TECHNICAL-ECONOMIC POTENTIAL OF PV SYSTEMS ON COLOMBIAN RESIDENTIAL SECTOR

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Abstract

Solar energy is the second most applied variable renewable source worldwide, after the wind. In 2014, its world installed capacity was around 177 GW. During the past years, the yearly new capacity of photovoltaic (PV) solar yearly new capacity has exceeded new wind projects, highlighting this new solar power trend. This study aims to estimate technical and economic potential of the solar PV in the Colombian residential sector taking into account characteristics such as socio-economic stratum, household electric power consumption, tariffs by utility and capital cost. Technical-economic simulation tools were integrated into a geographical information system ('GIS') to permit a spatial analysis. Results shows solar generation potential and its annual penetration potential for all socioeconomic strata within all Colombian municipalities up to 2030. The current technical potential is around 9.1 GWp (13.10 TWh/year), while the economic potential will be 3.2 GWp by 2030.

1. Overview

Photovoltaic (PV) solar has become a promising source of electricity generation in the last years. Worldwide, PV installed capacity has grown from 2.6 GW in 2004, to 177 GW in 2014. Recently, this development has become even steeper in which 60% of total current installed capacity have been added only in the past three years [1]. China and Japan have added 10.6 GW and 9.7 GW respectively in 2014, which represents 50% of total added capacity in this year. Germany remains having the highest installed capacity with 38.2 GW, which represents 21.58% of the total installed capacity worldwide [1].

In South America, Chile accounts for the highest installed capacity of about 493 MW [2], followed by Brazil with 50 MW [3]. According to [4], [5], the installed capacity in Colombia was 11.5 MWp in 2015. The highest irradiance in the South America region is in Chile with 2800 kWh/m^2 per year [6], followed by Bolivia with 2700 kWh/m^2 per year [7] and in the Brazilian case 2300 kWh/m^2 per year of irradiance was reported [8], [9]. It is worth to highlight that these irradiance values correspond to maximum values achieved in some regions of each country. In Colombia the top solar irradiation informed is 2200 kWh/m^2 per year [10]. The region in Colombia with the highest average radiation is Guajira, with 6 kWh/m^2 per day or 2190 kWh/m^2 per year, while average radiation in the Costa Pacifica is 3.5 kWh/m^2 per day or 1277 kWh/m2 per year, representing the lower radiation reported in the country [11]. The highest area in Colombia presents a solar irradiation rank between 4.5 – 5.0 kWh/m2. There are 8,055 km2 of available area with the best quality solar irradiation.

While solar irradiation in South America supports the development of a solar market, the region can be considered as an early stage region, but this circumstance offers a significant opportunity in order to develop the PV solar aiming long-term potential growth rates and the possibility to become world-leading. Furthermore, in the case of Colombia and equatorial countries, there is an advantage of having a stable resource throughout the year. This is possible because in the region the phenomenon of seasons is not evident.

Until 2014, there were no incentives for the promotion of non-conventional energy sources, especially those renewable sources, which could be integrated into the national grid (SIN). However, with the enactment of Law 1715 of 2014, the Colombian government made progresses in this area by establishing the legal framework and instruments for the promotion of the use of non-conventional energy sources.

2. Methodology

2.1. Methodological Procedure

In this study three main tools have been used. The first one is the RETScreen energy model, developed and maintained by the Government of Canada. The software was applied to quantify system power generation (kWh), from climate and system configuration data. Excel is the second tool used, it supports the computation of the Levelized Cost of Energy (LCOE) and the penetration of the technology over the time in the municipalities. The last one is a geographical information system (GIS) in order to present the results in a spatial analysis. The analysis has been split in 1120 municipalities obtained from [12], [13]. This study set up two different potentials, namely: technical and economic potential. The first one takes into consideration the net metering compensation system. The net metering system specifies an energy credit ("kWh credit") for the net energy exported to the grid that may be used on the following months until a pre-agreed period, from which credits might expire. The second one potential recognizes the grid parity, which is the time when the system LCOE is equal to the price of the energy purchased from the grid. Technical and economic potential have some particularizes, as follows:

- Technical Potential – the sum of the photovoltaic potential of all households within a specific municipality, based on its monthly electricity consumption. A specific household may just install a given amount of photovoltaic capacity that equals its own electricity consumption, otherwise this consumer would never recover all the energy sent to the grid based on the *net metering* compensation system. It was considered that apartments only harness 20% of the potential based on its energy consumption, due to rooftops constraints.
- Economic Potential – the yearly household potential that has reached grid parity. It means the *levelized cost of energy* (LCOE) of the photovoltaic system is equal or lower to the price of purchasing energy from the grid in that specific year. The economic potential it supposed to grow in time, both because more households reach grid parity for each new year and by the growth on the number of households itself[1].

The aspects considered in the model are solar radiation data, amount of household, residential power tariff and electricity consumption and energy system costs. All these data are available by municipality and socio-economic stratum. As a result, this study presents the introduction of photovoltaic solar power for all Colombian municipalities until 2030.

Houses and apartments share within the household sector for the entire country were estimated based on the values reported by [14] for the 16 main municipalities. For municipalities with 25,000 households or less, this study considered a 100% house share. For the ones beyond this level, it considered the share reported by [14] and shown in the Figure 1. Nevertheless, if there is not any information the study adopted the share reported for Popayán, which is the municipality with the less population considered in the survey.

[1] The household rates growth are calculated according with the forecasting done by [12].

