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Utilisation of the System Advisor Model to Estimate Electricity Generation by Grid-Connected Photovoltaic Projects in all Regions of Brazil

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Abstract

Brazil has a large potential for capturing solar energy because of its location being near the equator. Previous studies have concentrated on estimating this potential using data on irradiation levels, whereas few studies have conducted statistical modeling with software that incorporates various types of photovoltaic modules, inverter current efficiency, losses in the system, and data on local weather conditions. The System Advisor Model (SAM) calculates output performance based on local weather conditions and all the system components for photovoltaic (PV) power projects. It is therefore an effective engineering tool for determining the feasibility of a photovoltaic project before its implementation. The main objective of this paper is to use SAM to simulate electricity production from a theoretical 2 MW photovoltaic (PV) projects installed in 19 cities in all regions of Brazil. It also compares these estimates with other studies conducted in Brazil and in other countries with large amounts of PV generation. The theoretical implementation of 19 power plants of 2 MW in all regions of Brazil would provide up to 50 GWh to the national grid in the first year. Petrolina is the city with the highest simulated output of 3 GWh, whereas Curitiba is the city with the lowest with 2 GWh. The findings of this study confirm that Brazil has enormous potentiality for exploiting PV technologies in all its regions. Further studies using SAM are required to estimate the actual electricity generation of PV technologies in all Brazilian regions.

Keywords: *Simulation. Energy production. SAM. Solar energy. Brazilian potential*

1. Introduction

Brazil has a great potential for capturing solar energy due to its location in the inter-tropical region. Studies suggest annual electricity potential output for grid-connected projects accounting for about 6,897,050 TWh per year [1]. In the Amazon region of Brazil alone, the potential peak output of photovoltaic (PV) electricity is estimated to be hundreds of MWp (Megawatts peak) [2]. Solar PV is an excellent tool for developing remote regions of the country where the costs of conventional methods of electricity generation are too high for them to be implemented [3, 2]. Photovoltaic and alternative sources connected to micro-grids can also gradually replace usage of electricity generated by non-renewable plants such as petroleum, coal, and nuclear [4]. Recent work shows that energy demand tends to increase 1 GW per year because of insufficient supply and new ongoing developments within the country's territory [5]. While much literature focuses on describing Brazil's potential use of solar energy to generate electricity or for thermal uses, few studies have simulated photovoltaic projects in all Brazilian regions to produce electricity connected to the national or local grid. Previous studies have concentrated on presenting results for potential in terms of data on irradiation levels. Some of them have focus on creating maps to present region's potential to exploit solar energy based on

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radiation data from SWERA. However, few studies have done statistical modeling with software which incorporates various types of photovoltaic modules, inverter current efficiency, losses in the system, and data on weather conditions. Researches which include radiation data from SWERA, environmental data and performance of real world PV components can demonstrate even better results for each location potential to exploit solar energy. Investigations on future renewable energy development can be done through such modeling since it provides detailed information and simulation about the region's potential for renewable energy [6] in this case PV technology.

There is a couple of software that can be used to model photovoltaic output, one of them is the System Advisor Model (SAM), current version 2016.3.14, is a performance and financial model designed to simplify prediction and costs of electricity for grid-connected renewable systems such as PV power projects [7]. The SAM database includes information about photovoltaic modules, inverters, weather conditions, irradiation levels and all the system's components. The "SAM's performance models make hour-by-hour calculations of a power system's electric output, generating a set of 8,760 hourly values that represent the system's electricity production over a single year"[7]. SAM is an effective engineering tool for performing statistical analysis and determining the local potential for photovoltaic projects before implementation. Financial analysis can also be done using levelized cost of electricity (LCOE) with SAM.

This paper concerns the use System Advisor Model to simulate power output, as electricity, from 19 theoretical photovoltaic (PV) projects of 2 MW installed in cities across Brazil. The study moreover aims to compare the simulated results with previous studies conducted in Brazil and other leading countries in this field. The study did not focus on cost analysis evaluation for the theoretical project because of the amount of data generated during the simulation and the very different taxes adopted by each State of Brazil.

