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A Study of the Estimation of the Photovoltaic Potential at the Urban Level in Tropical Complex Terrain

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Abstract- This work considers photovoltaic solar energy as an alternative to promote the diversification of the energy matrix and contribute to improving energy access to the citizens of Medellín Metropolitan Area, Colombia, a tropical region conditioned by the topography and by the different urban morphology. The objective is to demonstrate the feasibility of the more sustainable and resilient energy use in tropical cities on complex terrain through energy production from alternative renewable sources. These outcomes are essentials because they could direct the design of policies and strategies that improve energy planning in cities under similar conditions. To achieve this, we assess how much of the energy demand can be generated within the city, integrated into the urban morphology at the roofs of existing buildings, including the topography effect. We use meteorological information and power measurements from three experimental solar panels. We analyze the photovoltaic energy potential in Representative Urban Areas and provide information relevant to the whole Valley's context to guide sustainable and resilient energy planning. One particular result is about the energy reduction factor due to cloudiness, which quantifies how energy would vary under the region's cloud conditions. According to the findings, these variations could be between 2% and 10%, depending on the time and month. In addition, the performance of solar panels is higher in the central section of the Valley and lower in the eastern slope. However, in the latter case, it is still favorable to cover a fraction of energy consumption.

Keywords Renewable energy sources; Solar energy; Solar radiation; Urban planning; Sustainable energy.

1. Introduction

Energy planning within cities is crucial for their development because it conditions the economic dynamics and their inhabitants' quality of life. Ideally, cities should be self-sustained. However, Colombian cities are vulnerable to electrical energy shortages in the face of the negative phase of ENSO [1], mainly due to their dependence on water availability as a resource, since nearly 68.8 % of the electricity in Colombia comes from hydropower plants [2].

Considering that cities have high energy consumption, efforts should concentrate on strengthening urban planning. One way is by incorporating alternative energy generation sources to improve resilience in the face of reduced hydropower generation due to climate variability and climate change [3, 4, 5]. The primary purpose of this work is to estimate the photovoltaic potential on a small scale, considering the urban morphology, the topographical and cloudiness conditions of the municipalities of the Metropolitan Area of the Aburrá Valley (MMA) in Colombia. In this sense, this study focuses on assessing the photovoltaic potential, which allows establishing the region's particular opportunities and limitations regarding urban energy planning. The application of these outcomes is essential for developing plans, projects, and policies that guarantee these cities' energy sustainability, establishing resilience strategies to mitigate and overcome climate-related challenges.

According to [6], the methods commonly used for data analysis applied to renewable energy research can have forecast or predictive purposes as reflected in the works of [7, 8, 9, 10] or descriptive purposes, such as [11, 12, 13, 14, 15]. This paper presents a descriptive study since it analyzes the information under the regional conditions to support the decision-making of regional authorities [11] towards a more sustainable and resilient urban planning, which is helpful for urban planners and investors.

Numerous previous works [11, 12, 14] that present solar energy as an alternative to supplying energy consumption justify this transition on the projected decline of fossil fuels. However, as mentioned before, the context of the Colombian cities marks an additional energy problem: dependence on the availability of a single resource, increasing vulnerability to climate variability. Diversification of the energy supply contributes to diminishing vulnerability to hydrological variability and climate change. Among the multiple energy sources, solar radiation has advantages over the others: its renewable, inexhaustible nature and its production is pollution-free [3].

Regarding assessing photovoltaic energy generation potential on roofs and facades, previous works use different methodologies, incorporating models that consider both the geometry of the buildings and the incident energy or analyzing data in geographic information systems, which is useful to estimate the behavior of the resource. In 2016, Li, Ding, Liu, and Wang [11] calculated the instantaneous solar radiation at pixel resolution in roofs of Xiuyuan, where they showed that the high-resolution information is helpful to identify the portion of roofs with high solar potential. Xu, Li, Zhang, Huang, Tian, Luo, and Du [13] presented a method to indicate the potential of photovoltaic energy generated at a residential level based on urban morphology and the obstructions it could cause. In the city of Fribourg in Switzerland, R. Compagnon [16] used a model based on the interaction between incident irradiance and buildings to find the fraction of the available surface area for solar energy use. K. K.-L. Lau, F. Lindberg, E. Johansson, M. I. Rasmussen, and S. Thorsson [17] studied four areas in Dar es Salaam. They compared the total irradiance reaching the roofs and facades of those buildings to assess its temporal variability using a 2D model of solar radiation (Solar Energy on Building Structures-SEBE) and digital surface models of the areas of interest. S. Izquierdo, M. Rodrigues, and N. Fueyo [18] used a hierarchical methodology to find the photovoltaic solar energy generation potential; they estimate the physical potential, which refers to estimating the amount of irradiation over the urban areas with representative building typologies. They also estimate the geographic potential considering the local restrictions that there would be for solar energy and the technical potential that incorporates the equipment used to transform the resource into electrical energy. D.A.Widodo, P. Purwanto, and H. Hermawan [12] recently followed this methodology to assess the rooftop photovoltaic potential in Semarang City and its carbon dioxide mitigation, estimating the supply of energy consumption larger than 40%. P. Redweik, C. Catita, and M. Brito [19] used 3D surface models to evaluate the photovoltaic potential on facades and roofs within the campus of the University of Lisbon. They use a model that calculates each pixel of the 3D mesh the global solar radiation using the SOL-TERM database), considering astronomical factors and variations of the resource due to the seasonal variability. These works have precious information, and they are part of the framework for small-scale renewable energy and energy planning at the urban level. A differentiating factor of the present work is the use of the buildings' morphology and factors such as the Valley's topography.

