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Potential of Photovoltaic Generation in the Putumayo Department of Colombia

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Abstract: The potential for generating electricity with photovoltaic systems is high in Colombia given its geographical position in the tropic. Some departments in Colombia have low electricity coverage and high rates. In the department of Putumayo there is a low coverage rate and high energy costs, while the solar radiation potential is high. Due to the geographical differences of the Putumayo subregions, the radiation potential for electricity generation is unknown. In addition, in this department the energy tariffs are above the national average. The objective of this paper is to determine the effective potential for solar photovoltaic power generation in the Putumayo department with a detailed methodology considering the information of different remote database and meteorological stations and some technical conditions. It was found that the highest effective solar potential occurs in the Amazon region, and the lowest in the Andean region in the Putumayo. On the other hand, when evaluating electricity consumption and tariffs in the regions, it is concluded that consumption can be satisfied with photovoltaic systems by producing self-generating electricity and distributed generation.

Keywords: Angstrom; sunshine; irradiation; effective potential; Colombia; Putumayo

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1. Introduction

Energy resources are vital elements for sustainable development, and despite the importance of electric energy as a resource, as reported by the World Bank in 2018, approximately one billion people in the world are living without electricity [1]. According to the Institute for Planning and Promotion of Energy Solutions (IPSE) for non-interconnected zones (ZNI) in Colombia and the Single Information System for Residential Public Utilities (SUI), Colombia's ZNI represent 52% of the country's territory [2]. In the case of the department of Putumayo there is a low coverage rate of 48.38% for rural areas [3]. The first auction of non-conventional renewable energy in Colombia was held in 2019; however, renewable sources will be connected to the main grid without providing energy solutions to the ZNI [4].

Fossil fuel energy production has been one of the main contributors to greenhouse gas emissions, the highest in history this last decade. Therefore, complementing the energy matrix with renewable energies (RE) is a necessity, especially considering the energy vulnerability of Colombia to the uncertainty presented by the phenomena of climatic variability such as El Niño [5].

To take advantage of RE resources, the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) publishes climatological data for Colombia, which shows that Putumayo's irradiation is in the range of 3 to 3.5 KWh/m^{2}day [6]. On the other hand, some researchers have conducted work to determine the solar energy potential in different regions of the country. Some studies have focused on the energy potential and the technical and economic viability of solar power plants in different regions of the country [7–9]. In addition, the performance of different solar panel technologies was evaluated [10–17].

It is important to note that the factors of losses due to shading orientation and inclination of systems close to the Earth's equator play an important role in the performance of solar systems [18]. Additionally, there are reported studies on the variation of solar brightness and the characterization of solar radiation using the Angstrom model [18–23].

In addition to the lack of electricity coverage, in the department of Putumayo there is low service quality and a high level of nonconformity due to the cost of electricity. Likewise, no RE studies have been done in the area, and the local solar energy potential is unknown. Therefore, the objective of this research is to determine the effective potential for solar photovoltaic power generation in Putumayo department with a detailed methodology considering the information of different remote database and meteorological stations and technical conditions. In this work it was estimates the effective generation potential through the consideration of some technical and geographic conditions.

The methodology developed for this research allows for calculating the potential of effective solar photovoltaic energy that can be generated in a certain place, taking into account the characteristics of the technology, the installation of the technology and losses generated, the usable percentage of the area of roofs of houses to install solar panels, the data on sunshine and temperatures taken by a weather station, and irradiance data taken by remote sensors. This methodology can be used globally. The results allow for evaluating the energy potential that can be generated in a populated area just using a portion of the roofs of private homes.

2. Materials and Methods

This work was carried out in one of the departments of Colombia, the department of Putumayo, which has the characteristics of two natural regions of Colombia, the Andean and the Amazon, as well as a transitional zone between the two called the Andean-Amazon region. The Andean region is characterized by the variety of natural geographic formations of the Andean mountain range. The Amazon region is characterized by a tropical forest in the extensive plain of the Amazon river basin. The Andean-Amazon region is characterized by a transition zone between the base of the mountain range and the beginning of the plain. Figure 1 shows the location of the department of Putumayo. The colors indicate the different regions. The Andean region is highlighted in blue, the Andean-Amazon region in yellow, and the Andean region in orange.

The coordinates of the IDEAM weather stations were located for each of the regions, to be able to request data series of solar brightness (n) and ambient temperature (Ta). In addition, for the same stations coordinates, data series were collected from remote sensors such as the National Aeronautics and Space Administration (NASA) [24], and the National Renewable Energy Laboratory (NREL) [25] which publish irradiance values. With the above data, monthly average daily irradiation values were calculated on the horizontal surface of each of the stations, to make statistical comparisons and identify errors in the remote sensor data. With the monthly solar irradiation data on the horizontal surface, and the irradiation on inclined surface, the effective energy that can be generated by a photovoltaic system could then be obtained. Finally, with the energy values that can be generated in each municipality, a comparison with the energy consumption reported by the SUI in each municipality was made. Figure 2 summarizes the methodology used in this work, followed by a more detailed description of each point.

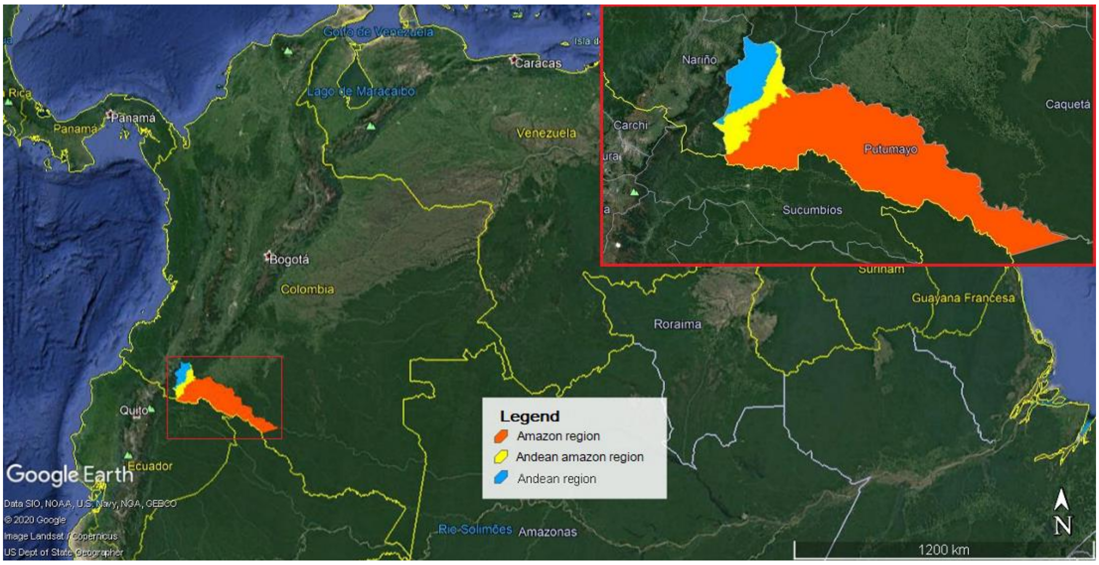

Figure 1. Location of the department of Putumayo and the Andean, Andean-Amazon, and Amazon regions.

