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## Photovoltaic Generation Potential of Paraná State, Brazil – a Comparative Analysis with European Countries

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### Abstract

The theme of sustainable development has increasingly impacted the spheres of Brazilian society and has contributed to greater awareness to the need of natural resources conservation as well as issues on how to continue promoting socio-economic development of regions. One of the key issues for sustainable development is the generation of electricity with more use of renewable sources and, therefore, less environmental degradation. In this scenario, historically, Paraná State of Brazil has been one of the largest producers of electricity in the country, almost entirely from hydraulic source, due to the large existing river basin in the state. However, the use of this source in Brazil is declining due to depletion of water potential and also the pressure of society with respect to environmental, social and economic impacts caused by damming of rivers and flooding of cities and areas to form large reservoirs. To overcome these limitations, other sources have been studied and used, such as biomass and wind. Photovoltaic generation has been contemplated in Brazilian government policies only to supply electricity with off-grid systems in remote locations. However, due to the recent Resolution 482/2012 of ANEEL (Brazilian Electricity Regulatory Agency), which establishes rules for micro and mini-generation of electricity, it is possible that consumers install grid connected photovoltaic systems up to 1 MWp, as have been widely used in the urban environment installed or integrated on roofs as a form of distributed generation, particularly in Europe, where counts with installed capacity in GW range, while in Brazil it counts only with a few MW. Given this new perspective of growth of the Brazilian photovoltaic electricity generation this paper presents the potential of solar photovoltaic power generation in Paraná State, Brazil, with a comparative analysis with the potential presented by some European countries. The presented solar and photovoltaic maps uses irradiation data obtained from SWERA project (Solar and Wind Energy Resources Assessment), which was coordinated in Brazil by National Institute for Space Research (INPE). The results of this analysis can contribute to development of public policies related to projects and researches in photovoltaic aiming to spread the use of this renewable energy source in Paraná.

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## 1. Introduction

The concept of sustainable development is a long process of evaluation of the relationship between society and the environment and as a continuous process several approaches try to explain this concept. Historically, this topic was first discussed by the World Conservation Union (WCU) through World Conservation Strategy white paper. The WCU paper suggests that for a sustainable development, ecological and social dimensions should also be considered, as well as the economics aspects of living and nonliving resources. Later, through the Brundtland Report, the concept of sustainable development was formally defined and published, intending to generate among environmental, economic and social dimensions [1].

There is a forecast of a significant overall increase in the per capita income by 2030, which may result in a higher consumption of energy sources due to improved quality of life and greater population affording possibilities [2]. These trends may influence government public policies concernment and needed strategies for the future investments in the energy area. Public policies should aim to solve social problems and after deployed, should be evaluated to assess whether the objectives have been reached. According to evaluation results, these policies must be improved, reformulated or discontinued [3]. In this way, it is necessary a strong presence of government agencies acting as regulator, monitor, executor, coordinator, inductor and funder of necessary actions for development of the country.

Within these aspects, the planning of the energy sector is extremely important to ensure the continuity of energy supply to the society at a lowest cost, lowest risk of shortages and with the lowest socioeconomic and environmental impacts, as well as serving as a tool for assistance in public policies formulation for the energy sector. Within this planning, a portion is directed to electrical power generation, a kind of energy that is essential for the current stage of society development, that comes from several sources of energy, renewable and nonrenewable [4].

Currently, the electrical power generation in a global way is mainly based on fossil fuels but shows a tendency to decrease this participation in world electric matrix, mainly due to a greater awareness and pressure from the society to search alternatives of less pollutant energy sources.

Although the share of fossil fuels and nuclear power in the electric global energy are very expressive, it shows a slight downward tendency data analyzed from 2008 to 2011. At the same time there is a growing trend for other renewables, not hydraulic, in the participation of the electrical power energy, such as biomass, wind and solar energies. Regarding to the generation of electricity by hydropower, although there was an increase between the years of 2008 and 2010, globally it has decreased in 2011, which may mean bigger society pressure against the use of this source, mainly due to the environmental and social impacts generated as well as the depletion of its potential [5] [6] [7].

