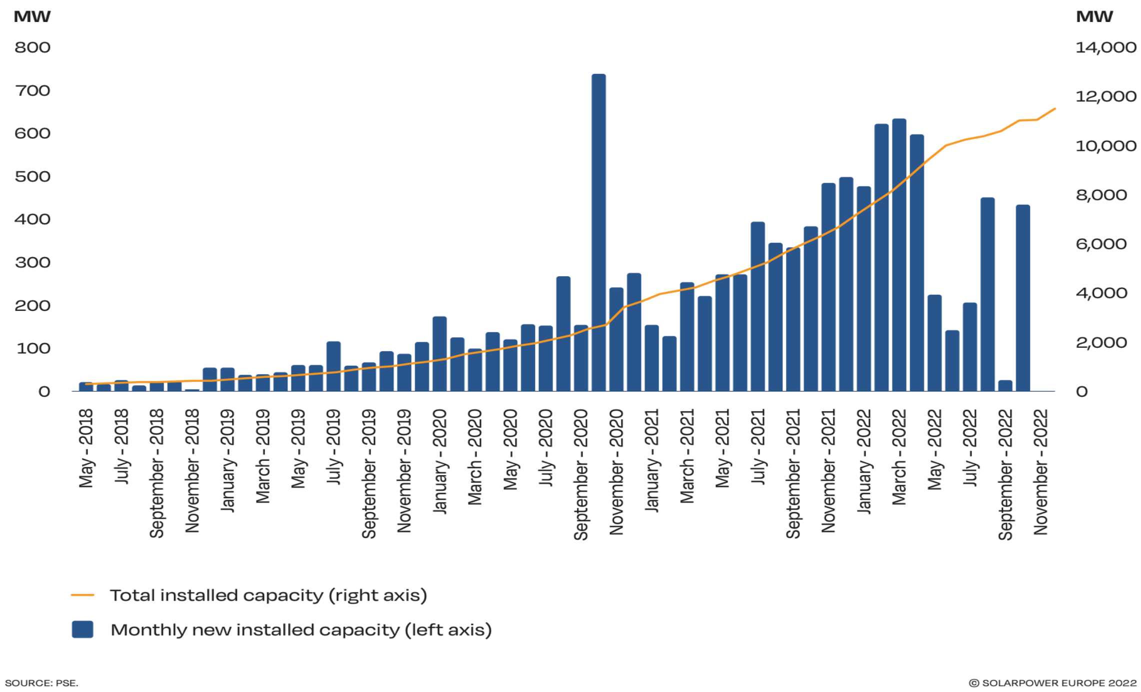


Figure 8. Total installed capacity and monthly new installed capacity of renewable energy sources in Poland. Source: SolarPower Europe.

The differences between these two systems are [12]:

- Net-metering system: With this system, the owner of the micro-installation produces his own energy, and he would have to pay just in case his own production is not enough to satisfy his consumption. In case he consumes less than what he generates, he is able to get some kind of credit. With this credit, the owner of the installation can be exempt from paying when his installation doesn't produce enough energy.
- Net-billing system: In this case, the owner of the micro-installation produces his own energy, but it is not worth it to produce more than what he consumes. In this system, you don't receive the "credit" as in the Net-metering one, in this case, you get paid for the excess at a fixed rate. The fixed rate is less profitable than the one with the Net-metering system.

This change in Polish regulations has stopped the growing tendency, as has been mentioned before. Besides this change, Polish citizens still think solar energy is the best renewable energy source, and they would accept having it in their neighborhoods.

The Energy Regulatory Office (URE), the office that carries out the auctions, thinks that 9 new GW of solar energy will be installed from now until 2027, and by 2030 50 GW are anticipated to be installed in Renewable Energy Sources (RES), believing that half of it is set to be provided by solar.

Globally, as has been mentioned before, the RES are being more and more supported due to the veto of the Russian fossil fuels and as Europe is looking forward to being energy independent.

1.2. Location of the installation

The installation will be located on the rooftop of building L-3 of the Politechnika Wroclawska, Na Grobli, 50-413, Wroclaw.

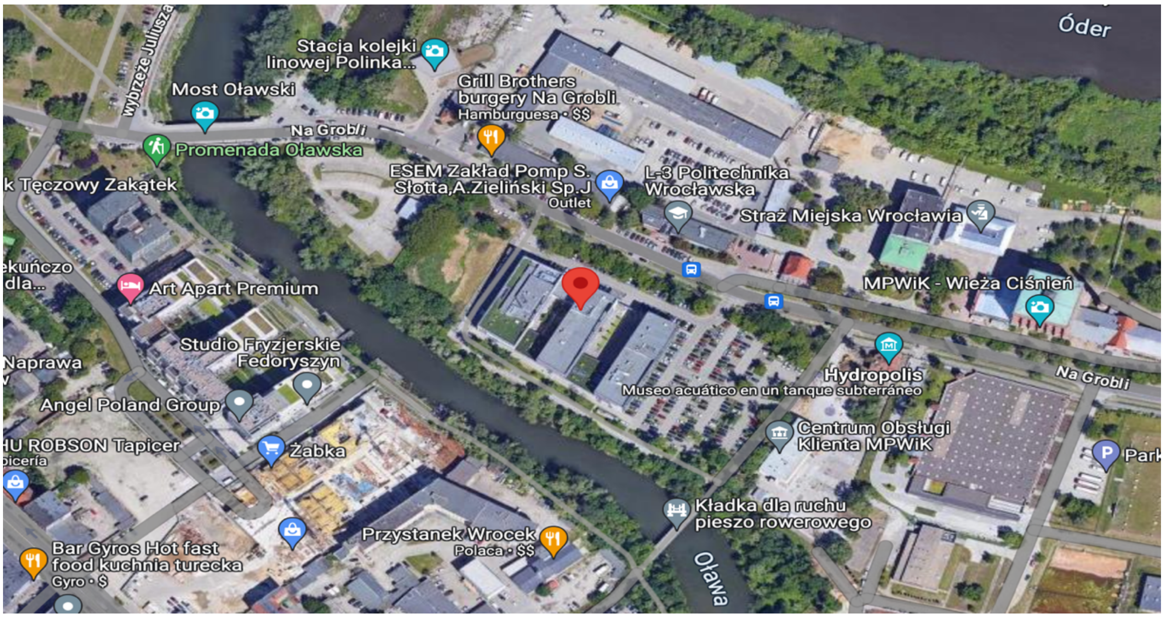


Figure 9. Geographical location of the project installation. Source: Google Maps.

The geographical coordinates of the building are:

Latitude: 51° 6' 15.61" N

Longitude: 17° 3' 15.397" E

In this location, some important and necessary data for the project can be gathered. Now, a study of the meteorological conditions for one day in specific in order to make a comparison between the different months and seasons of the year (Winter - Spring - Summer - Autumn) is going to be made. In addition, different parameters are going to be compared, such as Temperature and radiation (including Direct, Reflected and diffuse radiation).

2. Weather Conditions

2.1. Climatological Study

2.1.1. Temperature

Making a seasonal study of the temperature, can be seen how the temperature changes through the seasons and months. Having a look and comparing, the warmest month is September, with 27.8 °C, meanwhile, the coldest month is March (during the night), but during the day, comparing at 12 am, the coldest month is December with 5.16 °C.

From the data obtained [13], considering the night periods as well, can be stated that Wroclaw is a relatively cold city with an average temperature of 11.04 °C. The average temperatures per season when the sun is out:

- Winter (7 am – 16 pm): 5.4 °C
- Spring (5 am – 17 pm): 9.07 °C
- Summer (5 am – 21 pm): 21.7 °C
- Autumn (7 am – 18 pm): 15.2 °C

It is important to know that the temperature of the PV modules doesn't have an influence on the produced intensity, but it has an impact on the tension (which would be lower with more temperature), and this variation in the tension produces a reduction in the efficiency of the PV. So the closest the panel temperature is to 25 °C, the better. But 11.04 °C is not the worst case, some efficiency is being lost.