In 2017, the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM) quantified radiation for the Colombian Andean zone. According to this study, this region receives between 4.5 and 5 kWh/m^2 per year. However, this atlas does not detail the potential at the local level. It proposes improvements in the methods for adjusting the radiation values with a distribution of the more detailed measurements [20]. Recent studies on the estimation of residential solar potential in Colombia have mainly focused on descriptions of irradiance data in remote and energy-isolated areas, such as the Rosario Islands in the Caribbean [21], and in departments like Chocó, Meta, and Putumayo [22]. The works of [5, 23] do consider some places in the country's interior that are part of the interconnected national system (INS [24]). Although some of these works do not consider the Colombian territory's heterogeneity, they represent the beginning of an emerging applied research area in Colombia. A significant finding of these studies is that the country has good potential for solar energy in roof-mounted systems since the average daily irradiation values in the mentioned studies vary between 4.0 and 4.5 kWh/m^2 in the country's interior and reach an average range between 5 and 5.5 kWh/m^2 in the Caribbean region.

According to the above, the studies on this topic usually have in common the use of digital surface models or satellite images to generate estimates of photovoltaic potential through simulations of annual irradiance. Some of these studies compare them with ground sensor measurements, and some others emphasize the effects produced by urban morphology. However, they do not include topography or energy variations in their analysis due to the cloud patterns. Those are precisely the points this study intends to cover since it considers the use of information from drone overflights, experimental power measurements, the effect of topography, and cloud cover analysis to improve estimates of small-scale photovoltaic energy in tropical environments. Despite good solar availability due to astronomical factors [25], there could be limitations in usable energy due to cloudiness and topography [26, 27]. By analyzing the power measurements of three experimental photovoltaic systems, this work demonstrates the differential effect of topography on the amount of actual solar radiation in urban areas with similar buildings and different Valley sections. In this sense, to include this aspect in the research, digital photogrammetry with drones is used to obtain digital surface models. The main advantage of this technique is that it allows the representation of buildings and adjacent obstacles and their terrain at a very high resolution, less than 8 square centimeters. In addition, to improve the characterization of heterogeneous urban environments in complex tropical terrains, this work presents a characterization based on urban morphology representative of each section of the Valley. We then complement it by proposing a weighted factor of energy reduction due to cloudiness, improving the energy estimates for tropical places where cloudiness plays an important role, such as MMA.

2. Materials and Methods

The methodology of the present study has three main components: the first is the use of three experimental panels power records, the second is the characterization of the urban areas according to topography and building heights, and the third is a characterization of cloudiness in the region.

The experimental part consisted in registering and analyzing the power produced for 11 months using three polycrystalline solar panels at 80 and 100 watts installed in the Medellín Metropolitan Area (MMA), located in Colombia, in the Aburrá Valley. The location of the solar panels was selected to assess contrasting topographical sections within the urban area in the Aburrá Valley. Figure 1 shows the location of the contrasting points. For practical purposes, we call these points: West (W), Center-west (CW), and East (E). The power data record has a 60-seconds temporal resolution. The purpose of the experimental setting was to evaluate the performance rate and efficiency of the panels considering the cloud's radiative forcing.

Then, the urban area's characterization consisted of selecting six representative urban areas (RUA) within the Aburrá Valley. They should have a different urban morphology and represent different Valley sections, like the location of the experimental photovoltaic systems. Each RUA considers information about the type of roofs of their buildings to obtain an estimate of annual solar photovoltaic potential. This estimation relied on digital surface models (DSM) obtained after SIATA drone overflights over each RUA. In this way, it is possible not to lose sight of the Valley's particular conditions and include urbanization's heterogeneity. As a result, the selection included two sites on the western slope, two in the Valley center, and two on the eastern slope. Likewise, for each subsection, a place was chosen with buildings in vertical extension, cataloged as 'high buildings,' and another place cataloged as 'low buildings.' After that, we estimated the annual irradiation received on RUA's roofs and, subsequently, the energy generated. The estimation of the generated energy uses the results of the efficiency and performance rate calculations obtained from the power records, keeping the correspondence of the results of each experimental photovoltaic system to the energy estimates of the RUAs of that same section of Valley. Additionally, one considered the shading patterns induced by the terrain at two different times of the day. This shading highlights the importance of the mountains on the solar radiation at the surface level. The next step was calculating the percentage of the energy consumption for one person per square meter of the installed panel to overview the usefulness of photovoltaic systems in local conditions.