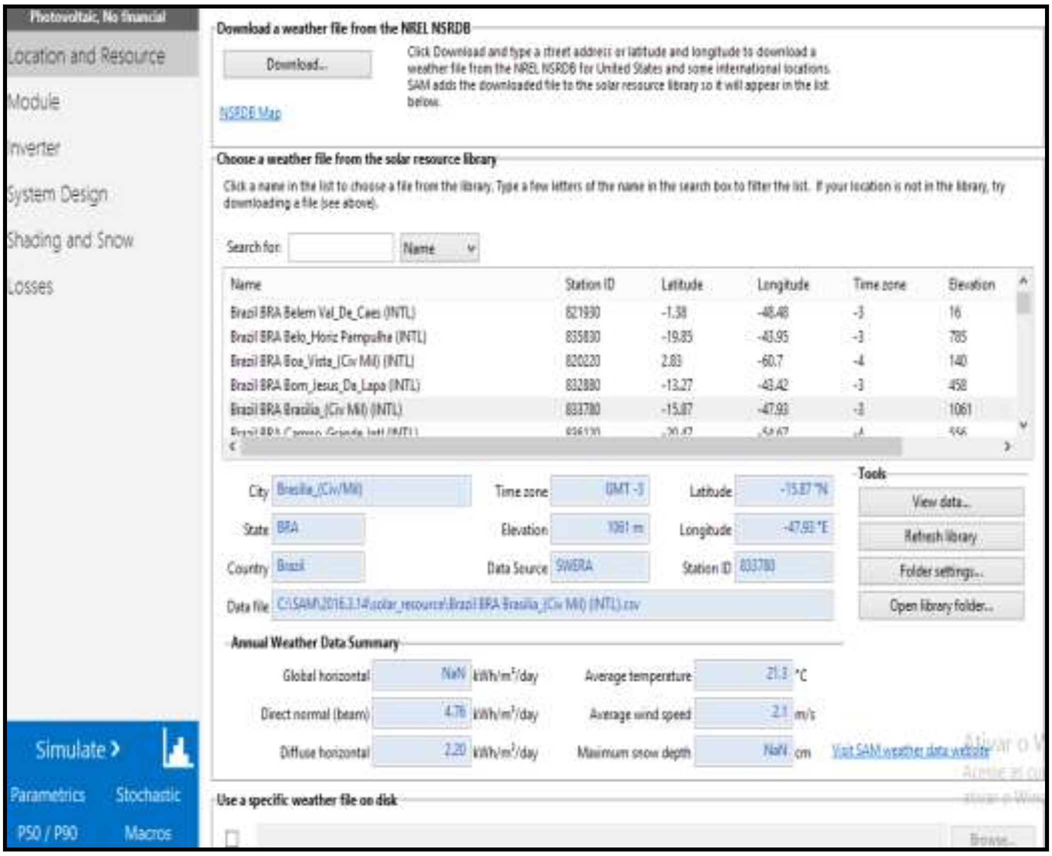
2. Experimental Details

Modeling with SAM requires users to complete two initial stages, which include selecting "model performance technology" (PV technologies option are photovoltaic detailed, photovoltaic PV watts, and high concentration PV) and selecting "the financial model performance" desired (a non-financial model is available to facilitate statistical estimation). The model has 17 different technology options to consider such as PV, wind, and biomass. Financial models allow users to perform statistics based on State taxes for renewable energies, project cash flows, and other financial characteristics. However, additional information makes calculating the simulation performance more complex.

In order to make this project an easy tool for estimating electricity production on a tie-grid plant, and yet to present as much detail as possible to demonstrate potential output, the 'photovoltaic detailed' setting of the simulation engine was used. This option allows the user to select the location, type of photovoltaic module, inverter, system design, shading and snow losses, and other losses. As the objective of this paper is only to estimate electricity production, the non-financial tool was selected. This tool allows the users to calculate electricity generation only by the photovoltaic modules without adding information regarding costs and taxes for the system. For a more detailed and complex project including cost comparison of project, the LCOE option can be selected to estimate financial outputs too. However, as pointed out in the introduction this paper did not focus on doing a financial analysis for each project due to the amount of data and differences in local taxes for each State.

SAM has 19 stations available in Brazil to model tie-grid power generation estimation for photovoltaic technology are: Belém, Belo Horizonte, Boa Vista, Bom Jesus, Brasília, Campo Grande, Curitiba, Cuiabá, Florianópolis, Jacareacanga, Manaus, Porto Nacional, Porto Velho, Petrolina, Recife, Rio de Janeiro, São Paulo, Salvador, and Santa Maria.

The model also requires users to decide the project components, namely photovoltaic modules and inverters. The photovoltaic module chosen for this project is the Canadian solar CS6P-255P because of its high efficiency. The inverter chosen is the Canadian Solar: CSI-28KTL-CT 480 V, due to its high capacity to convert direct current (DC) into alternating current (AC) (28000 kW). The concern here was to required few inverters for the project. The figure 1 displays the model interface for users to select each component of the project.



Download a weather file from the NREL NSRDB

Click Download and type a street address or latitude and longitude to download a weather file from the NREL NSRDB for United States and some international locations. SAM adds the downloaded file to the solar resource library so it will appear in the list below.

Choose a weather file from the solar resource library

Click a name in the list to choose a file from the library. Type a few letters of the name in the search box to filter the list. If your location is not in the library, try downloading a file (see above).