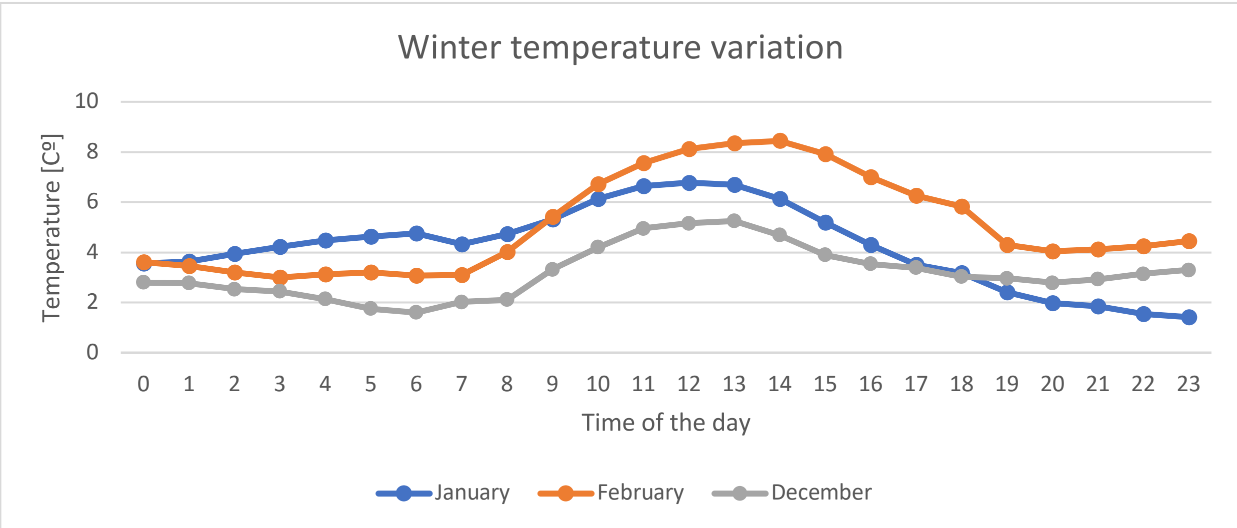


Figure 10. Winter Temperature variation in the project installation location

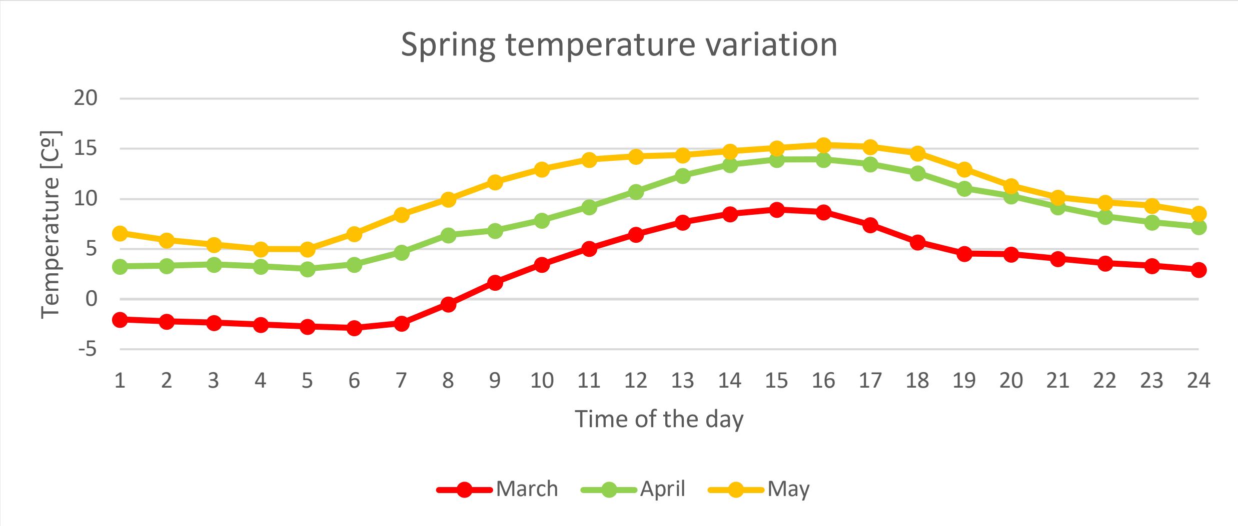


Figure 11. Spring Temperature variation in the project installation location

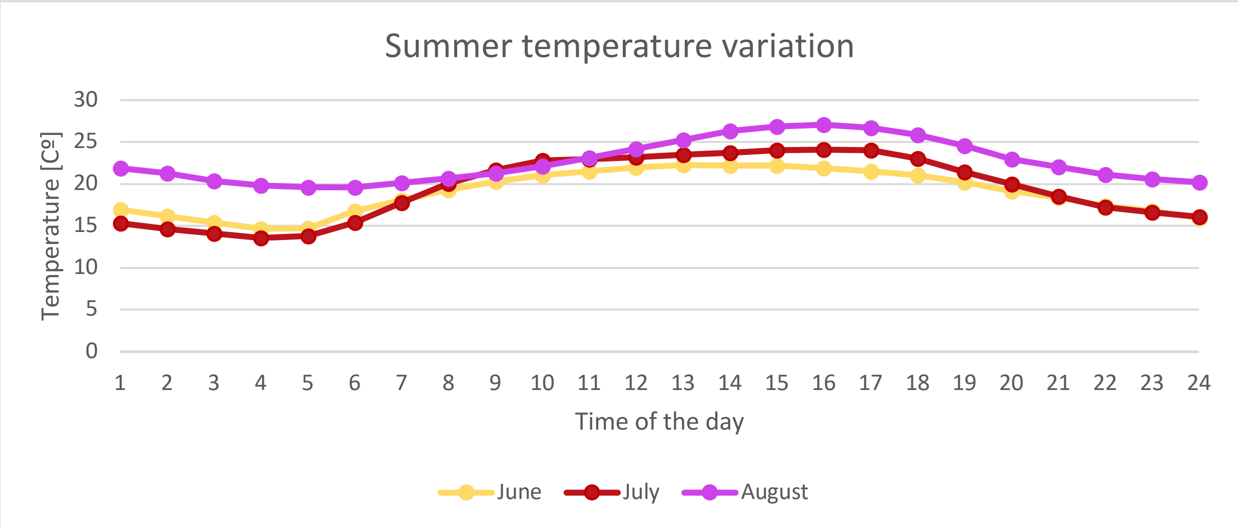


Figure 12. Summer Temperature variation in the project installation location

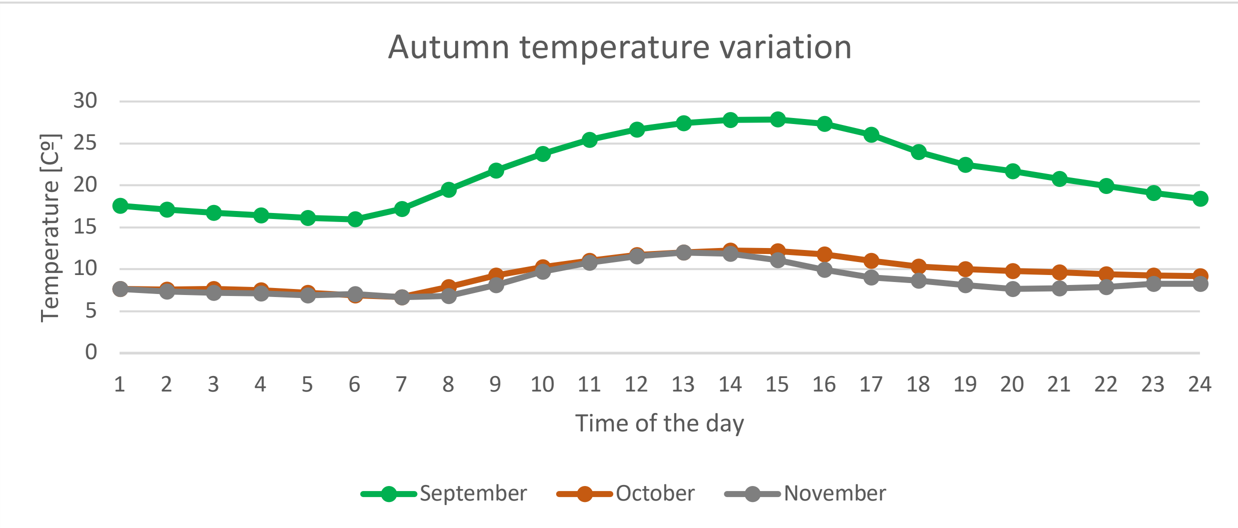


Figure 13. Autumns Temperature variation in the project installation location

This data is extracted from the database of the European Union, it also provides Wind velocity, but this parameter is not required for this project.

All the data collected is from the year 2020, due to the availability of the data in the databases.

The sun's height is an important parameter. Considering the installation in, approximately, a height of 2 meters, having a 12.86 degrees of sun height is not a bad parameter. In order to clarify the concept:

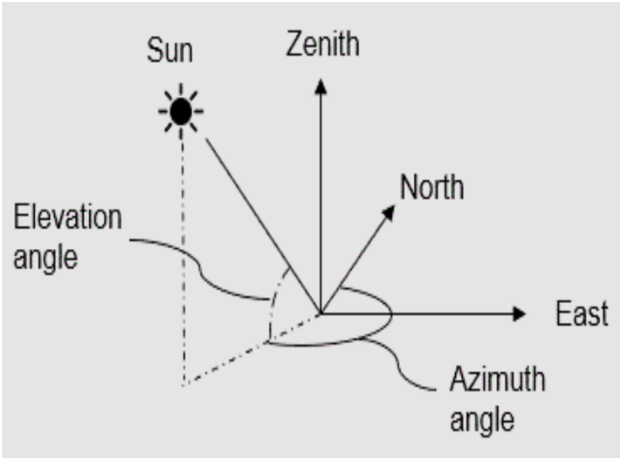


Figure 14. Solar angles [degree]

2.1.2. Solar Radiation

As the word radiation appears in a lot of different concepts, a definition is required. It is called solar radiation the intensity of the incidental solar electromagnetic radiation over a surface of a square meter. Inside this concept, three types are distinguished: Direct, diffuse, and reflected. The definitions are:

- Direct radiation: the radiation that comes directly from the sun without interference.
- Diffuse radiation: the radiation that comes from clouds or other parts of the firmament.
- Reflected radiation: the radiation that comes after reflecting on other objects or elements, such as the floor or other proximate elements.

So these parameters, the higher, the better. It will mean that more energy could be produced. It is not important how much direct radiation hits the PV installation because it works with radiation (no matter if it is direct, diffuse, or reflected), but of course, when the radiation reflects on a surface, not all of it will reach the PV installation. Each material reflects more or less radiation. The quantity of radiation that each surface will reflect is described with the albedo coefficient. Of course, direct radiation is preferred among the others.

Now, a study for the different types of radiation in the location of the project installation are going to be made.

2.1.2.1. Direct Radiation

Having a look at the graphs of direct radiation, can be seen that December was a cloudy month in winter. The month with the less direct radiation was October and the season with the worst data of direct radiation was, surprisingly, the summer season (considering the night periods).

In addition, just considering the sunny periods, and calculating the average:

- Winter (7 am – 16 pm): 249.33
- Spring (5 am – 17 pm): 284.40
- Summer (5 am – 21 pm): 125.07
- Autumn (7 am – 18 pm): 217.30

Not only during the night period, but the summer season also has the lowest direct radiation index during the day. Can be seen that the highest direct radiation index is obtained during the sunny period in the spring season with an index of 284.4 W/m².

It is clear to see that more a less all the seasons have a similar index of direct radiation except for the summer.

Looking closely at the graphs, cnsa be assured that the sudden downhills (unexpected low values), for example, in the months of December, July or August are due to cloudy or rainy days, May was an extremely cloudy or rainy month, the rest of the data seems pretty reasonable.

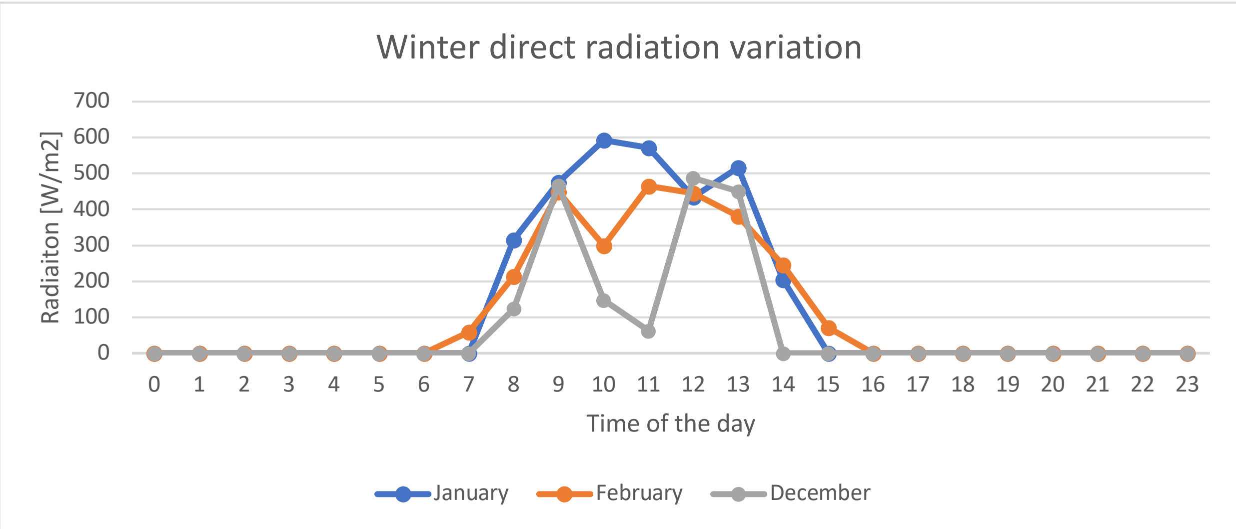


Figure 15. Winter direct radiation in Wroclaw [W/m²]

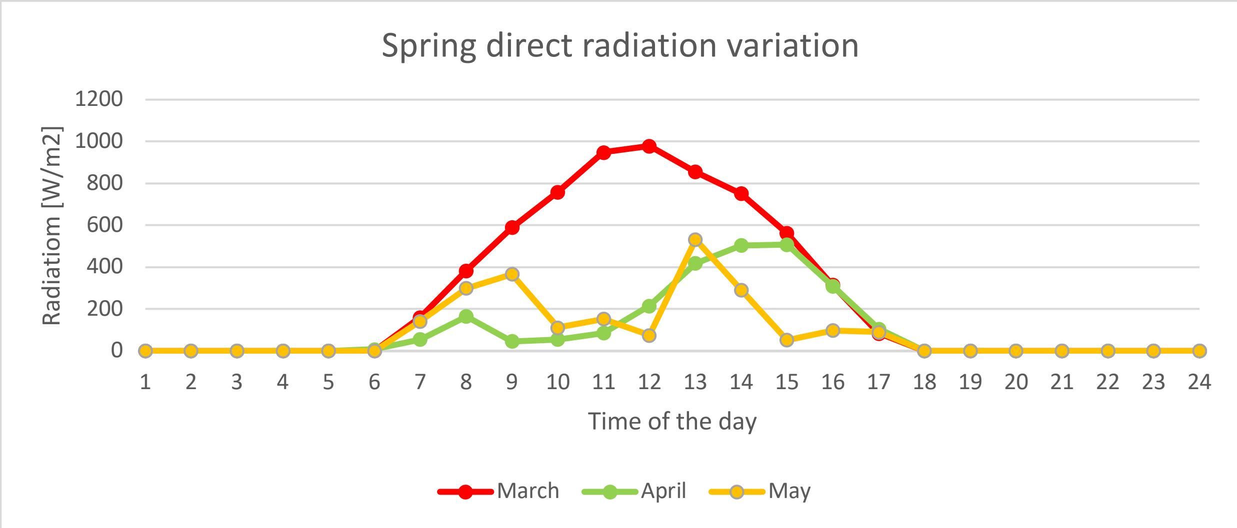


Figure 16. Spring direct radiation in Wroclaw [W/m²]

