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# Scenarios of photovoltaic grid parity in Colombia

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**Abstract**
In this article, we determined the residential Photovoltaic Grid Parity in 11 Colombian cities, by comparing grid energy prices offered by the local companies and the photovoltaic microgeneration cost for an average household. In order to do that, we developed a financial model, which considers the initial investment, cost of battery replacement, efficiency loss of photovoltaic technology and discount rate, among other variables, to determine the solar technology investment feasibility. It was found, in the base scenario, that on 2014 most of the considered cities have reached grid parity, while three of them will reach it between 2015 and 2021. Other scenarios, which consider higher discount rate, higher initial investment and slower learning curves, show similar results, where most cities will reach the grid parity before of 2028.

*Keywords*: Energy Microgeneration; learning curves; Grid Parity; Photovoltaic System

# Escenarios de paridad de red fotovoltaica en Colombia

**Resumen**
En este artículo se determina la paridad de red fotovoltaica residencial para 11 ciudades colombianas, comparando los precios de la electricidad ofrecida por las compañías locales y el costo promedio de generación fotovoltaica para un hogar. Para ello, los autores desarrollan un modelo financiero que considera la inversión inicial, el costo del reemplazo de las baterías, la pérdida de eficiencia del sistema fotovoltaico y la tasa de descuento, entre otras variables, con el fin de determinar la viabilidad de la inversión en energía solar. Los resultados indican, para el escenario base, que en el año 2014 la mayoría de ciudades han logrado la paridad de red, mientras tres de ellas la alcanzarán entre 2015 y 2021.Otros escenarios, que consideran mayores tasas de descuento, mayor inversión inicial y curvas de aprendizaje más lentas, muestran resultados similares, en los cuales la mayoría de ciudades alcanza la paridad de red antes del 2028.

*Palabras clave*: Microgeneración Eléctrica; curvas de aprendizaje, Paridad de Red, Sistemas Fotovoltaicos.

## 1. Introduction

Colombian energy regulation, issued by the "Comisión de Regulación de Energía y Gas" (CREG), defines "auto-generator", in the resolution 084 of 1996 [1], as the person who produces energy just for satisfy his own needs, can have the national interconnected system (SIN) support, but cannot sell the auto-generated energy to the national electricity grid.

Recently, Colombian government enacted the Renewable Energy Act [2], which aims to promote the development and use of non-conventional energy sources, especially those from renewable sources in the national energy system. It is expected this act to be formalized along the year 2014. Although this act covers microgeneration activity, it is not defined the interval of energy generation in which the generation activity can be considered on the micro level.

In this way, a possible option for energy microgeneration is through photovoltaic solar system (from now on, PV) implementation. This alternative is known for giving significant advantages over other generation systems; it uses solar sunshine for generation (which is available all over the world) [3], has low maintenance requirements [4], allows easily to add extra generation capacity [3,4], has a high modularity [5,6] and produces zero noises [5].

However, so far it is not done a viability evaluation for the PV system technology in Colombian cities from a financial microgeneration point of view. Whereby, a comparison between the grid tariff and the PV microgeneration cost is relevant in this territory to determine when the PV solar technology will be competitive with the grid support, which is known as Grid Parity [7].

A revision of the basic concepts about the PV technology, its components, operation, panel types and its efficiencies are presented below, followed by an explanation of the methodology, the main assumptions and the scenarios developed in the analysis, to finish with the results, discussion and conclusions about the Grid Parity State in 11 Colombian cities. Results show most of the considered cities have reached grid parity by the year 2014, while four of them will reach it at some point between 2015 and 2021.

The scope of this article is to discuss about feasibility of residential solar energy implementation, by making a financial evaluation to identify the PV grid parity time for several Colombian cities. At the end of the evaluation and from the results that we got, we highlight some policy issues that could act in benefit of the diffusion of the PV solar technology. Limitations were related with the availability of data about the solar irradiation for each city, and accurate information about the Grid Tariff offered by the local energy companies of the cities.

## 2. Photovoltaic solar system operation

PV system development began in 1870, when William Grylls Adams and Richard Evens Day discovered photovoltaic effect by using Selenium [8]. This effect consists in the transformation of sunshine in electrical power through photovoltaic cells [8]. The development of the first solar cell was in 1954 [3,9], and its commercial use began in the 80s [4]. Besides the cell, PV system includes other elements that make possible to operate them.

Among them, the batteries are responsible for providing power in the off sunshine periods, and answer to the photovoltaics intermittency [10]. For PV systems, batteries must be replaced after a certain amount of using years.

### *2.1. Efficiency and panels types*

A critical factor in solar energy generation is the PV system efficiency, which, according to Lynn [11], refers to the percentage of solar radiation that the module can transform into electricity. In other words, with a specific power, a big efficiency implies a low panel superficial area requirements. It is important to note that PV technology can convert sunshine into direct electricity and diffuse solar irradiation [9].

Theoretical efficiency limit of silicon crystalline cells is 28% in average [8], and in practice, the reached efficiency is very close to this value. Looking for improving their efficiency [9] and decreasing its high production costs [11], new types of cells different from traditional single and poly crystalline cells have been developed during last years [8, 9,11]; this is the case of single crystal, multi-crystalline thin film, amorphous, CIGS, CdTe and organic cells. The main characteristics of these new cells are related with alternative materials for their manufacturing, which can improve its efficiency, decrease its producing costs or make the cells lighter. However, so far the highest efficiency reached for a solar cell is still under 50% [12].