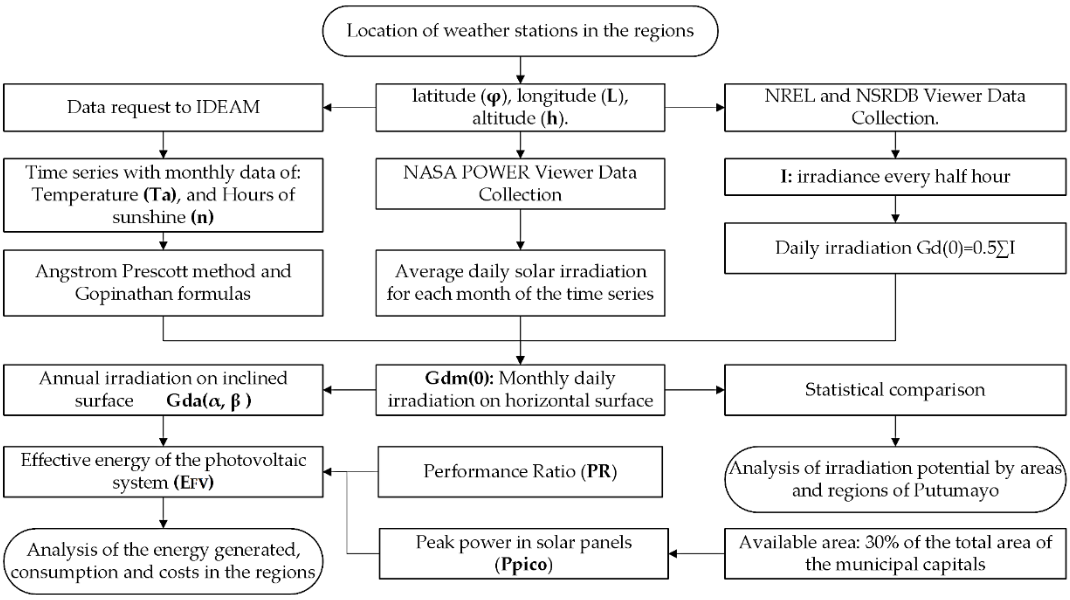

Figure 2. Graphical summary of the methodology used in this research.

2.1. Location of Weather Stations and Request for Data Series

The coordinates of the meteorological stations of the Putumayo department were in IDEAM's national catalog of stations (CNE) viewer [26], and the data series of temperature and solar brightness were requested. Additionally, the coordinates of the meteorological stations, the daily/monthly averages of irradiation data provided by the NASA POWER (Prediction of Worldwide Energy Resources) project, and the daily irradiance data provided in the NREL viewer, were downloaded. Data from each source were analyzed, and the daily averages of monthly irradiation was calculated, and statistical comparisons were made, as shown in Figure 2 and detailed below.

2.2. Calculation of Solar Irradiance with the Angstrom-Prescott Method and Gopinathan Formulas

The calculation of the monthly daily solar irradiation $G_{dm}(0)$ was made using data provided by IDEAM, as is detailed in other studies conducted in the area [27]. These calculations were made by applying Gopinathan expressions [18] and Angstrom method [19] modified by Prescott [20], as described below:

$$\frac{G_{dm}(0)}{Bo_{dm}(0)} = a + b\left(\frac{n}{N}\right) \tag{1}$$

where $Bo_{dm}(0)$ is the average daily monthly extraterrestrial irradiance on horizontal surface, $Bo_{dm}(0)$ it is the average daily extraterrestrial irradiation, N is the maximum duration of sunshine, n are the hours of sunshine recorded by IDEAM, and a and b are the coefficients of the equation which are calculated with the following equations validated by Gopinathan [18] for any location in the world:

$$a = -0.309 + 0.539 cos\varphi - 0.0693h + 0.290\left(\frac{n}{N}\right) \tag{2}$$

$$b = 1.527 - 1.027 cos\varphi + 0.0926h - 0.359\left(\frac{n}{N}\right) \tag{3}$$

2.3. Statistical Analysis for Comparison

The results of the irradiation calculation with the Angstrom-Prescott method were compared with NASA's POWER database and NREL's NSRDB (The National Solar Radiation Database), for which the following statistical parameters were evaluated. For the Mean Bias Error (MSE), which refers to the systematic error, positive values indicate overestimation and negative values indicate underestimation. For the Mean Percentage Error (MPE), which is an overall measure of the precision of the estimate, deviations of less than 10% are acceptable. The Root Mean Square Error (RMSE) shows the variation of the estimates with respect to the recorded data and is always positive. The t-statistic establishes the significance and allows the objective comparison of the models [21]. The results of these parameters or statistics should be close to zero. The mentioned statistics are calculated as indicated in Equations (4)–(7).

$$MBE = \frac{\sum_1^{n_o} RGe - RGm}{n_o} \tag{4}$$

$$MPE = \frac{\sum_1^{n_o} \frac{RGm - RGe}{RGm} \cdot 100}{n_o} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_1^{n_o} (RGe - RGm)^2}{n_o}} \tag{6}$$

$$t = \left[\frac{(n_o - 1)MBE^2}{RMSE^2 - MBE^2}\right]^{0.5} \tag{7}$$

where: RGm is the radiation measured or calculated with the data from the stations, RGe is the estimated radiation, and n_o is the number of observations.

2.4. Annual Irradiation on Inclined Surface $G_a(\alpha, \beta)$

Once the irradiation was evaluated $G_{dm}(0)$, the irradiation on an inclined surface $G_a(\alpha, \beta)$ was evaluated too, where α is the angle of orientation and β the angle of inclination. For the above, the global irradiation $G_{dm}(0)$ is decomposed as the sum of the monthly daily diffuse irradiation $D_{dm}(0)$ and monthly daily direct irradiation $B_{dm}(0)$. The condition described by Liu and Jordan (1960) according to which the relationship between the lightness index $\frac{G_{dm}(0)}{Bo_{dm}(0)}$ and the diffuse fraction $\frac{D_{dm}(0)}{G_{dm}(0)}$ is independent of latitude was considered [28]. Once the daily components of the irradiation $D_{dm}(0)$ and $Bo_{dm}(0)$ were obtained, the hourly irradiation on inclined surface $G_h(\alpha, \beta)$ was calculated, for which the model of the three components was taken. This model establishes that the incident irradiation is formed by the direct $B_h(\alpha, \beta)$, diffuse $D_h(\alpha, \beta)$ and reflected $R_h(\alpha, \beta)$ irradiation, and it is expressed as

$$G_h(\alpha, \beta) = B_h(\alpha, \beta) + D_h(\alpha, \beta) + R_h(\alpha, \beta) \tag{8}$$

where

$$B_h(\alpha, \beta) = \frac{B_h(0)}{cos\theta_{zs}} \cdot max(0, cos\theta_s) \tag{9}$$

with θ_s as the angle of incidence between the solar rays, θ_{zs} the normal to the plane considered, and the zenithal solar angle, obtained by means of their respective sinusoidal functions. To calculate the hourly direct $B_h(0)$ and hourly diffuse radiation $D_h(0)$, the following expressions from the Collars-Pereira model were used [29,30]. The diffuse irradiation component on the inclined surface $D_h(\alpha, \beta)$ was calculated by the Hay-Davies isotropic model, because in several studies it stands out for its precision and simplicity [31,32]. This model establishes that the diffuse irradiation on the inclined plane is equal to the sum of two components. The first is the circumsolar component $D^c(\alpha, \beta)$ coming directly from the sun, while the second is the isotropic component $D^I(\alpha, \beta)$ coming from the whole celestial hemisphere. The reflected component $R_h(\alpha, \beta)$ or albedo was calculated considering the reflectivity of the soil, ρ_r, as 0.2, assuming that the soil is horizontal, of infinite extension, and reflects light isotropically.

The hourly components were added to obtain the monthly average daily irradiation on an inclined surface. The value of the annual daily irradiation on inclined surface is approximately equal to the average of the $G_{dm}(\alpha, \beta)$ values. Finally, to obtain the monthly average of daily irradiation on an inclined surface $G_{dm}(\alpha, \beta)$, the hourly components were added $G_h(\alpha, \beta)$. The annual mean daily value irradiation on sloped surface $G_{da}(\alpha, \beta)$ is approximately equal to the average of the values of $G_{dm}(\alpha, \beta)$.

To determine the angles and the maximum irradiation, the previous procedure is repeated varying the angles. After knowing the angles, the angular losses were calculated to select an angle that has a suitable inclination for maintenance. With the selected angle, the irradiation $G_{da}(\alpha, \beta)$ was calculated. These values were averaged by region for each meteorological stations' zone and were taken as the irradiation of each municipality in the region. Finally, the annual irradiation $G_a(\alpha, \beta)$ was calculated as the product of $G_{da}(\alpha, \beta)$ by the number of days in the year.