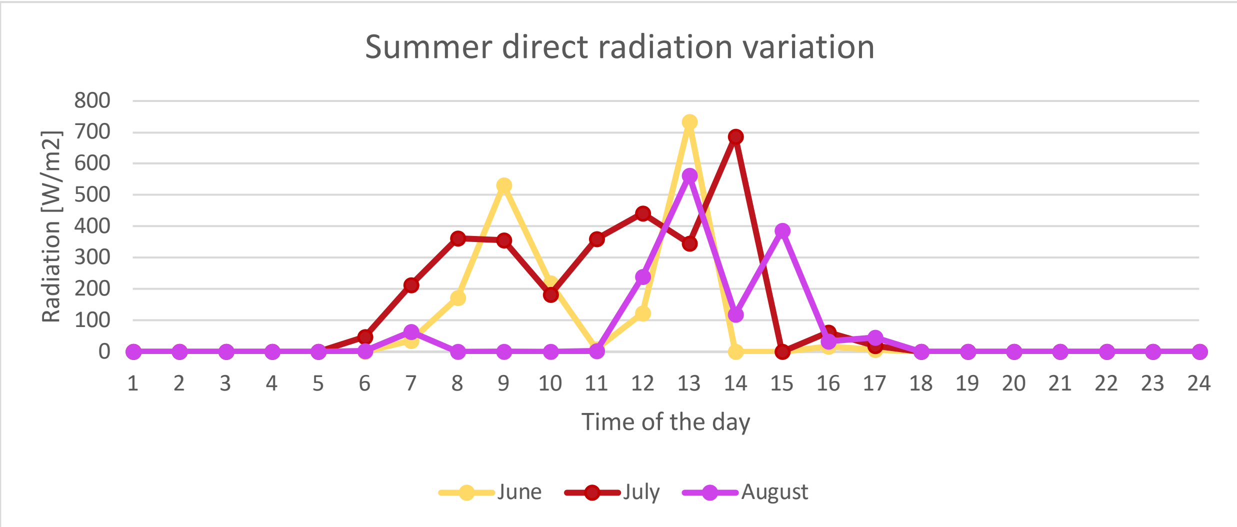


Figure 17. Summer direct radiation in Wroclaw [W/m²]

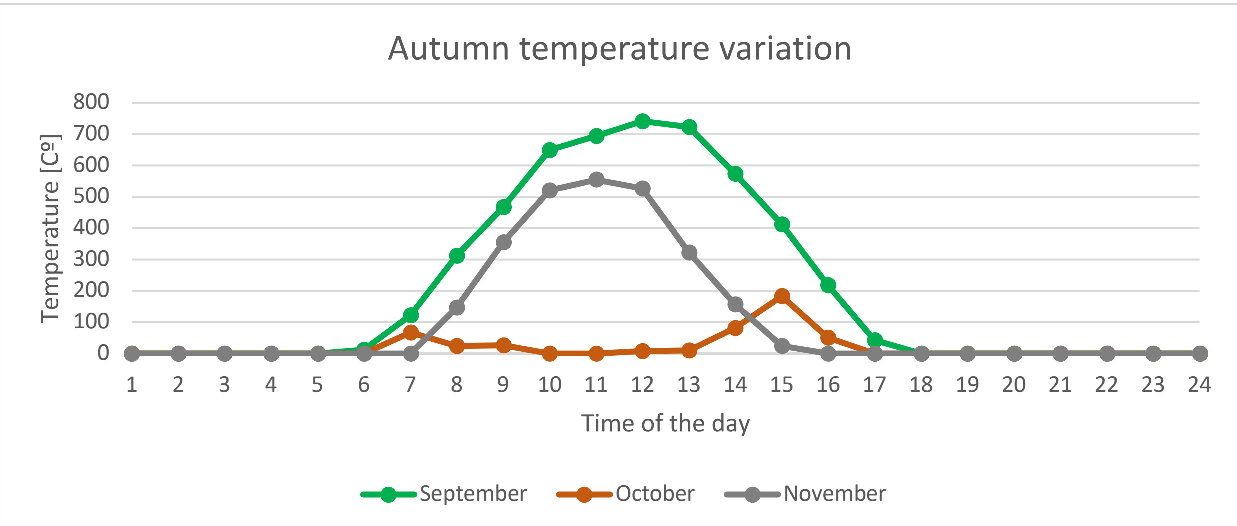


Figure 18. Autumn direct radiation in Wroclaw [W/m²]

2.1.2.2. Diffuse Radiation

Talking about Diffuse radiation, it is clear as can be seen almost in all seasons, the diffuse radiation is pretty good. Making a comparison between the different seasons, considering the night periods, the best diffuse radiation index is related to the summer season with 108.36 W/m². Not considering the night periods, the average diffuse radiation obtained per season is:

- Winter (7 am – 16 pm): 98.71 W/m²
- Spring (5 am – 17 pm): 176.84 W/m²
- Summer (5 am – 21 pm): 151.55 W/m²
- Autumn (7 am – 18 pm): 100.50 W/m²

So, during the sunny periods, the best season seems to be Spring. But, with a general vision the values are high, which means that Wroclaw is generally a cloudy or rainy city.

Looking for the highest and lowest value at 12 in the morning each month, the top value is obtained in June with 396.9 W/m² and the lowest in December with 117.24 W/m².

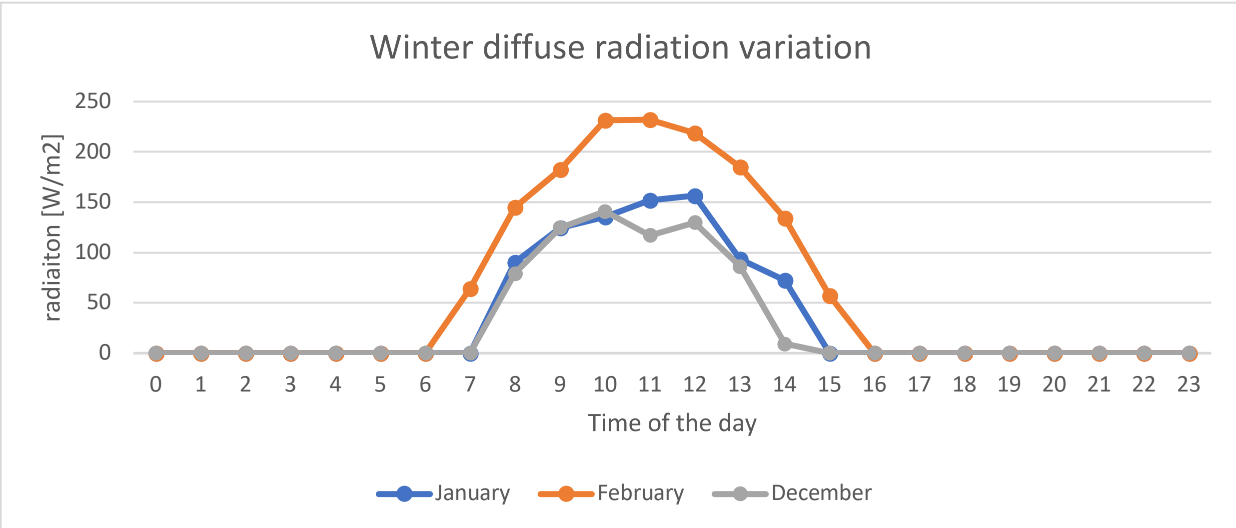


Figure 19. Winter diffuse radiation in Wroclaw [W/m²]

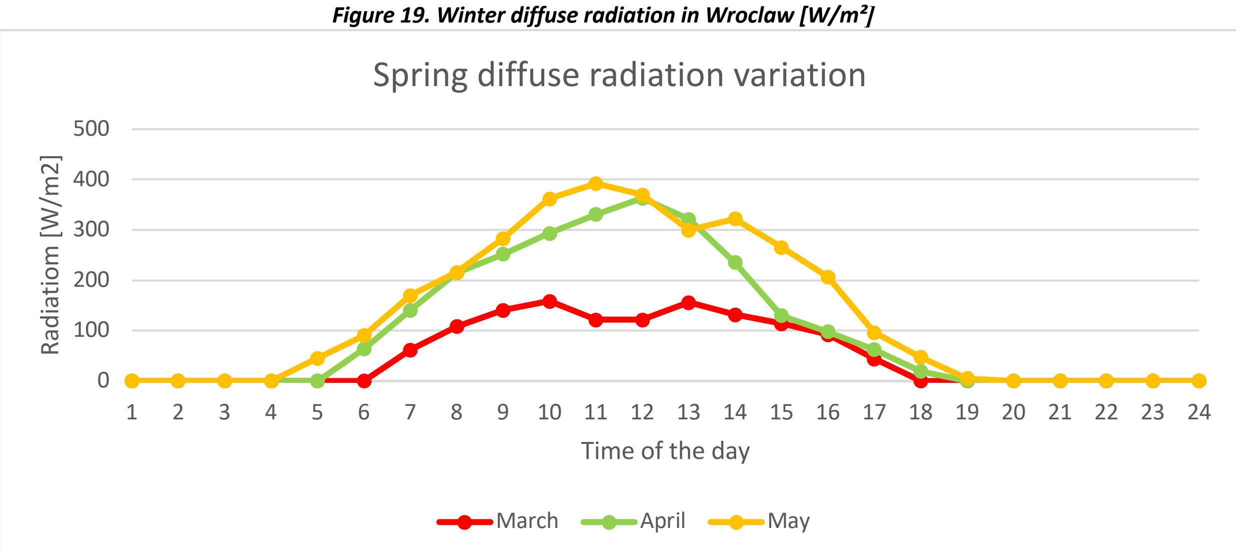


Figure 20. Spring diffuse radiation in Wroclaw [W/m²]

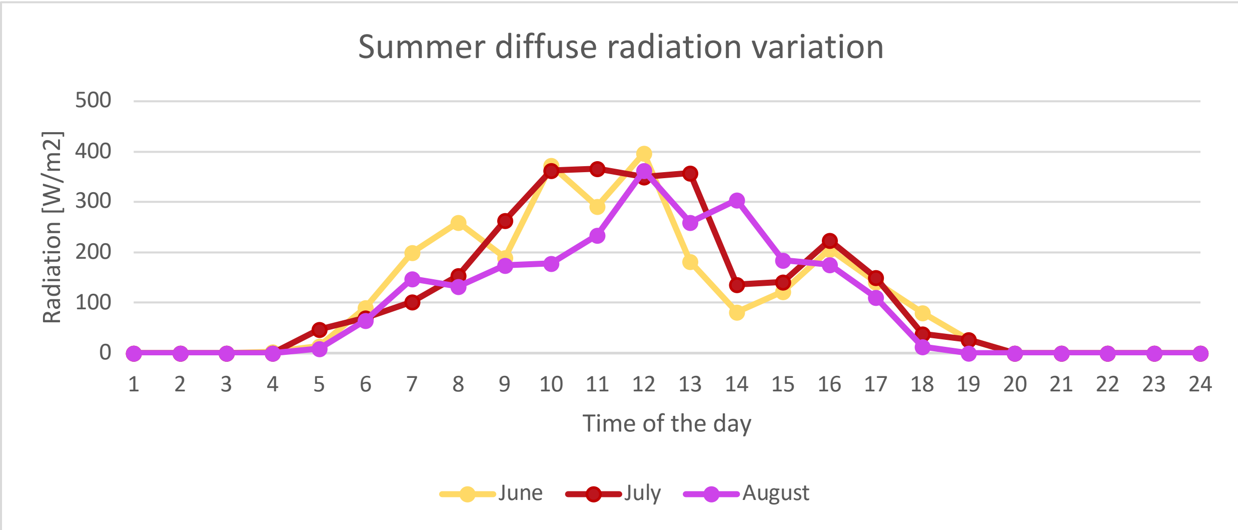


Figure 21. Summer diffuse radiation in Wroclaw [W/m²]

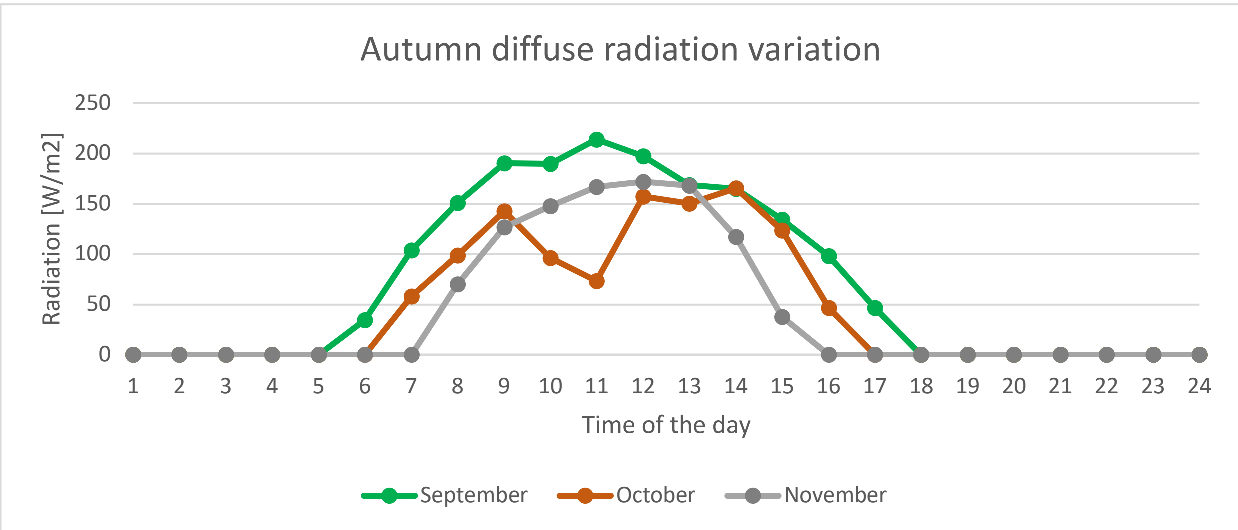


Figure 22. Autumn diffuse radiation in Wroclaw [W/m²]

2.1.2.3. Reflected Radiation

Talking about reflected radiation, as it is commonly known, is the radiation captured after reflecting in other objects such as the floor or walls. Having a look at the graphs, the values, in general, are pretty low. That is why the installation is located on the rooftop of a building, as a consequence not so much reflected radiation gets to the Photovoltaic panels.

