Renewable and Sustainable Energy Reviews 92 (2018) 160–170

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Photovoltaic energy in Colombia: Current status, inventory, policies and future prospects

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ARTICLE INFO

Keywords:
Renewable energy
Photovoltaic systems
Renewable energy policies
Photovoltaic prospects
Photovoltaic Inventory

ABSTRACT

Along with the development of renewable energies in the world and the initiatives for alternative energy implementation in Colombia, it is important to make a national revision regarding the implementation and use of solar photovoltaic energy in Non-Interconnected Zones (ZNI for its abbreviation in Spanish) and the National Interconnected System (SIN for its abbreviation in Spanish). The objective of this article is to identify the development that it has had and its future panorama as far as the solar photovoltaic energy is concerned. The study presents the projects that have been executed and the ones in execution during the last decade, and the capacity that has been installed up to the present day in both SIN and ZNI (Photovoltaic Inventory).

On the other hand, the document describes its social and political development at a national level, as well as legal aspects of the advantages and disadvantages of the recent Law 1715 signed in 2014. This law aims to promote the development and use of unconventional sources of energy, integrating them into the national energy system, allowing a promising future for these alternative technologies such as electricity generation from photovoltaic solar energy. Finally, the article shows the different opportunities in the ZNIs where the radiation potential reaches up to 6 kW h/m^2 day and the projects do not exceed the 2.25 MW of installed capacity in Colombia, contrasted with the national average that is around 4.5 kW h/m^2 day, surpassing the world average of 3.9 kW h/m^2 day. Likewise, it allows seeing the opportunities that the new law offers for the development of generation projects in the SIN at a mega and gigascale, and of smaller projects that enable self-consumption and sales to the network, as well as distributed generation projects and hybrid power generation projects.

1. Introduction

The world's integration of alternative energies or renewable energies has been consolidated in the political, industrial and community fields in the last 20 years, with a significant increase in the supply of technologies at the photovoltaic (PV), wind, biomass, geothermal and marine energy levels. This provides a contribution of 23.7% in 2014, from which only 1.2% is per solar energy action equivalent to 175 GW [1,2]. Given the present scenario 2016, it is to indicate that the source of renewable energy with greater potential is solar energy [1]. For this reason, this market has grown rapidly, between the year 2000 and 2015 the growth of photovoltaic installations was 41% [3]. At the continent level, it is estimated that countries such as Austria, Germany, the Netherlands, France, England and Spain represent 98% of photovoltaic installations connected in the European Union. Germany exceeds its capacity with 41.22 GW installed, followed by Italy and France with 19.27 GW and 7.13 GW respectively. Spain as a leading country has an installed capacity of 5.4 GW equivalent to 1.8% of the 294.16 GW installed in the world [4].

In the Asian context and in the first place, the Republic of China raised up to 28 GWp installed in 2014 [5–7], which highlights the commitment of this power country with the alternative technological development of the energy sector and capacity for the production of this type of energy. Similarly, in 2015 they installed 15.2 GW, reaching a total of 78.07 GW installed by 2016. Japan ranks second with an accumulated installed capacity of 42.75 GW [4]. India as an emerging economy of the Asian continent has an average population of 1240 million and more than 600.000 villages, where 1/3 of the population does not have access to the electricity grid, which represents almost 600 million people. India presents high solar radiation that can be susceptible to generate electricity from solar energy; an example of this is the solar radiation in the zones of Kolkata and Madras with approximately 5000 kW h per year [7]. In 2010, India created the goal of installing 20.000 MW of photovoltaic energy by 2022 from approximately 1100 solar plants. Currently the installed capacity in photovoltaic energy in this country is 9.010 MW [8–10].

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https://doi.org/10.1016/j.rser.2018.04.065
Received 8 May 2017; Received in revised form 12 March 2018; Accepted 14 April 2018
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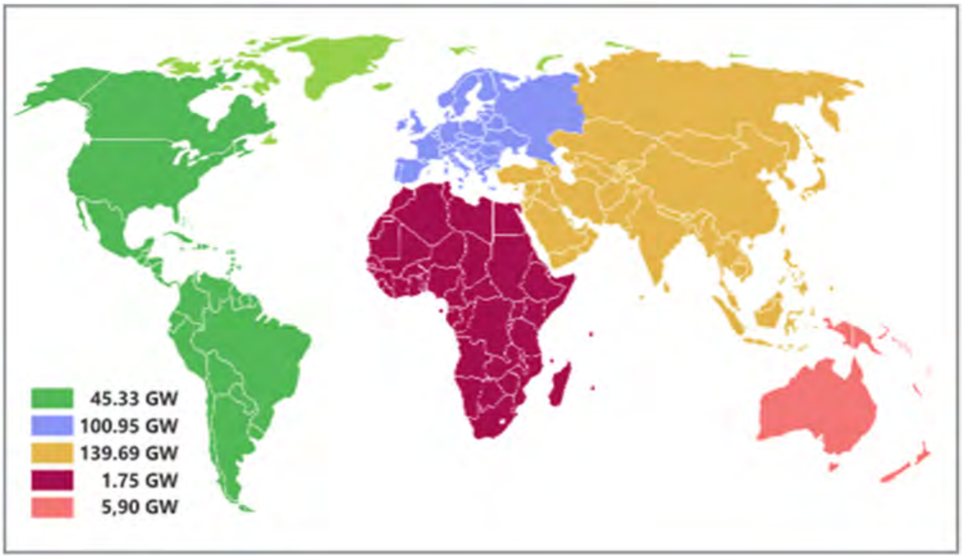

Fig. 1. Current worldwide installed capacity. Own elaboration.

Africa, being a continent with greater vulnerability to the effects of climate change, is beginning to gradually implement clean technologies. For example, in South Africa the potential in terms of solar energy, with a total of 194.00 km^2 of possible use in solar power. Currently the photovoltaic installed is used for lighting purposes, appliances, telecommunications, and water pumping. By 2030 it aims to install 8.4 GW with solar technology and by 2050 they expect to cover 14% of the energy supply [10]. Likewise, Nigeria and Egypt with 500 MW for 2025 and 700 MW for 2027, respectively.