PV solar systems lose efficiency according to their use. Most of the guarantees stipulate that in the last years of the system's life, it will work with an 80% of efficiency [13]. According to Lynn [11], and Ramadhan and Naseeb [14], the life time of the PV solar systems is about 20 years.

### *2.2. Grid Parity analysis of PV solar systems*

The grid parity analysis consists in the comparison between the cost of electricity produced by a specific generation system (which is not connected to the national electricity grid), and the price of purchasing power from the national electricity grid [15].

In order to determining the cost of electricity produced by PV systems and to perform a grid parity analysis, is it common to follow the Levelized Cost Of Energy (from this point on LCOE) methodology [3-7,9,14-20]. This methodology consists in a relation between the total expenditures of the solar technology (considering all its operation and maintenance requirements), and the electricity generated by the solar system, all during the PV system's lifetime. Notice that although the evaluation is done for a specific point in time, the methodology collects information from the whole PV system's lifetime in future.

Mathematical formulation of LCOE is presented in eq. (1).

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n}\left[\mathrm{C_t}/(1+r)^t\right]}{\sum_{t=0}^{n}\left[\mathrm{E_t}/(1+r)^t\right]} \quad (1)$$

Where

LCOE: Average lifetime levelized cost of energy [$/kWh]

$C_t$ = expenditures associated with the solar system in time = t (it includes investment, operation and maintenance expenditures and fuel expenditures)

r = discount rate

$E_t$ = electricity produced by the solar system in time = t

n = lifetime of the system

Note that this methodology considers the value of the money over time (which can be understood from the use of the discount rate concept in the numerator of eq. (1)), and attempts to distribute the costs among the total electricity produced. As a result, it is possible to find a kind of Net Present Value of the energy generated with the alternative system during the evaluation time. A formalization of the use of this methodology for the PV solar evaluation is developed by Hernández-Moro and Martínez-Duart [17].

Once the LCOE has been calculated, the final step of the grid parity analysis implies to compare this value with the current average price of electricity from the grid. It must be noted that this methodology does not allow considering expectations about changes on grid electricity prices over the financial evaluation horizon.

Different authors that implemented the LCOE method, have concluded that model results are specially sensible to specific variables, like local prices of electricity, PV system price, solar irradiation availability, financing methods [15] and discount rate [9,14].

World market selected places include those with the best combinations of solar irradiation [9] and high electricity prices [3,6], and countries with a leadership in the PV system installation (like Germany) [4]. One of these studies include more than 150 countries, considering around the 97.7% of world population and 99.6% of global electricity consumption [3].

Main results of LCOE application conclude that countries with higher solar irradiation and higher grid tariffs are the first to reach the grid parity state; this is the case of Germany [3], Italy, Hawaii and some areas in the United States of America [6,18]. Also, countries with good enough solar irradiation availability and high grid tariff, like South Africa and Egypt, will be the ones next to reach it [3].Some analysis has been done for mature markets characterized by the absence of public policy incentives (like Italy [21], for which authors conclude that the payback time is about five to six years for residential consumption). In some not so lighting areas in USA, the technology would reach grid parity around 2020 [19]. However, other countries with not special conditions but an interest in fighting against the climate change have also been include in the analysis, like Malaysia [20] (for which authors conclude that it would take up to 16 years for the country to achieve PV grid parity).

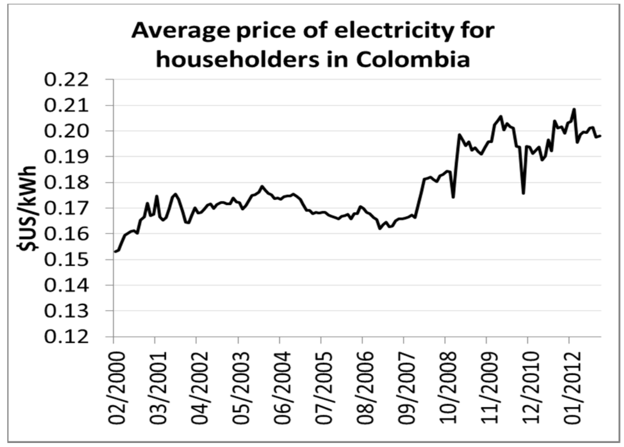
## 3. Photovoltaic solar generation in the Colombian market

Since 1994, the electricity sector in Colombia was liberalized, and generation, transmission, distribution and trading activities were open to competence. The final tariff, in general, consists in the sum of the prices of each activity [22-24]. Colombia has an annual demand of 62,882 GWh, with a peak demand of 9,380 MW in 2013 [25]

The generation price is formed through an electricity market, in which generators sell electricity to traders and other generators, through the pool or by bilateral contracts between generators and traders. Installed generation capacity is 14.5 GW [25]. Generation depends mainly on hydro resources (74% of generation) and thermal plants (19% of generation). Despite the great potential of the country for generating electricity by using renewable sources of energy (mainly mini-hydro, wind, solar and biomass sources), alternative generation has not been adequately explored in Colombia, and large hydropower plants and thermal dominate current expansion plans.

Meanwhile, the transmission price is set by the government, and is the same for all the country. The distribution price is set by the government as well, but depends on the demand served by each distribution firm. The demand is served by traders and it is possible to find differences in the prices of electricity among the diverse Colombian areas, not only because of the prices achieved by traders in the energy market, but because of the demand in each area.