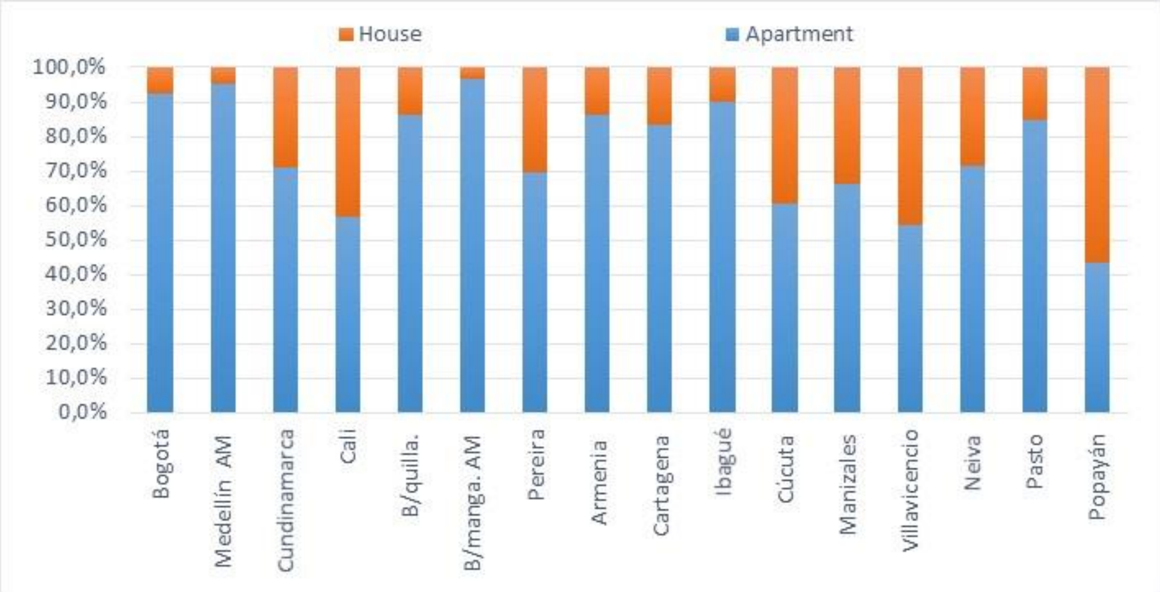

Figure 1. Percentage of house and apartments in Colombian municipalities. Own elaboration, based on Ref. [14]

2.2. Levelized cost of energy

The levelized cost of energy is calculated from the initial investment capital, discount rate as well as operation and maintenance costs, as follows.

$$LCOE_t = \frac{[CAPEX_t + OPEX_t] \Big/ \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]}{\sum_{t=1}^{T=25} E_{t-1}(1-x) \Big/ T} \qquad (1)$$

Where:

$LCOE_t$:	Levelized cost of energy in the year t
$CAPEX_t$:	Investment expenditures in the year t
$OPEX_t$:	Operation and maintenance expenditure in the year t
E_t:	Electricity generation in the year t,
x:	Deterioration of the module
i:	Discount % rate
n:	Economic lifetime of the photovoltaic system.

This investment is not uniform over the time; its value decrease annually by a learning of LR = 0.18 until 2020 and LR=0.16 from 2020 to 2030 [15]. Operation and maintenance expenditure is up to 1% of the initial investment of the system installed [16]. According to [16] a photovoltaic system needs very low maintenance cost over its lifetime. Inverter replacement needs may also be considered as operational expenditures as well. In order to include the photovoltaic module deterioration, an annual reduction factor of 0.5% on generation output has been applied [17] over an economic lifetime of 25 years [16], [18], [19]. The costs are annualized by the Equivalent Annual Annuity (EAA) method, which allows to distribute it uniformly for each year (Equation 1). It is worth to say that no discount has been applied on the annual energy output (denominator in the equation 1), since a discount should not be considered in a physics quantity. A discount rate of 7.9% p.a. has been considered, which guarantee a minimum return desirable [4].

3. Technical and Economical Characterization

3.1. Typical PV Module Size and System Configuration

The installed capacity potential for each household has been built under the logics of the net metering mechanism. The monthly household average electricity consumption was specified for each of the six strata group considered (see Section 3.3), within each municipality. Hence, a household consumer should adopt a PV capacity that generates up to its own electricity consumption on a year basis. Otherwise, some energy credits may never be recovered.

The system energy output has been calculated through the RETscreen energy model (Table 1). After the first year of generation, an annual reduction factor has been applied due to module degradation. Aiming the maximization of the energy output, the usual rule of thumb indicates that the tilt of the system array should be equal to the local latitude or quite close to this value [20], [21], although other studies come up with some variation of it [22]. Therefore, this study applied the local latitude. The optimal azimuth is oriented to the north for sites located in the southern hemisphere, and orientation to the south for sites located in the northern hemisphere [23], [24]. Thus, all Colombian systems have been oriented to the south, except the ones under the Leticia solar data.

Finally, this study used the polycrystalline silicon technology, as this is the most used worldwide. The module brand closed is also commonly used in different countries and may be easily applied in Colombia. Each system energy yield (Table 2), has been defined based in the system configuration (Table 1).

Table 1. Photovoltaic System Configuration

System Configuration	
Solar Tracking Mode	Fixed
Slope	Local latitude
Azimuth	South oriented*
PV Module Technology	
Technology	Polycrystalline silicon
Efficiency	14.1 %
Plate Capacity	240 Wp
Area	1.7 m^2
PV System Array	
N° Modules	**5**
Total Capacity	1.2 kWp
Inverter Capacity	1.0 kW
Inverter Efficiency	96%

*Except Leticia solar site

3.2. Solar Data

Solar resource database (global horizontal irradiance) was taken from [25]. This study selected 16 solar data sites randomly in order to cover the whole country. Thus, each municipality has been related to the closest solar site by a geo-processing tool. All solar sites are located in the northern hemisphere, except Leticia (negative latitude). The higher solar incidence occurs in the north of the country. According to [16] in the cities close to the Amazon forestry the solar irradiation is usually affected by cloudy days, predominantly in the summer.