So, including the night periods, the highest index of reflected radiation is obtained during the Spring season. On the other hand, not considering the night periods and comparing with the average per season:

- Winter (7 am – 16 pm): 4.43 W/m²
- Spring (5 am – 17 pm): 11.23 W/m²
- Summer (5 am – 21 pm): 8.48 W/m²
- Autumn (7 am – 18 pm): 6.05 W/m²

So it is clear that, during the sunny period, the highest index is obtained in the Spring season with an average reflected radiation of 11.23 W/m². Looking for the highest and lowest values during the year at 12 am, the highest is obtained in July with 21.85 W/m² and the lowest is obtained in December with 4.04 W/m².

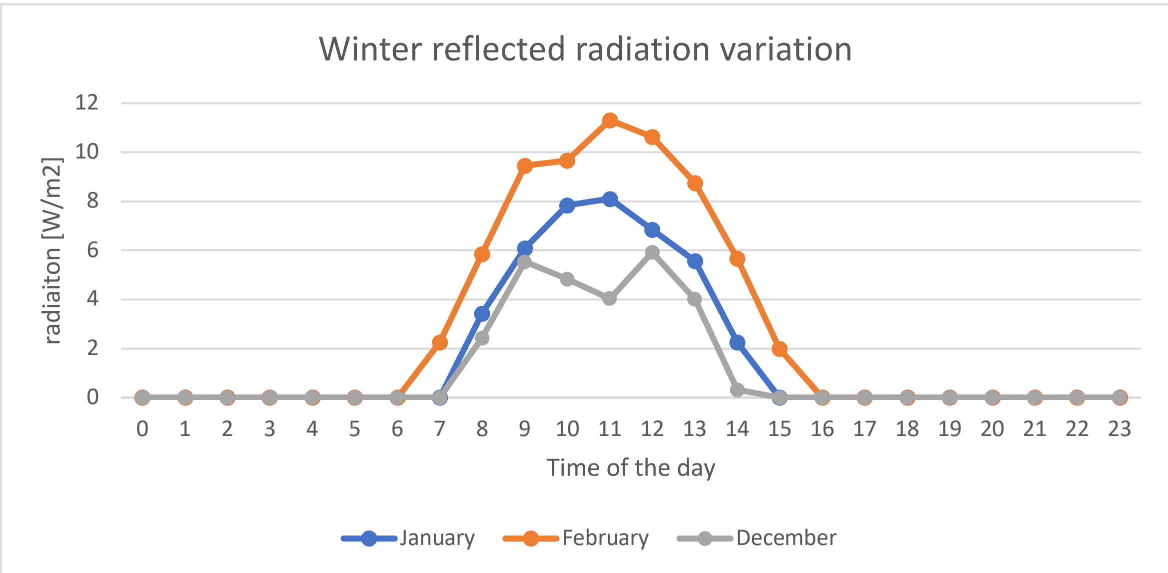


Figure 23. Winter reflected radiation variation in Wroclaw

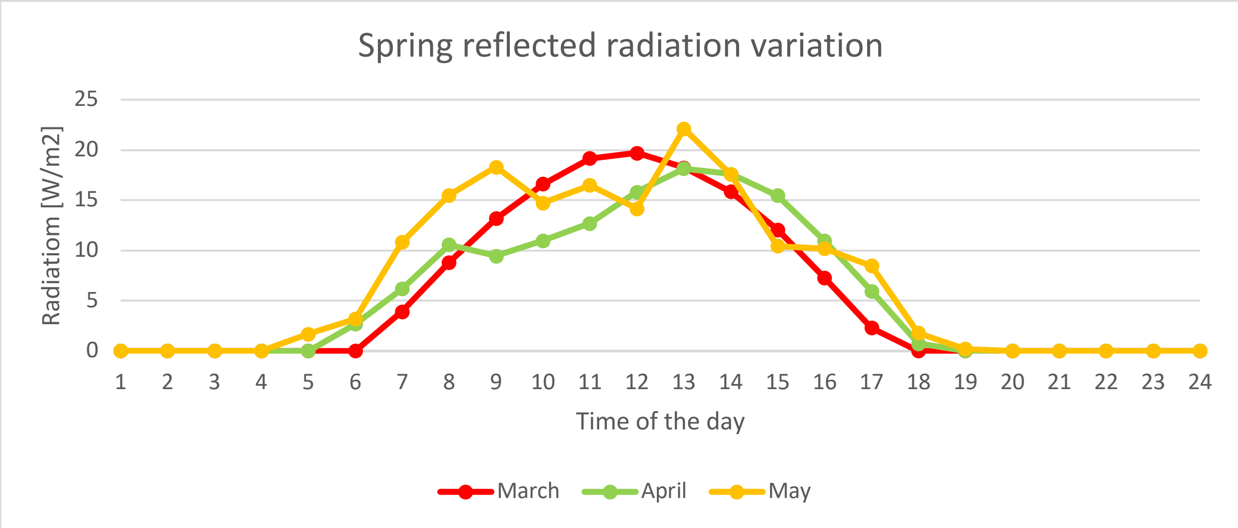


Figure 24. Spring diffuse radiation in Wroclaw [W/m²]

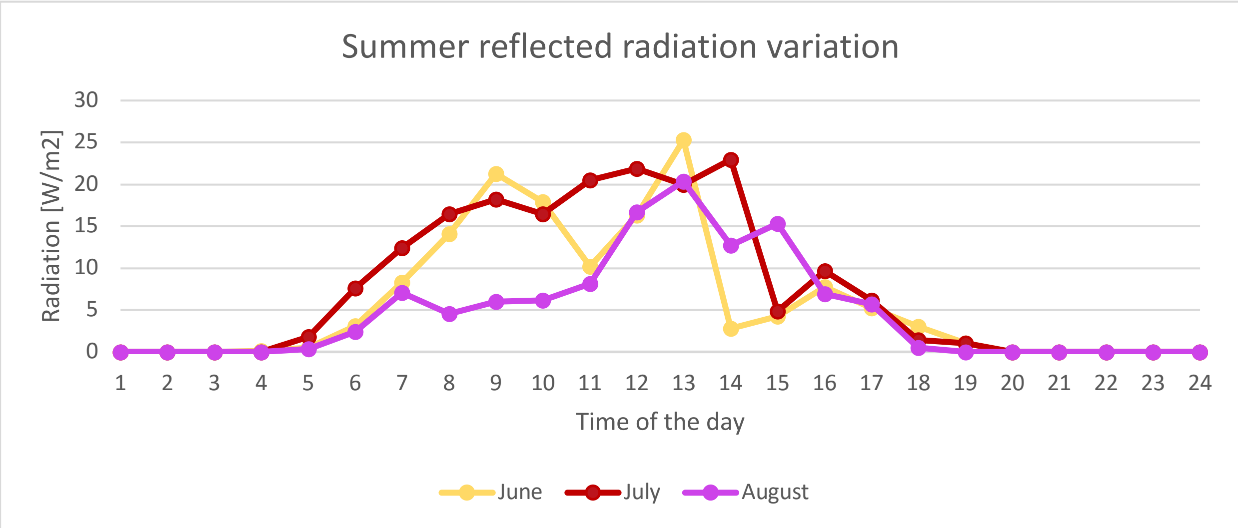


Figure 25. Summer diffuse radiation in Wroclaw [W/m²]

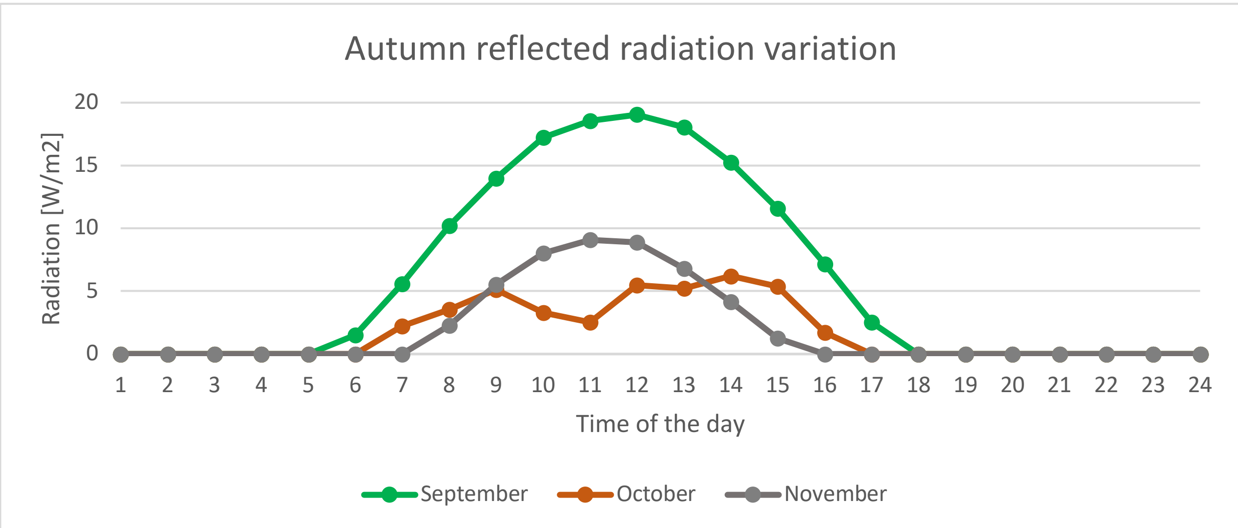


Figure 26. Autumn diffuse radiation in Wroclaw [W/m²]

2.1.2.4. Global radiation

Global radiation is a concept that has yet to be introduced in this report. Global radiation is, in a few words, the sum of all the types of radiation. So, this concept will give us a really good glance of the radiation each month of the year, allowing us to picture which month the installation will work better and which month the efficiency will be lower.

The equation is really simple:

$$Global\ Radiation = Direct\ Radiation + Diffuse\ Radiation + Reflected\ Radiation$$

Equation 1. Global radiation equation

There is no necessary introduction to these concepts, as have been explained before. Now, it is possible to show the graphs of the global radiation for each month and each season as has been done for the rest of the types of radiation.