Residential sector is the largest consumer of electricity (41% of the total energy consumed) followed by the industry sector (31% of the total energy consumed) [26].




*Values in constant 2013 dollars, excluding subsidies and contributions
Figure 1. Average Price of electricity for householders in Colombia.
Source: The authors. Data from CREG [27] and SUI [28]

Fig. 1 presents the growth in the average price electricity for household users in Colombia, without considering subsidies or contributions. It shows how the residential electricity price increased by 29.8% between 2000 and 2012. This fact represents opportunities for the microgeneration in homes through alternative sources, such as PV systems.

## 4. Methodology

This section explains the built model, the application case selected and the scenarios designed for the evaluation of residential PV grid parity in Colombia.

It was developed a financial model, which allows calculating the LCOE for a typical house in each city considered in this research, and comparing it with the price offered by the local utilities companies through the SIN.

The model is aggregated at the monthly level, it is to mean, that it is calculated the monthly cost of generating electricity with the PV solar system, versus the cost of buying the same amount of electricity in the national electricity grid (variations intra-day for every month are not considered). This is made for every one of the months that compose the horizon. The final aggregated cost of both types of generation is brought to Net Present Value and translated in terms of equivalent tariff. As a result, model allows knowing what cities have reached the grid parity for PV solar technology, and what cities have not. The main variables of the model are explained below.

*Horizon*: the time for the financial evaluation was 20 years. This horizon was chosen considering the warranty period offered by equipment's suppliers in the Colombian market [13], which, as Branker et al [15] argue, it is usually a reference point for the financeable project lifetime; it is reflected in the Lynn [11] and Ramadhan and Naseeb [14] works, who use the same period for their analysis.

Note that, according to eq. (1), the shorter horizon for evaluation the higher LCOE, because there is less generated electricity for distributing the same initial investment. So, the 20-year period can be considered a conservative selection, if it is considered that other authors argue that it is possible to include more years in the financial evaluation, such as 25 years [6,29], 25 to 30 [3], or even 25 to 40 [4].

*Discount rate:* given that LCOE is compared with the current electricity fee for the year 2014, without considering any possible changes on that tariff during the whole financial evaluation horizon (not even Colombian inflation projections), the discount rate should be free of inflationary effects and, at the same time, should reflect the opportunity cost regarding the closest investment option for the decision maker. For the Colombian case, we selected the risk-free rate reflected in the Fixed Term Certificates (CDT, because of its initials in Spanish), and subtracted from it the average inflation in last five years. The final discount rate can be understood as the "inflation premium" for the country.

*Initial investment:* it was considered a single-crystalline cell PV technology, given its high efficiency [11,12] and its market availability. The single-crystalline cells PV technology has a market price in Colombia of $USD 2430 in 2014 for a 0.6 kW module [30] (best commercial price found to date). Because the technology evaluated in this research, there are not operational expenditures to consider. Besides, this system doesn't need maintenance during the lifetime guarantee period [4,13].

*Battery replacement:* the analyzed PV system works with batteries, which must be replaced every five years. The 100 Ah batteries have a commercial price in 2014 of $USD 215 [13] (best commercial price found to date).

*Learning curve:* the learning curve describes the way that the technology's price is reduced as a result of the learning obtained by doing and cumulative production [6,7,29]. For the specific case, the PV solar technology has shown that when the cumulative market production is increased by 10 times, it cost is halved; at the same time, the production is doubled each two years [31]. It means that by 2021, the price should decrease about 50% regarding the price in 2014, and an additional 25% by 2028. It is important to clarify that a global PV learning rate can be used as a local rate, because it doesn´t make a distinction between global and local results [4].

Consequently, the evaluation was made for the following time intervals: (1) [year 2014, year 2034], (2) [year 2021, year 2041] and (3) [year 2028, year 2048]. In each one of those intervals, the price of the equipment is different, according to the learning curve described.

It is important to clarify that, in our model, the decreasing ratio of the technology price (because of the experience curve), applies only for the equipment, because there is little information about experience curves for batteries. Therefore, it was considered that the price of batteries remains the same as the price in 2014 over the evaluation horizon.

The authors consider that the generated electricity depends only on the installed capacity of the PV system, the availability of sunshine in the specific place and the degradation system rate. This formulation is shown in eq. (2).

$$E_t = Capacity \times (1 - d_t)^t \times cf \times hours\ per\ year \quad (2)$$

Where:

$E_t$ = electricity produced by the solar system in time = t

*Capacity:* total initial electricity that can be produced for the PV system [15]

$cf$: charge factor

$d_t$: degradation ratio in time = t

Taking into account the current electricity market regulation in Colombia, it is assumed that the energy that a household can use from the PV system will be the minimum between the electricity demand of a typical household and the electricity generated for the PV system according to eq. (3). It is to say, it is considered that in case of the electricity demand of a typical household in a specific city is lower than the electricity generated by the PV system, the excess electricity cannot be used or sold to the national electricity grid. Electricity demand of a typical household in each city considered in this analysis is assumed fixed over the whole evaluation horizon. Capacity, degradation rate and charge factor are explained below.

*Capacity:* it was considered a PV system with a capacity of 0.6 kW [30]. Notice that installed capacity remains invariable over analysis horizon, but the effective capacity decreases because of loss of efficiency of the equipment. The consideration of larger capacities would increase the total of energy generated, but also the investment price and battery replacement cost.