Clouds are the most critical factor affecting solar radiation at the surface in tropical areas [24]. Previous studies of the patterns of cloudiness [1] help characterize the general patterns of cloud influence on surface solar radiation. We propose a factor of energy reduction from observed cloud frequencies due to cloudiness, based on irradiance data in clear and cloudy sky conditions and cloud frequency. This factor provides a refinement of the estimates of energy generated.

2.1 Study area

The MMA is in the Aburrá Valley, a narrow valley in the Andean region of Colombia. Its total population exceeds four million. Figure 1 shows the geographical context of the metropolitan area, including the jurisdictional boundaries of the municipalities part of the MMA.

2.2 Data

Irradiance data was from the ground networks operated by SIATA (Early Warning System of Medellín and the Aburrá Valley) for the MMA. These records are at a 60-seconds resolution from 2016 through 2020. The pyranometers used are from Kipp & Zonen, and according to their manual, their measurements are 95% reliable [28], and their records undergo data quality processes before downloading. The experimental photovoltaic systems also have power records every 60 seconds for 11 months between 2019 and 2020, kept in the sensor's internal memory. The experimental solar panels and most of the SIATA network ground-based weather sensors used for the analyses share locations. Figure 1 also shows the three topographically contrasting points: W, CW, and E. The shapefiles to delimit the regions of interest are from [29].

To consider roof features and surrounding obstacles, we use digital surface models of each RUA obtained from drone overflights, they were available at different spatial resolutions, see Table 1. We also use a 30-meter resolution digital terrain model (DTM) [30] to evaluate the topography-induced shadow patterns over each RUA at two contrasting times of the day.

One can estimate hourly theoretical estimations of solar radiation on the surface using general principles [27]. In [31], they propose a model of theoretical solar radiation in clear sky conditions for mountainous regions according to the characteristics of the terrain.

Also, one estimated cloudiness from two sources: GOES16 band two and pyranometer data between 2018 and 2019. The first step is classifying cloudy and clear reflectance values following methods compiled in [32]. The second step is to calculate the frequency of cloudiness over the region. The last step is to compute the weighted cloud energy reduction factor.

The characterization of monthly energy consumption per person report from [33] provided an estimation of monthly energy covered per person.

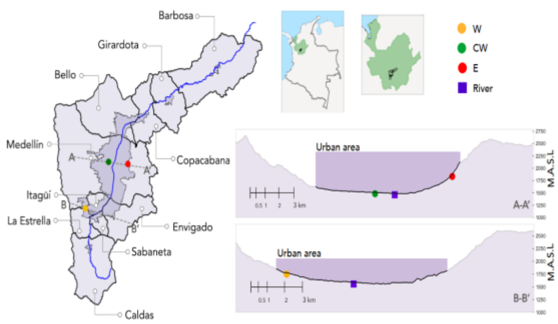

Figure 1. Plan view and location of the Aburrá Valley and its municipalities in Colombia and Antioquia. The map shows the three topographically contrasting points (W, CW, and E). The dotted lines on the plan map indicate the location of the cross-sections. A-A' and B-B'.

2.3 Experimental photovoltaic systems

The experimental photovoltaic systems belonging to SIATA received maintenance at least once a month. The two polycrystalline panels on the slopes have a nominal power of 100 W, the one in the center of the Valley, 80 W. All the systems, free of obstacles, are on buildings' roofs. The objective was to know how the response of solar panels would vary under regional conditions from actual measurements. As mentioned before, in the places where there was one of these devices, there was also a pyranometer, whose irradiance records supported the quality of the power data of the experimental photovoltaic systems.

3. Results and Discussion

3.1. Efficiency and Performance Rate

We use an efficiency indicator that relates $P\left[\frac{W}{m^2}\right]$, the amount of power per panel area recorded by the experimental photovoltaic systems, to $I\left[\frac{W}{m^2}\right]$, the solar radiation received at the same point. Their ratio is a "real efficiency",

$$\eta_{real}=P/I, \tag{1}$$

Notice that Eq. (1) follows basic thermodynamic principles [19].

The clear sky index is the basis for proposing a relationship with the real efficiency to estimate the effective solar radiation produced at the measurement point, considering clouds, the main limitation for photovoltaic energy generation.