In the American continent, the United States of America lead the photovoltaic field establishing a capacity of 40.3 GW by 2016 [4]. In countries of South America, photovoltaic energy has been venturing into more and more countries as an alternative to reduce impacts associated with climate change. As an example, Brazil being one of the countries that represent the 32% of the world's largest energy demand, however the high cost does not allow the inclusion of renewable energies so easily, for 2016 it was installed solar generation capacity of 51.1 MW, represented in 3851 independent photovoltaic installations [11]. In Fig. 1. We can observe the capacity that has been installed in the world, surpassing the 200 GWp represented by 47% and 34% in the Asian and European continents respectively. At the level of South America and Africa, the development of solar energy is slow.

Colombia, which belongs to the continent of America and is located in South America on the equatorial axis, has started to actively integrate itself into the field of energy sustainability and has penetrated the renewable energy matrix, allowing its commitment to reduce the economic dependence on fossil fuels and greenhouse gas emissions (GHG). Likewise, Colombia is increasing its alternatives towards economic, ecological and social efficiency following the example of the implementation of this type of technologies in developed countries.

The photovoltaic systems for electricity production in Colombia are less than 4% of the national electricity production. These systems have been positioning since the 70's with the arrival of efficient systems of thermal heating, which allowed the transition to a culture under the energy sustainability framework and gave way to a new century that is proposing technological offers and projects out of photovoltaic modules. Therefore, within the national energy model to be addressed in this document, Colombia is shown as a producer of electric power out of hydropower, being this one that generates the greatest energy impact in Colombia with 75.9% [12]. The renewable energy sources such as biomass, wind and solar have started to penetrate first in the populations with basic deficiencies in the service and that are not connected, because of their location in areas of difficult access, low capital development, deficits in infrastructure, and energy inaccessibility. This shows that areas with settlements that are characterized by conditions of vulnerability are the best option for this type of technology. Features such as difficult access, problems of public order and transportation logistics make the price drawn from Diesel to be between 0.4 and 0.53 US$/kW h.

The implementation of photovoltaic systems in Colombia has enabled 2% of the population in areas that do not have access to electric energy to meet their lighting, refrigeration and leisure needs, allowing them to expand their capacities and improve their quality of life. The systems that have been installed are mainly focused on the rural sector. Even with this panorama of positive development from the social and productive contexts, there are different barriers for an evolution of alternative generation technologies, being necessary to formulate programs in order to develop renewable energy sources that seek to diversify the national energy market and laws that extend the energy matrix and allow the implementation of self-consumption systems, distributed and hybrid [13].

This article presents a global and local overview regarding the use and utilization of clean energies fed by direct solar radiation, national policies that facilitate their access, and projects implemented at the level of Non-Interconnected Zones (ZNI for its abbreviation in Spanish), and from the National Interconnected System (SIN for its abbreviation in Spanish), covering from a macro and micro view, the photovoltaic era in Colombia and its legal and technical framework.

2. Energetic and political situation in Colombia

2.1. Social situation

Colombia is located in the northwestern region of South America on the equatorial axis; currently, it has 48.747.632 inhabitants located in 32 decentralized departments and its capital is Bogotá D.C. [14]. At the energy level, it is divided in two zones.

- Interconnected Zones, which have access to the electric power service through the National Interconnected System (SIN).
- Non-interconnected Zones (ZNI), identified according to Article 1 of Law 855 from 2003 as municipalities, districts, localities and villages that are not connected to the SIN, so this type of areas are supplied with energy through Diesel based generating plants, solar panels and small hydroelectric power stations, evidencing with this that the electrical infrastructure at national level has fallen behind