*Degradation ratio*: it was assumed an efficiency loss for the PV system at a rate of 1% per annum (degradation ratio); i.e, each year the energy generated by the PV system is decreasing in this value in regard to the energy generated in the last year. The assumed ratio corresponds with a conservative scenario, as other authors consider a value about 0.2% to 0.5% as reasonable [15].

*Charge factor*: it was considered the sunshine duration in a day. The sunshine duration in a period is defined by the World Meteorological Organization (WMO) as "the sum of that sub-period for which the direct solar irradiance exceeds 120 Wm-2" [32], and is measured in hours [32].

Table 1 presents the annual average of the available sunshine for the analyzed Colombian cities, according to historical data. Therefore, the analysis considers that PV solar panel can generate electricity only during the fraction of the day in which there is sunshine, according its capacity and depending on the degradation rate.

Finally, the electricity grid tariff for comparing the LCOE calculated for each city corresponds to the average of monthly tariffs for the first half of 2014 for each specific city, without considering subsides or taxes to the electricity for final consumer (in Colombia, it corresponds to the socioeconomic level No. 4 – middle-high). Because of the high uncertainty of the path of those tariffs in the future, these values don't increase over the time in our evaluation. The grid tariff considered for each city is presented in Table 1.

## 5. The Colombian case application

The PV grid parity state in Colombia was calculated for 11 cities of the country. The cities were selected according to its population and sunshine factor, trying to consider both light and dark cities cases. Table 1 presents the attributes for those cities.

Table 1.
Attributes of the cities included in the analysis

| City | Population | % | Av. Sunsh. factor | Average 2014 grid tariff [$US/kWh] |
|---|---|---|---|---|
| Bogotá | 7,674,366 | 16.3% | 18.2%* | $ 0.18 |
| Medellín | 2,417,325 | 5.1% | 21.2% | $ 0.19 |
| Cali | 2,319,684 | 4.9% | 21.1% | $ 0.19 |
| Barranquilla | 1,206,946 | 2.6% | 27.6% | $ 0.16 |
| Bucaramanga | 526,827 | 1.1% | 16.8% | $ 0.18 |
| Cartagena | 978,600 | 2.1% | 29.5%* | $ 0.16 |
| Cúcuta | 637,302 | 1.4% | 25.4%* | $ 0.19 |
| Ibagué | 542,876 | 1.2% | 24.1%* | $ 0.20 |
| Santa Marta | 469,066 | 1.0% | 32.0%* | $ 0.16 |
| Manizales | 393,167 | 0.8% | 17.5% | $ 0.19 |
| Riohacha | 240,951 | 0.5% | 31.3%* | $ 0.17 |

*Measure taken from the brightest point of the city
Source: population data from DANE [33], sunshine data from the Colombian Institute of Meteorology and Environmental Studies (IDEAM) [34], grid tariff data published by Sistema Único de Información de Servicios Públicos (SUI) [35]

Note that together, the cities group about 40% of Colombian population. Territories like Santa Marta have a high sunshine factor (32,0%), while other, like Note that, according to eq. (1), the shorter horizon for evaluation the higher LCOE, because there is less generated electricity for distributing the same initial investment. So, the 20-year period can be considered a conservative selection, if it is considered that other authors argue that it is possible to include more years in the financial evaluation, such as 25 years [6,29], 25 to 30 [3], or even 25 to 40 [4].

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Taking into account the current electricity market regulation in Colombia, it is assumed that the energy that a household can use from the PV system will be the minimum between the electricity demand of a typical household and the electricity generated for the PV system according to eq. (3). It is to say, it is considered that in case of the electricity demand of a typical household in a specific city is lower than the electricity generated by the PV system, the excess electricity cannot be used or sold to the national electricity grid. Electricity demand of a typical household in each city considered in this analysis is assumed fixed over the whole evaluation horizon. Capacity, degradation rate and charge factor are explained below.

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Finally, the electricity grid tariff for comparing the LCOE calculated for each city corresponds to the average of monthly tariffs for the first half of 2014 for each specific city, without considering subsides or taxes to the electricity for final consumer (in Colombia, it corresponds to the socioeconomic level No. 4 – middle-high). Because of the high uncertainty of the path of those tariffs in the future, these values don't increase over the time in our evaluation. The grid tariff considered for each city is presented in Table 1.

Bucaramanga and Manizales, have lower sunshine factors (around 16.8% and 17.5%, respectively), although have different grid tariff conditions ($USD/kWh 0.18 and $USD/kWh 0.19, respectively).

### *5.1. Scenarios*

In order to determine the project sensibility, we built a baseline scenario and stressed the model in three different ways to identify its answer to unlike system conditions and, consequently, if and when grid parity could occur in each case. Table 2 presents the value of the variables in each scenario.

Table 2
Scenarios

| | Scenarios | | | | |
|---|---|---|---|---|---|
| **Variable** | ***Baseline*** | **Risk averse** | **Higher cost** | **Slower learning curve** | **Bank funding** |
| Horizon | 20 years | 20 years | 20 years | 20 years | 20 years |
| Discount rate | 1.39% EA | 20% EA | 1.39% EA | 1.39% EA | 1.39% EA |
| Initial investment | $USD 2430 | $USD 2430 | $USD 3645 | $USD 2430 | $USD 2430 |
| Funding method | own equity | own equity | own equity | own equity | bank funding |
| Battery replacement | $USD 215 | $USD 215 | $USD 215 | $USD 215 | $USD 215 |
| Learning curve | (-50%, 2021), (-75% 2028) | (-50%, 2021), (-75% 2028) | (-50%, 2021), (-75% 2028) | (-25%, 2021), (-50% 2028) | (-50%, 2021), (-75% 2028) |
| Capacity | 0.6 kW | 0.6 kW | 0.6 kW | 0.6 kW | 0.6 kW |
| Efficiecy | -1% per year | -1% per year | -1% per year | -1% per year | -1% per year |
| Charge factor | depends on each city | depends on each city | depends on each city | depends on each city | depends on each city |
| Electricity grid tariff | depends on each city | depends on each city | depends on each city | depends on each city | depends on each city |

