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# Simulation and optimization of a parabolic trough solar power plant in the city of Barranquilla by using system advisor model (SAM)

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**Abstract**

Solar energy is one of the most mature technologies to produce electricity from renewable energy. This papers analyses the solar radiation potential in the city of Barranquilla (Colombia), located at 10°59'16" north and 74°47'20" west, for using Concentrated Solar Power technology (CSP) to generate electricity. Due to the lack of meteorological data in coastal areas of Colombia, Daily Integration Approach (DI) was used as the hourly radiation model. The DI model, along with radiation data from NASA-SSE (Surface meteorology and solar energy) were used to map the direct and beam radiation. The maps were plotted using the Matplotlib Basemap Toolkit in Python 2.7. The solar maps showed the high potential of solar radiation for CSP at the north coast of Colombia. Then, System Advisor Model (SAM) was used to perform a yearly simulation, in the city of Barranquilla, of a parabolic trough solar power plant of 50 MWe. The model included thermal energy storage (TES) with natural gas as backup and a sensitivity analysis was performed to find the optimum size which minimizes the Levelized Cost of Energy (LCOE). The results showed that for typical solar field cost, the minimum LCOE is around 25 cents/kWh which is still pretty high as compared with traditional systems but it has a positive impact on carbon footprint, using natural gas this value is reduced to 9.76 cents/kWh.


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Keywords: Solar Energy; Levelized Cost of Energy; LCOE

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## 1. Introduction

Worldwide energy consumption is growing quickly. According to BP statistical Review of World Energy, that growth was 2.5% in 2011, although lesser than 2010 (5.1%), its trend is growing in long term. As a consequence, it is expected a bigger consumption of fossil fuels and an increase of environmental problems.

Solar energy is a clean alternative to the worldwide energy requirements and for that reason is being used more and more.

Despite the renewable energy consumption is only 1.6% [1] of the total energy consumption, solar energy production grew through 2011, and photovoltaic energy rose 74% and thermal solar energy 37% [2]. Several countries around the world have been installing concentrating solar technologies, 90% of such technologies are parabolic trough solar power plants [2].

Colombia is rich in hydric resources then its energy comes from hydroelectric plants in 64%, thermal plants generates 30.8%, the rest are smaller and cogenerations plants and only 0.125% of energy comes from wind resources [3]. Despite the abundance of renewable energy resources their use are minimal [4].

There have been small-scale projects [5] and there are other ones to evaluate wind and solar resources in some regions in order to produce energy in large scale [6]

However, those projects have several limitations:

- Maps were done using geographical interpolation, although the information about solar radiation is monthly, it is necessary more information about the particular place to design a thermal or photovoltaic conversion system.
- Measurement stations are placed in Andin Region; then estimations on coastal regions are less reliable.

As a consequence, this job represents a great input to the country because solar maps were done using data from NASA-SSE [7] and various tracking modes. These are useful for design of photovoltaic or thermal solar plants.

This paper first describes the place of study, after shows the methodology that was employed to determine hourly solar radiation, and explains five solar tracking modes. Those results are used to build solar maps; finally, System Advisor Model (SAM) [8] simulates a parabolic trough solar power plant.

**Nomenclature**

| | |
|---|---|
| $a_s$ | Azimuth angle [°] |
| $\alpha$ | altitude angle [°] |
| $\beta$ | tilted angle [°] |
| $\delta_s$ | declination angle [°] |
| $\overline{D}_h$ | Long term diffuse radiation on a horizontal surface [W/m$^2$] |
| $\overline{H}_h$ | Long term total radiation on a horizontal surface [W/m$^2$] |
| $i$ | Incident angle [°] |
| $I_{b,c}$ | Beam radiation on a tilted surface [W/m$^2$] |
| $I_{b,h}$ | Beam radiation on a horizontal surface [W/m$^2$] |
| $I_{d,c}$ | Diffuse radiation on a tilted surface [W/m$^2$] |
| $I_{d,h}$ | Diffuse radiation on a horizontal surface [W/m$^2$] |
| $I_h$ | Solar radiation on a horizontal surface [W/m$^2$] |
| $I_c$ | Total radiation on a tilted surface [W/m$^2$] |
| L | Latitude angle [°] |
| $r_d$ | Daily ratio for diffuse radiation |
| $r_t$ | Daily ratio for total radiation |

| | |
|---|---|
| ρ | reflectivity |
| ω | sunrise angle [°] |

## 2. Place Description

Barranquilla is located on Colombian north coast named Atlantic coast (10°57'42" north latitude, 74°46'54" western longitude), its climate is dry tropical and its annual average temperature is 27.4°C. Because of its geographical and astronomical position it has a high potential of solar radiation. The table 1 shows the solar radiation available in Colombian regions:

Table 1 Solar radiation in Colombian regions [6]

| Region | kW /m²/year |
|---|---|
| Guajira | 1980-2340 |
| Atlantic coast | 1260-2340 |
| Orinoquia | 1440-2160 |
| Amazonia | 1440-1800 |
| Andina | 1080-1620 |

## 3. Methodology of hourly solar radiation calculation

Basically there are two groups of models to estimate total solar radiation over the earth: monthly averaged daily radiation models and monthly average hourly radiation.

Calculation of the hourly solar radiation received throughout the year is important for calculating the solar collector performance. Given the long term average daily total and diffuse irradiation on a horizontal surface, $\overline{H}_h$ and $\overline{D}_h$ respectively, it is possible to find the long term hourly solar radiation: $I_h$ and $I_{d,h}$. For this paper, values of $\overline{H}_h$ and $\overline{D}_h$ were obtained from satellite data [7], since satellite data provide useful information about solar radiation and meteorological conditions in locations where ground measurement data are not available.

Daily integration approach (DI Model) [9] was used as the hourly radiation model. Gueymard [9] developed the Daily integration approach to predict the monthly-average hourly global irradiation by using a large dataset of 135 stations with diverse geographic locations (82.58 N to 67.68 S).

Gueymard concluded that the daily integration model is the most accurate when is compared to the other models as: Collares-Pereira and Rabl Model CP&R [10] and Collares-Pereira and Rabl Model modified by Gueymard [11]. The instantaneous solar radiation on a horizontal surface, Ih, is the sum of the beam or direct radiation, $I_{b,h}$ and the sky diffuse radiation $I_{d,h}$.

$$I_h = I_{b,h} + I_{d,h} \tag{1}$$

Introducing the hourly to daily ratios $r_d$ and $r_t$ as:

$$r_d = \frac{I_{d,h}}{\overline{D}_h} \quad and \quad r_t = \frac{I_h}{\overline{H}_h} \tag{2}$$

Then, the beam radiation is:

$$I_{b,h} = r_t \overline{H}_h + r_d \overline{D}_h \quad (3)$$

The value of $r_d$ was found by Liu and Jordan [12] and the value of $r_t$ was adapted by Collares and Pereira [10] and then it was modified by Gueymard [9].

The total radiation is the sum of components consisting of beam $I_{b,c}$, sky diffuse $I_{d,c}$ and ground reflected $I_{r,c}$. The beam radiation is given by:

$$I_{b,c} = (r_t \overline{H}_h + r_d \overline{D}_h) \cos i / \sin \alpha \quad (4)$$

The total radiation is as follows:

$$I_c = I_{b,c} + I_{d,c} + I_{r,c} \quad (5)$$

Values for $I_{d,c}$ , $I_{r,c}$ and $\cos i$ depends on the tracking mode used. Those values were taken from [13] and are summarized on table 2. The following are the tracking modes used.

Case 1: Total radiation on a fixed surface south facing tilted at latitude angle.
Case 2: Total radiation on a surface tilted at latitude angle with East-West tracking.
Case 3: Total radiation on a surface tilted at latitude angle with azimuth tracking.
Case 4: Direct beam radiation on a horizontal surface with East-West tracking.
Case 5: Direct beam radiation on a surface with two axis tracking.

## 4. Solar radiation maps

Solar radiation maps for Colombian North Coast built on five solar tracking modes are shown in the following five graphs. The northern part of the maps (Guajira) has a high potential for solar energy. This potential decreases as it moves away from the coast. In Barranquilla, chosen place for simulation the radiation goes from 2377 kWh/m$^2$-year to 2612 kWh/m$^2$-year. It is obvious the solar energy potential is influenced by the tracking mode selected. The highest potential is for the case 2 (a surface tilted at latitude angle with East-West tracking, figure 1).