Search for:

Name	Station ID	Latitude	Longitude	Time zone	Elevation
Brazil BRA Belem Val_De_Caes (INTL)	821930	-1.38	-48.48	-3	16
Brazil BRA Belo_Horiz Pampulha (INTL)	835830	-19.85	-43.95	-3	785
Brazil BRA Boa_Vista_(Civ Mil) (INTL)	820220	2.83	-60.7	-4	140
Brazil BRA Bom_Jesus_Da_Lapa (INTL)	832880	-13.27	-43.42	-3	458
Brazil BRA Brasilia_(Civ Mil) (INTL)	833780	-15.87	-47.93	-3	1061

City: Brasilia_(Civ/Mil)
Time zone: GMT -3
Latitude: -15.87 °N
State: BRA
Elevation: 1061 m
Longitude: -47.93 °E
Country: Brazil
Data Source: SWERA
Station ID: 833780
Data file: C:\SAM\2016.3.14\solar_resource\Brazil BRA Brasilia_(Civ Mil) (INTL).csv

Annual Weather Data Summary

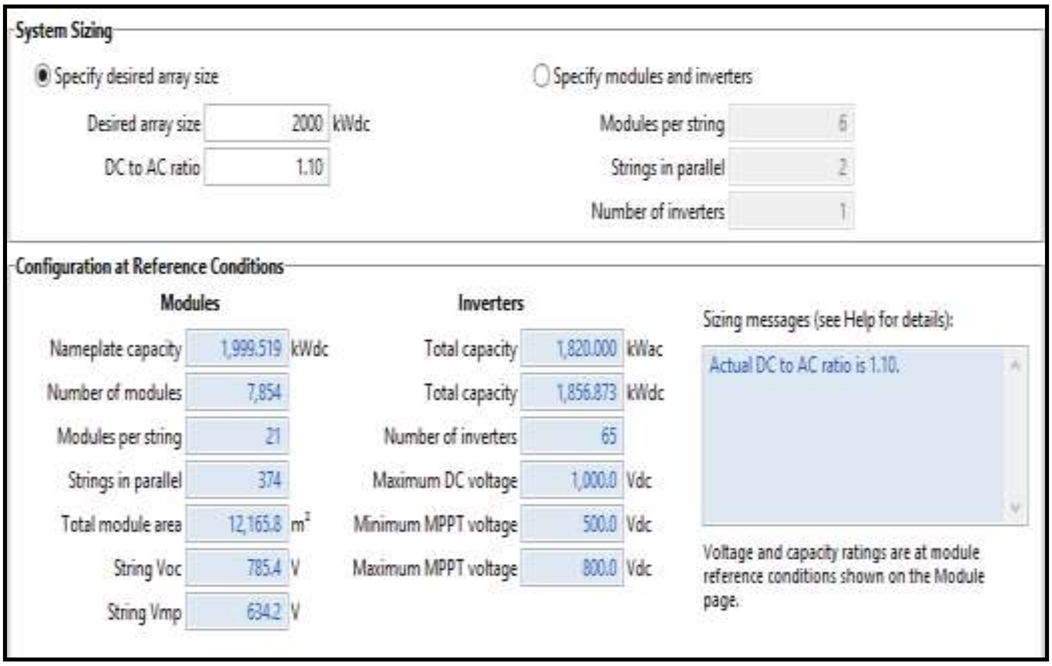
Global horizontal: NaN kWh/m²/day
Direct normal (beam): 4.76 kWh/m²/day
Diffuse horizontal: 2.20 kWh/m²/day
Average temperature: 21.3 °C
Average wind speed: 2.1 m/s
Maximum snow depth: NaN cm

Use a specific weather file on disk

☐

Figure 1. SAM Interface for a Photovoltaic Detailed, Non-financial, Project

The SAM system design tool allows users to specify either the desired array size or the number of modules per string and/or parallel and the number of inverters. It was chosen to model specifying only the array size of 2,000 kWDC (number MW DC), DC/AC ratio of 1.10 was set as suggested by SAM; the number of modules and arrangement were given in the model. The system sizing is shown in the figure 2.



System Sizing

● Specify desired array size
Desired array size 2000 kWdc
DC to AC ratio 1.10

○ Specify modules and inverters
Modules per string 6
Strings in parallel 2
Number of inverters 1

Configuration at Reference Conditions

Modules
Nameplate capacity 1,999.519 kWdc
Number of modules 7,854
Modules per string 21
Strings in parallel 374
Total module area 12,165.8 m²
String Voc 785.4 V
String Vmp 634.2 V

Inverters
Total capacity 1,820.000 kWac
Total capacity 1,856.873 kWdc
Number of inverters 65
Maximum DC voltage 1,000.0 Vdc
Minimum MPPT voltage 500.0 Vdc
Maximum MPPT voltage 800.0 Vdc

Sizing messages (see Help for details):
Actual DC to AC ratio is 1.10.