Table **2** shows the amount of municipalities allocated under a specific solar site. For instance, twenty-four municipalities consider the data from the city of Maicao, which is the one with the highest solar radiation in Colombia. On the other hand, sites with the lowest solar radiation are in the Pacific Coast. Although Nuqui, Puerto Asis e Tumaco have the lowest solar radiation, these values are higher than the best solar radiation in Germany, where is reported 3,8 kWh/m^2 per day or 1200 kWh/m^2 per year [26].

Table 2. Solar radiation horizontal data and PV system performance

Cities	Latitude (degree)	GHI ($kWh/m^2.day$)	Capacity Factor (%) (%)	Yield (kWh/kWp)	Municipalities
Arauca	7.1	4.83	16.06	1406.66	7
Bogotá D.C.	4.7	4.26	15.15	1326.88	179
Calamar	2.0	4.59	15.45	1353.47	14
Cali	3.6	4.66	15.87	1390.15	122
Cartagena	1.3	5.73	18.22	1596.48	140
Inírida	3.9	4.75	16.01	1402.07	6
Leticia	- 4.2	4.72	15.99	1401.16	5
Maicao	11.4	5.86	18.74	1641.41	24
Medellín	4.2	4.68	15.93	1395.65	179
Mitú	1.2	4.56	15.39	1347.97	13
Nuquí	5.7	3.95	13.42	1175.58	25
Piedecuesta	7.0	5.34	18.02	1578.14	139
Puerto Asís	0.5	3.76	13.01	1139.81	60
Puerto Carreño	6.2	5.21	17.22	1508.44	3
Sogamoso	5.7	4.48	15.37	1346.14	161
Tumaco	1.8	3.84	13.06	1144.40	43

3.3. Household socioeconomic stratum and electric consumption

Socioeconomic classification in Colombia is made by the National Administrative Department of Statistics (DANE). The classification is applied to the residential sector consumers which want to have access to the energy grid. Different energy prices are determined for each specific socioeconomic stratum[2], providing subsidies to lower income groups and levy contributions to the higher ones. Thus, those classified in strata 5 or 6 must pay a higher price for the public services contributing to the lower prices payed by the low income social classes (1, 2 and 3). In addition, the classification allows to identify geographically sectors with different socioeconomic characteristics in order to guide the planning of public investment, to carry out social programs such as expansion and improvement of public services infrastructure and roads, health and sanitation and educational service, beyond to charge differently taxes and guide land use planning. Municipality and social strata data have been taken from [13]. It was also possible to obtain information about energy consumption and households energy prices with the same disaggregation level.

3.4. Tariffs by utility

Tariffs by utility are used in order to calculate, mainly, the economic potential, when grid-parity is considered. Aiming to associate each social stratum to a specific energy price some assumptions had to be considered. Electricity unit costs are composed by the sum of the remunerations in the entire energy supply chain3. There are thirty-two commercialization utilities in the country, but seventeen of those have 96% market share [34]–[50]. For this study, the reference tariff is applied in the stratum 4, which has no subsidy or contribution. For instance, the highest unit cost (or tariff) in the stratum 4 for December 2015[4] was applied by Empresa de Energía de Cundinamarca S.A. E.S.P. (23.30 USD cents/kWh), while Electrificadora de Santander S.A. E.S.P. practiced the smallest one (18.15 USD cents/kWh). This study assumed that the

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[2] There are six socioeconomic strata in Colombia such as: 1 (Low-Low), 2 (Low), 3 (Medium-Low), 4 (Medium), 5(Medium-high), 6 (High). This classification considers both cadastral homogenous zones and physical characteristics of each residential building. For instance, land use, utilities in the zone, roads, topography, land value, materials of bathroom and kitchen are taking into account in the classification. The income of the population is not considering in this classification due to can be change in the short-term. It supposes both zones and characteristics of the building are a proxy of the income. In this sense, strata 1,2 e 3 correspond to the poorer people a strata 5 and 6 correspond to the richest people [52].

[3] Generation, transmission, distribution, commercialization, losses and restrictions.

[4] In order to express the tariff in USD, we considered the mean exchange rate for years 2014 and 2015, as follows US$1=COP$2200 COP [53].

contribution for both strata 5 and 6 is 20% over the reference tariff. In the same sense, it supposed the tariff in the strata 1, 2 and 3 gain a subsidy of 60%, 50% and 15%, respectively. This subsidy is only applied if the household consumption is less than 173kWh; otherwise these strata must pay the full reference tariff[5]. From these assumptions, this study computed the mean consumption of each stratum within the municipality and allocated the tariff according this result. It is important to highlight that different commercialization utilities may attend to the same municipality. For the sake of simplicity, this study has chosen the utility which has the largest number of consumers within a municipality. To be conservative, it has not applied any increase rate on utilities energy prices up to 2030, since the higher the energy prices the greater will be PV penetration.

3.5. Evolution of Prices for Distribuited PV System in Colombia

There is no Colombian photovoltaic manufacturing industry as of today. There are many panel photovoltaic, inverters and batteries suppliers, most of them made in China and India [44] . According to [4] the Colombian average PV cost is 4.8 USD/W, in line with the international market. As it shows in the Figure 2, average price in the United States is 5.25 USD/W; however, the lowest reported cost in this country is 3.5 USD/W. In South America, both Brazil and Chile have lower cost than Colombia. For instance, in the Chilean market the cost is 2.98 USD/W. Germany and China reported the lowest capital cost with 2.2 USD/W and 2.15 USD/W, respectively. These costs correspond to the peak capacity between 3-5 kW that can be considered as a small-scale project. For this study, a price 4.8 USD/W is taking into account for the base year 2015.