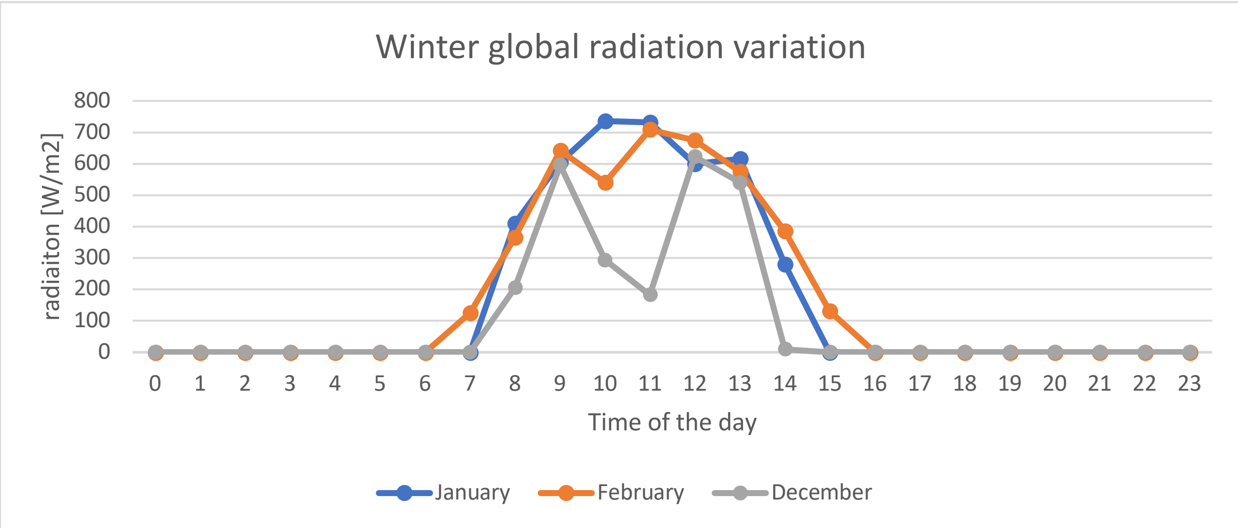


Figure 27. Winter global radiation variation [W/m²]

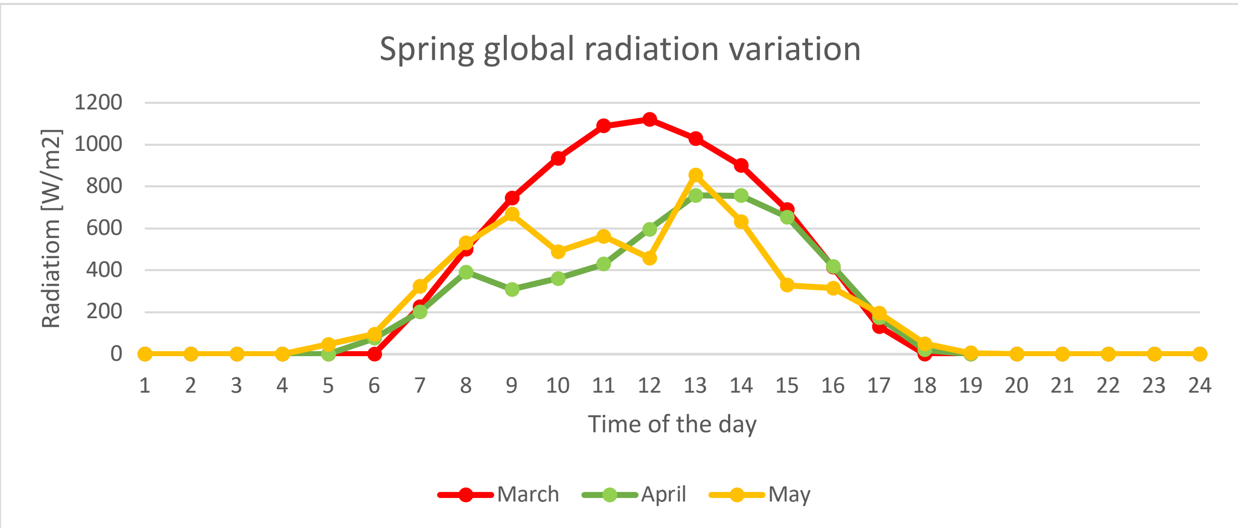


Figure 28. Spring global radiation variation [W/m²]

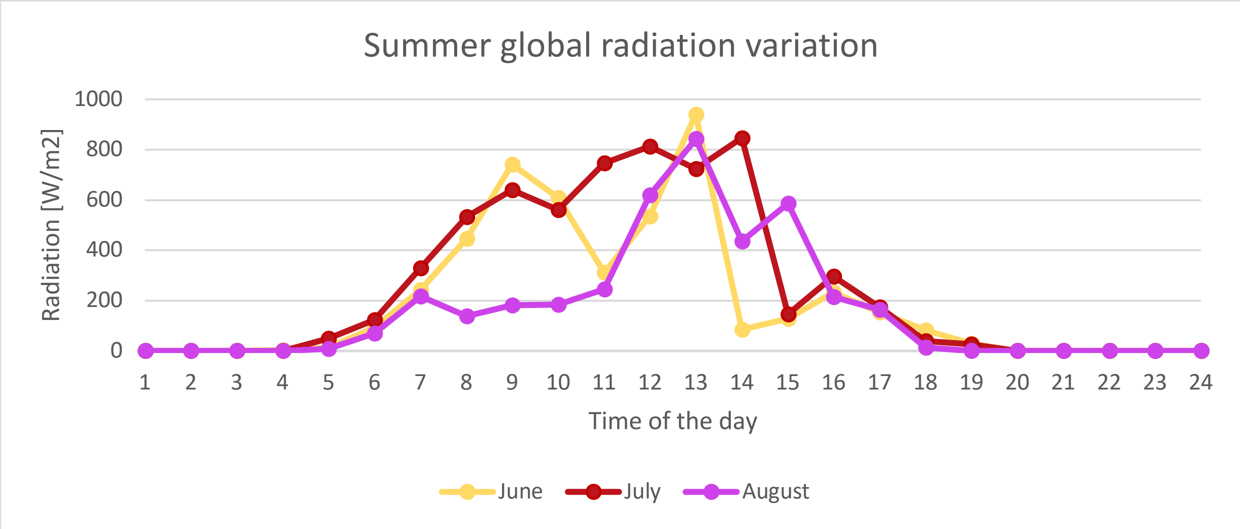


Figure 29. Summer global radiation variation [W/m²]

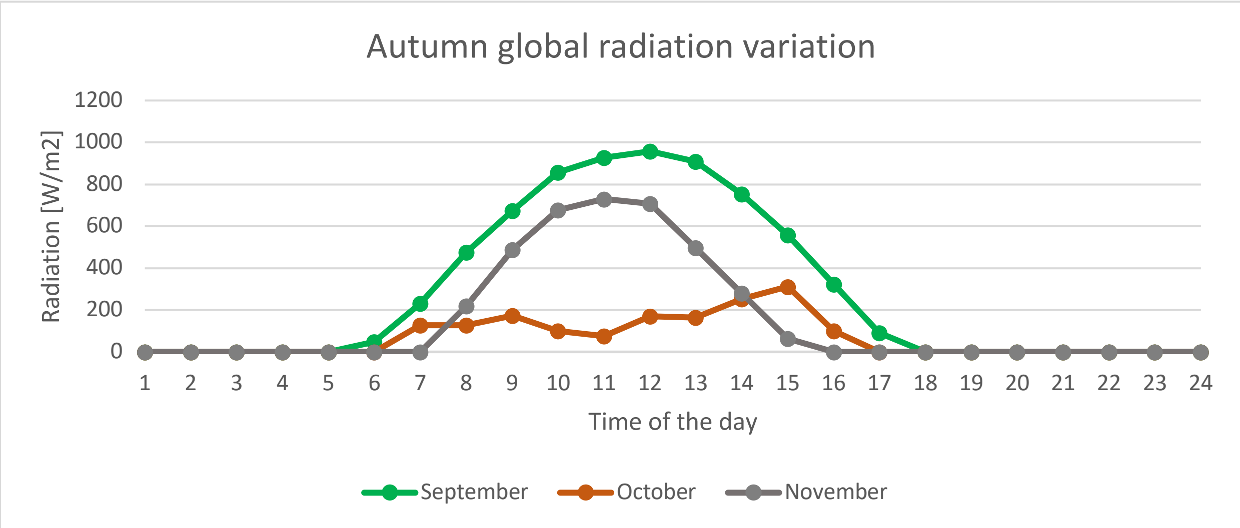


Figure 30. Autumn global radiation variation [W/m²]

Having a look at the graphs, the best global radiation parameters considering the night periods are founded during the Spring (with 256.65 W/m²) season, followed by the Summer (with 203 W/m²). Along this report, it is clear that Spring and Summer can be considered almost like a unique season, with very similar temperatures and radiation indexes as well.

Focusing only in the day periods (when the sun is out), the data obtained is:

- Winter (7 am – 16 pm): 352.47 W/m²
- Spring (5 am – 17 pm): 472.48 W/m²
- Summer (5 am – 21 pm): 285.1 W/m²
- Autumn (7 am – 18 pm): 323.86 W/m²

Now it is widely clear which season provides the biggest radiation index. Spring season, which includes the months of March, April, and May is the month where the global radiation index is bigger. But, as would later be demonstrated, is different from the season with the highest production indexes.

2.1.3. Sun Height

The sun's height is a really important parameter as well. It will affect how the sun falls upon the Photovoltaic panels. As this project is studying two situations, the first one with the panels completely horizontal, and the second one with a system that allows to vary the inclination of the panel. In the first situation, the sun's height would have a natural effect. In the second situation, the tracking system would be able to vary how the sun will fall upon the panels, trying to increase production as much as possible.

Now, a study about the sun's height depending on the season of the year is going to be made, to understand how the sun's height affects the energy production, and also a formula to obtain the sun's height and how will affect it will be developed.

2.1.3.1. Sun Height Formula

The sun height formula [14] will be able to determine the solar altitude angle (shown in Figure 31). The solar altitude angle is the angle formed by the Sun and the horizontal.

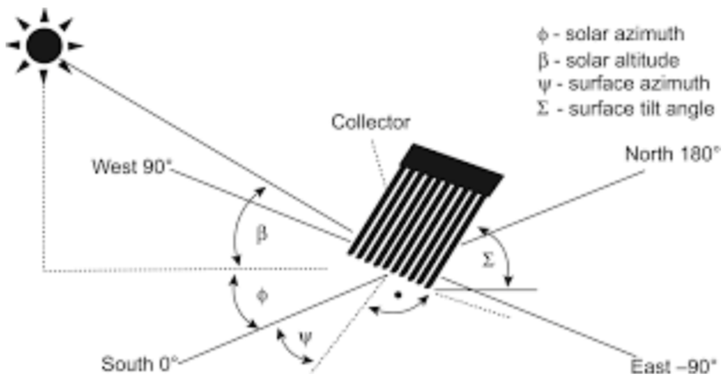


Figure 31. Solar angles [degree]

$$\sin\beta = \sin\alpha \times \sin\alpha + \cos\varphi \times \cos\varphi \times \cos\omega$$

Equation 2. Obtaining sin β

From this equation, it is worth to specify the following:

β: Solar altitude angle from the installation.

α: Sun declination, depending on the day of the year "j". The sun declination can be obtained with:

$$\delta = \phi \times \cos(C \times \frac{d - d_r}{d_y}) \Longrightarrow \delta = 23.5 \times \cos(360 \times \frac{j - 172}{365})$$

Equation 3. Obtaining δ

Where: ϕ: Tilt angle, in this case, 23.5 °.

C: Full 360 °.

d: Julian day (the actual day).

d_r: Julian day for summer solstice, in this case, 172 (173 if it is a leap year).

d_y: Number of days of the year, In this case, 365 (366 in case of leap year).

φ: Latitude of the city of Wroclaw (Poland) ¡, in this case, 51.6 °.

ω: omega will be the hourly angle in degrees. To obtain this value:

$$\omega = 15 \times \tau_{s1} - 180$$

Equation 4. Obtaining ω

Where:

τ_{s1}: Solar time or, in other words, local time. It can be obtained by:

$$\tau_{s1} = \tau + \frac{4}{60} \times (\lambda_{loc} - \lambda_{odn})$$

Equation 5. Obtaining solar time " τ_s1"

And from Equation 5 it must be specify:

τ: Hour in the day [h]

λ_{loc}: Local time of the references [h], in this case, $\lambda_{loc} = 0$

So Equation 5 lasts like this:

$$\tau_{s1} = \tau + \frac{4}{60} \times (\lambda_{loc} - 0)$$

Equation 5. Obtaining solar time " τ_s1"

The graphs below show how the sun's height or solar altitude angle varies depending on the month of the year. The months are grouped together by months. Having a look at the data, the months with the highest solar altitude are May, June, and July with pretty similar values, approximately 60 degrees. Moreover, the lowest solar altitude is assigned to the months of December and November, with 15 and 20 degrees, respectively.