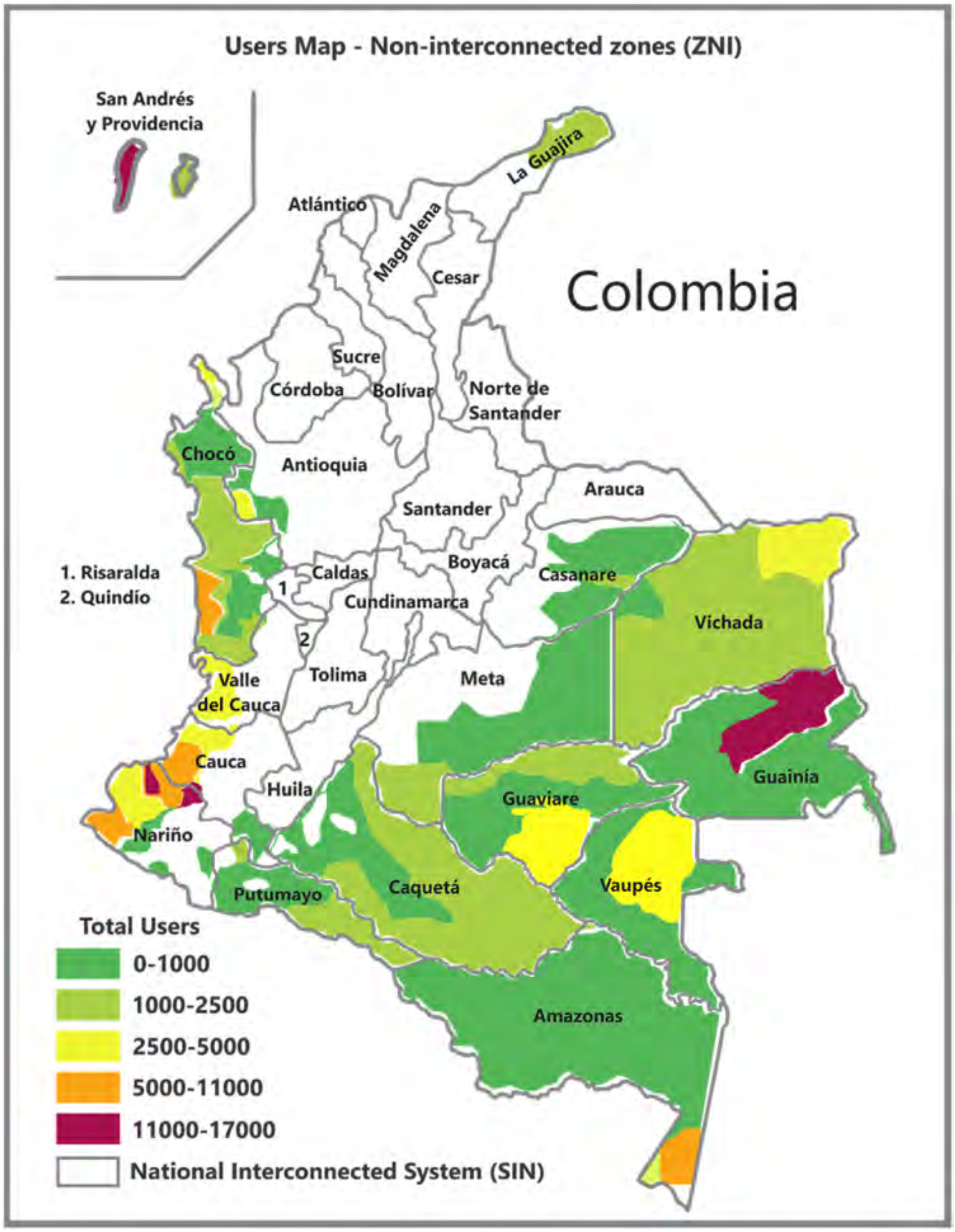

Fig. 2. Location of ZNI and SIN. Own elaboration.

and there is a high possibility of promoting alternative energies.

According to the Institute for Planning and Promoting Energy Solutions for Non-Interconnected Zones (IPSE for its abbreviation in Spanish) there are 90 municipalities in Colombia belonging to the ZNI, covering about 52% of the National territory; Which include 32 departments, 5 departmental capitals, 39 municipal capitals and 1.448 localities (Fig. 2). Likewise, the National Interconnected System (SIN) connects 48% of the national territory and serves 97% of the population [15]. In terms of the number of households that have access to the electricity grid in Colombia, it is currently provided with 12.1 million since 2005, represented by 95.8% of the total Colombian population [16], identifying that of the total electricity generated around 70% of the consumption is residential [17].

Colombia has a deficit of energy access in most island territories, and must implement specific solutions for the supply of electricity [18]. The main problems that appear in these places are the changes in rainfall caused by the El Niño/La Niña phenomenon and the infrastructure limitations due to the geography of the Colombian territory. The previous thing causes that the accessibility to the electrical power in these ZNI is difficult, being covered by small hydraulic plants, photovoltaic panels, and Diesel generators [19].

The fact that Colombia is located on the equatorial axis and has privileged climatic characteristics, such as constant temperatures during the year, benefits the method of obtaining energy by solar radiation. For that reason, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM for its abbreviation in Spanish) together with the Mining and Energy Planning Unit (UPME for its abbreviation in Spanish) developed a schematized reference document detailing the solar radiation in the soil in different regions of the country [20]. The potential of solar energy at a global level in Colombia is 4.5 kW h/m^2/day and the area with an optimal solar resource is the Península de la Guajira, with 6 kW h/m^2/day of radiation, surpassing the world average of 3.9 kW h/m^2/day. In the referenced link [21], there is an interactive map of the radiation indices in Colombia by IDEAM.

2.2. Energy policy

Electricity generation in Colombia is done through hydro plants (64%) [22], which is the main factor that makes Colombia occupies the 16th place of 129 countries in the ranking of environmental sustainability of the World Energy Council. The rest comes from thermal plants and only 4.5% from unconventional sources of renewable energy [23]. In the same way governments are concerned about the diffusion of these technologies, for this reason the design and implementation of policies in the renewable market is essential, without these policies the stability and sustainability of the renewable energy market is put at risk [17].

In Colombia, the energy demand is increasing, according to the Mining and Energy Planning Unit (UPME). The projection is that between 2010 and 2020 demand will grow at an average rate of 3.4% [25]. Consequently, the environmental problems caused by the generation of current energy from conventional sources and the depletion of natural resources, lead to the promotion of the use of alternative generation sources at present in the country, through a regulatory framework and the creation of state entities responsible for controlling and managing this field. First, the regulatory framework has allowed the development and growth of renewable energy in the country through its evolution, taken as a starting point Colombia's participation in the Kyoto Protocol on climate change in 1997 with the Law 629 of 2000 [26,27]. Which promotes the Rational and Efficient Use of Energy (URE for its abbreviation in Spanish) with the Decree 3683 of 2003. Then with the objective of promoting the implementation of unconventional energies in the country, Law 1665 of 2013 is created. Finally, Law 1715 of 2014 [24] to regulate the integration of renewable energies in the national energy system, especially for non-interconnected areas (ZNI) [28], also, incentives for projects of this kind, such as VAT (value added tax) exemption, fees payment and reduction in income tax payment. These are the laws and decrees defined to deal with alternative energies in Colombia. Although great efforts have been made to massify, encourage and extend these initiatives, even more specific regulation is needed, which contemplates all the stages from design to development, distribution and all types of energy generation from renewable sources.

In Colombia, from the perspective of institutions and laws, the promotion of Renewable Energies is validated. First of all, at the institutional level with direct responsibilities in the promotion of alternative energies, there are seven (7) leading entities that we currently find in this process:

- The Ministry of Mines and Energy (MME for its abbreviation in Spanish).
- The Mining and Energy Planning Unit (UPME for its abbreviation in Spanish).
- Energy and Gas Regulatory Commission (CREG for its abbreviation in Spanish).
- Institute for Planning and Promoting Energy Solutions for Non-Interconnected Zones (IPSE for its abbreviation in Spanish).
- Intersectoral Commission for the Rational and Efficient Use of Energy and Non-Conventional Energy Sources (CIURE for its abbreviation in Spanish).
- Financial Support Fund for Energizing the Non-Interconnected Zones (FAZNI for its abbreviation in Spanish)
- National Royalties Fund (FNR for its abbreviation in Spanish) [15,24].