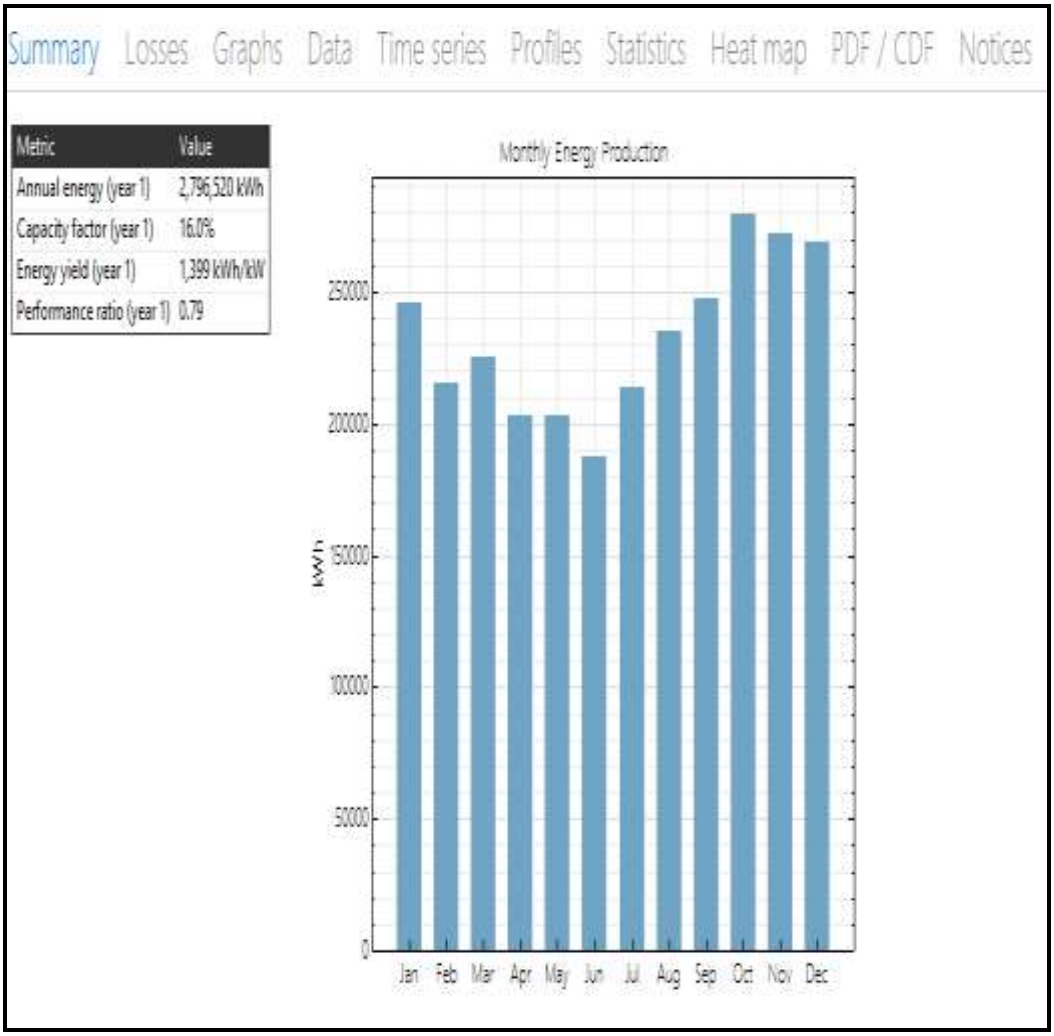
Voltage and capacity ratings are at module reference conditions shown on the Module page.

Figure 2. System Sizing Interface

Shading, snow, and losses were not varied: they were all set, with values automatically specified in the model. The final stage was to carry out a statistical analysis for each selected location. After processing all outputs for electricity generation, the data were put into an excel sheet where all data was analyzed and compared.

3. Results and Discussions

Photovoltaic panels generate DC current and need a converter to switch this electricity to AC. Although SAM displays power generated in DC and AC, AC values are only presented in this paper mainly because this is the current type used for delivering electricity to residences and businesses. When data is simulated in the modeling, it is exhibited as a summary with annual energy monthly energy production, and energy losses all for the first year operation. Other information can also be acquired on 'statistics' option of the system. The simulation interface is shown in the figure 3, this example presented is the simulation done for the city of Belem.



Metric	Value
Annual energy (year 1)	2,796,520 kWh
Capacity factor (year 1)	16.0%
Energy yield (year 1)	1,399 kWh/kW
Performance ratio (year 1)	0.79

Figure 3. Simulation Interface, Example for the City of Belem

3.1. Annual Energy Production

The first estimate done by the software is the annual energy production, which includes a monthly energy production too. Due to the large amount of data, only annual energy production is presented in this paper. Figure 4 shows all values, in kWh, of annual electricity generated (AC) of the modeling simulation for each location.