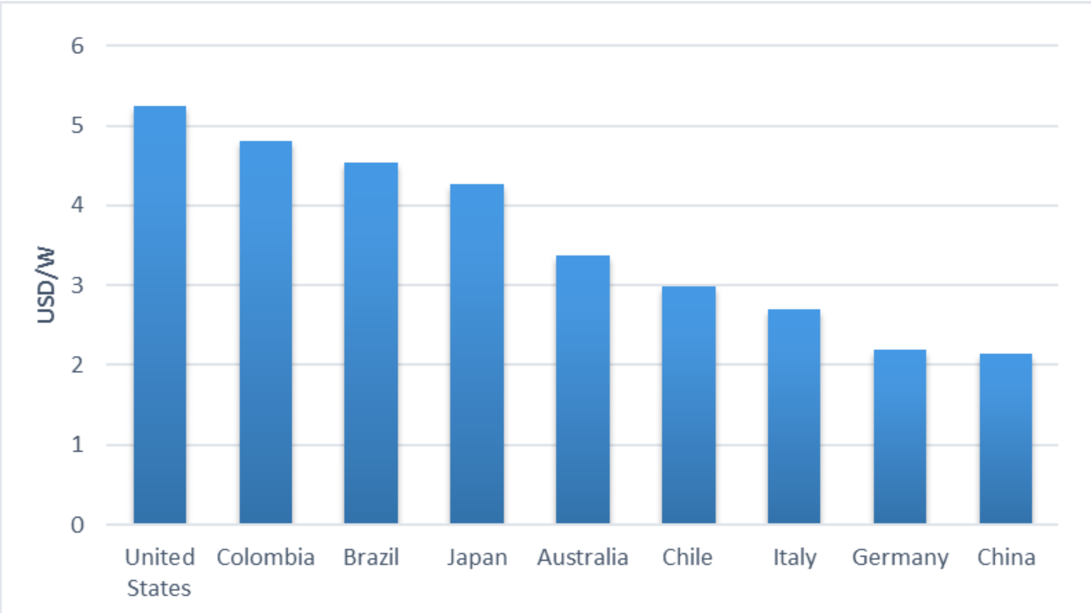

Figure 2. Capital cost of solar PV rooftop. Based on Ref. [1], [4], [16], [45], [46]

In the short and medium term, there are no clear incentives or plans to consolidate a national photovoltaic industry. Thus, Colombia should continue importing photovoltaic solar systems mainly from China. This study considered a learning rate approach, based on previously studies [47]–[51]. It should be noted that labor and installation cost are two variables directly related to local markets characteristics, that may vary from a region to another.

4. Technical and Economical Characterization

4.1. Technical potential

[5] The contributions and subsidies are according with the Law 142/1994 sets. The law aforementioned considers as a subsistence consumption 173 kWh/month as well. It means, consumers from the strata 1, 2 and 3 consumers have right to receive a subsidy if their consumption is less than this value.

The current PV distributed installed capacity in Colombia is 11.5 MWp. Technical potential directly depends on number of household and the houses and apartments shares within it. As mentioned, a technical potential has been defined under a net metering logic. The Colombian technical potentials is 9.1 GWp or 13.10 TWh/year (Figure 3-Figure 4)[6], that is nearly 22% of the technical potential calculated in [16] for the neighbor country Brazil. The highest potential occurs in Bogotá with 840 MWp, followed by Cali, Cartagena and Medellin with 430 MWp, 332 MWp and 272 MWp, respectively. As a result of the assumptions considered, most of the technical potential is in the most populated municipalities. The household type (house or apartment) is another weighting factor. If analysis is done by stratum, results show that 88% of the technical potential occurs in strata 1, 2 and 3. For instance, in Bogotá and Cali findings indicate that the highest potential is in stratum 3. In Cartagena the best potential is found in strata 1 and 2, which may never be explored, since these households has low average income. These findings indicate that there is still a huge potential to develop and the policy should be aim to support it, mainly in the strata 1, 2 and 3.