These organizations work on policies and incentives for the multiplication of successful experiences in the field of clean energies. Likewise, the only law that promotes renewable energy is the current Law 1715 from 2014 [28], which aims at promoting the development and use of non-conventional sources of energy, mainly the ones with renewable basis, in the national energy system by means of their integration into the electricity market, their participation in non-interconnected areas, the reduction of greenhouse gas emissions and the energy supply security.

The previous Law is promoting the development of solar technology in the country by way of incentives for projects at a residential, commercial and large scale. These strategies are materialized through: tax reduction for a period of 5 years, accelerated depreciation of assets, exemption from VAT on goods related to the project and the exemption of the customs tariff [16]. Likewise, there are limitations such as the commercialization of this type of technology, given that so far it is not marketable by private agents, but instead, there must be a direct connection with the CREG. Another limitation is the cost of alternative facilities that are even higher compared to most countries with developed solar industry, being similar to those of EEUU. PV solar technology is still not profitable in Colombia, inasmuch as the value for its implementation and transfer is very high due to the scarce maturity of the market and the lack of current regulation (3.2 US$/W installed compared to 1.9 US$/W in Germany, at a large scale).

There are several barriers presented in the development of Renewable Energies at the solar level in Colombia. In the past, the first barrier at the level of solar self-generation technology was the inability to deliver surplus energy to the grid by this type of system. There was no policy that indicates the use ratio of this type of energy source. Until March 2017, the Ministry of Mines and Energy issued Decree 348 on small-scale self-generation surpluses, known as small-scale: "Self-generation whose maximum power does not exceed the limit established by UPME 0281 of 2015 [29].

The conditions are:

- The electrical energy produced by the natural or legal person is delivered for its own consumption, without the need to use assets of use of the Regional Transmission System and/or Local Distribution Systems.
- The amount of excess or surplus energy may be any percentage of the value of your own consumption.
- The generation assets can be owned by the natural or legal person or third parties and the operation of said assets can be developed by the owners or by third parties.

Likewise, a new resolution was issued by the CREG "Creg030 of 2018" in which the mechanism is defined so that residential users of all strata, as well as commercial and small industrial, produce energy mainly to meet their own needs and can sell surpluses to the interconnected system. This production is small scale (up to one megawatt) [30].

The second barrier is that which corresponds to the subsidy policy that favors the consumption of Diesel, with this energy potential prevailing at low costs over renewable systems. The third barrier is the lack of identification in the consolidated information of the participation of renewable energy systems in terms of installed capacity and energy generated as indicated by UPME 2015, affirming the necessary management of inventorying all types of projects. Principal objective of this work respect to the photovoltaics projects [31]. Without real information, the real costs of investment and operation will not be disclosed, such as the successes or failures of the system, misinforming the possibilities of new energy forms. The last barrier is the cost of investment, being the main barrier that hinders the application of these systems especially in ZNI, due to its initial investment required, operation and maintenance costs that can not be paid by the vulnerable communities belonging to the ZNI when considered low income [16]. Legislation currently only includes tax reductions and exemptions, with insufficient support for low-income communities to employ these types of systems. In short, to increase the integration of renewable energy is important to increase research and development of new technologies that allow competition in terms of reducing production costs and greater efficiency by reducing fossil consumption. Also, implement better public policies and programs that encourage the generation of photovoltaic energy [32].

It is important to indicate that currently according to the Legislative Act No. 155 of 2017, the resources of the Science Technology and Innovation Funds; of Regional Development, and Regional Compensation, will be made in accordance with the National Development Plan and the development plans, as well as development plans of territorial entities of the territorial entities, indicating that fifty percent (50%) of the resources to finance programs and/or projects in science, technology and innovation of the departments, municipalities and districts, will be destined to the development and the utilization of the Non Conventional Sources of Renewable Energy. This will allow priority to be given to vulnerable regions and the use of this type of technologies is guaranteed [19].

3. Solar energy inventory in Colombia

Due to its location on the equatorial zone, Colombia counts with a solar radiation that is steady in certain areas of its territory, obtaining some of the highest worldwide indexes registered along with those of Africa. Even so, less than 3% of the consumed energy comes from solar source, wasting such high energy resource, presenting a low development of this technology and a low exploitation of this comparative advantage at a global level. Currently in the Colombian national territory, the installation of photovoltaic infrastructure corresponds to about 5.28 MW (about 20.000 solar panels/electric energy), distributed in 46% in the ZNI and 54% in the SIN.

This paragraph briefly describes the photovoltaic projects that promote alternative clean energies carried out in social, industrial and productive projects in the field of electric energy.

3.1. National interconnected system projects

Colombia has been involved in the field of renewable energies since the 1980s, starting with projects at the micro level in the thermal and electric fields, ending the century with photovoltaic plant of up to 1000 solar panels to provide electric energy in recreational, productive and educational centers, among others. It is identified at the national level that out of the 32 departments adding the Capital District of Colombia, 15 departments with access to the National Interconnected System (SIN) have an installed capacity of 2.44 MW. In this totality, priority development is registered in 5 departments with an equivalent of 1.9 MW attributed to Cundinamarca, Atlántico, Valle del Cauca, Antioquia and Norte de Santander.