2.5. Effective Energy Calculation E_{FV}

To evaluate the effective energy that can be generated by a photovoltaic system, the standard of the international electronic commission IEC 61724 [33], which establishes the following equation, was employed:

$$E_{FV} = \frac{G_a(\alpha, \beta) P_{pico} PR}{G_{STC}} \tag{10}$$

where: G_{STC} is the solar irradiation under standard conditions equal to 1 kW/m^2, $G_a(\beta, \alpha)$ is the irradiation in a year calculated in the previous section. PR is the Performance Ratio or performance of the installation which is calculated according to the methodology proposed by Mulcué Nieto and Mora [26], as described in Equations (11)–(13).

$$PR = 0.0011\left(A_1 \cdot e^{-2\left(\frac{\alpha-\alpha_0}{W}\right)^2} + A_2 \cdot e^{-2\left(\frac{\alpha+90}{W}\right)^2} - \beta - 5\right) + 0.117 \cdot PR_{\max} \tag{11}$$

$$A_1 = -1.1 \cdot |\varphi| + 60,\ A_2 = -0.1 \cdot |\varphi| + 65,\ W = -1.1 \cdot \varphi + 92,\ \alpha_0 = -1.4 \cdot \varphi + 92 \tag{12}$$

$$PR_{\max} = k_{sist} \cdot [1 + \gamma(1.12 \cdot T_a - 10)] \tag{13}$$

where β corresponds to the inclination, α to the azimuth and φ to the latitude, all in sexagesimal degrees, T_a is the ambient temperature, γ is the temperature coefficient which depends on the panel technology. The system constant defined as k_{sist} depends mainly on the application of high standards in the design and quality of the equipment, with values of 0.662 and 0.820, for average and optimal systems, respectively.

To calculate peak power $\left(P_{pico}\right)$ that can be installed, the area of the roofs of the municipalities was measured using photographs reported by Google Earth. Given the heterogeneity of roofs, a 30% of this area was taken as the area available to install solar panels.

2.6. The Cost of Generated Energy

With the values of energy that can be generated in each municipality, a comparison was made with the energy consumption reported by the SUI in each municipality. A comparison was also made between the cost of energy in each municipality and the Levelized Cost of Energy (LCOE) of solar systems reported by the International Renewable Energy Agency (IRENA).

Moreover, this paper uses LCOE as economic plain metric for plant-level cost. The LCOE is a methodology proposed by the International Energy Agency (IEA) in [34] to quantify the cost of energy using the system costs for energy systems. We use the LCOE to quantify the cost of energy for a photovoltaic system of 1 kW. The LCOE is given by Equation (14).

$$LCOE = \frac{\sum (capital_t + O\&M_t + W_t)(1+r)^{-t}}{\sum E_{MWh}(1+r)^{-t}} \tag{14}$$

This equation uses the capital cost of a photovoltaic system (capital), operation and maintenance (O&M) cost, other associated costs (W), the appropriate return rate r, and the annual energy production (E_{MWh}).

3. Results

It was found that for the department of Putumayo and its borders, IDEAM has ten meteorological stations in operation which provide among their different variables, monthly average temperature, and total monthly solar brightness data. Figure 3 shows the location of each meteorological station in the different regions of the department. Table 1 shows the coordinates of each station: the altitude, the average interannual temperature, and the year of the beginning and end of the data series. As can be observed there are data series with 27 or more years, in this work the data from 1985 to 2012 were selected to make the comparison between the different stations in the same time range. It is important to note that the calibration of sensors that measure direct and global radiation, whether pyrheliometers, pyranometers, or actinographs, uses an Absolute Cavity Pyrheliometer of first order precision, certified by the World Reference Center for Solar Radiation (WRR) in Davos, Switzerland, and following ISO standards. Calibration consists of determining the calibration factor K, which adjusts the radiation values to those of the standard reference.

3.1. Calculation and Analysis of Solar Radiation Data for Different Regions and Stations

Figure 4 presents the average sunshine for each month of the year considering the data series from the weather stations. Two important facts can be highlighted: first, there is more sunshine in the summer months and less in the winter months for the three geographical areas under study. Second, in all the stations of the same zone there is consistent data; for example, in the three stations located in the Andean zone, there are fewer hours of brightness than in other regions. Third, there is a higher value of brightness in the Amazon region, and this value of solar brightness decreases as we approach the Andean region.

Figure 3. Location of IDEAM's weather stations with sunshine data in the department of Putumayo.

Table 1. IDEAM stations with solar brightness data in the department of Putumayo.

Region	Name of the Station	Latitude (°)	Longitude (°)	Altitude (m)	Years of the Series	Average Temperature (°C)
Andean	El Encano	1.16	−77.161	2830	1985–2017	11.67
	Michoacán	1.198	−76.961	2100	1978–2017	15.73
	Primavera	1.168	−76.933	2067	1984–2014	15.53
Andean-amazon	Mocoa	1.157	−76.652	650	1985–2017	23.01
	Villagarzón	1.034	−76.619	440	1969–2017	24.32
Amazon	Umbría	0.839	−76.570	362	1986–2012	24.96
	Valparaíso	1.195	−75.704	270	1969–2017	25.88
	Tres Esquinas	0.738	−75.236	219	1977–2015	25.65
	Tagua	−0.06	−74.665	153	1974–2017	25.76
	Leguizamo	−0.18	−74.776	147	1978–2017	25.68

In Figure 4b we can see the results of the average monthly daily irradiation, which were obtained with Angstrom—Prescott method and the Gopinathan formulas explained in the methodology. It is evident that as a tendency of the solar brightness the behavior of solar irradiation is greater in summer and less in winter, and there is greater irradiation in the Amazonian zone and less in the Andean zone. In addition, in Figure 4b, it is observed that three groups of irradiation values are marked which correspond to the three regions of Putumayo. This behavior of the irradiation values is because the irradiation, besides depending on the solar brightness, depends on the zone's altitude and latitude, as observed in the Angstrom-Prescott equations and the equations proposed by Gopinathan.

Taking the above irradiation values, the average daily irradiation of each weather station was calculated with a 95% confidence interval (CI) and is presented in Figure 5. As can be seen, the stations in the Amazon region have the highest irradiation values with an annual daily average of 4.35 kWh·day/m^2 while the Andean region has the lowest irradiation values with an annual daily average of 2.60 kWh·day/m^2. The Andean-Amazonian region, as a transition zone, has an annual average daily irradiation of 3.67 kWh·day/m^2. The large differences in solar irradiances depending on the site are given by the different geographical conditions of Colombia, as well as by the location of the stations. Some stations are in the valley and others in the mountains; however, both topologies can be in the same region. In addition, as the meteorological stations are scattered throughout the department, which presents these different topologies, solar irradiations will differ greatly from one site to another.