The main source of energy in Brazil comes from hydropower, mainly because of the potential available in large river basins, existed almost all over Latin America. However, the environmental impacts caused by the implementation of hydropower plants are high, due to the vast flooded areas, needed for the formation of its reservoir [8]. After the hydraulic source, follow up fossil and nuclear fuels and non-hydraulic sources such as biomass and wind power [9]. Table 1 shows the share of energy sources in the electricity production in the Global and Brazilian energy matrix.

Table 1: Energy share of global electricity production by energy source for years 2008, 2010, 2011, and Brazil for year 2011. Source: [5] [6] [7] [9]

Source Type	REN21 - RENEWABLE ENERGY POLICY NETWORK FOR THE 21ST CENTURY RENEWABLES GLOBAL STATUS REPORT (GSR)			BRAZILIAN ENERGY BALANCE 2012 (reference data year 2011 - %)
	REN21 2010 (reference data year 2008 - %)	REN21 2011 (reference data year 2010 - %)	REN21 2012 (reference data year 2011 - %)	
Fossil fuel and Nuclear	82.0	80.6	79.7	11.0
Hydropower	15.0	16.1	15.3	81.9
Other Renewables (non-hydro)	3.0	3.3	5.0	7.1
<b>TOTAL</b>	<b>100.0</b>	<b>100.0</b>	<b>100.0</b>	<b>100.0</b>

In order to decongest the generation, transmission and distribution systems of electricity in some countries of Europe, especially Germany, Italy and Spain, the scenario has favored the distributed generation. In this system, consumers end up generating some or all of the energy needed to reach their personal needs, mainly through photovoltaic systems, which allows the excess of energy to be sent to the electric distribution system.

Grid connected photovoltaic (PV) systems presents a new concept of generation of clean and renewable energy, and has registered a world growth greater than off-grid photovoltaic systems.

In Brazil there is not yet a significant deployment of grid connected PV systems with relevant installed power, that makes it difficult an analysis of impacts in the electrical system. These systems can be seen as a form of distributed generation (DG) installed along feeders of distribution grid, connected to low or medium voltage, and contribute to provide energy next to the point of consumption.

The Investments in grid connected PV systems were restricted for many years at universities and research centers, with the aim of studying the benefits and feasibility of this technology with a few facilities focused to the effective power generation. This was due to the high costs of implementing this technology in Brazil, although there was a cost reduction around 40% between 1996 and 2006 [10], and 60% between 2009 and 2011 [11]. In the total cost of deploying a grid connected PV systems, approximately 60% corresponds to the acquisition of photovoltaic modules, and the remaining 40% is related to the preparation and installation of the structure, inverters, transformers and other necessary components [12].

Much of the investment in grid connected PV systems, mainly in Europe, happened thanks to the public policy incentives adopted to promote the development of photovoltaic technology. Following this trend, it is expected that the same will happen in Brazil, although the Brazilian situation concerned to hydraulic reserves still influences and even postpone the adoption of public policies more pronounced for the use of other renewable sources.

In 2011, the ANEEL (Brazilian Electricity Regulatory Agency) released the Call No. 13/2011 - Strategic Project: "Technical and commercial arrangements for solar photovoltaic generation insertion in the Brazilian energy matrix", which foresees the addition of 24.58 MWp of installed power, being a few of them related to the Solar Stadiums programs for the 2014 World Cup [13]. In the following year, it was published the 482/2012 regulation, also from ANEEL, and from that on it begins the era of the distributed micro and mini generation in Brazil, that has allowed the electricity consumers generate part or all of their potential of electrical consumption using photovoltaic generators that work alongside the distribution network. In this regulation were stipulated the type and maximum power of the generators and their respective generation category, where: for micro generation the generators have power up to 100 kWp (kilowatt peak); for mini generation, it is systems with an output exceeding 100 kWp up to 1 MWp [14]. Therewith, some initiatives have already begun to be implemented in 2011 and 2012, making the total

implanted in Brazil exceed the 3 MWp, which is a value far below of those existed in other countries, especially in the Europeans ones.

In Brazil, the State of Paraná is one of the largest producers of electricity through hydropower due to the large number of rivers basins, but it has a pre-disposition for analysis and application of other sources such as biomass, wind and photovoltaic power. In relation to the photovoltaic source applications and studies are in the embryonic phase, requiring from the state of Parana more investments in this sector. But despite this huge hydroelectric potential, the exploitation of that is also declining due to the depletion and also due to the pressures of society and public and environmental entities.