The clear sky index, K_t^*, is the ratio of the measured radiation (I) to the modeled radiation under clear sky conditions (I_c) [34, 35, 36]. In this study, I is taken from the pyranometer records in each of the points of interest, and I_c is from the radiation model in clear sky conditions [31]. This index directly relates to clouds' presence because pyranometers' measurement is sensitive to their passage and related to theoretical surface radiation under clear sky conditions. Therefore,

$$K_t^* = I/I_c. \tag{2}$$

A linear relationship between real efficiency and clear sky measurement was fitted using a robust technique (see Figure 2). The procedure consists of dividing the total data set into subsets of equal size, computing each subset's median, and fitting a linear line to the resulting medians. The slope of each line indicates the efficiency of the experimental solar panels in terms of the clear sky index. This efficiency is in terms of the actual cloudiness conditions.

The results obtained through this method indicate that the Center-West has a greater capacity to convert the amount of solar energy that reaches it into electrical energy than the other two points under the condition of cloudiness imposed by the clear sky index. On the contrary, the East was the one that obtained the lowest value of this relationship and, therefore, a lower value in the capacity to convert solar energy into electricity. Besides, the "t-student" test evaluated the adjustment. The test shows that the three adjustments belong to the same distribution with a 95 % confidence.

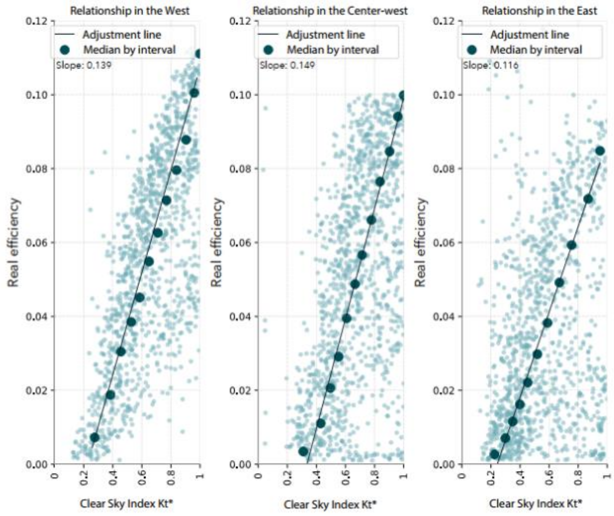

Figure 2. Efficiency indicator obtained for the three measurement points, based on the slope of the relation between the "real efficiency" and the clear sky index.

The results of the performance rate were: 42.04% for the West sectional point, 50.02% in the Center-West, and 29.60% in the East. As this factor is proportional to the panels' modular efficiency, these results indicate the losses were larger at the East and smaller at the Center-west.

From the outcomes of this section, one can conclude that there is an effect a topography-induced effect on the power generated by photovoltaic systems within the Valley. It is captured by the records of the experimental photovoltaic systems since both indicators were lower in the East section of the Valley compared to the other two sections. Despite having in the East section of the Valley a photovoltaic system with a nominal power of 100W, its generation is lower than in the other two experimental photovoltaic systems, being better in the photovoltaic system of the Center-West section, which has a nominal power of 80W.

3.2. Estimation of Energy Generated at Residential Level

All cities are different, and the topography is a decisive condition for the municipalities in the Valley. Besides, urban morphology changes over time, and the region is very heterogeneous due to high population density and the combination of formal and informal urban dynamics. MMA land use planning was not precise for many years because land uses were only defined to satisfy momentary needs and lacked vision in the long term [37]. Due to this problem, the purpose of this section is to present estimates of the energy generated at the residential level using the previous results and the products derived from drone overflights. Thus, this section frames the practical utility of photovoltaic energy on a small scale in a realistic context.

Six representative urban areas represented the diversity of the urban structure and topographical characteristics of the Valley. These areas consider the Valley's particular conditions and include the heterogeneity of urbanization in the ten municipalities. Thus, two were chosen on the western slope, two in the center of the Valley, and two on the eastern slope, maintaining the working pattern that exists so far with the experimental photovoltaic systems. Besides, one proceeded to get information on contrasting urban morphologies for each division or section of the Valley, considering two places for each subsection, with high, low, and mixed altitude buildings. Table 1. summarizes this zoning using information from [40, 41]. See also Figure 3 to note the differentiated patterns of urban morphology in the region. These ortho-photos come from drone overflights and are part of the SIATA information used.

Other factors play a role in selecting the representative areas to increase the impact from a population perspective. Therefore, one constructed a filter to determine the population density obtained from the Ordinance and Management Plan of the Hydrographic Basin of the Aburrá River [38], whose information indicates that the highest population densities are in the municipalities of Bello, Itagüí, and Medellín. The other factor was the urbanization rate, of which municipalities such as Bello, Envigado, Itagüí, Medellín, and Sabaneta also stand out.

Table 1. Information of the representative urban areas (RUAs).