Table 2 Incidence angle, diffuse radiation and reflected radiation for five solar tracking modes [13]

| Case | Cos i | $I_{d,c}$ | $I_{d,c}$ |
|---|---|---|---|
| 1 | $\cos\alpha \cos a_s \sin L + \sin\alpha \cos L$ | $r_d \overline{D}_h (1+\cos L)/2$ | $r_d \overline{D}_h (1-\cos L)/2$ |
| 2 | $\cos \delta_s$ | $r_d \overline{D}_h (1+\cos L \cos\omega)/2$ | $r_d \overline{D}_h (1+\cos L \cos\omega)/2$ |
| 3 | $\cos\lvert\alpha + L - 90°\rvert$ | $r_d \overline{D}_h (1+\cos L)/2$ | $r_d \overline{D}_h (1-\cos L)/2$ |
| 4 | $\sqrt{(1-(\cos\alpha)^2(\cos a_s)^2)}$ | 0 | 0 |
| 5 | 1 | 0 | 0 |

## 5. CSP plant simulation

Parabolic trough solar power plant is the most widely used solar technology around the world [2]. This section shows the selection of parameters and key elements required by a design using SAM. Data for temperature and speed of wind were obtained from meteorological station 800280 (SKBQ) located on Barranquilla city. Data for solar radiation were calculated from DI model and direct beam radiation on a horizontal surface with East-West tracking. It was supposed that a geographical surface for the installation is available.

**Heat transfer fluid**: VP-1 is a synthetic fluid has desirable properties such as:

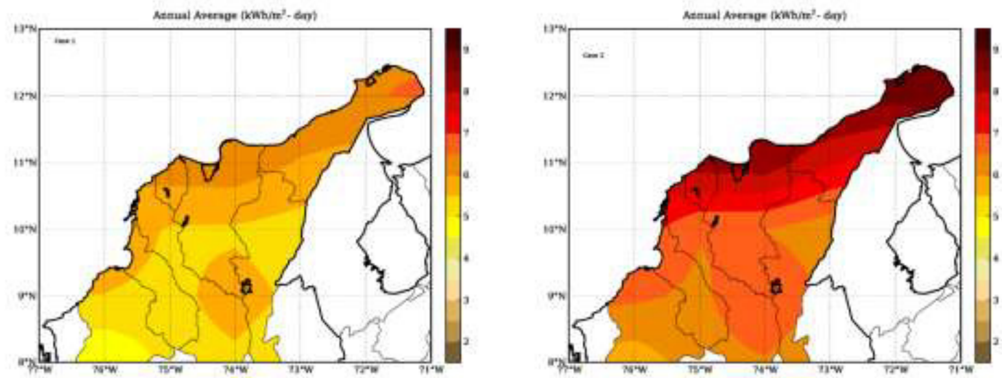
- High thermal stability, it works efficiently from 12 to 400°C.
- Its melting point is high.
- Vapor pressure is appropriate for this range of temperature.

These properties select that fluid taking account the operating temperature for parabolic trough solar plants (125 – 400°C).

**Type of collector**: Euro trough ET 150 was selected considering the following criteria:

- Low cost.
- Easy installation.
- Rigid structure.
- High optical performance.
- Less specific weight.

**Type of receiver**: The performance of the collector is highly influenced by the receiver; then it is necessary to select the type of receiver carefully. Just a few companies manufacture solar receivers for parabolic troughs (Siemens, Schott, Archimede Solar, HUIJIN). We have compared the most used in the construction of CSP solar plants: Siemens and Schott. The differences among these manufacturer's products are minimal, they are shown in table 3. Tube selection is determined by costs of acquisition, maintaining and transport. This project uses Schott PTR 70.