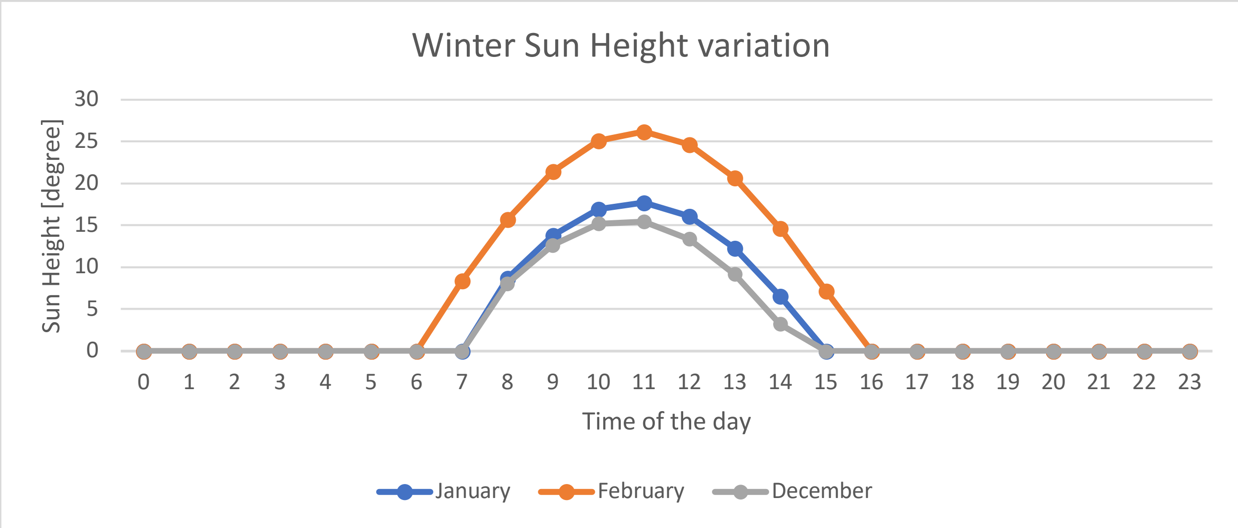


Figure 32. Winter sun height variation in Wroclaw [degree]

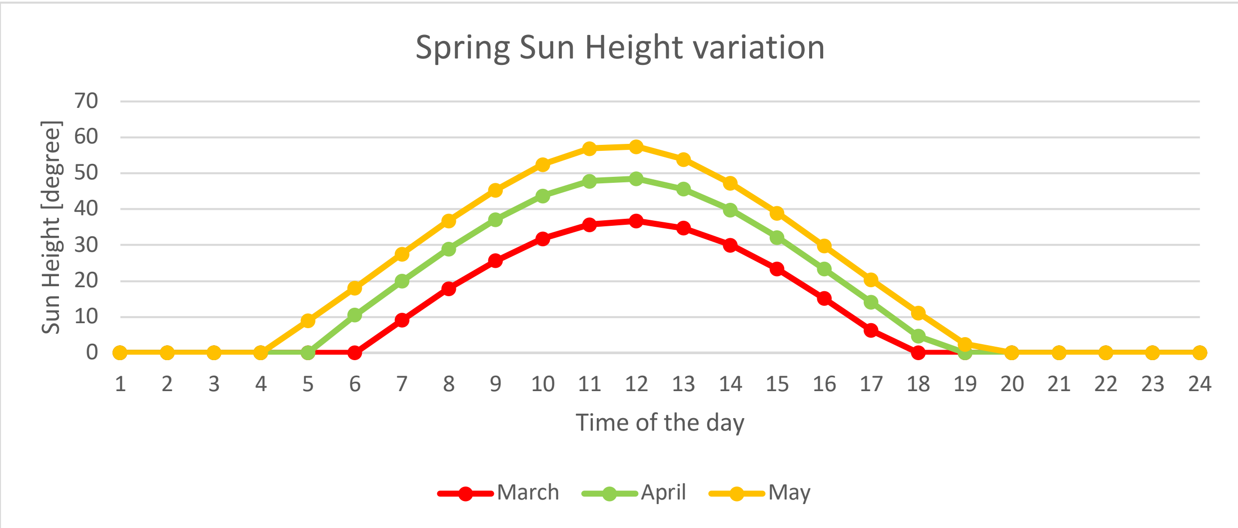


Figure 33. Spring sun height variation in Wroclaw [degree]

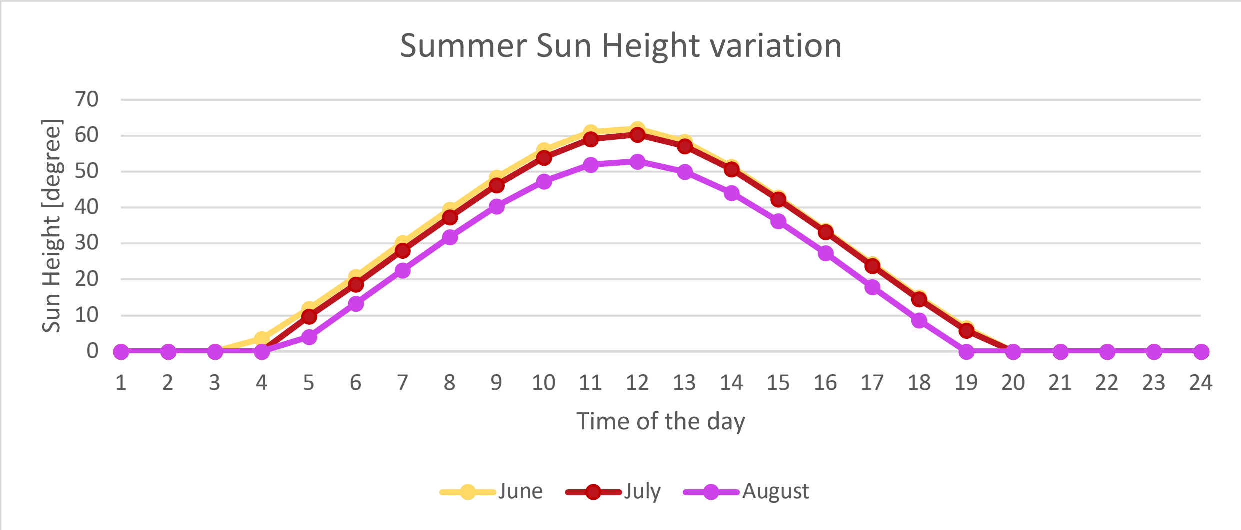


Figure 34. Summer sun height variation in Wroclaw [degree]

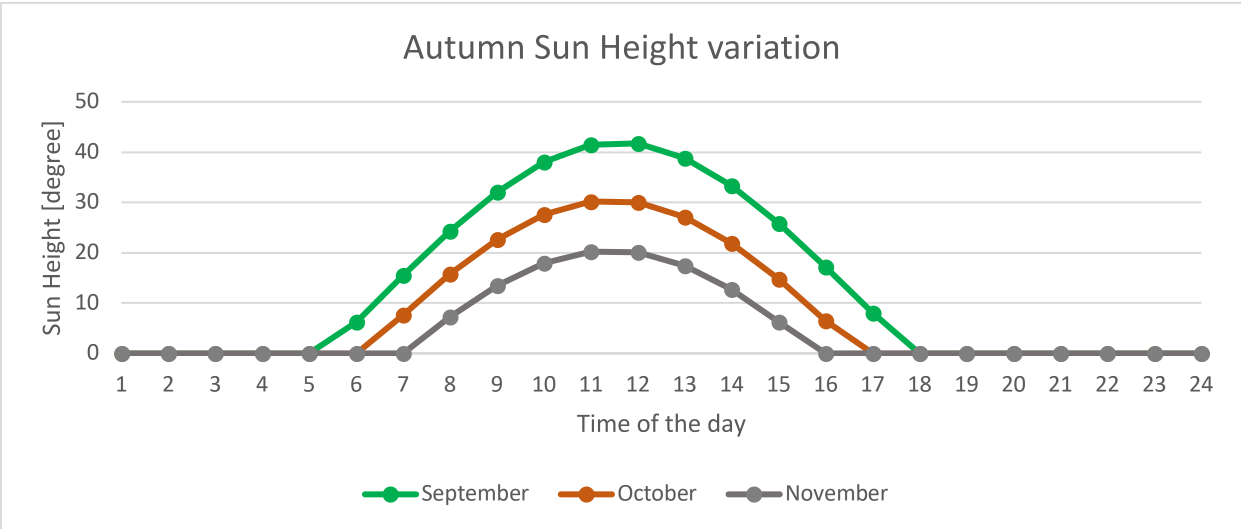


Figure 35. Autumn sun height variation in Wroclaw [degree]

3. Electricity Production

3.1. Types of Panels

Firstly, a brief study of the different types of panels [15] might be interesting in order to introduce the different technologies available in the market.

3.1.1. Crystalline Silicon panels

Crystalline Silicon panels are the most used, almost all the market is dominated by this type of panel. This technology is really mature in terms of efficiency and production costs. Inside this category, two different types of panels exist, which are the Monocrystalline silicon panels and Polycrystalline silicon panels. Describing each of them:

- Monocrystalline Silicon Panels: These types of panels are built of high-purity homogeneous crystalline silicon crystals. These crystals are obtained from de growth of a cylindrical threadlike crystal. After growing, the cylinder is cut into “panels” of approximately 200-250 µm thick. This crystal is then put down to a process to create small lines, with the unique purpose of minimizing the bending losses.

  The main advantage of this type of crystal is its efficiency, 14-17%, and its durability.

- Polycrystalline Silicon Panels: the different crystals which are contained in these panels are organized in different directions and with different forms. The process to obtain this type of crystal is a bit different, the polycrystalline is obtained by casting the silicon and then cutting it in “panels” of 1800-3000 µm thick.

  The efficiency of these panels is not as good as the monocrystalline ones, with 12 to 14%, but are cheaper. The durability is also less than the monocrystalline ones.

What is expected from this technology is to increase efficiency and a possible reduction of cost production.

3.1.2. Thin Layer Panels

The Thin Layer panels are commonly semiconductor materials in the form of a gaseous mixture, contained in polymer, glass, or aluminum support. The thickness of the semiconductor layer is really small (a few micras). This means that when producing these panels, there is a big saving in terms of materials. There is a wide variety of materials that can be used to produce these panels (amorphous silicon, CdTeS, GaAs, CIS, CIGS, CIGSS)

Depending on the material used, the efficiency varies. In the worst case, amorphous silicon has 5-6%. The CdTeS panels have a bigger efficiency, with 10-11%.

From all these Thin Layer Panels, the best option is the GaAS technology, with an efficiency of 25-30%, but the production costs are very high, and the availability of the material is really short. So this GaAS technology is only used in very specific applications, where the weight and dimensions are key factors.

The CIS, CIGS, and CIGSS are in development where the silicon is replaced by allies. This technology has an efficiency of 10-11% with constant efficiencies.

3.2. Installation project

3.2.1. Fixed installation

In the installation for this project will be used the monocrystalline silicon panel. The characteristics of the specific panel will be:

Maximum Power of a single panel	350 Wp
Total number of panels	1 panel
Total electrical power of the installation	350 wp
Temperature coefficient of Pmax	-0,38
Panel's efficiency under STC conditions	18%
Geometrical dimensions of a single panel	1960 x 991 x 40 mm
Inverter's efficiency	0,97
Wire's efficiency	0,99

Table 1. Characteristics of the Photovoltaic panel installation

Knowing the characteristics of the panels/installation, the study of the capacity of production of electricity in the installation can be started. In order to do that, firstly, is required to assume the Brzezicki et al.(2021) regarding solar panels [16]. The power production follows the next equation:

$$P_{PV} = P_{max} \times \frac{GI}{G_{STC}} \times (1 - \frac{\gamma}{100} \times (T_{NOCT} - T_{CELL})) \times \eta_{inv} \times \eta_{wire} \times N$$

Equation 6. Total power production of the installation

Specifying and explaining some of the parameters:

P_{PV}: Electricity produced by the installation, measured in W.

P_{max}: Maximum rated power per panel, measured in W/panel.

GI: Current global irradiance, measured in W/m².

G_{STC}: Solar radiation in standard test conditions (STC), measured in W/m². It will be considered as $G_{STC} = 1000$.

γ: Temperature coefficient of P_{max}, measured in %/°C.

T_{CELL}: Current cell temperature, measured in °C.

T_{NOCT}: Normal operating cell temperature (NOCT), measured in °C. It will be considered as $T_{NOCT} = 45$ °C.

η_{wire}: Efficiency of the wire of the installation.

η_{inv}: Efficiency of the inverter of the installation.

N: total number of Photovoltaic panels in the installation.

To obtain the current cell temperature of the installation, required to obtain the production of the installation, the Equation 7 is going to be used:

$$T_{CELL} = T_{a,DBT} + \frac{GI}{G_{NOCT}} \times (T_{NOCT} - T_{a,NOCT})$$

Equation 7. Temperature of the cell equation

Specifying and explaining some of the parameters:

T_{CELL}: Current cell temperature, measured in °C.

$T_{a,DBT}$: Current ambient temperature of the dry-bulb thermometer obtained from the database.

$T_{a,NOCT}$: Ambient temperature in normal cell operating conditions. It will be considered as $T_{a,NOCT} =$ 20 °C.

G_{STC}: Solar radiation in normal cell operating conditions, measured in W/m². It will be considered as $G_{NOCT} = 800$.

And the rest of the parameters are already explained for the previous formula (production of the panel).