Urban Zone	Area (m^2)	Resolution DSM (cm)	Category	Municipality
Santa Cruz	106073	4 x 4	Center-Low buildings	Itagüí
Bosque El Chuscal	134470	6.13 x 6.13	East-High buildings	Envigado
Calasanz	202860	7.87 x 7.87	West-High buildings	Medellín
Campo Valdéz Nº2	173275	4.67 x 4.67	East-Low buildings	Medellín
Jesús María Valle	1344656	6.24 x 6.24	West-Low buildings	Medellín
Aguacatala Nº2	35220	3.23 x 3.23	Center-Mixed buildings	Medellín

Figure 3. Ortho-photos of each RUA showing the different urban morphologies.

Various tools of the ArcGIS 10.4 [39] software helped to estimate the average annual irradiance. The estimation of the annual photovoltaic energy generated on the roofs of the RUA starts from the delimitation of the polygons from the ortho-mosaics shown in Figure 3. Then one proceeds to estimate the photovoltaic energy generated on rooftops using the efficiency and return rate for each selected zone of the Valley, as obtained in the previous section.

Besides, two contrasting hours of the day made explicit the differences in solar radiation received in the topographically different sections of the Valley. Figure 4 shows the results of this procedure. Then, using the azimuth and elevation of the sun, one calculates a shadow map from the DTM (Digital terrain model), obtaining the percentage of pixels of the polygon that would be entirely in the shade at that time of day. The contrasting times were 09:30 and 15:30.

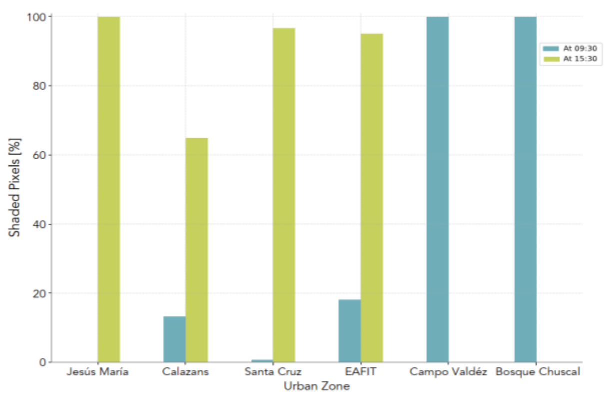

Figure 4. Percentage of 30 m pixels of each RUA with terrain induced shadows at two contrasting hours of the day.

These results confirm a differentiated effect of the topography on the incident radiation on each RUA throughout the day, indicating that the complex topography of the Valley affects the radiation that would be usable during daylight hours.

To calculate the solar energy generated in each polygon or roof, the area of each one is multiplied by the average solar irradiation it will receive during the year, using the efficiency of the panels and the performance rate calculated in the previous section. In this way, it was assumed that the solar panels in each section of the Valley are of the same type as those used in experimental study to maintain consistency: the panels on two RUA slopes are of 100 W, and in the RUA on the Valley base are 80 W panels. This also means that the estimates generated are linked to power measurements under real conditions.

The "Solar radiation of areas" algorithm of ArcGIS 10.4, based on the methods proposed by [40, 41], considers radiation as the sum of direct and diffuse radiation, not considering reflected radiation because of their insignificant contribution. So far, this method's main weaknesses are that it falls short of estimating diffuse radiation because it minimizes atmospheric processes that could contribute to the absorption and scattering of radiation.

Figure 5 presents the results of the energy generated on the rooftop polygons of the urban areas representative for each of the Valley sections.

The results obtained in the estimates are listed and described below, divided according to the section of the Valley to which the RUAs correspond.

3.2.1 Urban areas in the West of the Valley:

In the roofs of the greater area of the RUA West-High buildings, located in the sector of Calasanz, in the city of Medellín, it is possible to generate up to 78.67 *MWh* per year. On the other hand, the polygons representing roofs of the smaller area can generate 4.22 *MWh* per year.

The roofs in the sector of Jesus Maria (Medellin), which correspond to the RUA West-Low buildings, could generate energy in a range of 21.13 *MWh* to 3.33 *MWh* per year, depending on the area of the roofs.

3.2.2 Urban areas in the Center of the Valley:

The roofs of the mixed buildings in the RUA Center in Aguacatala, in Medellin, could generate up to 193.73 *MWh* per year. On the other hand, the lower roofs of that RUA can yearly generate 4.18 *MWh*.

The low industrial buildings of the RUA Center, Santa Cruz (Itagüí), can generate up to 715.80 *MWh* per year. In contrast, the minimum generation is 4.18 *MWh* on the smaller roofs.

3.2.3 Urban areas in the East Valley:

In Bosque El Chuscal, Envigado, low buildings of the RUA East, on the eastern slope of the Valley, depending on the roofs' area, the generation varies from 59.72 *MWh* to 2.55 *MWh* per year.

In Campo Valdez, Medellin, East RUA, the low buildings could generate between 1.39 *MWh* to 15.52 *MWh* per year.