With an overview of the energy initiatives powered by solar energy, Fig. 3. Graphically depicts the installed capacity at the level of Grid Interconnected Systems, taking into account that only 15 out of 32

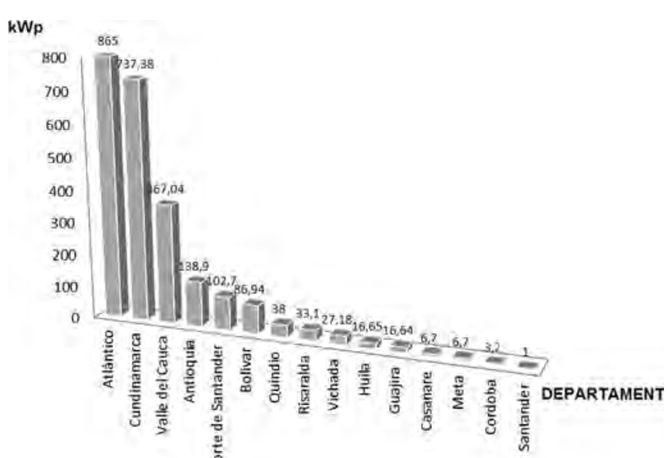

Fig. 3. Installed capacity – kWp (SIN). Own elaboration.

Table 1
PV micro energy projects at national level. Own elaboration.

Department	Installed capacity < 5 kWp	Participation
Antioquia	10.9	22%
Bolívar	8.5	17%
Cúcuta	6.36	13%
Aguachica-Cesar	0.5	1%
Valle del cauca	7.2	15%
Norte de Santander	5.38	11%
Atlántico	2.3	5%
Bogotá	7.63	16%
TOTAL	**48.77**	**100%**

departments at a national level have participated with photovoltaic power projects, from which Atlántico, Cundinamarca, Valle del Cauca and Antioquia are the departments with the largest projects in photovoltaic systems for electric power generation. Cundinamarca and more exactly Bogotá, participates with a total of 865 kWp of installed capacity, with a total of 9.050 solar panels installed in different types of infrastructures, from recreational to educational.

The photovoltaic development of the SIN is present in 15 departments, from which 60% are categorized as medium and small photovoltaic projects with installations smaller than 100 kWp. First, Cartagena (Bolivar) presents a total assembly of 356 PV modules equivalent to 86.94 kWp. Quindío registers a capacity of 38 kW installed, followed by Vichada with 27.18 kWp. Then, departments such as La Guajira and Huila with 16.65 kWp. Meta, Córdoba and Casanare have an installation of less than 10 kWp but higher than 5 kWp. Montería (Córdoba) implemented a solar system of 16 PV modules with a production of 3.2 kWp.

Similarly, micro scale projects under 5 kWp are highlighted in the SIN. Table 1, lists the departments where micro-energy projects have been installed. The highest participation is observed in Antioquia and Bolivar with 22% and 17% respectively. Antioquia presents two projects built in the academic field. The Universidad Pontificia Bolivariana - campus Laureles installed solar panels equivalent to a total installed power of 4.9 kWp, and The EAFIT University presented the installation of a parasol for computer or mobile connections. Bolivar presents installations in a private context with a total of 8.5 kWp installed.

3.1.1. Cundinamarca

The department of Cundinamarca has a total of 737.38 kWp installed capacity in the interurban area and the capital city of Bogotá. There are two outstanding solar implementations installed in recreation centers and supermarkets that are considered as macro projects. The largest facility can be found in the supermarket Alkosto Avenida 68, located in the north-eastern area of Bogotá, which presents an installed capacity of 268.5 kWp generated by 1.053 PV modules [33] Fig. 4(a). The second solar installation in Bogotá is built in Plaza de las Américas Shopping Center, with an installation of 810 PV modules in an area of 1.020 m^2, producing approximately 24 MW h per month.

In the educational context, the Ramon Jimeno District School has implemented a photovoltaic project with an installation of 148 PV modules (35.5 kWp). Similarly in 2013 in the municipality of Chia, the Rochester School developed a photovoltaic solar system of 19.74 kWp connected to the grid, obtaining an average return of 4.46 kW h/kWp/day. The Jorge Tadeo Lozano University in its 33 m^2 solar roof presents 24 PV modules with an installed power of 6 kWp [34]. In the same way, the EAN University joins the group of energy generation from photovoltaic systems presenting in 2016 an installation of 25 PV modules, with an installed capacity of 7.75 kWp [35] Fig. 4(b).

In connection with the private entities, Autogermana car dealership has installed a solar photovoltaic system of 20 kWp connected to the grid on the roof of the building. This project has a total of 80 PV modules of 250 Wp. On the other hand Codensa, the energy company in

(a) (b)

Fig. 4. Solar PV installation in Bogotá. (a) Alkosto (b) EAN University. Own pictures.

Bogotá, has proposed a photovoltaic solar system of 42 kWp, this one has a total of 168 panels of 250 Wp and its projected annual generation is 50.75 MW h/year [36].

In the area of service centers with installed capacities between 10 and 40 kWp, the restaurant La Fama located in the north-eastern part of Bogotá can be presented with a small photovoltaic system of 1.8 kWp connected to the grid. In a like manner, the Technological School of the Central Technical Institute presents a photovoltaic solar system of 22.44 kWp, generating 33.37 MW h/year. The José Celestino Mutis Botanic Garden has a solar photovoltaic system of 39 PV of 245 Wp. In Tocancipá, the interurban zone has a facility with 28 solar lamps of 33 W and 16 reflectors of 22 W, with a solar potential of 12.69 kWp installed; this energy production connected to the grid is used in the Armed Forces Ancient Museum building for the lighting and electricity of the grounds. Finally in Medina, there is a solar powered system for the electrification of the departmental educational headquarters in La Mesa de los Reyes with an installed solar power of 1.470 Wp.

In educational centers in Cundinamarca and Bogotá, low development in this type of energy is registered, despite the fact that academic institutions are an important training line in the axis of a society. On the contrary, greater investments in the field of Renewable Energies are perceived in private entities.

3.1.2. Atlántico

In the department of Atlántico there is a total of 865 kWp installed. The first project belongs to the supermarket Éxito Panorama with a roof installation of 2.070 PV modules built on an area of 6300 m^2 (Fig. 5). This facility has a total capacity of 507 kWp. The second plant is the one from the company Autonorte-Barranquilla with 400 PV modules with a solar potential of 100 kWp injected to the grid. The third and last private project is identified as a solar photovoltaic system of 12 kWp connected to the grid, for a total of 48 panels of 245 Wp [37].