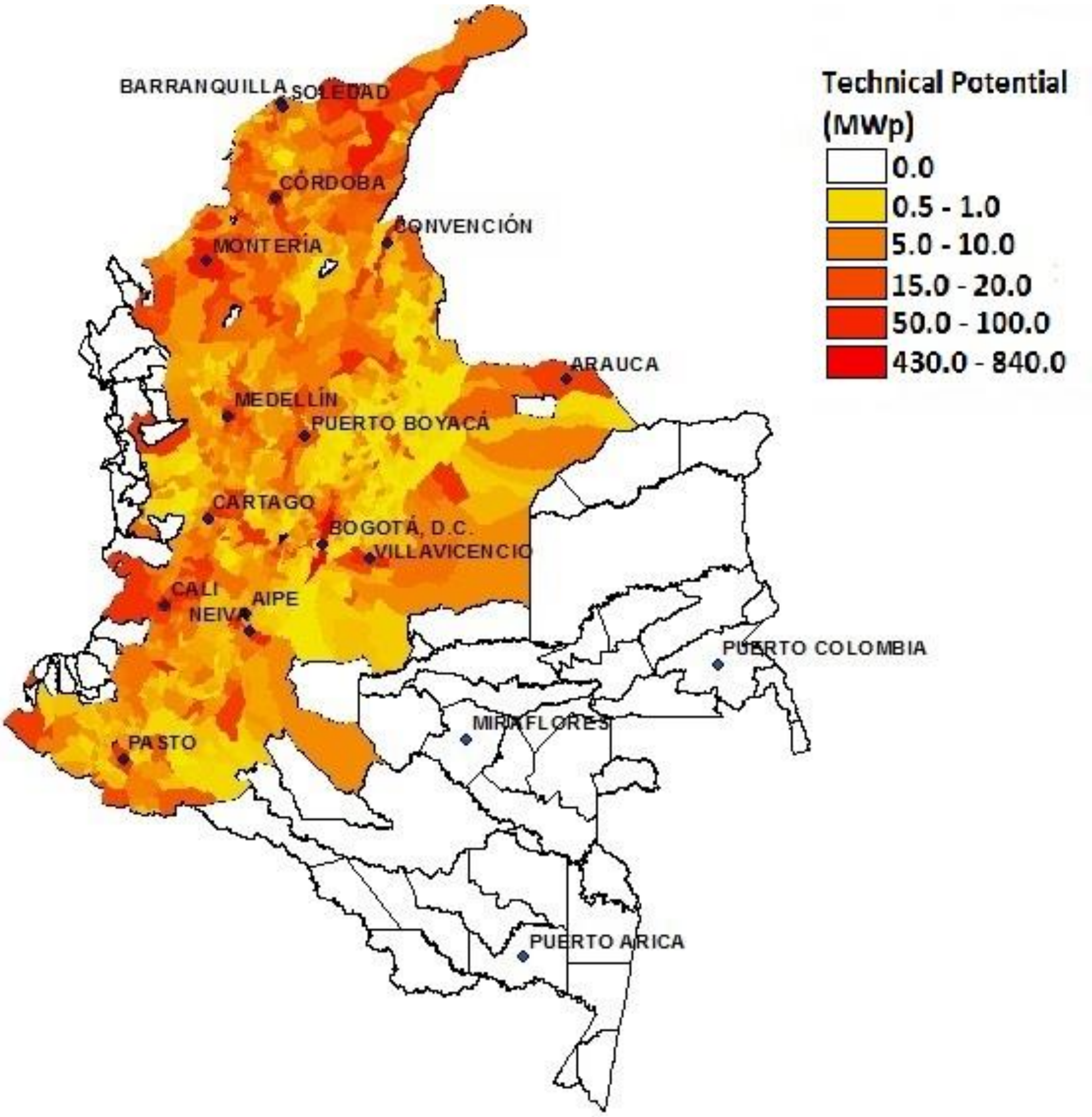

Figure 3. Technical potential for distributed PV installed capacity in the residential sector in Colombia (MWp) – year 2015

[6] There are no data about consumers, consumption and tariffs in [13] related to municipalities without color in the figures.