Source: the authors

In all scenarios, the evaluation horizon is 20 years, the price of batteries is $USD 215 and they must be replaced every five years, the equipment capacity is 0.6 kW (with a degradation ratio of 1% per year and a charge factor that depends on the specific city). For the baseline scenario, the discount rate is 1.39% EA, the learning curve occurs according to literature information [31], and the initial investment is $USD 2430 (made from the investor's own equity).

The other four scenarios were designed by changing the discount rate, the value of the initial investment, the learning curve achieved and the funding method, thus:

1. *Risk averse scenario:* this scenario considers the high-risk perception associated with a new technology. In this case, investors can demand a higher discount rate in the project cash flow, in order to cover the higher perceived risk. In order to include this risk factor, a discount rate of 20% EA was considered in the risk averse scenario.

2. *Higher price scenario:* because the PV solar technology is not produced in Colombia, but it must be imported, there is no certainty about its final price for the consumers. Additional taxes and duties can take place at the moment of importation and legalization of the technology in the territory. Hence, this scenario considers a 50% higher technology acquisition price.

3. *Slower learning curve scenario:* a slower learning curve behavior was assumed in this scenario, given it is impossible to know with certainty which the global production of technology will be. This scenario considers that price decreases over time by a half of what is expected according to literature.

4. *Bank funding scenario:* in order to include the possible situation in which investor gets the funding from the banking system, this scenario evaluates the project considering that equipment can be funded through a bank loan. This option mitigates the initial effort that an investor must do for purchasing the equipment by using his own equity. For the model, the financial interest rate is the regular in the Colombian market for a consumer loan (about 25% EA), and the financial horizon is five years.

Reader must keep on mind that, in the four scenarios, the evaluation was made for the three-time intervals described before.

## 6. Results and discussion

Results for each scenario are presented below by graphs, which show the time when, given the specific place conditions, Colombian cities reach the grid parity.

X axe (horizontal) represents the hours per month of sunshine, and the Y axe (vertical) represents the equivalent electricity tariff reached with the PV solar generation (in $USD per kWh). Cities are located in the 2D graph according to their sunshine and their 2014 local grid tariff.

The lines show the grid parity price for the three years considered. Note that the lines get down over time because of the learning curve considered in the model. Cities located above a specific line have reached the grid parity for the