Fig. 5. Solar panels installation – EXITO Store.

3.1.3. Valle del Cauca

In Valle del Cauca whose capital Cali is considered the third largest city in the country, they have assembled 1.190 PV modules, for a total of 246 kWp installed in its entirety. These are concentrated in 8 projects executed between 2010 and 2016, in academic and recreational buildings, among others. The largest photovoltaic installation in this city corresponds to the one made by the Universidad Autónoma de Occidente, which in 2015 installed 638 PV modules being a system of 127.6 kWp output, producing approximately 15.000 kW h monthly average [38]. Also, supermarkets Alkosto installed 516 PV modules in an area of 750 m^2, with a capacity of 118 kWp. In the interurban area-municipality of Yumbo, a photovoltaic plant of 294 PV modules is installed by the Pacific Energy Company (EPSA by its abbreviation in Spanish), which produces approximately 6.227 kW h/month [39]. In the municipality of Buenaventura, the fishermen's association PIMPESCA from the Cajambre River installed a solar system that allows the operation of lighting, computers and refrigeration by means of the implementation of 10 solar freezers with a solar power of 8 kWp.

3.1.4. Antioquia

The second largest department in the country has a total capacity of 138.9 kWp in photovoltaic systems within the various projects in both the capital and the inter-urban area. In the regional sector of Girardota, 184 PV modules have been installed, from which the motorcycle company Incolmotos Yamaha has placed 144 PV modules with a total solar power of 36 kWp connected to the grid. This infrastructure expects to have a capacity of 44 MW h, avoiding an emission of 11.95 t of CO_2/year due to its use and utilization.

3.1.5. Norte de Santander

Norte de Santander is located in the northeastern part of the country. This department presents a solar radiation of 4.0–4.5 kW h/m^2 and projects have been developed only in its capital city Cúcuta. Solar systems were installed in several private centers in the city. In conclusion, there are a total of 399 PV modules implemented, equivalent to a total capacity of 108.8 kWp. Sixty percent of the facilities are private.

3.2. Projects in ZNI

Most of the executed projects are carried out by the Institute for Planning and Promoting Energy Solutions for Non-Interconnected

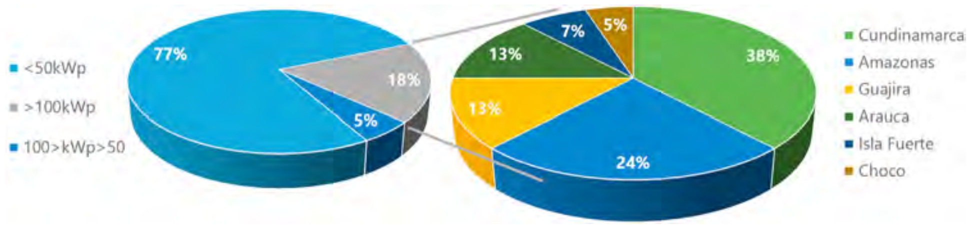

Fig. 6. ZNI installed capacity. Own elaboration.

Zones (IPSE for its abbreviation in Spanish). The disadvantages of working in the ZNIs are attributable to a poor implementation to the distribution network in these interconnection areas, due to its construction and operation costs. In the last decade, there is a total of photovoltaic development of 2.25 MWp in ZNIs in 23 departments. Fig. 6. Shows that 18% of the executed projects correspond to solar fields greater than 100 kWp, and 77% to projects smaller than 50 kWp.

The macro projects in ZNI with installed capacities greater than 100 kWp are located in the departments of Cundinamarca, Amazonas, Guajira, and Arauca (Fig. 6). An example, Nazareth and Puerto Estrella (Department of Guajira), exhibit a solar garden installed by the IPSE [40]. This is a solar-Diesel hybrid system for the generation of electric energy made from the layout of 1.200 PV modules with a capacity of 320 kWp and eight solar trackers with a total installed capacity of 100 kWp (Fig. 7[a] and [b]). Isla Fuerte is represented with 7% of the installed capacity in ZNI in Colombia, with a photovoltaic installation of 175 kWp respectively. Cundinamarca, which is a department belonging to the ZNI and SIN, observes a priority development with a total of 981 kWp installed, being 90% of the executions in Yacopi (Cundinamarca).

Regarding small projects, development can be observed in several departments such as La Guajira with the SENA program in Fonseca region, with the installation of PV modules for a solar pumping and cooling system (1.35 kWp). At the same time, the Foundation of Cerrejón Guajira has developed a solar system for water pumping with an installed solar capacity of 740 W. On the other hand, the IPSE made a photovoltaic installation of 40 kWp in the most populated island in the world called Santa Cruz del Islote with a population of about 493 inhabitants in an area of extension of 0.01 km^2 (Fig. 8[a] and [b]).

Table 2 shows the relation of photovoltaic projects in the ZNIs. Fifty-two specific projects in 19 departments are presented here, with a total of 2.8 MWp installed. The relationship between surface area, population and photovoltaic capacity installed in each department is analyzed, which promotes an energy development of 34%, 22%, and 12% in the departments of Cundinamarca, Amazonas, and Guajira respectively.

Amazonas is the department with the largest area in Colombia (100.000 km^2); its population is below 100.000 inhabitants and has an average radiation of 3.5–4.0 kW h/m^2. It occupies the second position in solar photovoltaic installations and it currently has an installed capacity of 611.9 kWp. Antioquia is the third department with the largest number of inhabitants (6.534.764), it is reported that in ZNI there is a low photovoltaic development (75.74 kWp).

Taking into account that Colombia is mostly a desert area, what was presented above confirms the deficit of photovoltaic development in the ZNIs, that underutilize the solar resource and the great territorial extension.

4. Future picture of the solar energy

The energy transition that Colombia is going through with the change to non-conventional renewable energy as the main means of energy production is beginning to gradually reduce the use of fossil fuels and coal. According to the UPME, by 2020 it aims to achieve up to 30% of energy contribution with non-conventional renewable alternatives. According to the National Energy Balance, 67% of the energy consumption comes from fossil sources, 13% biomass and 20% corresponds to the consumption of electric energy. Current electricity demand is approximately 61.684 GW h/year.