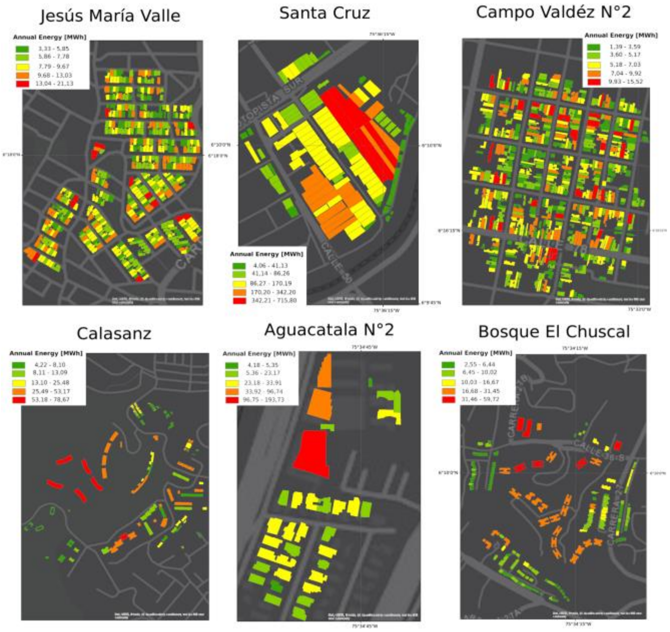

Figure 5. Annual photovoltaic energy generation on the roofs of each RUA. Energy is in *MWh*. Note that the color scale is different in each case.

Figure 5 shows that among the three sections of the Valley, the urban areas located in the center have the highest electricity potential. On the contrary, the urban areas of the eastern section of the Valley have the lowest. This behavior is the product of the use of the performance parameters calculated in the previous section and which in turn obey the power and irradiance measurements in each section of the Valley.

The energy estimated in Figure 5 is favorable for the MMA place in comparison to the other places. It fluctuates in a range between 715.8 *MWh* and 1.39 *MWh* per year. It is better than the ranges fluctuation found in other estimation studies such as the one carried out by [42] for Miraflores de la Sierra, where the ranges of the annual estimates were between 162.4 *MWh* and 1.6 *MWh.*

The roof area is the primary control of the different sites' energy generated. See results in Figure 5. It shows that the central section of the Valley is where the polygons with the most extensive roof areas, which is typical for the two sectors' land vocation, industrial in Santa Cruz and Services in Aguacatala. The hillsides' urban zones in the category of "low buildings" have less roof area because they correspond to constructions with traditional residential horizontal extension. On the other hand, the hillsides' urban areas in "high buildings" are mainly apartment blocks within residential complexes. In either case, in the slopes' urban areas, the same polygon could correspond to more than one home.

Figure 6 helps to verify the previous statement. It shows that the energy generated in the eastern RUAs is lower than in the western slope, even though they have similar areas. These differences are due to the contrasts in the topographic location within Valley, evidencing that the topographic conditions within the study region affect the amount of irradiation that can be taken advantage of in different locations. Also, notice that the performance indicators used the experimental photovoltaic system of the west slope.

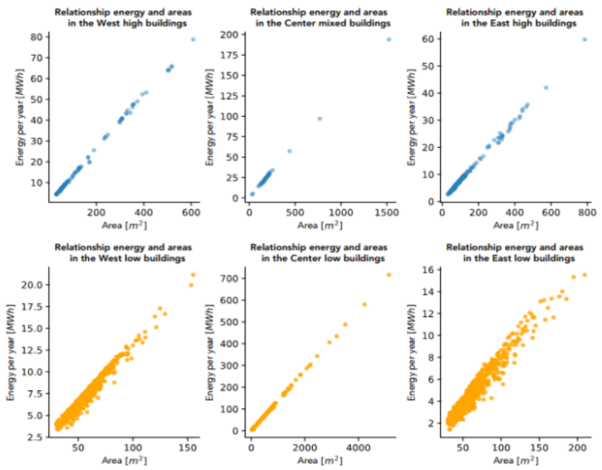

Figure 6. Relation between the available areas and the energy generated in each RUA.

3.3 Percentage of Monthly Energy Consumption from solar panels

Based on the estimation of the average energy generated in each RUA, this section estimates the percentage of monthly energy consumption per person covered by each square meter of the installed panel. For this purpose, one uses information from the socioeconomic stratum [43] and average monthly energy consumption per person [44]. Figure 7 presents the results for each RUA.