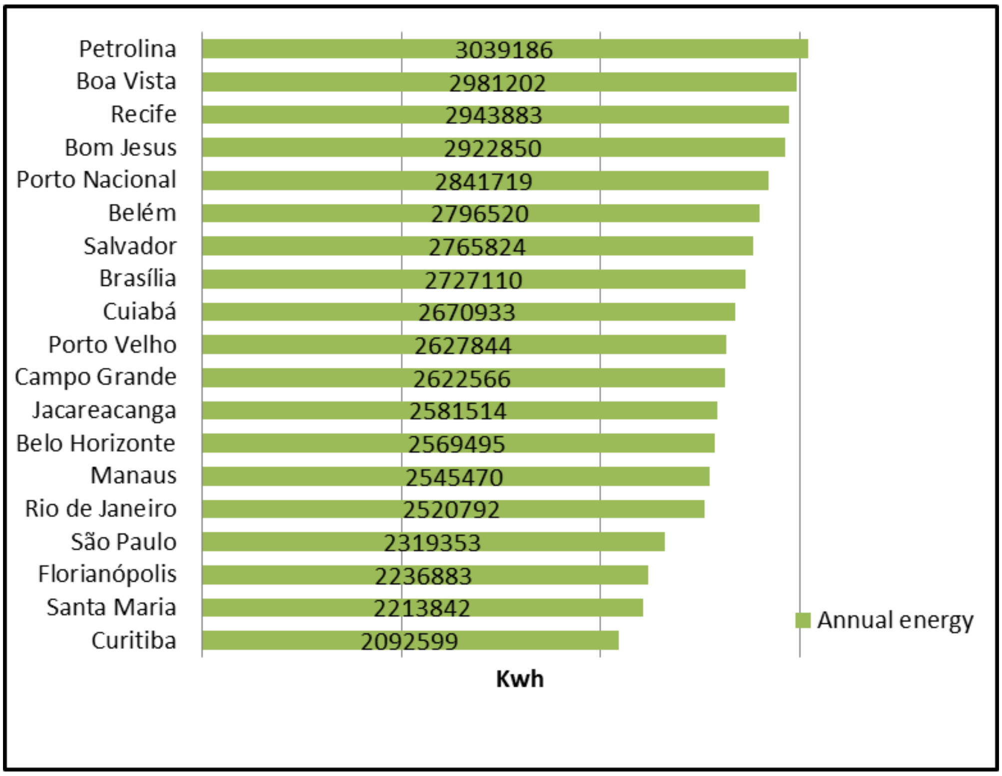


Figure 4. Annual Electricity (estimated AC) in kWh

Petrolina, Boa vista, Bom Jesus, and Recife exhibited the most power generation output varying from 2.9 to 3.0 GWh (first year). Except Boa Vista, all these cities are in the northeast region of Brazil. These results demonstrate the high potential of this part of the country to exploit solar energy based on radiation levels in the Brazilian Atlas of Solar Energy [3]. Other cities with high electricity output results were Porto Nacional, Porto Velho, and Belem (northern Brazil); Salvador (Northeast); Brasilia, Cuiabá, and Campo Grande (Midwest of Brazil). The annual production in these ranged from 2.6 to 2.8 GWh. Medium values of power production output, average of 2.5 GWh, were in: Jacareaganca, Manaus (northern Brazil); Rio de Janeiro, Belo Horizonte (southeast). Finally, the lowest annual energy production calculated by the modeling was found in the following cities: Florialópolis, Santa Maria, Curitiba (Southern Brazil), and São Paulo (southeast of Brazil), with values varying from 2.0 to 2.3 GWh. Although South region cities had the lowest outcome for photovoltaic projects, Dassi *et al*. [8] claimed that it is feasible to exploit solar energy in southern Brazil through photovoltaic technology especially during warm seasons when electricity consumption rises. They based their research on a 0.1 MWp photovoltaic project installed on a university campus of a southern Brazilian city. The system average output was 13,691 kWh/year, which represented 25% of the electricity consumed by the Institution.

The Amazon region (northern Brazil) has considerable potential to exploit PV electricity [3]. Estimative point out potential varying from ten to hundreds MWp [2] although the isolation of this region makes it challenging to connect PV projects to the electricity grid. The photovoltaic potential in the Amazon region can however be extracted using hybrid PV energy/Diesel. Projects mixing PV and Diesel have been a reliable technology for producing electricity in remote communities in the Amazon [2, 9].

The findings confirm the potential for exploiting solar energy in the entire country. The figure 2 shows the locations of the cities taken into account in this paper along with their annual average electricity generation (in GWh) estimated using SAM.