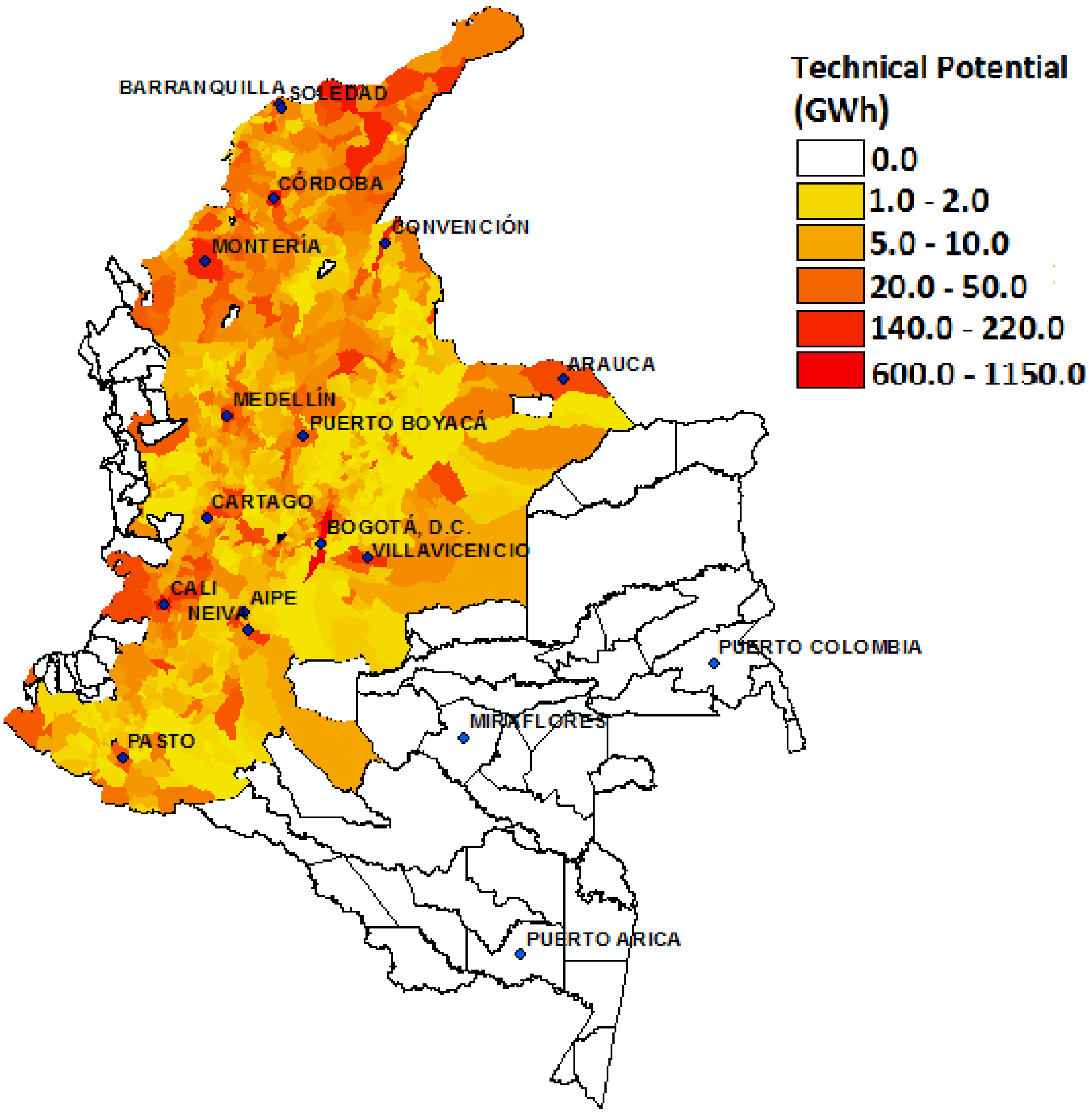

Figure 4. Technical potential for distributed PVenergy generation in the residential sector in Colombia (GWh) – year 2015

4.2. Economic potential

4.2.1. Levelized Cost (LCOE) and grid parity

The economic potential is calculated from the relationship between LCOE and local tariffs, in order to figure out in which municipalities and strata grid parity is obtained and when it is achieved. The price of the energy annually delivered by the system is given by the LCOE, which has been calculated for each of the 16 solar sites. Investment expenditures considers a PV system of 4,8USD/Wp [4]. Figure 5 shows the LCOE for 16 solar sites. Because of the considered learning rate, system LCOE in a specific year is different than the previous year. For instance, PV energy would cost 296.24 USD$/MWh for a system under the Bogota solar data in 2020, but the same energy would be delivered by 225,14 USD$/MWh in 2030.

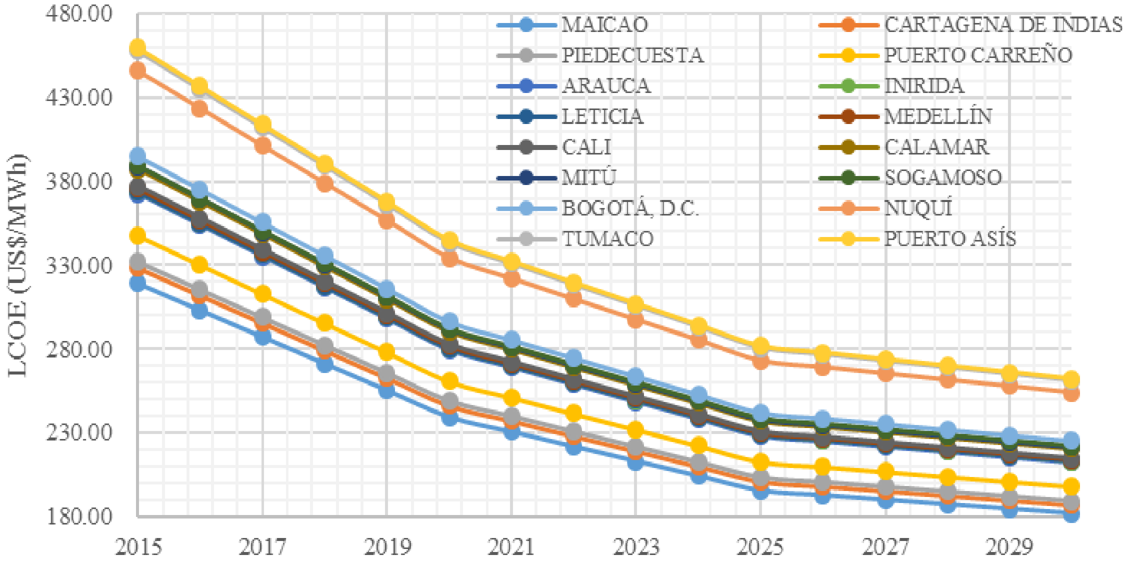

Figure 5. LCOE for the 16 solar sites in Colombia

Grid parity is achieved when LCOE is equal or lower to the price of purchasing energy from the grid in that specific year. As a consequence of contributions and subsidies scheme, this study considers the tariff for strata 5 and 6 is more expensive than for strata 1, 2 and 3. In this sense, the expected result is the difference between LCOE and tariff is lower in strata 5 e 6 than strata 1, 2 and 3. For year 2015 no municipality reach grid parity In stratum 1, Riohacha has the lowest difference between LCOE and the tariff (123 USD$/MWh) and Tumaco displays one of the highest value (365 USD$/MWh). Different reasons explain this result, namely: a) average radiation is better in the north of the country than Pacific Coast, so LCOE is lower for Riohacha as the municipality is located in the north, and, b) The household average consumption in Riohacha is 291kWh/month, while in Tumaco is 90kWh/month.

Riohacha´s household tariffs are, in general, higher, since the average local consumption is greater than the maximum liable for receiving subsidy as contemplated in the law. According to these average consumptions in the stratum 1, the tariff practiced in Riohacha is USD$200/MWh (Electrificadora del Caribe S.A. E.S.P. utility) and in Tumaco is USD$90/MWh (Centrales Eléctricas de Nariño utility). Regarding to stratum 6, Santa Marta city, supplied by Electrificadora del Caribe S.A. E.S.P, has the lowest value and thus it is the municipality closest to parity.

The difference between LCOE and tariff in the national capital Bogotá, falls from 317$USD/MWh (Stratum 1) to 162$USD/MWh (Stratum 6). Result in year 2030 shows several municipalities that achieve the grid parity from both strata 1 and 6. In stratum 1, Cartagena, Barranquilla e that do not achieve grid parity in 2015 but achieve it in 2030. It is interesting to note the stratum 1 in Bogotá will not achieve the grid parity even in 2030.Whilst, in the stratum 6, 984 municipalities achieve the grid parity. Some of them has already achieved economic viability in 2021, like Valledupar, Riohacha and Santa Marta, while, Barranquilla and Cartagena had reach it by 2022. The main municipalities which will achieve later grid parity are Cali (2024), Medellín (2025), Pasto (2027) and Bogotá (2028). The economic potential it supposed to growing up over time, since more households reaches grid parity for each new year and also by the growth of the number of households itself.