Concerning to the exploitation of solar energy in the state of Paraná, in virtue of its geographical location found in the southern region of Brazil, much has been asked about the potential of this energy in the state, and the feasibility of applying this source in its respective electrical energy matrix, what makes necessary in Paraná a more detailed study about this topic.

Facing that, this study was conducted this way: a brief explanation of solar radiation found in Brazil. Then it will show the way how the Photovoltaic Map of the State of Paraná was prepared, with the respective values for the annual and seasonal daily averages. Just after that, there will be a comparison between the map of the state of Paraná Photovoltaic with the Europe one. On the end there will be an analysis of the values found in the respective maps surveyed, and then it will present the final conclusions about this work.

## 2. Methodology

The Brazilian Solar Energy Atlas, published in 2006, shows the annual average daily total global solar irradiation incident at the Brazilian territory, and the maximum value of global irradiation occurs in the northern state of Bahia, near the border with the state of Piauí, with values of 6.5 kWh/m<sup>2</sup>.day, predominantly semi-arid weather with low rainfall throughout the year (approximately 300 mm/year) and the annual average cloud cover lowest of Brazil. In contrast, the lowest global solar irradiation occurs in the northern coast of the Santa Catarina state, characterized by the occurrence of rainfall well distributed throughout the year, with values of 4.25 kWh/m<sup>2</sup>. day [15].

For the grid connected PV systems, one should consider the radiation data into the slope. Figure 1 shows the map of daily solar radiation incident on a plane with slope equal to the local latitude, setting that maximizes the capture of the solar energy, not considering the local topography and surface albedo [15].

One of the difficulties founded by researchers in the photovoltaic area is to be able to compare the maps prepared for Brazil with maps of other countries or regions. This comparison is not always visually easy to do, due to the differences between the scales and the colors used to represent the levels of radiation in the several maps of countries or regions in different continents.

To produce the maps yearly total and daily average seasonal of Paraná, it was considered the same criteria used by the European Commission for the preparation of European Photovoltaics maps. The maps represent yearly sum of global irradiation on horizontal and optimally inclined surface, and data values are given as kWh/m<sup>2</sup>. The same color legend represents also potential solar electricity [kWh/kWp] generated by a 1 kWp system per year with photovoltaic modules mounted at an optimum inclination and assuming system performance ratio 0.75. In the state of Paraná, for the reason of being in the south of the equator, the orientation of the system should be the geographic north.

The Performance Ratio (PR) is the relationship between the Yield (kWh/kWp) and the number of sunshine hours to 1000W/m<sup>2</sup> incidents in the photovoltaic panel, usually linked to a year of operation. This magnitude is expressed in percentage [19]. Otherwise, it is possible also to say that this value represents the performance discounting losses in the system such as: losses in the inverters, in the

connections, and specially losses due to the temperature elevation in the modules because of the environmental temperature. The use of these calculations PR 0.75 is important to standardize and facilitate comparison of results between different regions productivity, since most grid connected PV systems deployed in Europe have this performance or higher, according to the data presented by [20].

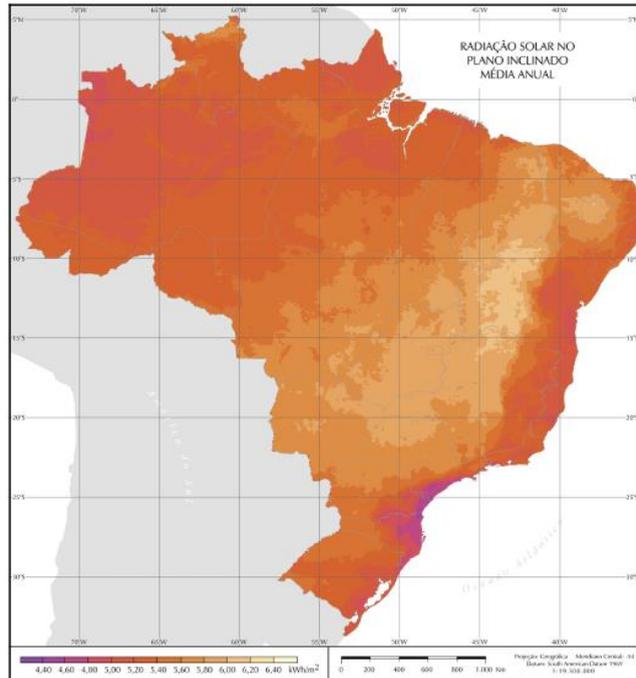


Fig. 1. Map of annual average daily solar irradiation on a plane tilted in angle equal to the pixel's latitude. Source: [15]

### 3. Results and discussion

Based on the values of radiation in the inclined surface (with slope equal to the latitude of the place), obtained in the database of the Brazilian Atlas of Solar energy and assumptions adopted, it was developed solar and photovoltaic maps of the state of Paraná.