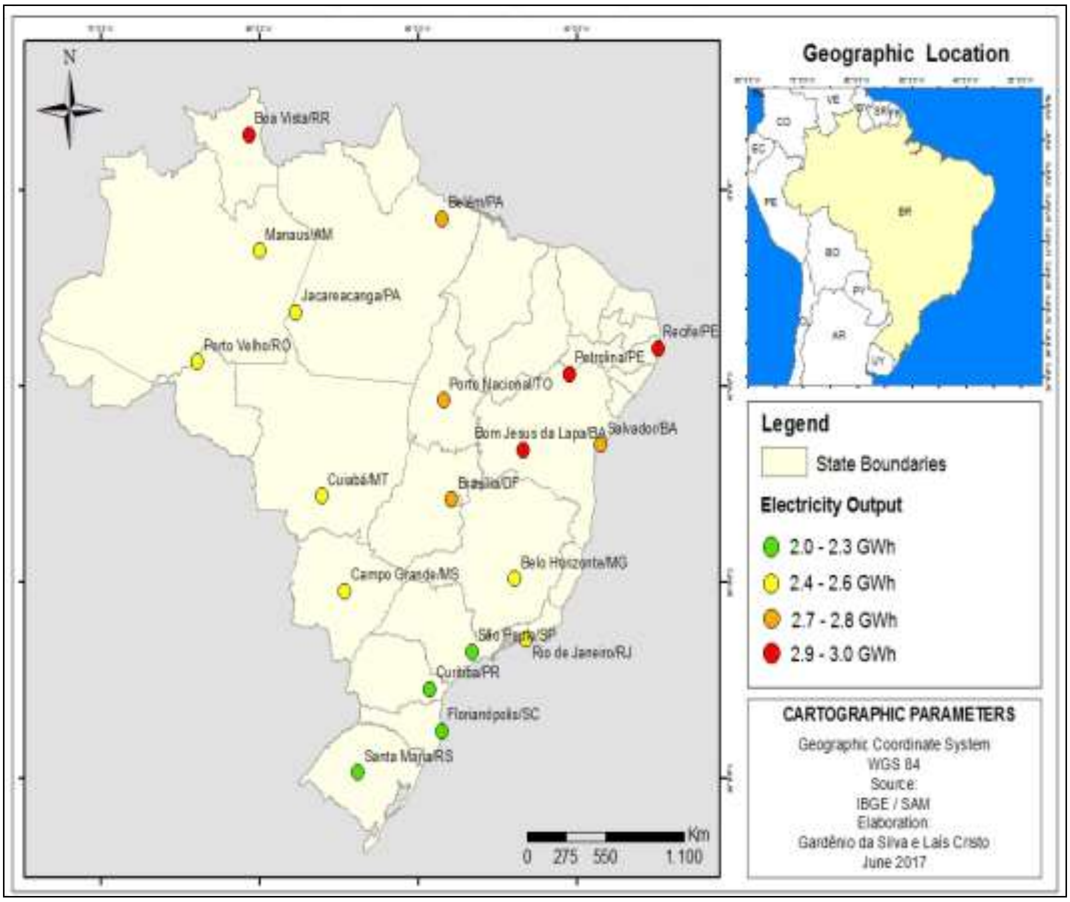


Figure 5. Electricity Output Simulated with SAM for Each City

3.2. Monthly Energy

Since the solar energy input varies when it reaches out the atmosphere accordingly to the earth's location and local characteristics, there will be differences in the amount of electricity generated by the installation each month [10]. Some caracteristics that might affect energy output include: cloudiness, temperature, dust on top of the panels, and humidity which can deteriorate some components of the system. SAM, however, takes into account some losses on the system. Figure 6 shows the monthly electricity generation to demonstrate fluctuations in modeled electricity by month. As a result of the amount of data modeled on this paper (228 results in total representing each month and all 19 cities), two cities in each Brazilian region were selected to display the monthly energy simulated. The locations are: Boa Vista, Belém, Recife, Bom Jesus, Santa Maria, Curitiba, Belo Horizonte, São Paulo, Cuiabá, and Campo Grande.