4.2.2. Spatial analysis

In this section the results are shown spatially, validating the chronological order of the PV systems penetration in the Colombian residential sector. The economic potential is 3.2 GWp by 2030. Distinctively from technical potential, the uppermost economic potential by 2030 is in Cartagena, Barranquilla, Santa Marta, Montería y Valledupar with 449.1 MWp, 264.2 MWp, 186.5 MWp, 156.0 MWp, and 155.5 MWp, respectively, which achieve grid parity by 2022. The first strata to achieve economic feasibility are strata 5 and 6. For instance, in Cartagena an installation of 22.4 MWp in stratum 5 and 40.2 MWp in stratum 6 are feasibility by 2022. Regarding to the stratum 1, Santa Marta and Valledupar will achieve economic feasibility with installation of 54.5 MWp and 46.9 MWp respectively by 2025. In the Bogotá case the economic feasibility is achieved in 2028 with an installation of 43.8 MWp and 65.4 MWp for the strata 5 e

6, respectively. The total economic potential in Bogotá is 111.4 MWp by 2030, which represents the municipality with the sixth economic potential of the country in the end of the study period. This kind of analysis can be done for whole Colombia detailed by stratum within each municipality.

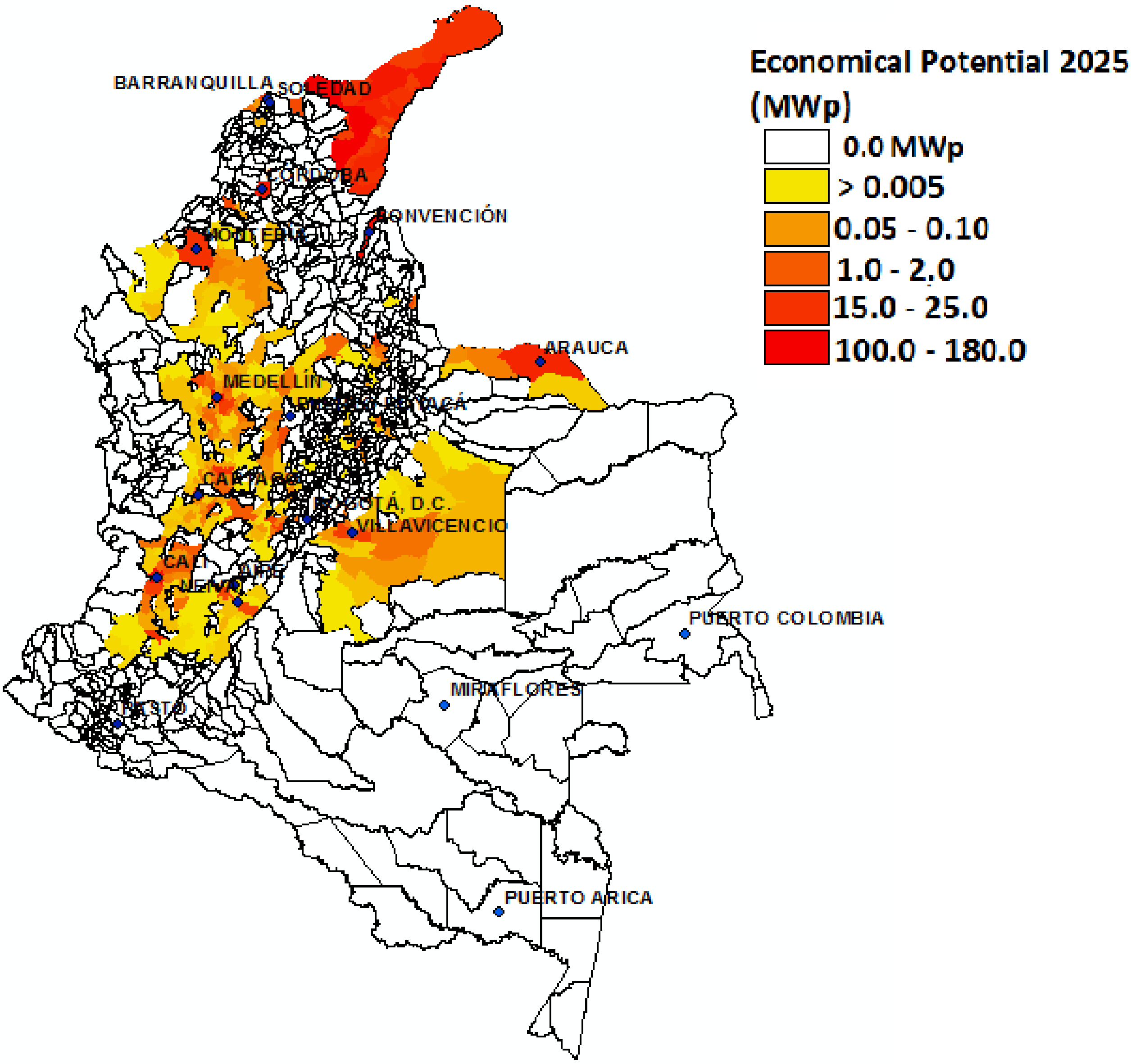

Figure 6. Economic potential for PV installed capacity in municipalities that reached grid parity (Year 2025)