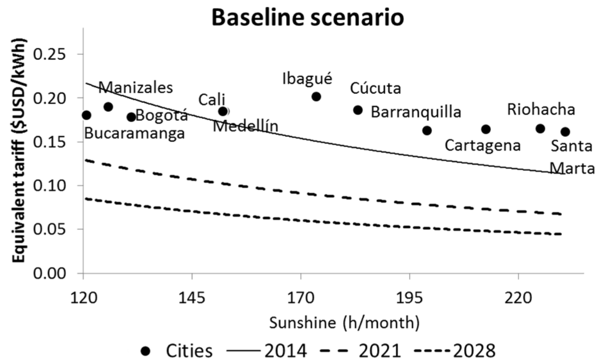

Figure 2. Grid Parity: Baseline scenario.
Source: the authors

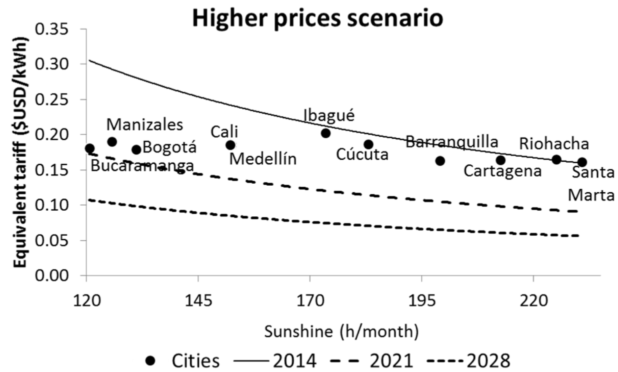

Figure 4. Grid Parity: higher prices scenario.
Source: The authors

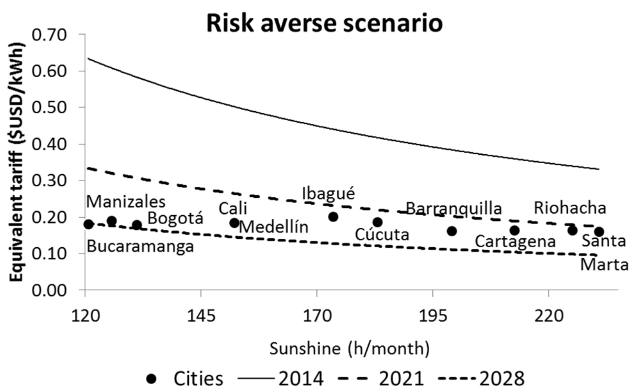

Figure 3. Grid Parity: risk averse scenario.
Source: Author's elaboration

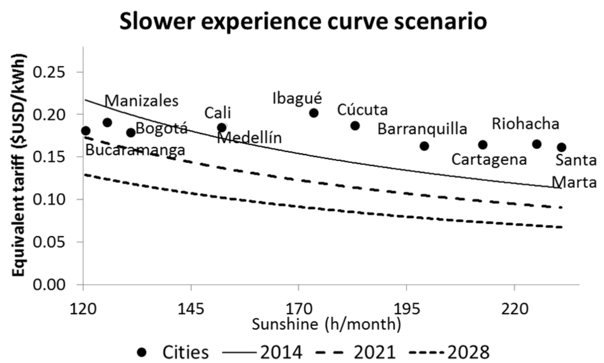

Figure 5. Grid Parity: Slower learning curves scenario.
Source: The authors

year associated with the line, and cities below have not reached the grid parity yet. Fig. 2 shows the results for the baseline scenario.

In the baseline scenario, eight Colombian cities (Cali, Medellín, Ibagué, Cúcuta, Barranquilla, Cartagena, Riohacha and Santa Marta) have reached the Grid Parity in 2014, and other three cities (Bucaramanga, Manizales and Bogotá) will reach the grid parity before 2021.

Note that those cities with the higher number of sunshine hours reach the grid parity faster than those ones with lower sunshine. For some cities, like Medellín and Cali, the equivalent solar tariff is really close to the grid tariff (with differences about 7.5% and 7.1% regarding the grid tariff, respectively), but for cities like Santa Marta or Riohacha, the difference can be considered relevant (29.8% and 29.6% regarding the grid tariff, respectively).

For this scenario, the equivalent solar tariff is placed between $USD/kWh 0.11 and $USD/kWh 0.22 for the year 2014, USD/kWh 0.07 and $USD/kWh 0.13 for the year 2021 and USD/kWh 0.04 and $USD/kWh 0.08 for the year 2028.

Figs. 3 to 6, present the results with different system conditions. Fig. 3 shows the results for the risk averse scenario.

When it is considered a higher discount rate (20%), no city reaches the grid parity state by 2014; 10 out of 11 cities do it at some point between 2021 and 2028, and just one city (Bucaramanga) reaches the grid parity only after 2028. So, the more risk aversion, the more delay reaching the grid parity. Even so, with a discount rate which is more than 14 times the normal rate for a regular project, most of the Colombian cities included in this analysis achieves the grid parity before 2028.

Unlike the baseline scenario, the corresponding solar tariff for the risk averse scenario is placed between $USD/kWh 0.33 and $USD/kWh 0.63 for the year 2014, USD/kWh 0.17 and $USD/kWh 0.33 for the year 2021, and USD/kWh 0.10 and $USD/kWh 0.18 for the year 2028. It means that, in average, the equivalent tariffs are 2.56 times higher regarding the baseline scenario under the risk averse scenario's conditions. Fig. 4 presents the results for the higher price scenario.

Fig. 4 shows the results when the technology acquisition price is 50% higher than the considered in baseline scenario. With this assumption, the grid parity is reached by two cities in 2014, and the other nine cities reach it at some point between 2014 and 2021.

The equivalent solar tariff for the higher price scenario takes place in between $USD/kWh 0.16 and $USD/kWh 0.31 for the year 2014, USD/kWh 0.09 and $USD/kWh 0.17 for the year 2021, and USD/kWh 0.06 and $USD/kWh 0.31 for the year 2028. It means that, in average, the corresponding tariffs are 1.34 times higher than the tariff in the baseline scenario.

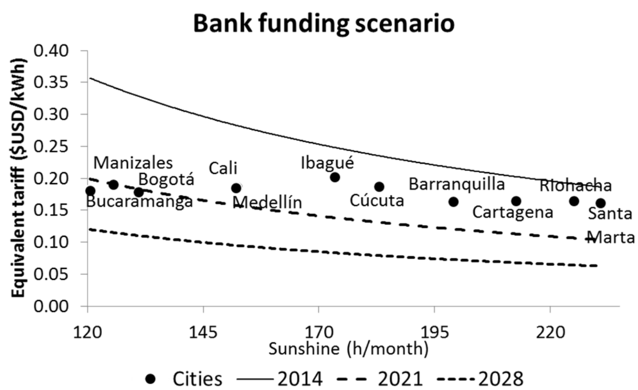

Figure 6. Grid Parity: Bank funding scenario.
Source: The authors

In the Fig. 5, the results for the slower learning curve scenario are shown.

The effect of reducing the speed of the learning curve by half of the expected speed doesn't change the grid parity state for any of the analyzed cities. Like in the baseline scenario, Bogotá, Manizales and Bucaramanga reach the grid parity state between 2014 and 2021 in spite of the slower reduction on equipment's prices.

However, the percentage difference between the equivalent solar tariff and the grid tariff is reduced for Bogotá, Manizales and Bucaramanga. In this baseline scenario, the corresponding solar tariff was 33.7%, 35.1% and 28.7% (respectively) lower than the grid tariff, while for the slower learning curves scenario, those differences are 11.0%, 13.0% and 4.4% respectively.

Fig. 6 presents the results for the Bank funding scenario.

Cali, Medellín, Ibagué, Cúcuta, Barranquilla, Cartagena, Riohacha and Santa Marta cities reach the grid parity at some point between 2014 and 2021 when equipment's bank funding is considered. Other cities, like Bucaramanga, Manizales and Bogotá reach this state at some point between 2021 and 2028 (this point seems close to 2021).