The Figure 2 shows a map that presents the yearly sum of global irradiation incident on optimally-inclined with north-oriented photovoltaic modules and the estimated yearly sum of photovoltaic electricity generation for a 1 kWp system with an optimally-inclined PV panel and performance ratio of 0.75.

The Figure 3 shows seasonal maps with daily annual average irradiation incident on optimally-inclined with north-oriented photovoltaic modules and estimated daily annual average of photovoltaic electricity generation of a 1 kWp system with optimally-inclined PV panel and performance ratio of 0.75.

With the elaborated maps, shown in the Figures 2 and 3, that use the same colors and scale irradiation and generation of electricity used by the European Commission, it is possible to make important comparisons between the values of the state of Paraná and values found in the European countries, comprehensibly for photovoltaics professionals as well as of the other areas, especially those involved in public policy development.

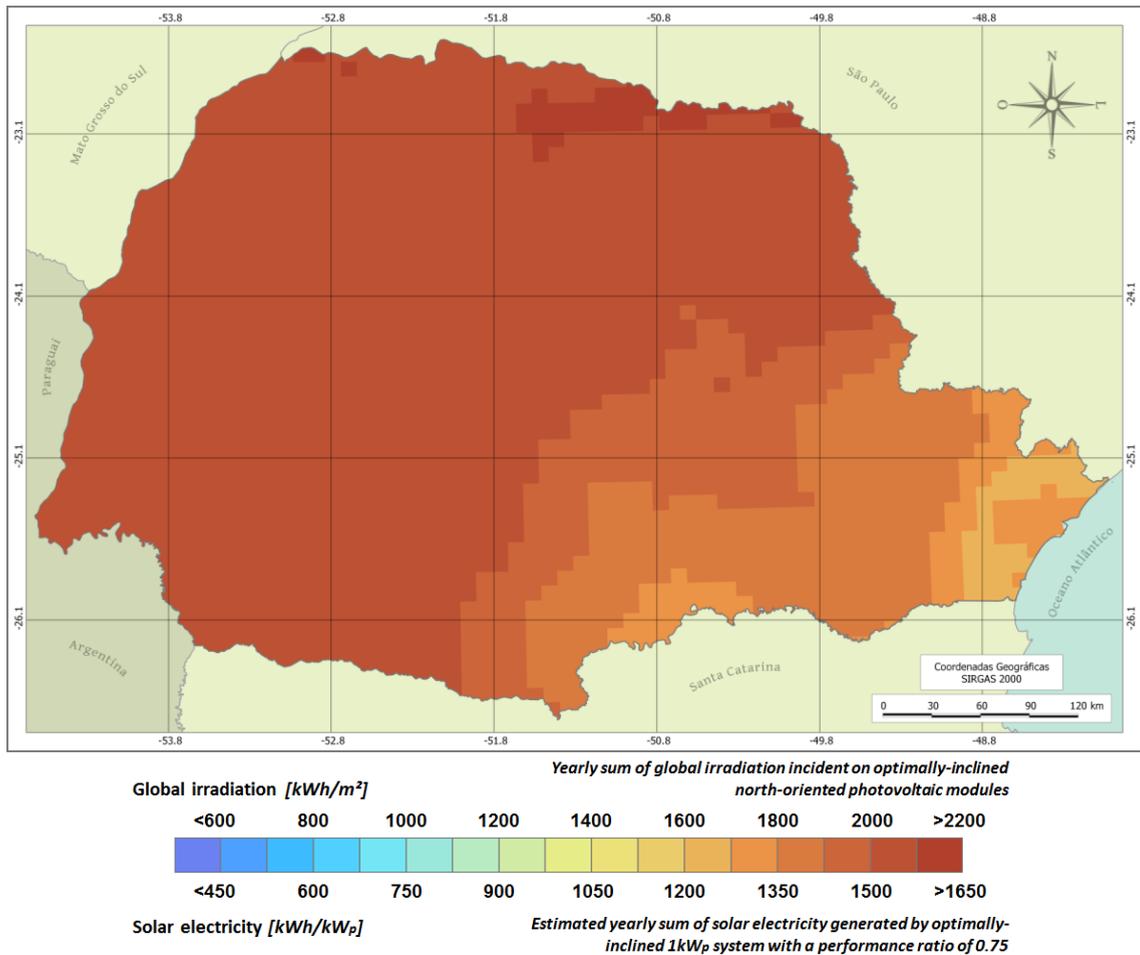


Fig. 2. Solar and Photovoltaic Map of the State of Paraná – Yearly Sum

The map in Figures 2 and 4 shows the great photovoltaic potential of Paraná state, which presents values of the total annual solar radiation on the slope between 1600 and 2200 kWh/m<sup>2</sup>, and estimated values of electricity generation between 1200 and 1650 kWh/year, considering a PV 1kW<sub>p</sub> with performance ratio 0.75.

Considering the seasonal photovoltaic maps for the State of Paraná - Brazil, shown in the Figure 3, it was found also the follow values of estimated daily average productivity:

- Spring: between 3.29 e 4.52 kWh/kW<sub>p</sub> for an average day of the year;
- Summer: between 3.50 e 4.52 kWh/kW<sub>p</sub> for an average day of the year;
- Autumn: between 3.50 e 4.32 kWh/kW<sub>p</sub> for an average day of the year;
- Winter: between 3.09 e 4.11 kWh/kW<sub>p</sub> for an average day of the year.