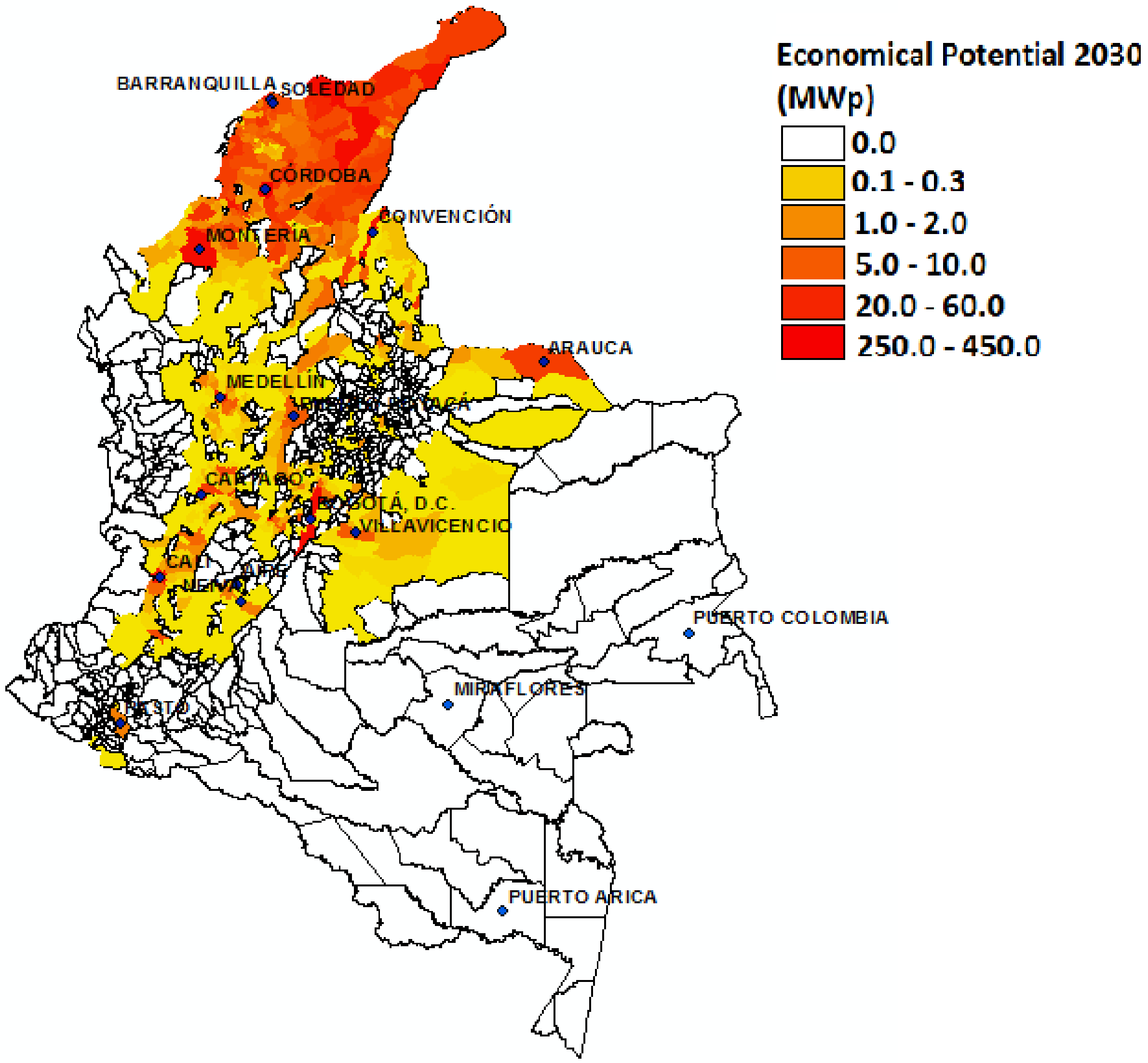

Figure 7. Economic potential for PV installed capacity in municipalities that reached grid parity (Year 2030)

5. Conclusion and further research

This study showed technical and economic potential of residential PV in Colombia taking into account a set of assumptions for its calculations. Findings indicate technical potential, defined under a net metering logic, is allocated in the most populated municipalities (9.1 GWp or 13.10 TWh/year). The highest potential occurs in Bogotá with 840 MWp, followed by Cali, Cartagena and Medellin with 430 MWp, 332 MWp and 272 MWp, respectively. Meanwhile, economic potential, calculated from the relationship between LCOE and local tariffs, shows that PV feasibility is found firstly in the municipalities with both the best solar resource quality and the highest power tariffs. Findings in year 2030 shows several municipalities that achieve the grid parity from both strata 1 and 6. In the stratum 1, Cartagena, Barranquilla e Cartagena that do not achieve grid parity in 2015, do it in 2030. It is interesting to note stratum 1 in Bogotá will not achieve the grid parity even in 2050.

To analyze the technical and economic potential of PV system in the Colombian residential sector is important taking into account the new regulatory framework establishing objectives for the renewable energy non-conventional integration. Law 1715/2015 pointed out the renewable energy integration in the national grid. In spite of the fact, there is not a particular regulation for residential sector. Resolution CREG 024/2015 regulates the self-production energy in large scale but it is necessary to issue a corresponding regulation for self-producer energy in small scale in order to incentive and to encourage the PV solar panels installations in the Colombian residential sector.

In order to improve this study, it is necessary to comprehend aspects besides purely economic issues, such as the labour availability, consumer knowledge of the solar technology by local citizens, financial opportunities in an environment with multiple options, market barriers, among others. The identification of these aspects will allow to estimate the market potential. Hence, it is worth to recognize market barriers of the economic potential calculated already. In order to overcome the market barriers and to turn most of the economic potential into market potential, some energy policies should be explored.

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