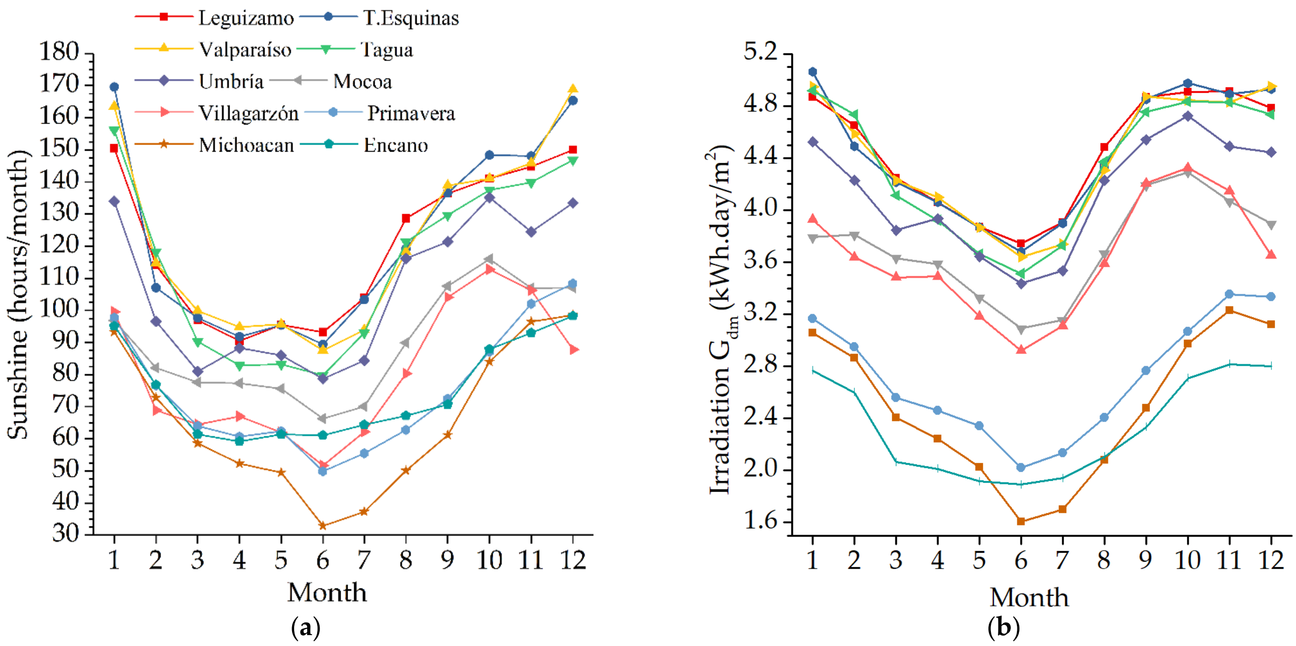

Figure 4. Results of data from IDEAM weather stations: (**a**) Average hours of sunshine per month; (**b**) Average daily solar irradiation per month.

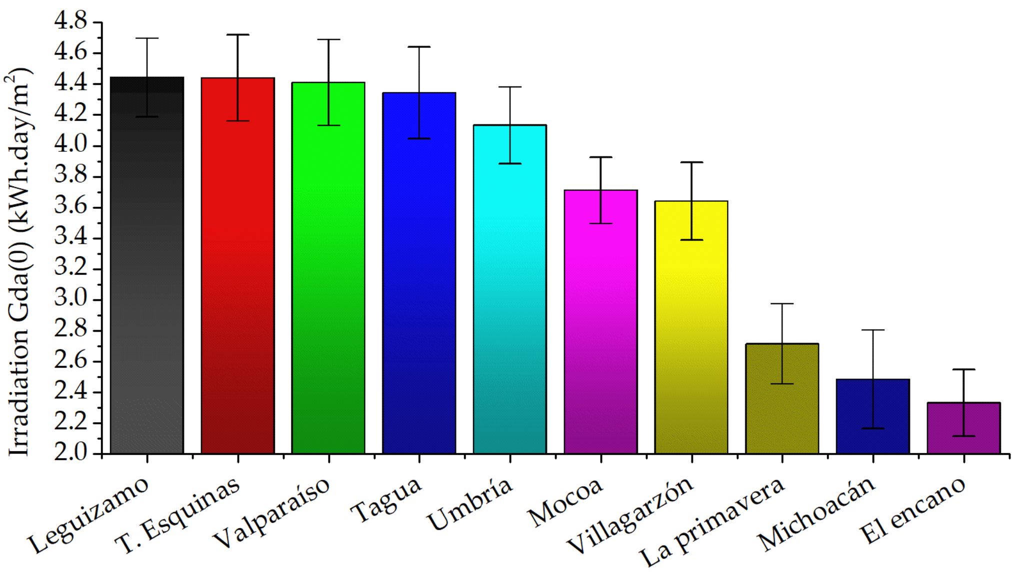

Figure 5. Location of IDEAM's weather stations with solar brightness data in the department of Putumayo.

Following the analysis of the databases with remote sensors, the NREL data series were taken. This database reports solar irradiance values on horizontal surface every half hour from 1998 to 2015 and with a spatial resolution of 4 km by 4 km. In addition, NASA's data series reporting monthly average daily irradiance data with a resolution of 0.5° by 0.5° (approximately 55 km by 55 km) were taken. These series have data for the period 1981 to 2017. With the above data, the irradiation values were calculated for each zone respectively, which can be seen in Figure 6a for NREL and Figure 6b for NASA. As clarification due to NASA's resolution, the data covers areas with more than one station. As can be seen in Figure 6b, the Villagarzón, Mocoa, Primavera, and Michoacán stations are less than 55 km away from each other, so they are represented by the same irradiation value. These data are not reliable since the stations belong to both the Andean and Andean-Amazon regions, which have different geographic and climatic conditions, which as indicated in Figure 6a,b, have different irradiation values.

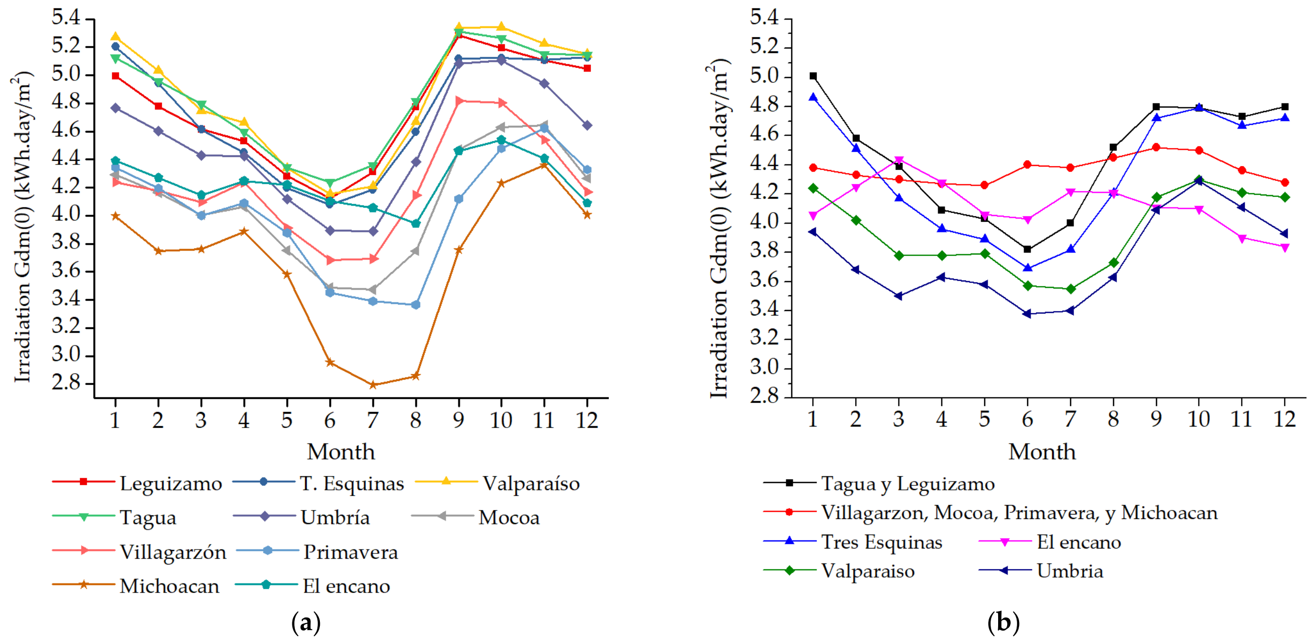

Figure 6. Results of daily monthly averages of solar irradiation from remote sensor databases: (**a**) NREL database; (**b**) NASA database.

With the monthly irradiation data $G_{dm}(0)$ from NREL and NASA, daily averages of annual irradiation $G_{da}(0)$ were calculated and the error and adjustment statistics presented in Table 2 were obtained. From these values, it is possible to identify that the NASA data does not fully match the NREL data, since the NASA remote stations cover large regions with several NREL stations. For the Encano station, for example, there is the least statistical error when comparing the values reported by both databases, which indicates that NASA's remote sensors are actually taking radiation values from that site and can differentiate them from the nearby region where the other Andean zone databases are located. However, for the Villagarzón, Mocoa, Primavera, and Michoacán stations, NASA reports the same radiation value, 4.37 kWh/m^{2}day even though two of them are in the Andean zone and the other two in the Andean-Amazon, while NREL establishes different and lower values.

Table 2. Comparison of irradiance values (G_{da}) calculated from NREL and NASA databases.