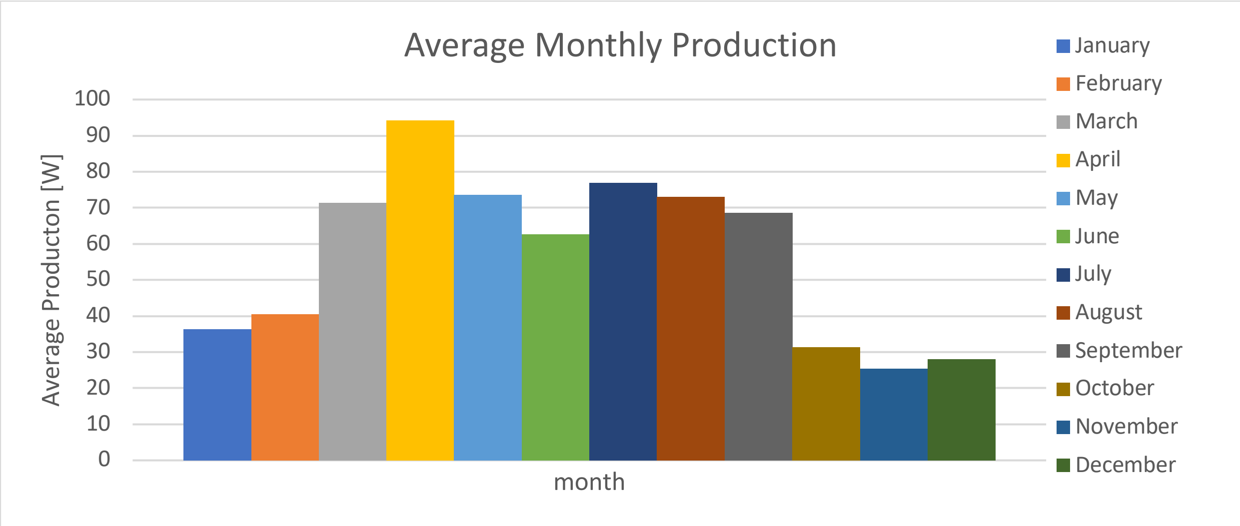


Figure 36. Average monthly solar energy production with the fixed installation [W]

So, focusing on the graph of the average production for one panel, it is clear that the months with the worst index of production are November with 25.45 W, October with 31.39 W, and December with 28.01 W. On the other side, the months with the best production indexes are April with 94.08 W, July with 76.88 W, and May with 73.55 W.

It is clear then that the season with the best production index is Spring (with 79.76 W per month), followed by Summer (with 70.86 W per month), pretty far from the other two seasons, Autumn (with 41.82 W per month) and Winter (with 34.94 W per month). Having a look at the global radiation and sun height figures, previously shown, it was predictable that the seasons with the highest production indexes were going to be Summer and Spring because those were the ones with the highest indexes. And as has been mentioned previously, electricity production depends on global radiation and cell temperature, being the average cell temperature per season:

Winter	6,51
Spring	16,66
Summer	26,08
Autumn	15,13

Table 2. Average cell temperature per season [°C]

So, putting together the cell temperature and the global radiation, it is now clear which are the months and seasons with the highest production indexes.

If this data is compared with the global radiation data, it is clear that Spring was going to be the season with the highest production index, because the radiation was the highest, followed by Summer, so the data is coherent.

Moreover, If only the sunny period is considered, the average obtained is:

- Winter: 128.11 Wh
- Spring: 167.63 Wh
- Summer: 97.58 Wh
- Autumn: 111.44 Wh

A considerable difference between this average and the previous one is shown here. This is due to the fact that this average is done for a particular day (the 15th day of each month), so there were probably really sunny days in winter in comparison with the summer period.

In the graphs below, it is possible to see the variation in production per month and per season (for the 15th day of each month). Having a look, the graphs represent what has been mentioned before. Autumn and spring on these specific days are the seasons with the highest production indexes.

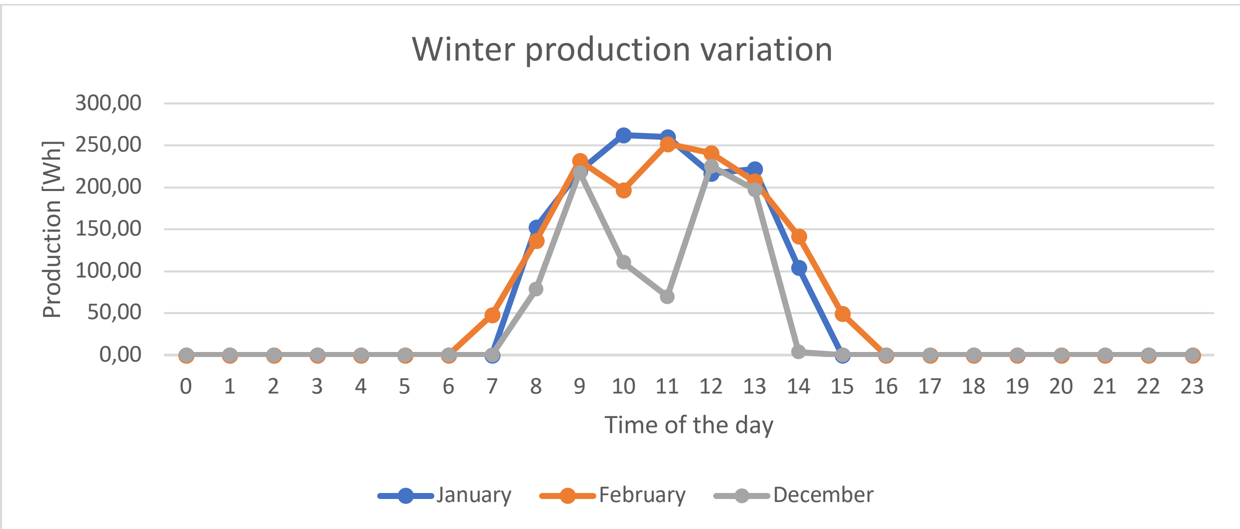


Figure 37. Winter production variation [Wh]

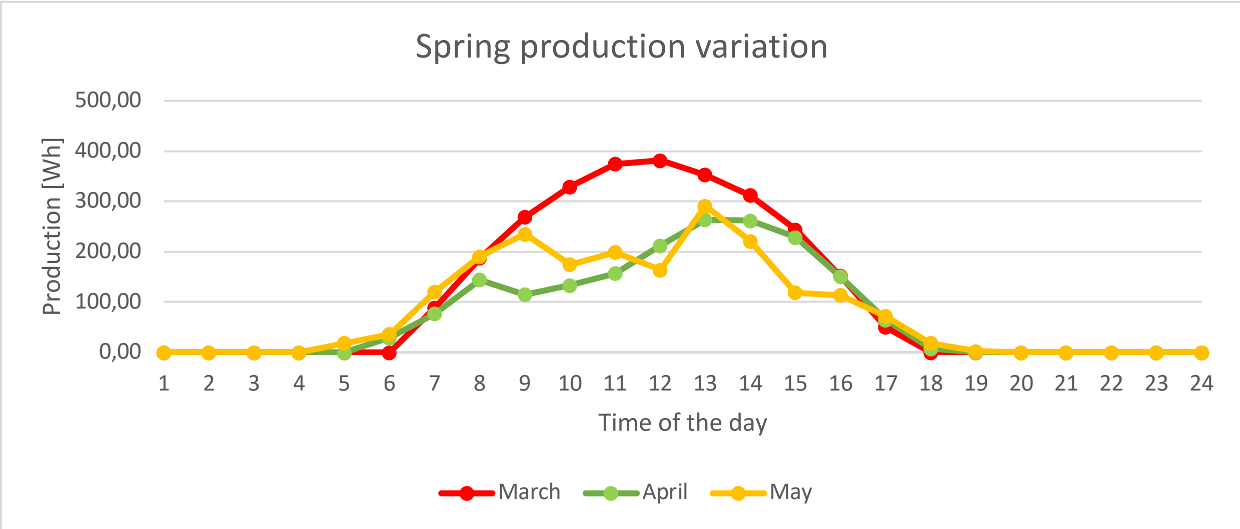


Figure 38. Spring production variation [Wh]

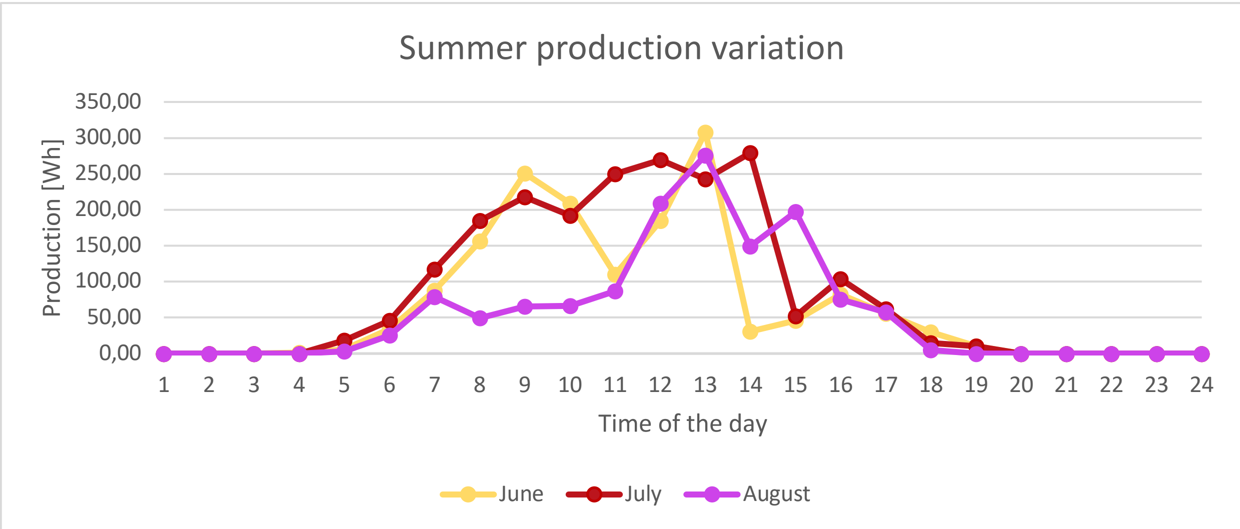


Figure 39. Summer production variation [Wh]

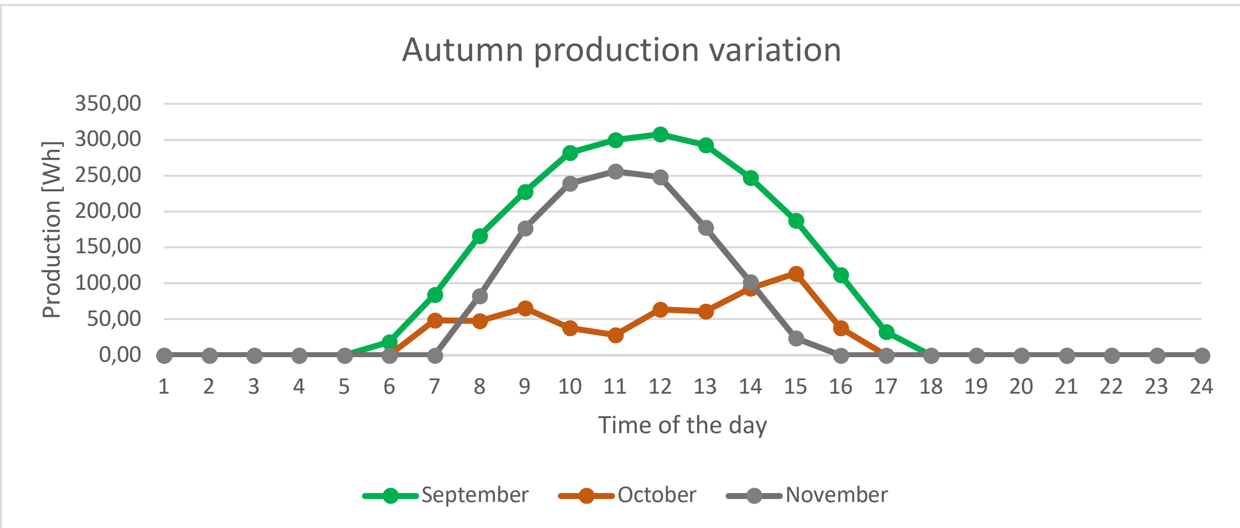


Figure 40. Autumn production variation [Wh]

3.2.2. Tracking system installation

3.2.2.1. Lagrange method for interpolation process by polynomials

Joseph-Louis Lagrange [17], an Italian mathematician, physicist, and astronomer, developed the Lagrange Interpolating polynomial method, which was published in 1795. This method is the unique one that is able to interpolate a given set of data of a low degree.