Recognizing that photovoltaic technology is the most viable for ZNI zones because of the average radiation in Colombia, it is recognized that there is a deficit at the National level, inasmuch as less than 3% of the population is supplied with this type of energy. It is important to know that more than 40% of the population does not have good quality services nor constant electricity, and receive only 4 h of energy services per day coming from Diesel plants (98%) and a low percentage of renewable energies (1.2%).

Fig. 9. Presents the installed photovoltaic capacity (kWp) by department in Colombia. This is specified in ZNI and SIN. The figure confirms that 50% of the country does not have any renewable solar development (southern area of Colombia). There is a continuous development in the central area of the country (Bogotá), Atlantic coastal zone and Pacific sector. La Guajira, department that presents the highest radiation at national level with 5.5–6 kW h/m^2 has a low level of development in photovoltaic solar technology, despite its great extension in surface that is 20.848 km^2.

(a) (b)

Fig. 7. PV installation and solar trackers. Nazareth and Puerto Estrella Towns, Guajira Department. (a) PV installation, (b) Battery store. Own pictures.

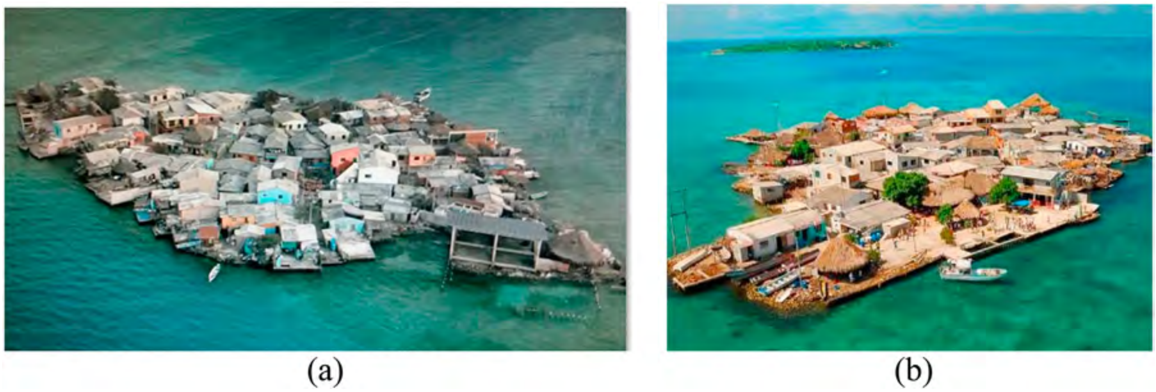

Fig. 8. Solar PV installation. Santa Cruz del Islote, Bolivar Department.

Fig. 9. Presents the country's inventory of solar photovoltaic projects up to 2017. Together with the online map of each project, they present a perfect overview of the conditions of the country for foreign investments and possible projects in areas with low electricity coverage and high generation costs as a result of the use of Diesel.

There are different future energy visions in Colombia, the document Expansion Plan of the Generation-Transmission Reference (2015–2029), which was prepared by UPME, proposes eight possible scenarios from the energy generation matrix of the country. These specify that between 4.208 and 6.675 MW of expansion are required for the next decade. An alternative scenario shows a solution with all types of primary energy sources, both conventional and non-conventional, indicating that wind and coal are the ones that would provide greater energy capacity, directly 1.000 and 1.200 MW. Solar energy in the latter is presented on a small scale.

The lack of vision and regulation until recently of this type of energies in Colombia was possibly due to the technical barriers that influence the low conversion efficiencies of the photovoltaic modules, to the current limitations in the performance of the components of the system such as batteries, the lack of logistics experience in the ZNI, the lack of energy policies, the little experience in the photovoltaic sector and the disbelief in this type of systems by companies in general. The storage system in off grid projects is the most important concern. However, it is important to identify the vulnerability of the country to climate change or as evidenced from 2010 to 2011, in the face of the La Niña phenomenon, leaving more than three million people affected, about 7% of the national population [23].

Recognizing wind as part of the renewable energy matrix to be developed in Colombia, it is seen as a strong option for the country. This is by reason of the decreasing costs of this type of technology and the excellent wind potential in some areas of the country [41]. Wind would be an excellent complementary technology in the SIN, especially in the Atlantic coast where the problems of electricity generation are very high.

Regarding the vision or perspective of Law 1715 (2014) and its current regulation, the law offers tax incentives, valorization schemes for surplus energy of self-generation systems at a small-scale, as well as the identification of easy access procedures to the legal incentives and their promotion by means of actions planned by public entities.

Regarding Law 1715 of 2014, it covers public and private agents, provided they intervene in the definition of sectoral policies in the development and use of non-conventional sources of energy. This Law promotes the development of unconventional sources of energy, exactly on renewable energies, for a sustainable economic development, greenhouse gas emissions and the security of energy supply, through the integration to the electricity market, its participation in the non-interconnected areas and other energy uses. This is done as a result of tax incentives, schemes for valuing surplus energy from small-scale self-generation systems, as well as, identification of easily accessible procedures for Law incentives and their promotion through actions planned by public entities.

The present law allows the fulfillment of Colombia in terms of renewable energies, efficient energy management and reduction of greenhouse gas emissions, thus it will have as its purpose.

- Encourage the inclusion of unconventional sources of energy in the Colombian energy system.
- Establish cooperation and coordination mechanisms between the public sector, the private sector and users for the development of unconventional sources of energy.
- Through national, departmental and municipal entities, development of programs and policies for the promotion of renewable energies.
- Encourage investment, research and development for the production and use of renewable energy.
- Establish the legal regulations to establish national strategies in order to contribute to this law.
- Guide public policies and define the tax, accounting and participation instruments in the Colombian energy market.

The perspective of the National Development Plan is to prioritize royalty resources from the science, technology and innovation sector of the departments, municipalities and districts that will be used for the development and use of Non-Conventional Renewable Energy Sources [19].