Region	Station Area	NREL $G_{da}(0)$ (kWh/m^{2}day)	NASA $G_{da}(0)$ (kWh/m^{2}day)	MBE (kWh/m^{2}day)	MPE %	RMSE (kWh/m^{2}day)	Statistic t (kWh/m^{2}day)
Amazon	Leguizamo	4.75	4.46	−0.29	6.13	0.32	7.64
	Tagua	4.84	4.46	−0.38	7.87	0.39	12.12
	Tres-Esquina	4.73	4.33	−0.39	8.40	0.40	26.24
	Valparaíso	4.85	3.94	−0.90	18.44	0.92	15.97
	Umbría	4.52	3.76	−0.76	16.68	0.78	15.67
Andean-Amazon	Villagarzón	4.21	4.37	0.16	−4.43	0.35	1.67
	Mocoa	4.08	4.37	0.29	−7.96	0.47	2.53
Andean	Primavera	4.02	4.37	0.35	−9.84	0.55	2.73
	Michoacán	3.66	4.37	0.71	−21.94	0.88	4.52
	El encano	4.24	4.12	−0.11	2.51	0.28	1.47

This means that NASA's remote sensors are unable to differentiate these zones. The adjustments between both bases are adequate for Villagarzón, Mocoa and Primavera (errors less than 3%), but not so much for Michoacán, where higher values of the statisticians are presented. For clarification, the Michoacán station is in the Andean region in which there are a variety of microclimates that are presented by the thermal floors of the mountain range. Therefore, between one geographic point and another close to it in this zone, which contain the Umbría and Valparaíso stations, are different climatic conditions. The MPEs exceed 10%, i.e., comparisons between the two databases are not acceptable. For the other three stations, the MPEs are less than 10%, i.e., the data are comparable, although the t-statistic is high.

The errors obtained between NASA and NREL were up to 22%, which can be explained by the different scale resolutions between both databases, and by the different topographic conditions in the Putumayo department. A possible way to resolve these discrepancies may be to identify the variations in geographic relief, before using the NASA data. An average or interpolation calculation could then be performed between areas with different heights above sea level. However, if the study area is very heterogeneous, it would be best to use data from weather stations or NREL.

After statistical comparisons were made between the irradiation results from the NREL and NASA remote sensor databases, these irradiation results were compared with those from the IDEAM weather stations. The average radiation values and statistics for each station are presented in Tables 3 and 4. In Table 3, it is observed that according to the comparison statistics between IDEAM and NREL, the NREL irradiation values are overestimated for all zones. In addition, for the Andean region, MPEs are not acceptable as they are above 10%. This behavior can be explained by taking into account that the Andean region has a particular topography that, as mentioned above, generates diverse microclimates even in areas close to each other, so on-site radiation measurements are required. The best adjustments and the least error between IDEAM and NREL occur in the Amazon region's stations. This may be because this zone has more homogeneous climatic conditions that do not vary abruptly as in the Andean zone.

Table 3. Comparison of irradiation values G_{da} from IDEAM weather stations and NREL remote sensor data.

Region	Station Area	IDEAM $G_{da}(0)$ (kWh/m^{2}day)	NREL $G_{da}(0)$ (kWh/m^{2}day)	MBE (kWh/m^{2}day)	MPE %	RMSE (kWh/m^{2}day)	Statistic t (kWh/m^{2}day)
Amazon	Leguizamo	4.44	4.75	0.31	−7.28	0.33	9.40
	Tagua	4.34	4.84	0.50	−12.09	0.53	9.33
	Tres-Esquina	4.44	4.73	0.29	−6.80	0.31	9.75
	Valparaíso	4.41	4.85	0.44	−10.18	0.45	14.92
	Umbría	4.13	4.52	0.39	−9.71	0.41	10.10
Andean-Amazon	Villagarzón	3.64	4.21	0.57	−16.18	0.58	14.40
	Mocoa	3.71	4.08	0.37	−10.17	0.39	10.43
Andean	Primavera	2.71	4.02	1.31	−49.95	1.32	22.50
	Michoacán	2.48	3.66	1.18	−50.79	1.21	14.80
	El encano	2.33	4.24	1.91	−85.76	1.93	20.82

Table 4 shows the comparison between the IDEAM and NASA data sets. It is evident that all the irradiation data from the Andean and Amazonian-Andean region are overestimated, and according to the MPE, not acceptable as they have an error greater than 10%. However, the Amazon region has a lower error with a better adjustment. In general, it can be observed that for the Amazon region the results of NREL and NASA compared to IDEAM have better fit and less error. This is because the region is characterized by similar geographical and climatic conditions as a plain with a tropical climate in all its extension.

Table 4. Comparison of irradiation values G_{da} from IDEAM weather stations and NASA remote sensor data.

Region	Station Area	IDEAM $G_{da}(0)$ (kWh/m^{2}day)	NASA $G_{da}(0)$ (kWh/m^{2}day)	MBE (kWh/m^{2}day)	MPE %	RMSE (kWh/m^{2}day)	Statistic t (kWh/m^{2}day)
Amazon	Leguizamo	4.44	4.46	0.02	−0.65	0.11	0.69
	Tagua	4.34	4.46	0.12	−3.20	0.20	2.50
	Tres-esquina	4.44	4.33	−0.10	2.20	0.14	3.99
	Valparaíso	4.41	3.94	−0.46	10.10	0.52	6.57
	Umbría	4.13	3.76	−0.37	8.59	0.41	6.58
Andean-Amazon	Villagarzón	3.64	4.37	0.73	−21.62	0.83	6.19
	Mocoa	3.71	4.37	0.66	−18.90	0.74	6.46
Andean	Primavera	2.71	4.37	1.66	−65.39	1.71	12.34
	Michoacán	2.48	4.37	1.89	−85.31	1.96	11.46
	El encano	2.33	4.12	1.79	−81.90	1.86	12.69

With the previous monthly and annual irradiation data from IDEAM, NREL, and NASA, the daily interannual averages of irradiation were obtained for each region of Putumayo. As can be seen in Figure 7, the results from IDEAM and NREL have the same tendency of higher irradiation in the Amazon region to lower irradiation in the Andean region; this behavior is given by the natural changes of the regions. The Andean region has a mountain range with heights of 2800 m, which has its base in the Andean-Amazon region at altitudes of 500 m and continues with a plain that extends towards the Amazon at altitudes of 140 m above sea level. On the other hand, it can be observed that the results of the NASA data do not have the same behavior as the other two database results, which is because the NASA data have a resolution of 55 km by 55 km and cover areas that have different geographical and climatic conditions.

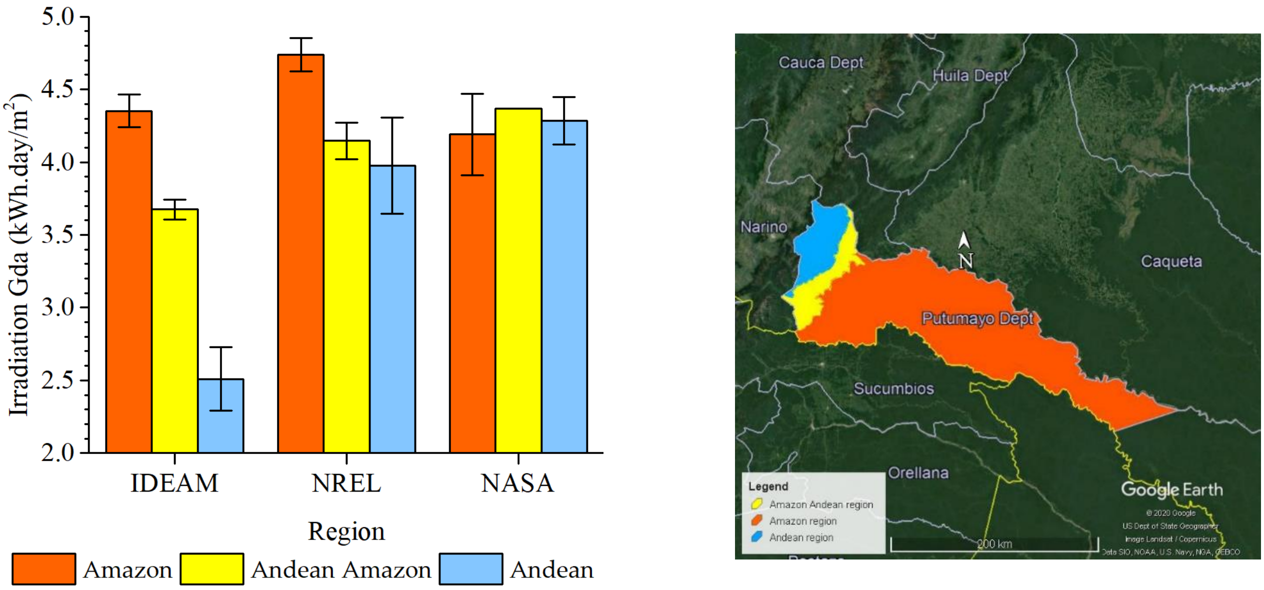

Figure 7. Annual daily average of radiation $G_{da}(0)$ for the IDEAM station areas using different databases.