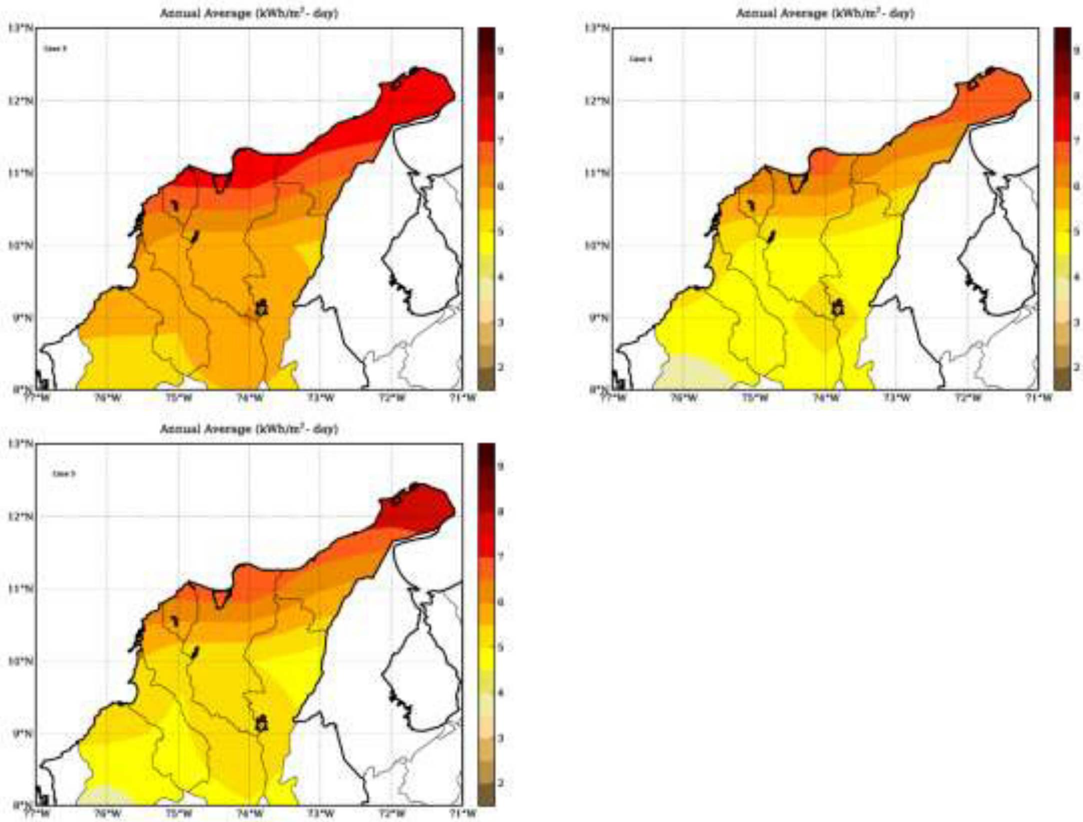



Fig. 1 Solar radiation maps for five tracking systems.

Table 3 Technical characteristics of the receivers

| Characteristic | Schott PTR 70[14] | Siemens UVAC 2010[15] |
|---|---|---|
| Transmissivity | ≥ 96% | ≥ 96.5% |
| Absorptivity | ≥ 95% | ≥ 96% |
| Emissivity | ≤ 10% a 400°C | ≤ 9% a 400°C |

**Storage System**: This project uses thermal storage in order to avoid solar dependence and satisfy demand requirements when is required. Storage media is synthetic oil VP-1 that is the same for collectors of the solar field. For this reason, it requires only one tank for charge and discharge.

**Steam turbine selection:** Model SST-700 [15] was selected considering its use in thermal solar plants and its flexibility to fluctuations in availability of energy, also increase the efficiency of the system because vapor preheating. This model is widely used in energy generation especially in combined cycle or solar thermal power station.

**Solar field size**: The project starts with an installed power of 50 MWe, additionally it considers a generation of 10% from natural gas to prevent problems. SAM analyzes how to dispatch thermal storage and fossil resource. The latest can be done by two ways: the first one uses Minimum Backup Level generates energy when there is low radiation and it is used for starting the system. The second is the mode of Supplemental Operation assumes a safety reserve as a percentage of max capacity of the system. These characteristics permit to schedule the dispatch considering the demand.

The Solar Multiple was determined by optimizing Levelized Cost of Energy (LCOE) [16] for several time of energy storage (TES)but without dispatch programing from storage or natural gas; the results are show in table 4.

Table 4 Summary of optimization results

| TES(hours) | 6 | 8 | 10 |
|---|---|---|---|
| SM | 1.3 | 1.3 | 1.3 |
| LCOE (cents/kWh)) | 24.6 | 24.83 | 25.54 |
| Annual Energy (kWh) | 76.657.802 | 77.874.891 | 77.513.739 |
| Capacity Factor (%) | 17.7 | 18.0 | 17.9 |

These results were compared against those obtained using scheduling with thermal storage and natural gas. It was used the appropriate scenario for the region. The scenario consists of six periods set by colors. The schedules are shown in tables 5 and 6.

Two first columns in table 6 show at least storage of 10% of the max capacity of the system, in order to start; third column shows is possible to send 100% of the energy from the storage system to the power block, whenever necessary; fourth column is used to support the increased demand period with natural gas when the system requires it. Under this new scheme the optimization of LCOE was done for different values of TES, the result was a solar multiple of 2 and a TES of 6. This is shown in table 7.