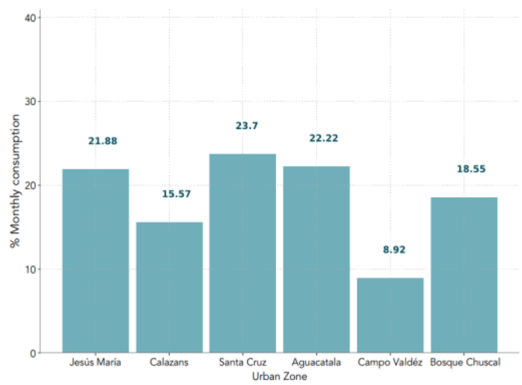

Figure 7. Estimation of the per person monthly energy consumption for panel unit area (m^2) for each RUA.

As in the previous section, the results obtained here indicate that in the RUAs of the Center, up to 23.7% of a person's consumption could be covered per square meter of solar panel installed. In contrast, in the RUA of the eastern section, at least 8.92% of the consumption could be covered. Concerning the above results, two considerations may lead to a possible underestimation of energy generation because the diffuse radiation and the panel technology may differ from those considered here.

3.4 Cloud frequency

In tropical studies, it is essential to characterize the cloudiness patterns that may influence the variability of energy estimates. A region may have favorable astronomical conditions throughout the year for the incidence of solar radiation. However, cloudiness can limit the amount of readily useful radiation [26].

To describe the average conditions of the temporal patterns of clouds in the Valley, we generated hourly and monthly average frequency graphs using satellite images of GOES 16 [45]. In both cases, we calculate them from the reflectance values that exceeded the cloudiness threshold in each hour, masking out those that corresponded to clear or mixing zone scenarios. Figure 8 shows these results.

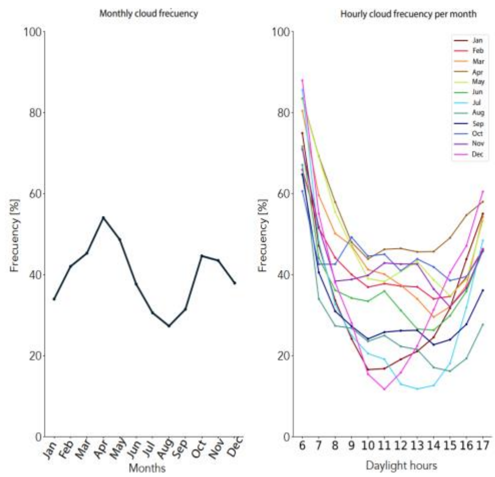

Figure 8. Average cloud frequency and hourly cloud frequency for each month over the study region.

Figure 8 exposes hourly and monthly average cloud patterns, with an explicit bimodal behavior. The two maximum and two minimum correspond to the wet and dry seasons of the region. Those peaks correspond with the passage of the inter-tropical convergence zone (ITCZ) [46]. The hourly frequency shows a maximum at 6 am and a minimum between 10 am and 2 pm, with monthly variations. Both panels show that the average conditions in the region are always subject to clouds, which gives importance to the estimation of usable surface solar radiation for photovoltaic generation, the objective of the next section.

3.5 Weighted Energy Reduction Factor

Although the Digital Surface Model allows to include the effect of the obstacles against the incident radiation, the ArcGIS 10.4 tool does not consider the clouds' effect. Nevertheless, in such a rainy place as Colombia, this effect is not negligible [46, 47]. Therefore, this paper developed a cloud reduction factor to correct for this effect, represented by Eq. (4), derived from Eq. (3).

The cloud reduction factor $f_r(h,m)$ for each hour h and month m is the fraction that, multiplied by the corresponding clear sky irradiation, gives the average irradiation considering the frequency of cloudy and clear days. Let the respective frequencies be c_{freq} and $1-c_{freq}$; the respective average, clear, and cloudy irradiations be I_{avg}, I_{clear}, and I_{cloud}. Therefore, the proposed equation is

$$I_{avg} = (1-c_{freq})I_{clear} + c_{freq}I_{cloud} = I_{clear}[1-\frac{I_{clear}-I_{cloud}}{I_{clear}}c_{freq}] \quad (3)$$

Therefore, the cloud reduction factor is

$$f_r = 1-\frac{I_{clear}-I_{cloud}}{I_{clear}}c_{freq} \quad (4)$$

Then, to estimate the energy produced on the roofs considering cloudiness, the factor $f_r(h,m)$ is applied to the maximum and minimum of energy generated at each RUA every hour (dotted line). Figure 9 shows the reduction of the maximum energy generated in each RUA and its variations by the $f_r(h,m)$. Similarly, Figure 10 indicates the minimum energy generated.

Both Figures (9 and 10) show a reduction, due to cloudiness, in the energy that ArcGIS estimates. The most adverse months for photovoltaic energy generation are April and October, and the most favorable December and July. Besides, both figures indicate that from 6 to 9 am the reduction of energy is greater than in the afternoon hours, mainly in months like April, May, and October. The hours of larger generation are between 10 am and 2 pm, being higher during December, January, and July.