To support the previous regional analysis, statistical comparisons were made between the results of data taken from IDEAM's meteorological stations and those from NASA and NREL remote sensors. As it can be seen in Table 5, the irradiation data of the Andean region presents t, MBE, MPE, and RMSE statistics higher than the other regions, which represents a bad adjustment and high error of the data. In contrast, the Amazon region presents statistics with lower values than the other regions, indicating that these data have less error and better adjustment between compared data. It can be observed that the NASA data have higher comparison statistics than the NREL data, therefore the NREL data fit better and with less error than the IDEAM data. As explained above, these errors are because the Andean region has a variety of microclimates due to the thermal floors of the mountain ranges and to the high extension covered by the database.

Table 5. Comparison of IDEAM-NASA and IDEAM-NREL irradiance values G_{da} by region.

Data and Statistics		Amazon Region	Andean-Amazon Region	Andean Region
IDEAM-NASA statistical comparison	MBE (kWh/m^{2}day)	−0.16	0.70	1.78
	MPE %	3.79	−18.95	−71.27
	RMSE (kWh/m^{2}day)	0.28	0.70	1.78
	Statistic t (kWh/m^{2}day)	1.45	20.00	26.65
IDEAM-NREL statistical comparison	MBE (kWh/m^{2}day)	0.39	0.47	1.47
	MPE %	−8.90	−12.87	−59.19
	RMSE (kWh/m^{2}day)	0.39	0.48	1.50
	Statistic t (kWh/m^{2}day)	9.99	4.81	6.50

3.2. Energy Generated by Solar Photovoltaic Systems in the Regions of Putumayo

To evaluate the effective energy E_{FV} that can be generated by a photovoltaic system in Putumayo, the standard of the IEC 61724 [33] described in the methodology was followed. To determine the energy generated, it was necessary to calculate the irradiation and the PR for each station and the averages for each region. The irradiation $G_{da}(\alpha, \beta)$ for each station was calculated with the irradiation $G_{da}(0)$ obtained from data information from the IDEAM data bases. To obtain the PR, different combinations of α and β angles were evaluated. It was found that the optimal angle of inclination, β, is between 2° and 5.5°; however, for maintenance of the systems, an angle of 10° was selected. It should be noted that the average angular loss of irradiation for this tilt angle is less than 1%. The orientation angle, α, is taken to be equal to 0° for facilities located north of the equator, and 180° for facilities located south. With these angle values, the PR for each station and the average for each region were determined.

The relationship between the ambient temperature Ta, obtained for each locality through databases, and the Performance Ratio PR of the photovoltaic system is given by the Mulcue-Llanos model [29] and described in Equations (11)–(13). The configuration was assumed an optimal system considering high quality equipment and design with a k_{sist} = 0.820, and a maximum power point with the temperature of −0.0044 °C^{-1}, which corresponds to crystalline silicon technology. With respect to the variable temperature, the average of the series studied for each zone of the weather stations was taken.

With the results obtained from PR, the energy that can be produced with a panel system with a peak power of 1 kW was calculated. The results of these calculations are shown in Table 6. In general, the PR value decreases for the high temperature areas such as the Amazon region, and it is higher in the lower temperature areas such as the Andean region. Although the PR values in the Andean region are high, their irradiation is low, so the energy values generated by the same system of solar panels installed in the Andean region are lower than when installed in the other regions. As can be seen in Table 6, the Amazon region has the highest value of energy produced, almost doubling the value of energy produced in the Andean region, which means that the use of solar panels is more profitable in the Amazon region.

Table 6. Solar irradiation on inclined surface and energy production with a solar system of 1 kWp in optimal conditions.

Region	Station Area	Environment Temperature Ta (°C)	Annual Solar Radiation $G_a(\alpha,10)$ (kWh/m^{2}day)	PR	Energy Produced (kWh/year)	Average Energy Produced (kWh/year)
Amazon	Leguizamo	25.68	1942.24	0.751	1458.04	1429.96
	T. Esquinas	25.65	1959.48	0.751	1471.22	
	Valparaíso	25.88	1945.88	0.750	1459.45	
	Tagua	25.76	1886.39	0.750	1415.63	
	Umbría	24.96	1786.32	0.753	1345.45	
Andean-Amazon	Mocoa	23.01	1558.31	0.760	1184.18	1167.45
	Villagarzón	24.32	1523.31	0.755	1150.72	
Andean	Primavera	15.53	1073.34	0.786	843.25	775.47
	Michoacán	15.73	974.26	0.785	764.74	
	Encano	11.67	899.24	0.799	718.43	

The calculation of the energy that can be produced from the available roofs of the municipalities of the department of Putumayo requires calculating the peak power, for which it was necessary to determine the area of the roofs of the municipalities of the department of Putumayo. Google Earth Pro was used for this calculation. Based on the image of the area for 2020 (Figure 8), the urban areas and the roof areas were measured. The area available for the installation of solar panels was determined assuming 30% of the roof area as available. Figure 8 shows the sectors measured for the municipality of Sibundoy. The perimeter areas or urban areas is highlighted in blue, and the roof measurements are highlighted in yellow, Table 7 shows the values of the areas obtained.

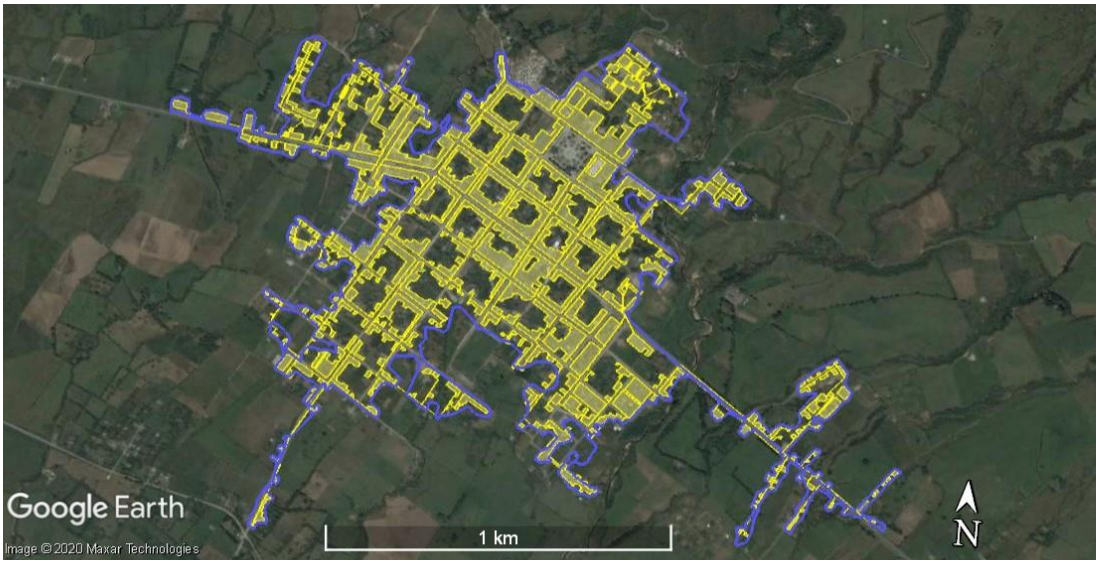

Figure 8. Area of the roofs of the municipality of Sibundoy. Source: Modified from Google Earth.