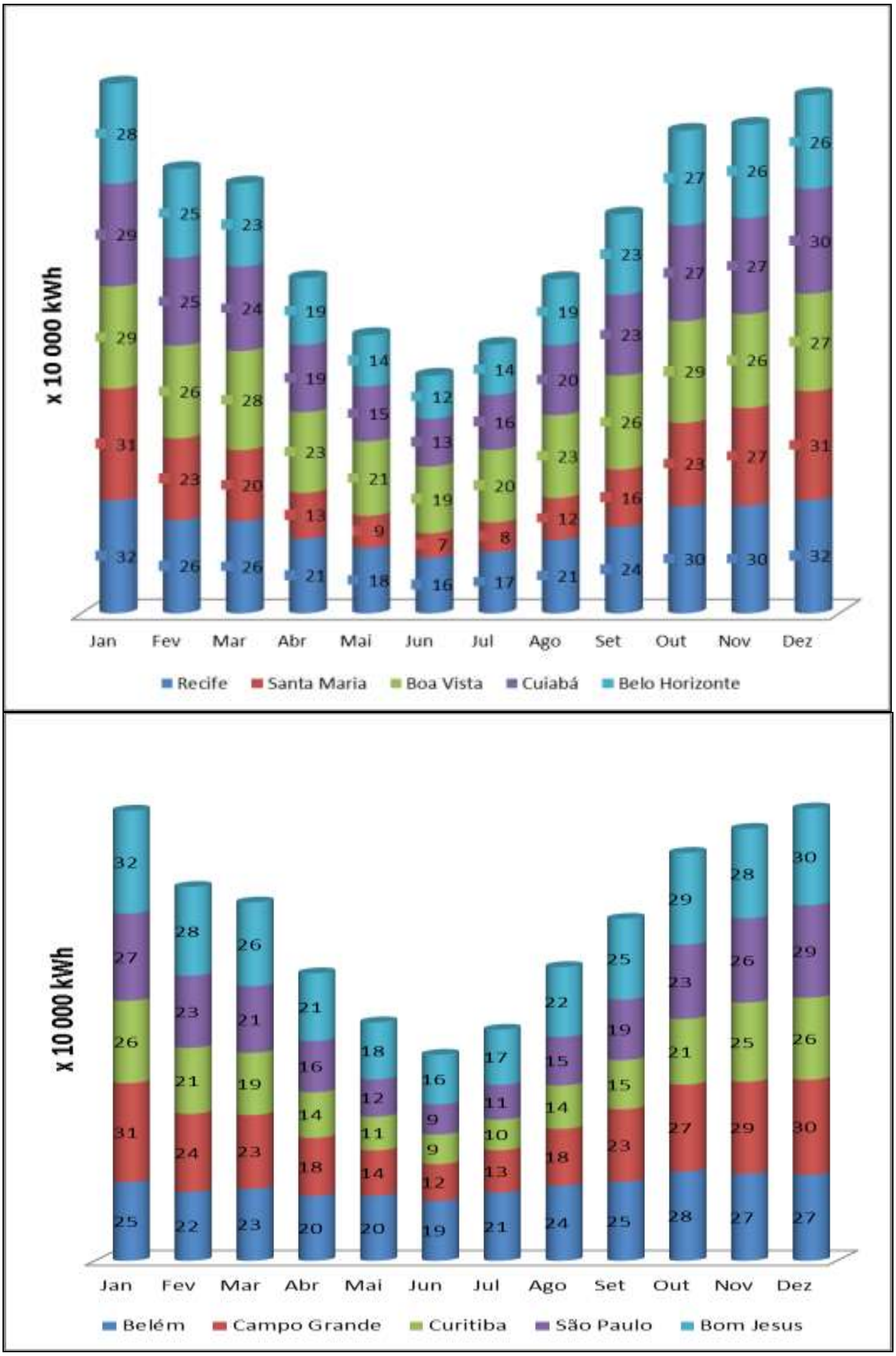


Figure 6. Monthly Energy Production Simulated by SAM, in 10,000 kWh

Re: Recife. SM: Santa Maria. BV: Boa Vista. Cu: Cuiabá. BH: Belo Horizonte.
Be: Belém. CG: Campo Grande. CT: Curitiba. SP: São Paulo. BJ: Bom Jesus.

Some cities, *e.g.* Belem, Boa Vista, Porto Nacional, present a relativity constant electricity production due to their geographical location being near the equator. Other cities far from the equator such as Santa Maria, Curitiba, Rio de Janeiro, and São Paulo are influenced by their latitude and longitude. However other parameters, such as nebulosity, affect the solar irradiation that reaches the surface of the earth, changing the amount of energy available to photovoltaic modules, resulting in these monthly fluctuations [10]. The variation found in Belém corresponds to the simulation conducted by Silva and Souza [11]. The results are also similar to those obtained in southern Brazil [8]. Pereira *et al.* [3], analyzing the solar irradiation and other parameter in a 10 year study, concluded that the northeast has the greatest potential to utilize solar power, followed by Midwest, Southeast, Northern, and South regions. In this paper a different trend in solar electricity potential in Northeast, North of Brazil, Midwest of Brazil, Southeast of Brazil, and Southern Brazil, respectively. There is therefore a need for more studies using SAM on additional locations (stations) to acquire data and compare simulated photovoltaic electricity production with the potential given in the literature.

3.3. Annual Energy Yield

Viana *et al.* [12], analyzed Brazil's PV generation through satellite-derived direct irradiation and performance data based on Spain's PV system, obtained PV potential in Brazil varying from 1400 to 2300 kWh/kW/year. Azzaoui [1] estimated that a 3 kW PV power system generates enough electricity to exceed annual residential electricity consumption which ranges from 1800 KWh (in the north) to 2000 WKh (in the south). However, values calculated through SAM range from 1,047 kWh/kW/first year (Curitiba) to 1,520 kWh/kW/first year (Petrolina less than found in Viana *et al.* [12] and Azzaoui [1], shown in table 1. The reason for the differences in energy yield compared to Viana *et al.* [12] is not known although both studies use Solar and Wind Resource Assessment (SWERA) as the data source. It might be related to the fact that this study uses both weather conditions and PV system performance in Brazil while the other studies took weather data from Brazil, but PV system performance from a Spanish system. Additional studies of the actual PV power generation in all regions of Brazil, based on both local performance and weather data, are therefore needed.