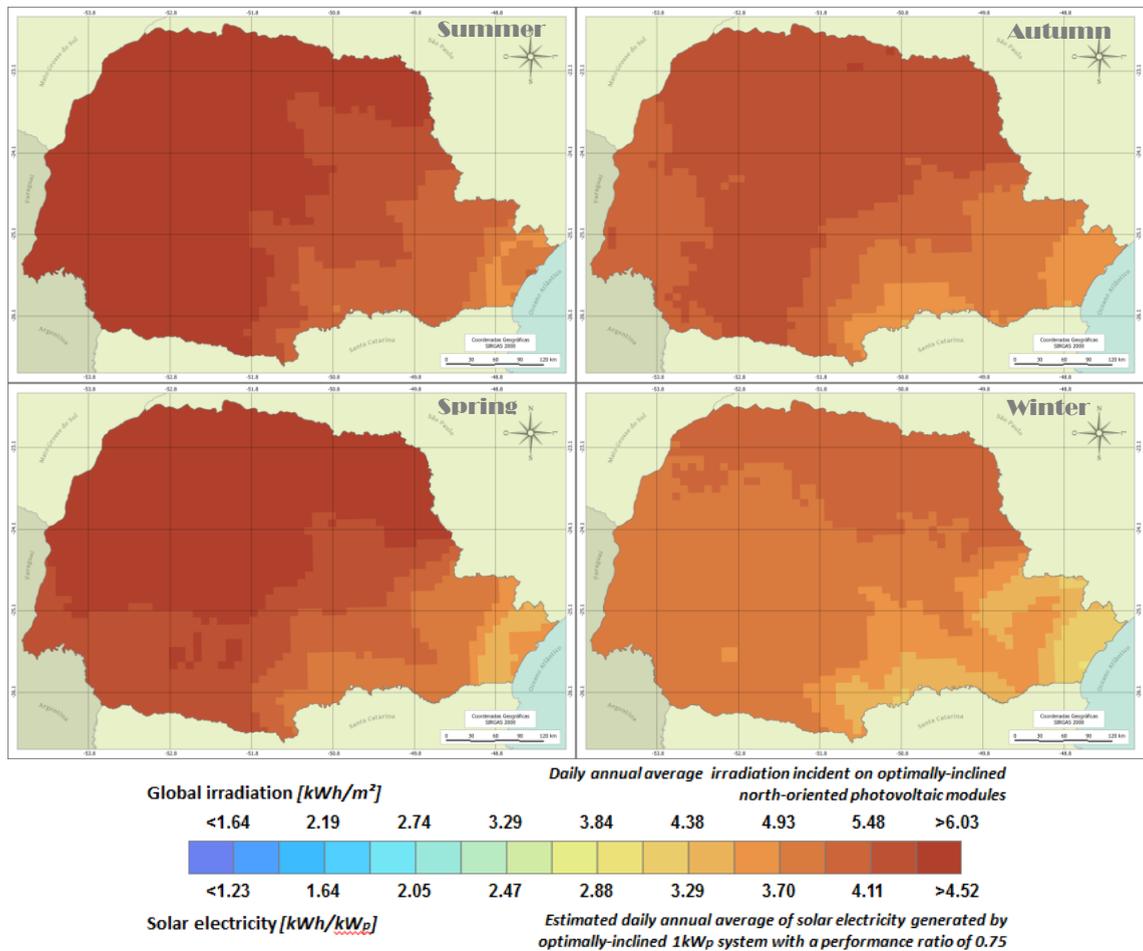


Fig. 3. Photovoltaic Map of the State of Paraná - Seasonal Daily Annual Averages

To compare Photovoltaic Maps of the State of Paraná with the ones of some regions of Europe, it was selected five countries with the highest total installed capacity of grid connected PV systems, with exceeding values of 1GWp, based on the year 2012 [16]. Thus it was selected: Germany, Italy, Spain, France and Belgium. These countries have respectively the following installed capacity by 2012, according to [16]:

- Germany: 32,411 MWp
- Italy: 16,250 MWp
- Spain: 5,100 MWp
- France: 4,003 MWp
- Belgium: 2,567 MWp