Table 7. Roofed area and percentage available for the municipalities of Putumayo according to measurements made in images available in Google Earth Pro software.

Municipality	Image Year	Urban Area (km^2)	Roof Area (km^2)	Available Area (m^2)	Available Area (m^2)	Region
Santiago	2006	0.224	0.080	23,915	203,942	Andean
Colon	2011	0.401	0.143	42,807		
Sibundoy	2006	0.934	0.332	99,722		
San Francisco	2006	0.351	0.125	37,498		
Mocoa	2017	2.4	0.869	260,737	375,258	Andean-Amazon
Villagarzón	2016	1.1	0.382	114,521		
Puerto Guzmán	2017	0.3	0.122	36,489	856,805	Amazon
Puerto Caicedo	2016	0.4	0.133	39,945		
Orito	2017	1.8	0.627	188,166		
Puerto Asís	2016	3.2	1.151	345,356		
Valle del Guamuez	2017	1.2	0.424	127,204		
San Miguel	2017	0.4	0.142	42,546		
Puerto Leguizamo	2016	0.7	0.257	77,099		

From these values, the peak power for each municipality was calculated considering the area occupied by the 250 Wp panels (each panel has an area of 1645 mm × 997 mm). With this peak power, the calculation of the effective energy that can be generated by the system in each municipality and region was made, for which the average of the optimum PR of the stations in the region was taken. Table 8 shows the results of these calculations. It is evident that the region with the highest energy production is the Amazon region and the municipality with the highest production is Puerto Asís.

Table 8. Peak power and energy generated in the municipalities and regions of the department of Putumayo.

Municipality	Peak Power in Available Area (MWp)	PR	Solar Irradiation Per Year Ga (a, b) (kWh·day/m^2)	Produced Energy (MWh/year)	Average Produced Energy (MWh/year)	Region
Santiago	3.645	0.790	982.3	2828.3	24,119	Andean
Colon	6.525	0.790	982.3	5062.5		
Sibundoy	15.201	0.790	982.3	11,793.5		
San Francisco	5.716	0.790	982.3	4434.6		
Mocoa	39.745	0.758	1540.8	46,398.6	66,778	Andean-Amazon
Villagarzón	17.457	0.758	1540.8	20,379.3		
Puerto Guzmán	5.562	0.751	1904.1	7953.9	186,768	Amazon
Puerto Caicedo	6.089	0.751	1904.1	8707.2		
Orito	28.683	0.751	1904.1	41,016.9		
Puerto Asís	52.644	0.751	1904.1	75,281.5		
Valle del Guamuez	19.390	0.751	1904.1	27,728.3		
San Miguel	6.485	0.751	1904.1	9274.3		
Puerto Leguizamo	11.752	0.751	1904.1	16,806.2		

It was found that in Putumayo a total of 277.7 GWh/year can be generated with this type of solar photovoltaic systems; enough energy to cover the entire energy demand of the department, since according to the SUI report in 2016 in Putumayo a total of 67.0 GWh/year was consumed. Taking into account the SUI report for 2016, and according to the historical data analyzed, this consumption represents 24% of what can be generated in an average year with a solar panel system.

Table 9 shows the annual electricity consumption reported by the SUI for each municipality in the department, both for areas connected to the national electricity grid and non-interconnected areas. When reviewing this data, it can be identified that in each region the percentage of consumption is low in relation to what could be generated, thus the Andean region would consume 33.38%, the Andean-Amazon region would consume 28.04%, and the Amazon region would consume 24.14%.

Table 9. Residential consumption of the areas connected to the national electricity grid and the ZNI in the department of Putumayo.

	Electricity Consumption Residential (MWh)									
Municipios y Año	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Santiago	1088	1125	1107	1020	988	1093	1141	1168	1206	1180
Colon	1097	1151	1144	1062	1041	1255	1222	1216	1266	1271
Sibundoy	3662	3789	3792	3618	3559	4008	4242	4328	4361	4386
San Francisco	1212	1260	1268	1215	1176	1297	1363	1341	1341	1288
Mocoa	10807	11101	11451	12056	12991	13847	14442	13905	14265	15522
Villagarzón	3228	3468	3730	3810	4367	4770	4713	4820	5223	5643
Puerto Guzmán	1122	1157	1393	1332	1450	1809	1412	1523	1749	2014
Puerto Caicedo	1456	1790	1601	1585	1663	1889	2008	2120	2245	2499
Puerto Asís	11267	16961	11968	12432	13284	14497	14919	15354	15877	17027
orito	6051	6817	6968	6906	7231	8113	8032	7884	8356	8991
San Miguel	1118	1199	1264	1229	1454	1506	1792	1996	2172	2475
Valle del Guamuez	4498	4479	4548	4757	4864	5272	6021	6631	6983	7615
Puerto Leguizamo (ZNI)							3475	3651	4073	
Puerto Guzmán (ZNI)							1098	1100		
Total, Putumayo	46605	54297	50233	51022	54069	59357	64781	67036	69117	69911

Source: Single information system for residential public services (SUI). Retrieved from http://www.sui.gov.co (accessed on 27 August 2019).

According to the population census of the National Administrative Department of Statistics (DANE) carried out in 2005, for 2018, Putumayo was projected to be inhabited by 358,896 people [35]; and according to the SUI report these people consumed 69,911 MWh/year. Considering the DANE and SUI reports, in Table 10 the consumption per inhabitant of each municipality and the average consumption of the municipalities of Putumayo are reported. According to these data in 2018 on average one person in each municipality of Putumayo consumed 213 kWh of residential electric energy per year. With this consumption and an installation of a 1 kWp solar system, such as the one described in Table 6, the demand of three people in the Andean region and six people in the Amazon region could be supplied.

Table 10. Residential electric energy consumption per inhabitant in Putumayo.

	Consumption Per Person (kWh/hab)			
Year	**2015**	**2016**	**2017**	**2018**
Santiago	109	111	113	110
Colon	221	219	226	225
Sibundoy	300	304	305	305
San Francisco	192	188	187	179
Mocoa	343	324	326	348
Villagarzón	223	227	245	264
Puerto Guzmán	106	110		
Puerto Caicedo	138	145	153	170
Puerto Asís	248	253	258	274
Orito	153	147	152	160
Valle Del Guamuez	35	38	41	46
San Miguel	227	245	252	269
Leguizamo	225	237	265	
Promedio	194	196	210	213

By comparison, compiling the costs of electric energy from the SUI found that in the zones connected to the national grid in the department of Putumayo, the costs are above the Colombian average, and the costs of the ZNI of Putumayo are higher, almost tripling the costs of the national average (see Table 11). The costs of electric energy in Colombia are increasing yearly. From 2017 to 2018 they went up approximately 5%, while the costs of solar energy, according to IRENA, decreased. Therefore, over the last 10 years this decrease was 82%, and from 2018 to 2019 it was 13%, reaching almost seven cents (USD 0.068) per kWh [36].

Table 11. Energy costs in Putumayo by company and municipality.