Table 1. Annual basis Electricity Output Simulated with SAM

City	Energy yield (year 1)
Petrolina	1,520 kWh/kW
Boa Vista	1,491 kWh/kW
Recife	1,472 kWh/kW
Bom Jesus	1,462 kWh/kW
Porto Nacional	1,421 kWh/kW
Belém	1,399 kWh/kW
Salvador	1,383 kWh/kW
Brasília	1,364 kWh/kW
Cuiabá	1,336 kWh/kW
Porto Velho	1,314 kWh/kW
Campo Grande	1,312 kWh/kW
Jacareacanga	1,291 kWh/kW
Belo Horizonte	1,285 kWh/kW
Manaus	1,273 kWh/kW

Rio de Janeiro	1,261 kWh/kW
São Paulo	1,160 kWh/kW
Florianópolis	1,119 kWh/kW
Santa Maria	1,107 kWh/kW
Curitiba	1,047 kWh/kW

3.4. Comparison of Potential between regions of Brazil and other places

Germany is the world leader in photovoltaic electricity generation, yet Brazil, with its lower irradiation levels, has 40% greater potential to exploit solar energy than Germany [13]. The results of this paper, together with the conclusions of Pereira *et al*. [3], documents that southern Brazil is the region with the lowest output for PV power production in comparison to the other regions. However, the state of Paraná, south Brazil, demonstrated to have irradiation levels 52% greater than Germany, 27% higher than Italy, and 13% superior than Spain. These values account for the higher mean productivity in the summer season, while comparing months of minimum productivity (winter season) Brazil has 40% more irradiation than Germany, 17% more than Italy, and 4% more than Spain [14].

Despite this immense potential to use solar energy for different uses such as thermal or photovoltaic, the majority of Brazilian's electricity production comes from hydroeletric plants, although power production from these plants has decreased because of droughts [5, 1]. Approximately 64% of all projects in operation throughout the country are hydropower-related while PV power plants represent only 0.02% of operational projects [15]. There is a need to diversify the Brazilian energy matrix, specially after the hydrological crisis of 2013 which contributed to a decrease of generation from hydropower plants. Because of this crisis, thermal coal power plants were turned on in order to meet the electricity demand in the country. This led to an increase in environmental pollution as well as increases in taxes on energy generation. Natural events such as droughts, plus growth in demand by utilities during daytime, can promote use of PV electricity because of the high irradiation levels [5, 2]. Silva and Souza [11], suggested that hydroelectric dam reservoirs could be used to site floating photovoltaic panels in order to supply electricity. Solar power plants in reservoirs would use otherwise unused areas, moreover, photovoltaic projects produce clean energy in a silent and reliable way [16]. Studies also indicate that in 2009 CO_2 emissions decreased by more than 100 thousand tonne as a result of of solar panels projects in Brazil [17]. Successful floating PV projects have been installed in North Korea, producing electricity that is sold to the national grid [18]. A empirical study showed that floating PV power increases energy production by 11% due to cooling provided by the contact with the water surface [19]. The large potential electricity production from photovoltaic projects in Brazil would therefore be increased if new projects were installed on the surface of reservoirs. Unfortunately, SAM does not simulate floating PV power or calculate the effects of cooling systems on PV power.

4. Conclusions

Brazil is a country with a great potential to exploit solar energy to generate electricity through PV projects. The theoretical implementation of 19 plants of 2 MW each in all regions of Brazil would produce, approximately, 50 GWh total in the first year. A study in sourthern Italy comparing the simulation carried out with SAM and a real PV performance showed that SAM understimated electricity output by 3% [21]. This means that the electricity potential may be higer than 50 GWh. Higher temperatures on the tropic tend to decrease photovoltaic effiency [22]. However, if the systems were installed on floating structures there might be an increase of 11% in electricity output due to cooling effect. The electricity generated in PV plants could be integrated into the national grid, thereby contributing to diversify the Brazilian Energy Matrix. Moreover, remote areas such as the Amazonic region, which has a large potential to havesrt sunlight for photovoltaic projects, could attend its energy demand without huge environmental impacts caused by big projects such as hidropower plants. Output levels will change depending on the technology used in the project components which may increase or reduce electricity generation; however, changes in electricity production resulting from different technologies will be estimated with SAM.

The present paper has demonstrated photovoltaic electricity output based on SAM's real life simulation performance. There have been some differences in annual basis electricity output in comparison with other studies which mainly used SWERA, but a PV system performance from another country. Cities located in northeast of the country presented the best results, as aspected according to the literature data. North of the country (Amazon region) has also demonstrated great capacity to exploit solar energy; the literatures do not point out good output performance to this region due to the great cloudiness in the area. The simulation with SAM has presented otherwise results.

It has also been shown that SAM is an excellent tool for estimating electricity prodiction from PV projects and for comparing the potential of different sites before implementation of renewable energy power plants [22, 20]. Petrolina was the city with the highest simulated output of 3 GWh, whereas Curitiba presented the lowest generated output of 2 GWh. Cities in south region of Brazil exhibited the smallest simulated electricity generation in comparison to the other cities in Brazil, but literature studies on radiation levels show greater potential of this region for exploiting solar energy than countries that are leaders in field of PV electricity generation such as Germany, Italy, and Spain. In addition, in the southern region, the city of Santa Catarina has installed the biggest solar plant project in operation in the country with a capacity of 1 MW [5].

The findings of this study confirm Brazil's potential to exploit PV technologies in all regions of the country's territory. Further studies using SAM or other software which incorporates local weather conditions and component performance are required in order to estimate the actual electricity generation using PV technologies in all Brazilian regions. Studies addressing financinal aspects of PV projects with the SAM simulation electricity output model are also necessary.

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