Table 5 Programming state

| | 12 a:m | 1a:m | 2a:m | 3a:m | 4a:m | 5a:m | 6a:m | 7a:m | 8a:m | 9a:m | 10a:m | 11a:m | 12a:m | 1p:m | 2p:m | 3p:m | 4p:m | 5p:m | 6p:m | 7p:m | 8p:m | 10p:m | 11p:m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Feb | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Mar | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Apr | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| May | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Jun | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| Jul | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| Aug | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| Sep | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| Oct | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Nov | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Dec | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |

Table 5 Programming of the storage and natural gas

| TES(hours) | Storage w/solar | Dispatch w/o solar | Turb. Out fraction | Fossil fill Fraction | Payment Allocation factor |
|---|---|---|---|---|---|
| Period 1: | 0.1 | 0.1 | 1 | 1 | 2.064 |
| Period 2: | 0.1 | 0.1 | 1 | 0.5 | 1.2 |
| Period 3: | 0.1 | 0.1 | 1 | 0 | 1 |
| Period 4: | 0.1 | 0.1 | 1 | 0.5 | 1.1 |
| Period 5. | 0.1 | 0.1 | 1 | 0 | 0.8 |
| Period 6: | 0.1 | 0.1 | 1 | 0 | 0.7 |
| Period 7: | 0 | 0 | 0 | 0 | 1 |
| Period 8: | 0 | 0 | 0 | 0 | 1 |
| Period 9: | 0 | 0 | 0 | 0 | 1 |

Two first columns in table 6 show at least storage of 10% of the max capacity of the system, in order to start (87440 MWt), third column shows is possible to send 100% of the energy from the storage system to the power block, whenever necessary; fourth column is used to support the increased demand period with natural gas when the system requires it. Under this new scheme the optimization of LCOE was done for different values of TES, the result was a solar multiple of 2 and a TES of 6. This is shown in table 7.

Using fossil fuels the annual energy generation goes from 151 251 921 kWh without storage to 174 346 510 kWh with storage and the capacity factor goes from 34.9% to 40.2%.

Table 6 Programming results with storage and natural gas

| | |
|---|---|
| TES(hours) | 6 |
| SM | 2.0 |
| LCOE (cents/kWh)) | 9.76 |
| Annual Energy (kWh) | 174.346.510 |
| Capacity Factor (%) | 40.2 |

**Financial variables**: Several default values of variables are kept and others are changed.

- Inflation rate is fixed at 4% taking account historical behavior and its trend.
- Real rate is 6% considering reference values of the country.
- Sales tax is an average of 5% according to Law 99 of 1993[b].

Property tax is not included because SAM discounts it from income and sale tax and that does not apply in Colombia. It is supposed a linear depreciation. Information about cost can be obtained from [8] .

- Site improvement $\$54/m^2$
- Solar Field: $\$161/m^2$.
- Mirrors: $\$28/m^2$,

The summation of these three items allow obtaining the solar field cost of $\$243/m^2$

A 50MWe generation is required; therefore the power system costs are $581kWe. In storage $27,1kWht using heat transfer fluid VP-1 and the land cost $50000. Other values not listed were taken for default.

**Results:** This plant can generate 174 346 MWh yearly. Maximum production is obtained in May – August (figure 8) because those months are the hottest and there is more availability of solar radiation. Another important topic is that when there is more radiation (at noon) is being performed more consumption; then does not required stored energy. Barranquilla requires 4 140 GWh then this plant can supply 50% of this demand.
LCOE gives an average price of annual energy, it considers yearly operating costs and initial investment, therefore can be used as a decision criterion of investment. For this case, the LCOE is 9.76 cents/kWh. Costs for building and operation are the following:

- Direct costs (investment on solar fields, power block, storage, heat transfer fluid, fossil resource): $ 244.278.974,31
- Indirect costs (land cost and taxes):$62.020.606,18

As a result, Total costs are $306.299.580, 50.

## 6. Conclusions

New energy supply sources, especially if they are renewables, must be of interest for governmental institutions. Colombian north part has favorable climatic conditions to build solar plants using photovoltaic or thermal technologies. Guajira has a high potential for solar energy, this potential decreases as it moves away from the coast. The solar energy potential is influenced by the tracking mode selected. The highest potential is for the case when a surface is tilted at latitude angle with East-West tracking, then this is appropriate for CSP technologies. The big problem with this technology

[b] Actually that law does not consider thermal solar generation, just specify percentage values for hydroelectric and thermal generators, the taxes are 6% and 4% respectively.

is related with the surface requirement and the cost associated. Solar maps contain important information that can guide further studies of solar potentiality of this region. This is relevant because there are still isolated areas that do not have the energy service.

Using SAM can be shown that Barranquilla's average energy demand can be satisfied for a CSP plant in a 50% (50MWe and storage system of 6 hours). The total cost and the LCOE are according to the minimum established by [1]. Besides these costs depend of the location and the level of available solar resources.

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