Invoiced Value of Cost Per kWh Consumed (USD/kWh)					
Company	**Municipality**	**2015**	**2016**	**2017**	**2018**
Empresa de energía del valle de Sibundoy EMEVASI S.A E.S.P	Santiago	0.13	0.15	0.16	0.17
	Colon	0.13	0.15	0.16	0.17
	Sibundoy	0.13	0.15	0.16	0.17
	San Francisco	0.13	0.15	0.16	0.17
Empresa de energía del putumayo EEP S.A E.S.P	Mocoa	0.12	0.15	0.15	0.17
	Villagarzón	0.12	0.15	0.15	0.17
	Puerto Guzmán	0.12	0.15	0.15	0.17
	Orito	0.12	0.15	0.15	0.17
Electrificadora del Caquetá S.A E.S.P	Puerto Guzmán	0.13	0.15	0.15	0.17
Empresa de energía del bajo putumayo EEBP S.A E.S.	Orito	0.14	0.15	0.15	0.17
	Puerto Asís	0.14	0.15	0.15	0.17
	Puerto Caicedo	0.14	0.14	0.15	0.17
	San Miguel	0.14	0.14	0.15	0.17
	Valle Del Guamuez	0.14	0.14	0.15	0.17
Empresa solidaria de servicios públicos agua viva de Puerto Guzmán E.S.P.	Puerto Guzmán (ZNI)	0.35	0.35		
Empresa de servicios públicos domiciliarios de Puerto Leguizamo EMPULEG E.S.P.	Puerto Leguizamo (ZNI)	0.26	0.25	0.29	
Average cost in Putumayo		0.15	0.17	0.16	0.17
Average cost of the interconnected zones in Colombia		416.4	486.5	487.8	514.9

Now, if we considering 25 years of solar system lifetime, return rate of 12%, a capital of USD 1000, operation, maintenance, and other associated cost at 1%, a capacity factor of 16%, the obtained value of LCOE from Equation (13), whit the energy generated for this type of solar photovoltaic systems, is of 0.10 USD/kWh. This value is comparative to the IRENA (USD 0.068 USD/kWh). According to these analyses, the implementation of solar systems in Putumayo is technically and economically feasible.

4. Discussion

Both at the beginning and at the end of the year, there are higher values of solar brightness, which decrease toward the middle of the year. The Amazon region has higher hbs values (Tres Esquinas station has the highest value with 123 hbs per month), while the Andean region has the lowest values (Michoacán station has the lowest value with 66 hbs per month). On the other hand, the radiation calculated from the Angstrom-Prescott method is higher at the end and beginning of the year and decreases toward the middle of the year (Leguizamo and Tres Esquinas stations (in the Amazon region) with maximum values of 4.44 kWh/m^{2}day and El Encano station (in the Andean region) with a minimum value of 2.33 kWh/m^{2}day). This behavior is characteristic of Colombian regions. These results show that the solar brightness values directly affect the irradiance calculation values; however, the effects of altitude and latitude cannot be ruled out.

To validate the calculated irradiance results with data from IDEAM meteorological stations, the NREL and NASA remote databases were evaluated. All irradiance data and results show the same monthly trend, with maximum values at the beginning and end of the year, and minimum values in the middle of the year. The NREL irradiance data, as well as the values calculated with the IDEAM data, show higher average irradiance in the Amazon region and lower in the Andean region. Although the data reported by NASA show a maximum average in the Andean region and a minimum in the Amazon region, these differences are possibly due to the difference in the resolution of the remote databases.

The comparison statistics between irradiance values, taking as a reference the values calculated with IDEAM data, are acceptable (less than 10%) for both NREL and NASA in the Amazon region, while the MPEs are higher than 10% in the other two regions: there is overestimation. The high errors of both remote bases in the Andean and Andean-Amazon regions are most likely due to their spatial resolution, since they cover areas of 4 km by 4 km for NREL and 55 km by 55 km for NASA, meaning that in these mountainous regions there is lack of precision covering small areas. Having on-site measurements, i.e., with meteorological stations, is advisable when performing radiation analysis for the installation of solar systems to avoid inaccuracies in data collection due to spatial resolution.

To evaluate the effective potential of solar energy in Putumayo, an inclination angle of 10° was selected as the system would have losses of less than 1%. For maintenance reasons this angle is better than the smaller angles. This situation usually occurs in the installation of photovoltaic systems in the tropical zone where the optimum angle is usually between 2° and 6°; however, systems are usually installed between 6° and 10°.

The calculations of the installation PR and the energy produced were obtained for each one of the zones. The PR with the highest value occurred in the Andean region where the temperature is lower, whereas the lowest PR occurred in the Amazon region where the temperature is higher. The maximum PR for an optimal installation is at the Encano station with a value of 0.799 and a minimum for the Tagua and Valparaíso stations of 0.750. A photovoltaic system in the Amazon region would produce 1429.96 kWh/year, the Andean-Amazonian 1167.45 kWh/year, and the Andean 775.47 kWh/year, approximately half of the Amazon region.

According to the results, the municipality that would produce the most energy is Puerto Asís with a value of 75,281.5 MWh/year and the one that produces the least is Santiago with a value of 2828.3 MWh/year. The Putumayo would produce a total of 277.7 MWh/year. The Amazon region would produce 67% of the Putumayo total, 24% would be produced in the Andean-Amazon region and 9% in the Andean region. These results were obtained with an average PR value and considering an available area of 30% on roofs in the populated centers of the municipal capitals, with 250 Wp solar panels.

With the municipal results, a total of 277.7 GWh/year can be generated in Putumayo. With the energy produced, it is possible to cover more than what has been consumed in Putumayo in recent years. According to the SUI report, in 2016 Putumayo consumed a total 67.0 GWh/year, of which 4.7 GWh/year were from ZNI consumption in the municipalities of Puerto Guzmán and Puerto Leguizamo. In 2017, 69.1 GWh/year were consumed without adding the energy consumption of the ZNI of Puerto Guzmán, and in 2018 69.9 GWh/year were consumed without adding the energy consumption of the ZNI of Puerto Guzmán and Puerto Leguizamo.

According to the SUI report in 2016, the utility company Agua Viva de Puerto Guzmán billed the cost of energy at USD 0.35/kWh for a consumption of 1.1 GWh/year, and the Puerto Leguizamo Utility Company billed the cost of energy at USD 0.25/kWh for a consumption of 3.6 GWh/year. The average cost of energy in Putumayo in 2016 was USD 0.17/kWh and the average for Colombia was USD 0.14/kWh. According to these data, the cost of energy in Putumayo is above the national average, and it is more expensive in the ZNI. For photovoltaic solar system, the calculated LCOE was USD 0.10/kWh, this value is still below the reported ones for the Putumayo department.

5. Conclusions

The Putumayo solar irradiation values taken from the remote databases of the NREL and NASA, when compared with the values calculated with data from the IDEAM meteorological stations, show acceptable ranges in the Amazon region, but the differences are notorious in the Andean and Andean-Amazon regions. This is because the spatial resolutions of remote databases are very large, covering large areas as if they had the same irradiation value, and in these mountainous regions there are a variety of zones and climates.

Using less than 30% of the available area of the roofs of the municipal capitals of Putumayo, to install solar panel systems, an effective electricity potential can be generated with which the entire electrical energy demand of the department can be covered. The potential with photovoltaic systems would be adequate to produce electricity for self-generation and distributed generation in the municipalities of Putumayo.

In this paper, some models widely used by different researchers are combined, this made it possible to calculate the electrical energy that a photovoltaic solar system can generate. For the photovoltaic solar calculation, the characteristics of the technology, the solar brightness data, the altitude, the ambient temperature and the latitude of the place were considered. As can be seen, mathematical models involving the different variables of the photovoltaic systems were used and rigorous and precise results were obtained.

With the municipal results, a total of 277.7 GWh/year can be generated in Putumayo. With the energy produced, it is possible to cover more than what has been consumed in Putumayo in recent years. According to the SUI report, between 2016–2018, Putumayo consumed an average of 68.7 GWh/year, of which more than 7% were ZNI consumption.

The average cost of energy in Putumayo in 2016 was USD 0.17/kWh and the average for Colombia was USD 0.14/kWh, according to the SUI report. From to these data, the cost of energy in Putumayo is above the national average and more expensive in the ZNI. With photovoltaic solar system, as discussed in this work, the calculated LCOE of USD 0.10/kWh is still below the reported values for the Putumayo department. Therefore, new sources of energy such as solar photovoltaic offers a great opportunity.

The energy costs of Putumayo and Colombia are higher than the LCOE level energy costs globally produced with solar panel systems. According to IRENA the costs of solar energy over the last 10 years has decreased by 82%, and from 2018 as of 2019, it decreased by 13% reaching almost seven cents (USD 0.068) per kilowatt hour (kWh). As can be seen, the energy costs of Putumayo are higher than the average for Colombia, and among the Putumayo municipalities the highest costs are those of the ZNIs. The high costs of energy in Putumayo, the potential for solar irradiation, and the low LCOE of renewable energies, justify investing in solar panel systems throughout Putumayo.

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