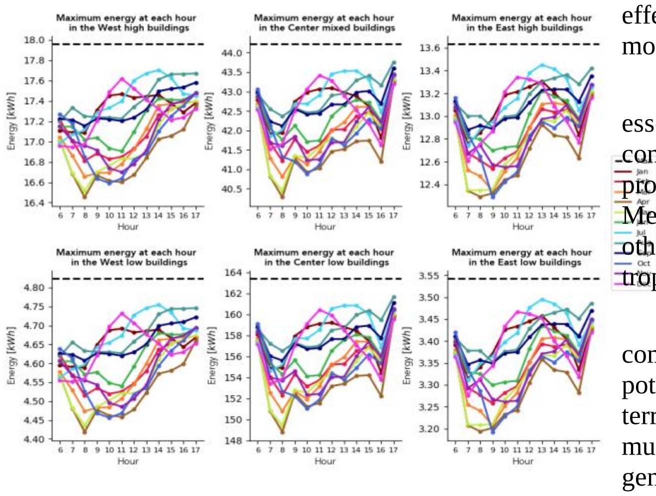

Figure 9. Maximum hourly energy generated in each RUA and its reductions because of cloudiness for the 12 months.

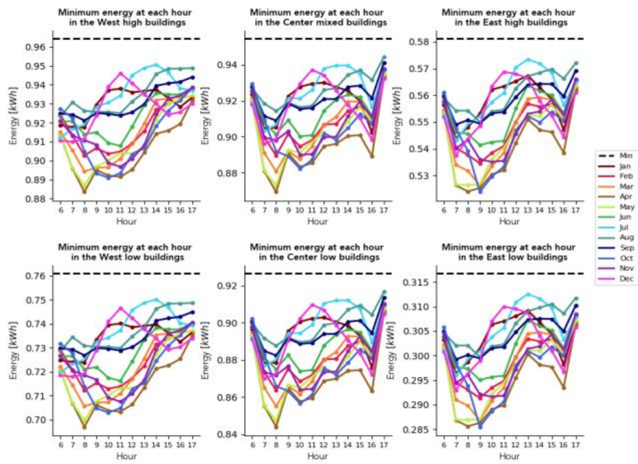

Figure 10. Minimum hourly energy generated in each RUA and its reductions because of cloudiness for the 12 months.

It is also worth noting that according to Figure 10, the RUA East-Low Buildings (Campo Valdéz) has the lowest global power generation scenario during April. On the other hand, the best global energy generation scenario is the RUA Center-Low Buildings (Santa Cruz) in December and July. Thus, the clearest months correspond to the region's dry seasons and the months with the greatest reduction in energy correspond to the rainy seasons [48].

4. Conclusions

The results presented in this work demonstrate the feasibility in terms of the potential of photovoltaic generation in the study region. This feasibility supports decision-making and investment towards the use of alternative energy sources that allow reducing the energy vulnerability of Colombian cities. The main novelty of this work lies in incorporating the effects of topography and cloud cover, contrasting urban morphologies, and the use of information from overflights.

Energy estimates for small-scale photovoltaics are essential for achieving sustainable development because they contribute to improving energy access for citizens and promote more resilient city energy planning. The Metropolitan Area of the Aburrá Valley case shows that other urban environments with terrain complexity and tropical meteorology must rely on holistic studies.

The methodology presented in this work offers a comprehensive estimation of small-scale photovoltaic energy potential that considers the particularities of complex tropical terrain, such as the Metropolitan Area of the Aburrá Valley municipalities. It also evidences the effect of power generation differentiated between topographic sections of the Valley from measurements of experimental photovoltaic systems and quantifies the effect of cloudiness as a factor reducing surface solar radiation in the tropics.

The efficiency indicator of the experimental photovoltaic systems quantifies each panel's efficiency, considering the influence of clouds. The efficiency is higher in the Center-west experimental panel and minimum for the East one, even though the nominal powers are 80 and 100W, respectively. This indicates that there is a topography-induced effect that is differentiated between sections of the Valley and is captured by the experimental photovoltaic system records.

To perform a concrete characterization of the estimates, six Representative Urban Areas characterized the different urban morphology patterns and topographic sections within the Valley. The available roof area is the main factor for the energy delivered by small-scale facilities in the Metropolitan Area of the Aburrá Valley, followed by a preferential location in the Valley's Center.

The results of the energy estimations in the Representative Urban Areas were different according to the section of the Valley despite sharing the same urban morphology categories. Although the eastern slope results were less than for the other two sections of the Valley, they are still favorable for covering a fraction of the energy consumption.

Tropical environments, such as the Metropolitan Area of the Aburrá Valley, have a constant cloud pattern, and this was demonstrated by calculating cloud frequencies over the region of interest. With this, and with the irradiance data under cloudy and clear sky conditions, we developed an energy reduction factor due to cloudiness (f_r). According to this, the energy estimated could have a reduction close to 10% at 8 am. However, around midday, this can only be 2%, in favorable months such as December.

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