Although the cash flow for individuals is relaxed in this scenario, the inclusion of the bank funding delays the grid parity achievement regarding the baseline scenario. This is because the financial rate is higher than the discount rate, it is mean, higher than the second most profitable alternative for individual's investment. It supposes individual's choices are not as profitable as the banking system is, which is truth for most of the people in developing countries, like Colombia.

## 7. Conclusions

According to the results, grid parity is reached for eight cities (Cali, Medellín, Ibagué, Cúcuta, Barranquilla, Cartagena, Riohacha and Santa Marta) in the baseline scenario before the year 2014 (and, of course, in the slower learning curve scenario for the same year, because prices are still the same). For all the 11 cities in the baseline scenario, the slower learning curve scenario, and the higher price scenario, the grid parity is reached before the year 2021; and for all the cities in all considered scenarios before 2028 (except Bucaramanga in the risk averse scenario).

These results point out the viability for installing solar generation in Colombia in the consumer side, since in most of the scenarios and cities the grid parity will be achieved before 2021. Because the results in the baseline scenario are not affected by government mechanisms, it is possible to say that this parity grid is reached with the current state of the technology, the sunshine conditions of the territory and the electricity tariffs in the cities.

Considering a sensitive analysis on risk aversion, price of the technology, speed of learning curves and funding options, the whole spectrum of tariffs is covered for two scenarios: the baseline scenario, in the lower limit, and the risk aversion scenario, in the upper limit. For the year 2014, equivalent solar tariff for the territories with low sunshine goes from 0.33 to 0.63, which represents a difference of 2.92 times from the risk averse scenario tariff regarding the baseline scenario. This difference is getting shorter along time, and it is of 2.59 times for the year 2021, and 2.16 times for the year 2028. While for the baseline scenario some cities get the grid parity before the year 2014, for the risk aversion scenario the grid parity is reached only after the year 2028 for all cities. In this sense, the baseline scenario is an optimistic case.

It is important to consider that the project's viability also depends on policy issues, such as subsidy mechanisms oriented to decrease the value of the initial investment, or to provide cheaper credit lines for green investors could bring forward the grid parity time of PV solar systems, which could even accelerate the learning curve and, therefore, rebounds in more proper conditions for the diffusion of this technology.

Sensitive analysis gives some clues about these policy issues. Baseline scenario can only be reached having a suitable vigilance of the technology's prices, so that price remains at affordable levels for consumers; otherwise, with an increase in the prices, subsidies (directed to suppliers or consumers) and other government market mechanisms will be required to reduce the final price of the technology. Related to this, it is also important to set a low interest rate in case of bank loans; it could be achieved with subsidies addressed to the funding institutions instead to suppliers. Moreover, it is necessary to keep a low discount rate, which means to keep a low risk aversion; strategies oriented to familiarize the population with the technology (like demonstration projects or free trials, among others) can be helpful in this goal. The lower the prices of the technology, credit lines and risk aversion, the closer the baseline scenario and the faster the diffusion of the PV solar systems.

Whereby, it is important to make, as future work, different analysis of financial, tributary and fiscal incentives to improve the PV solar implementation in Colombia.

Also, analysis oriented to evaluate the acceptance of the technology by the population, which go beyond the cost-benefit evaluations, could enrich the understanding of the diffusion of the PV solar systems in the Colombian market.

## References

[1] CREG, Resolución 084 de 1996. 1996,
[2] Congreso de Colombia. Ley 1715 de 2014. 2014 [Online]. Available at:

http://www.secretariasenado.gov.co/senado/basedoc/ley/2006/ley_1117_2006.html.
[3] Breyer, C. and Gerlach, A., Global overview on grid-parity, Progress in Photovoltaics: Research and Applications, 21 (1), pp. 121-136, 2013. http://dx.doi.org/10.1002/pip.1254
[4] Bhandari, R. and Stadler, I., Grid parity analysis of solar photovoltaic systems in Germany using experience curves, Solar Energy, 83 (9), pp. 1634-1644, 2009. http://dx.doi.org/10.1016/j.solener.2009.06.001
[5] Blum, N.U., Wakeling, R.S. and Schmidt, T.S., Rural electrification through village grids—Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia, Renewable and Sustainable Energy Reviews, 22, pp. 482-496, 2013. http://dx.doi.org/10.1016/j.rser.2013.01.049
[6] Breyer, C., Gerlach, A., Mueller, J., Behacker, H. and Milner, A., Grid-parity analysis for EU and US regions and market segments– Dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio, 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany, pp. 21-25, 2009.
[7] Pérez, D., Cervantes, V., Báez, M. J. and González, J., Pv Grid Parity Monitor, Eclaeron, 2012.
[8] Chen, C.J., Physics of solar energy, Wiley, Hoboken, NJ, USA, pp. 177-208, 2011. http://dx.doi.org/10.1002/9781118172841.ch9 http://dx.doi.org/10.1002/9781118172841
[9] Peters, M., Schmidt, T.S., Wiederkehr, D. and Schneider, M., Shedding light on solar technologies—A techno-economic assessment and its policy implications, Energy Policy, 39 (10), pp. 6422-6439, 2011. http://dx.doi.org/10.1016/j.enpol.2011.07.045
[10] Joshi, A.S., Dincer, I. and Reddy, B.V., Performance analysis of photovoltaic systems: A review, Renewable and Sustainable Energy Reviews, 13 (8), pp. 1884-1897, 2009. http://dx.doi.org/10.1016/j.rser.2009.01.009
[11] Lynn, P.A., Electricity from sunlight : An introduction to photovoltaics, Wiley, Hoboken, NJ, USA, pp. 25-72, 2010. http://dx.doi.org/10.1002/9780470710111 http://dx.doi.org/10.1002/9780470710111.ch2
[12] NREL. Best research- cell efficiencies, National Renewable Energy Laboratory. 2013 [Online], [Accessed: May 13th of 2013] Available at: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg..
[13] Sersolar. Energía solar [Online], [Accessed: May 14th of 2013] Available at: http://www.sersolar.ca/..
[14] Ramadhan, M. and Naseeb, A., The cost benefit analysis of implementing photovoltaic solar system in the state of Kuwait, Renewable Energy, 36 (4), pp. 1272-1276, 2011. http://dx.doi.org/10.1016/j.renene.2010.10.004
[15] Branker, K., Pathak, M.J.M. and Pearce, J.M., A review of solar photovoltaic levelized cost of electricity, Renewable and Sustainable Energy Reviews, 15 (9), pp. 4470-4482, 2011. http://dx.doi.org/10.1016/j.rser.2011.07.104
[16] Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D. and Zhengrong, S., Re-considering the economics of photovoltaic power, Renewable Energy, 53, pp. 329-338, 2013. http://dx.doi.org/10.1016/j.renene.2012.11.029
[17] Hernández-Moro, J. and Martínez-Duart, J.M., Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution, Renewable and Sustainable Energy Reviews, 20, pp. 119-132, 2013. http://dx.doi.org/10.1016/j.rser.2012.11.082
[18] Swift, K.D., A comparison of the cost and financial returns for solar photovoltaic systems installed by businesses in different locations across the United States, Renewable Energy, 57, pp. 137-143, 2013. http://dx.doi.org/10.1016/j.renene.2013.01.011
[19] Reichelstein, S., and Yorston, M., The prospects for cost competitive solar PV power, Energy Policy, 55, pp. 117-127, 2013. http://dx.doi.org/10.1016/j.enpol.2012.11.003
[20] Lau, C.Y., Gan, C.K. and Tan, P.H., Evaluation of solar photovoltaic Levelized Cost of Energy for PV grid parity analysis in Malaysia, International Journal of Renewable Energy Resources, 4 (1), pp.28-34, 2014.
[21] Chiaroni, D., Chiesa, V., Colasanti, L., Cucchiella, F., D'Adamo, I. and Frattini, F., Evaluating solar energy profitability: A focus on the role of self-consumption, Energy Conversion and Management, 88, pp. 317-331, 2014. http://dx.doi.org/10.1016/j.enconman.2014.08.044
[22] Congreso de Colombia. Ley 142 de 1994 - Ley de Servicios Públicos Domiciliarios, 1994.
[23] Congreso de Colombia. Ley 143 de 1994 - Ley Eléctrica, 1994.
[24] Comisión de Regulación de Energía y Gas - CREG, 2008, Resolución No. 097 de 2008.
[25] XM. NEÓN - Información Inteligente. 2013 [Online]. [Accessed: February 1 of 2013], Available at: http://sv04.xm.com.co/neonweb/.
[26] Unidad de Planeación Minero Energética (UPME). Balance Minero Energético - 2010. 2010 [Online], [Accessed: February 1 of 2013], Available at: http://www.upme.gov.co/GeneradorConsultas/Consulta_Balance.aspx?IdModulo=3..
[27] Comisión de Regulación de Energía y Gas - CREG. 2013 [Online]. [Accessed: November 19th of 2013], Available at: http://www.creg.gov.co/html/i_portals/index.php.
[28] Sistema Único de Información de Servicios Públicos - SUI. 2013 [Online], [Accessed: November 19th of 2013], Available at: http://www.sui.gov.co/SUIAuth/logon.jsp.
[29] Lund, P. D. Boosting new renewable technologies towards grid parity – Economic and policy aspects, Renewable Energy, 36 (11), pp. 2776-2784, 2011. http://dx.doi.org/10.1016/j.renene.2011.04.025
[30] Alta Ingeniería. Energía Solar en Colombia. Energía Solar en Colombia y Renovables. 2014. [Online], Available: http://www.altaingenieriaxxi.com/.
[31] Partain, L.D. and Fraas, L.M., Wiley Series in Microwave and optical engineering : Solar cells and their applications, 2nd ed., Wiley, Hoboken, NJ, USA, pp. 3-153, 2010.
[32] World Meteorological Organization, Guide to meteorological instruments and methods of observation, 7th ed. (8), Chairperson, Publications Board, Geneva 2, pp. I.8-1 to I.9-1, 2008.
[33] Departamento Nacional de Estadística, Estimación y proyección de población nacional, departamental y municipal por área 1985-2020, DANE Proyecciones Poblac. [Online], [Accessed: November 21th of 2013]. Available at: http://www.dane.gov.co/index.php/poblacion-y-demografia/proyecciones-de-poblacion.
[34] Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), Promedios Climatológicos 1981-2010., Características Clim. Colomb. [Online]. [Accessed: February 14th of 2014], Available at: http://institucional.ideam.gov.co/jsp/812..
[35] Sistema Único de Información de Servicios Públicos - SUI. 2014 [Online], [Accessed: November 19th of 2013], Available at: http://reportes.sui.gov.co/fabricaReportes/frameSet.jsp?idreporte=ele_com_096.

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