The problem of interpolation consists in the following: Given the values y_i corresponding to x_i, where I = 1, 2, 3 . . . , n, a function f(x) of the continuous variable x is to be determined which satisfies the equation [18]:

$$y_i = f(x_i) \; for \; \mathrm{i} \; = \; 1, 2, 3 \ldots, \mathrm{n}$$

One thing is necessary, f(x) must correspond to $x = x_0$. Another important thing is that the values of the arguments can be assigned arbitrarily.

The Lagrange interpolation considers the following function:

$$f: [x_0 , x_n] \Longrightarrow \mathrm{R}$$

This function is controlled by the following table or similar:

x_i	x_0	x_1	x_n
$f(x_i)$	$f(x_0)$	$f(x_1)$	$f(x_n)$

Table 3. Example of the Lagrange method

Where the x_i are called nodes and are not necessarily equally distanced from each other. The final objective of this method is to find a polynomial $P(x)$ of degree n that approximates the function $f(x)$ in the interpolation nodes.

The theorem itself looks like this:

Lagrange interpolating polynomial is the polynomial of degree n that passes through (n+1) points $y_0 = f(x_0)$, $y_1 = f(x_1)$, etc. Let:

$$P(x) = \sum_{j=0}^{n} P_j(x)$$

Where:

$$P_j(x) = y_j \times \prod_{i=0,\ i\neq j}^{n} \frac{x - x_i}{x_j - x_i}$$

Developing this equation for the case of $n = 3$, which is the case of this project:

$$P(x) = y_1 \times \frac{(x - x_2) \times (x - x_3)}{(x_1 - x_2) \times (x_1 - x_3)} + y_2 \times \frac{(x - x_1) \times (x - x_3)}{(x_2 - x_1) \times (x_2 - x_3)} + y_3 \times \frac{(x - x_1) \times (x - x_2)}{(x_3 - x_1) \times (x_3 - x_2)}$$

Equation 8. Lagrange interpolating polynomial for n =3

3.2.2.2. Purpose of the tracking system

The reasons for implementing a tracking system are simple. The difference between investment from the fixed and non-fixed installations has yet to be mentioned, but the main reason for implementing a tracking system is the improvement in the electricity production of the installation.

This tracking system, as has been mentioned previously, would not modify the direction (north, south, west, or east) but will modify the slope of the panels. This would be done with the objective of having the panel the majority of the time ready to receive sun radiation. As is known, the sun's radiation obtained by the solar panel is maximum when the surface of the panel is perpendicular to the sun's radiation (direct radiation). That is why the tracking system will help the installation to grow electricity production.

To elaborate on the calculations of this system, the Lagrange method for interpolations will be used as to obtain the radiation obtained per each angle, distinguishing between the positions contained in the database, which will make possible the application of the Lagrange method. The data obtained from the database will be for 0°, 30°, 45°, 60°, and 90°, with these different positions and the Lagrange method, the calculations for every position will be possible.

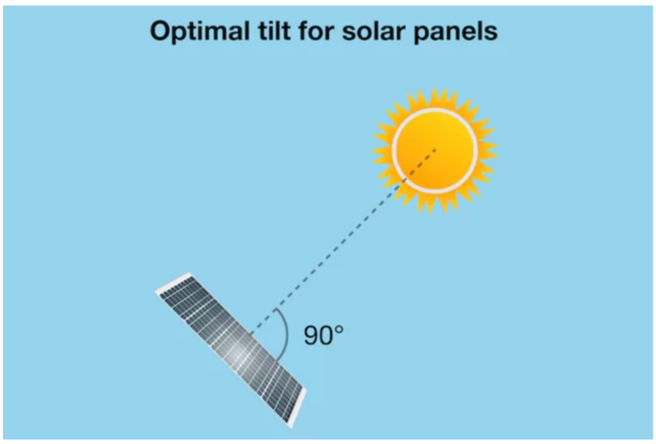


Figure 41. Optimal tilt for solar panels

3.2.2.3. Results of the tracking system

Making the calculations implementing the tracking system, the production, as was predicted, increases.

The variation of electricity production obtained for one panel is about 1.4 KW in comparison with the fixed installation.

Total production without tracking system [MW]	0,499
Total production with tracking system [MW]	0,501
Difference of production [KW]	1,342
Difference of production [%]	0,268%

Table 4. Production with and without the tracking system and difference

The graph below shows the average production per panel per month with the tracking system installation. And it requires a close look to appreciate the differences.

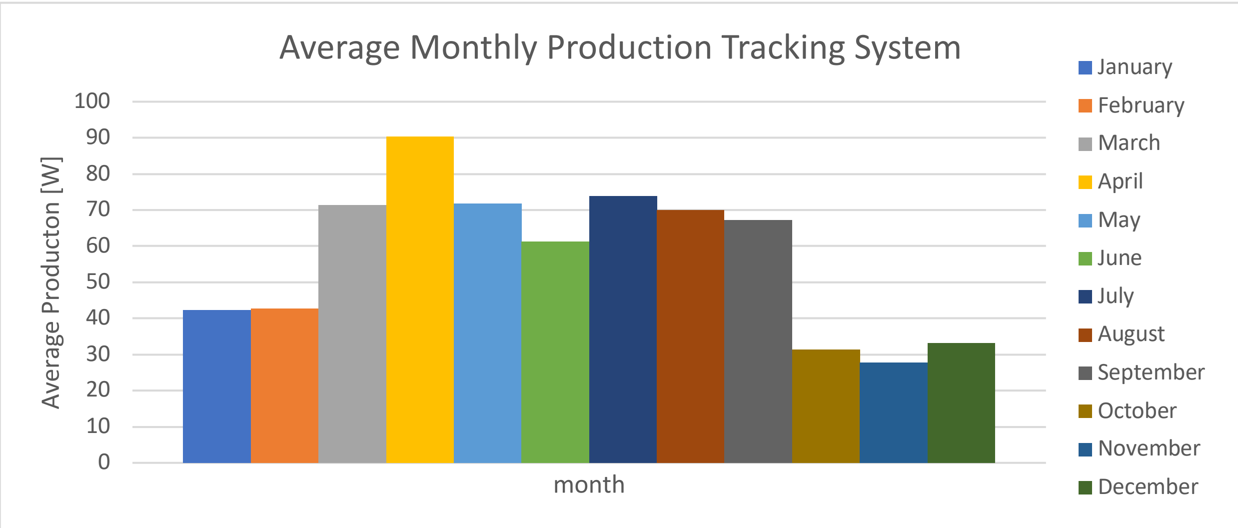


Figure 42. Average monthly production with the Tracking System

So the variation appears mainly in the months of April and January, in the rest of them is minimum. In some months (where the variation is negative), the tracking system installation produces less than the fixed one. If a table with the variation percentage per month can be seen the following:

Month	Fixed Installation production [W]	Tracking System Installation prodcution [W]	Difference [%]
January	36,37	41,46	12,27%
February	40,44	43,20	6,39%
March	71,35	73,48	2,90%
April	94,08	88,61	-6,18%
May	73,56	73,42	-0,19%
June	62,58	61,19	-2,28%
July	76,89	73,89	-4,05%
August	73,13	67,18	-8,87%
September	68,62	66,92	-2,53%
October	31,39	32,22	2,56%
November	25,46	28,68	11,25%
December	28,02	32,25	13,14%

Table 5. Variation in the percentage of the production comparing fixed and tracking system installation

Of course, and as is shown in Table 4, there is more production with the tracking system than with the fixed one, as has been mentioned. So the months where the difference is positive compensate for the negative ones.

We should overline that the negative values that appear in the summer period are generated due to the fact that the tracking system limits the access of indirect radiation to the solar panels. In the Summer period in Poland, there is usually cloudy weather, so the indirect radiation has the same level as the direct radiation at that time

4. Summary And Conclusion

4.1. Summary

Firstly, in this project, it has been mentioned how the energy situation in Poland is currently, also a brief comment on the Spanish Energy infrastructure has been mentioned.

Moreover, the different policies Europe is pushing to implement and how Poland and other European countries are trying to follow their directives have also been mentioned.

Secondly, the location of the installation and the weather conditions of the location have been mentioned and analyzed. The analyses have shown that the spot for the installation wasn't bad, having good temperature and radiation indexes, considering that it is in Poland.

Thirdly, the production of the fixed installation has been studied. But first, a brief introduction of the different types of panels and the one that has been Hoosen for the installation. Then the process of how the production would be calculated is mentioned, making it clear that the big factors that influence the production of the installation are the global radiation and the temperature of the cell.

The fixed installation, a panel with a slope of 45 degrees, facing the south, and with a monocrystalline silicon panel, produces a total value of 0.4994 MW per year. It is a good value, considering, again, that it is located in Poland.

On the other hand, the tracking system installation, where (being redundant, includes a tracking system) with the same type of panel, again facing the south but in this case with a system that allows the panel to "follow" the sun in order to be always perpendicular to the direct radiation, where the maximum production is obtained.

This tracking system installation, which changes the slope of the panel depending on the position of the sun, obtains a total production of 0.501 MW per year.

4.2. Conclusion

In conclusion, countries from the European Union can or can't be on the same page with the European Union on green politics. But the truth is that they have to comply with it.

In this project, it has been considered the option of a fixed installation where the production is satisfactory, considering that a typical installation in Poland it is predicted with 1 Wp installed power, so generates approximately 1 KW electricity/year. As an example, 10 panels (with a surface of approximately 20 x 10 meters, so not quite big) would produce 5 MW per year.

Knowing the price of electricity in Poland, as shown in Figure 43 [19], is 550 Zloty per MW, with the currency conversion (1 Zloty is 0.22 Euros), a price of 122.81 Euros is obtained per MW per year. Definitely, saving around 600 Euros (122.81 Euros x 5 MW) per year is enough money to consider the project.

On the other hand, implementing the tracking system with the costs this modification carries, may not be worth it. As a tracking system estimation cost [20], we can say around 470 Euros per panel in the cheapest case, and around 970 Euros in the worst case.

Besides this, the increase in production is not covering the extra cost. As has been shown previously, the difference is around 0.27%, achieving 1.3 KW per year. Definitely, investing that extra amount of money again after the installation of the solar panels, meaning only an increase in the savings of 0.16 Euros per year, which is ridiculous, is not worth it.

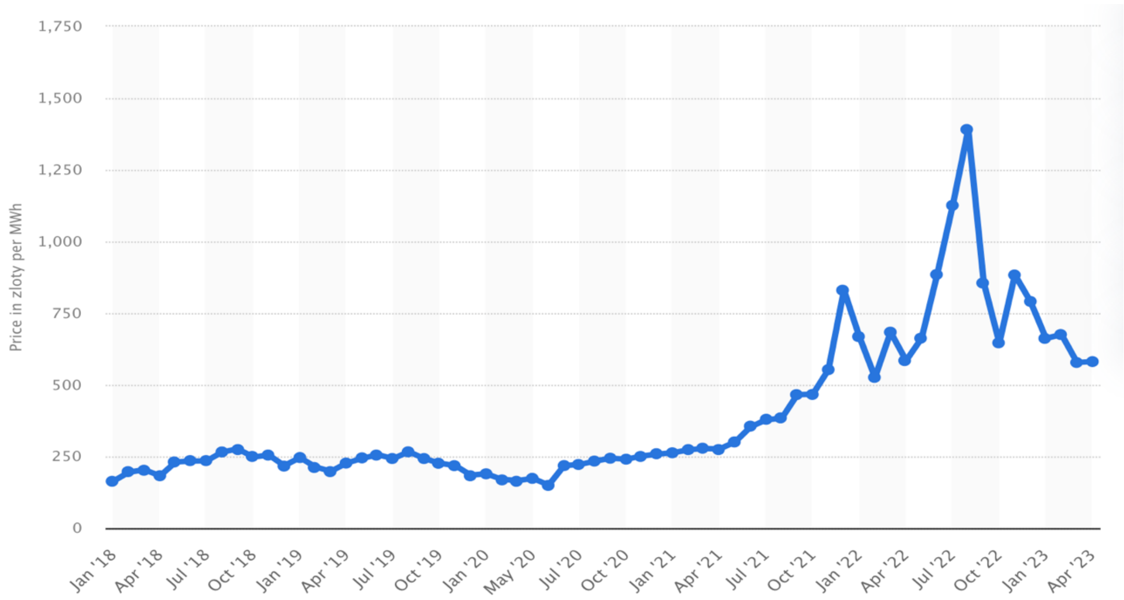


Figure 43. Variation of the electricity price in Poland per MW. Source: Statista 2023 [19]

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6. APPENDIX

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