The selected countries stand out with their respective installed capacities not only in Europe but also in relation to the Total Global installed, which in 2012 reached nearly 100 GWp. Concerning to America, almost all capacity is concentrated in the U.S. with 7.2 GWp installed [16].

The Figure 4 shows the solar irradiation and estimated photovoltaic electricity generation maps for Paraná and European Countries for comparison.

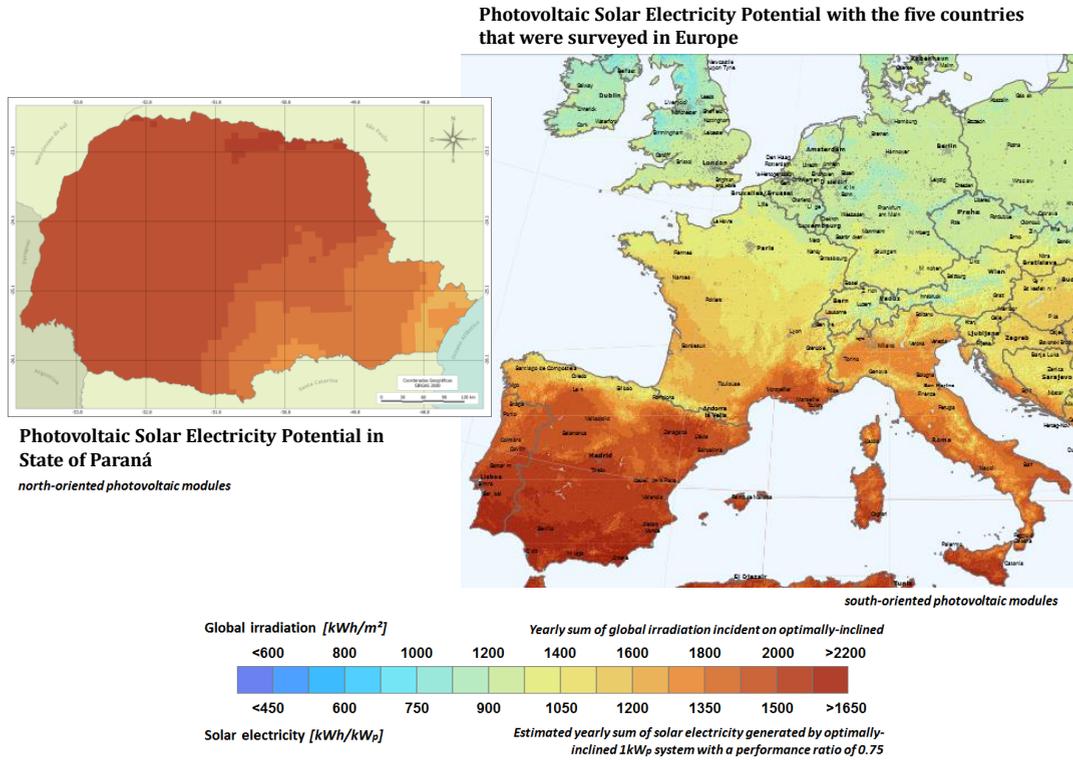


Fig. 4. Solar irradiation and estimated photovoltaic electricity generation maps for Paraná and European Countries. Source: European map adapted from [21]

Comparatively, using the example of Germany, where by 2012 the installed capacity reached about 32.4 GW<sub>p</sub> [16], the levels of solar irradiation in the inclined plane found are approximately 40% lower than those obtained in Brazil [17] [18].

For the five selected countries it was found the following total annual productivity estimated values and average annual daily respectively, as [21], watched in the Table 2:

Table 2: Productivity estimated values Total Annual and Average Annual Daily. Source: adapted [21]

Countries	Productivity Estimated (kWh/kW <sub>p</sub> ) - PR 0.75			
	Total annual		Average annual daily	
	Min value	Max Value	Min Value	Max Value
Germany	788	1088	2.16	2.98
Italy	600	1650	1.64	4.52
Spain	900	1613	2.47	4.42
France	825	1500	2.26	4.11
Belgium	850	1000	2.33	2.74

The Figure 5 shows the comparison of data yield in kWh/kW<sub>p</sub> with PR 0.75, obtained from the Paraná photovoltaic maps and the five selected countries [21], showing the minimum and maximum values obtained. Figure 5 shows a small variation between the minimum and maximum estimated annual electricity in Germany, Belgium and the state of Paraná, and major variations in Spain, France and Italy.

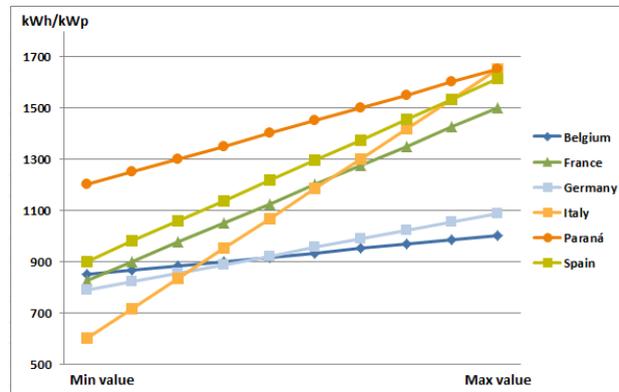


Fig. 5. Maximum and Minimum Electricity values generated estimated in the state of Paraná and the five selected countries

The data presented in the state of Paraná, even during the winter time when the irradiation values are much lower compared to other periods of the year, the productivity values for an average day (between 3.09 and 4.11 kWh/kWp) are still higher than the yield for an average day of the year in Germany (between 2.16 and 2.98 kWh/kWp), Belgium (between 2.33 and 2.74 kWh/kWp), and similar to those found in France (between 2.26 and 4.11 kWh/kWp), as watched in Table 2.

#### 4. Conclusion

The objective of this research was to present an initial analysis of the productive potential through of grid connected PV systems for the state of Paraná, Brazil.

The development of Photovoltaic Map of the State of Paraná enables the regions to be known and their different potentials estimated electricity generation for each 1kWp installed in accordance with the defined assumptions, and performance ratio of 0.75, both annually and seasonally.

The development of the photovoltaic map of Paraná, Brazil, with the criteria established by the European Commission, provides a comparison of the presented results with other countries photovoltaic maps of Europe, just as it was the case of the five selected countries.

The photovoltaic maps of the state of Paraná with the seasonal average daily radiation and productivity show that even in periods of low sunlight (winter), the presented values are higher than those found in Germany and Belgium, and similar to those found in France, showing that even in this period of low irradiation, the state of Paraná has a very significant potential.

Not coincidentally, the purpose of comparison with the five European countries with the largest installed capacity, is to promote the need of the creation of specific programs to encourage the research and development of this important renewable energy source in the state of Paraná, as the huge potential to be tapped by this source of energy in the state, and the complementarity with other sources of the electricity generation such as wind and hydropower.

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