Today, successful cases are perceived in terms of the generation of renewable energies in Colombia, large production companies, educational institutions, non-profit foundations, among others, opted for self-generation and cogeneration of alternative energies. This is due to Law 1715 of 2014, generating approximately 85% of the energy it consumes and delivering to the SIN about 30 MW, which, added to the savings in the facilities, implies 10% of the national savings target [19]. The UPME and the Ministry of Mines and Energy have demonstrated the profitability with this policy. According to UPME, the cost of implementing the incentives set forth in Law 1715 of 2014 would be 554 million dollars, with a benefit of 775 million dollars in the economic aspect, but in turn, there will be social and environmental benefits such as the reduction of emissions and lower impacts on health. All of the above in the next fifteen years (2032) [19].

5. Conclusions

Due to the existing institutional policies in the country, it can be inferred that in light of the investment deficit by public entities regarding renewable energies and incentives to promote its use, there is a shortage in the execution of photovoltaic projects in the SIN. It is identified that 70% of the projects executed at the macro and micro level are owned by private entities mostly located in the Atlantic, where

Table 2
Micro PV projects in ZNIs.

Department	Area (km^2)	Population (inhabitants)	Community	Installed capacity Wp
Guajira	20.848	985.498	Nazareth - Puerto Estrella	325.000
			Maicao-Manaire -Uribia	800
			Comunidad Wayuu	1.960
			Comunidad Ishipa Wayuu	240
			Fonseca (Sena)	1.350
			Manaure (Centro de Salud)	580
			Fundación Cerreón Guajira	740
Antioquia	63.612	6.534.764	Municipio Andes (Santa Rita)	540
			Centros educativos rurales	59.000
			Municipio Ituango	12.500
			Puerto Berrío	3.000
			Porce III	700
Meta	85.635	979.683	Municipio Puerto Gaitan	15.200
Guainía	72.238	42.123	Municipio San Felipe	8.310
Cauca	29.308	1.391.889	Vereda El Cerrito, Piamonte	3.250
			Santa Rosa, Timbiquí	2.500
Chocó	46.530	505.046	Nuquía	9.000
			Unguía	86.940
			Municipio Titumate	16.560
Córdoba	23.98	1.736.218	Lórica	2.340
Sucre	10.670	859.909	Puerto Verrugas	525
Bolivar	25.978	2.122.021	Carmen de Bolívar (El Salado)	220
Magdalena	23.188	1.272.278	Etnia indígena Kogi Dumingeka	13.760
			Comunidad Kankawarwa	12.000
			comunidad indígena Arhuaca Kantinurwa	6.670
			Comunidad Simonorwa	7.000
Guaviare	53.460	112.621	Municipio Calamar	2.400
			Municipio San José	3.900
Cundinamarca	24.210	2.721.368	Paratebueno	1.440
			Caparrapi y la Peña	1.920
			Ubalá	18.000
			Yacopi	960.000
Amazonas	109.665	77.088	San Martin de Amacayacu, Macedonia, Puerto Nariño	121.000
			Macedonia	165.000
			Puerto Nariño	308.000
			Resguardo Mocagua	8.200
			Resguardo Santa Sofía	9.700
Islas	–	–	Isla Múcura	30.000
	26	68.283	Isla San Andrés	25.000
	3		Isla Fuerte	175.000
	0.01	493	Santa Cruz el Islote	40.000
	17	5.140	Isla Santa Catalina y Providencia	8.000
Vichada	100.242	73.702	Puerto Carreño	20.000
			Camaribo	7.080
Norte de Santander	21.658	1.367.716	Chinacota	3.000
			Villa del Rosario	3.000
			Salazar de las palmas	2.100
			Todelo	1.800
Valle del Cauca	22.195	4.660.438	Comunidad de San Antonio	15.000
			Sevilla (Fincas la Sirena y la Risaralda)	1.560
Santander	30.537	2.071.016	Barbosa	1.000
Arauca	23.818	265.190	Municipio Arauca y Puerto Rondón	318.000

high radiation is present. In like manner, it is evident that the projects executed by public entities do not present a process of maintenance or monitoring over time, which affects the sustainability of these facilities.

Photovoltaic development in Colombia is of 5.28 MW installed between Non-Interconnected Zones and zones belonging to the National Interconnected System, with a greater development in the Bogotá Capital District (Bogotá D.C.), considering that it is a zone of low solar radiation, but of high economic capacity.

There is a low development of solar infrastructure in the educational facilities, although they should be an example of both formative and photovoltaic execution in the axis of a sustainable society.

Colombia is mostly a desert region with high levels of solar radiation, this characteristic and what has been presented above confirms the deficit of photovoltaic development in the ZNI that waste the solar resource and the great territorial extension.

A deficit is identified in the three elements that allow photovoltaic development in a country: politics being the first, seen from the legal framework, elimination of barriers, proposals, and incentives, among others. The research as second, seen from the efficiency energy, saving and technological development. Finally the monitoring, which allows, to maintain in real time how much project evaluating the achievements based on error and success.

Fig. 9. ZNI and SIN PV projects by departments. Own elaboration.

References

[1] Hussain A, Arif SM, Aslam M. Emerging renewable and sustainable energy technologies: state of the art. Renew Sustain Energy Rev 2017;71:12–28.

[2] Buga A, Zaborowicz M, Boniecki P, Janczak D, Koszela K, Czeka W, et al. Short-term forecast of generation of electric energy in photovoltaic systems. Renew Sustain Energy Rev 2018;81:306–12. [July 2017].

[3] Gonçalves P, Sampaio V, Orestes M, González A. Photovoltaic solar energy: conceptual framework. Renew Sustain Energy Rev 2017;74:590–601. http://dx.doi.org/10.1016/j.rser.2017.02.081. [December 2016].

[4] Masson G, Brunisholz M. 2016 Snapshot of Global Photovoltaic Markets [Iea Pvps T1-312017]. 2017. p. 1–16.

[5] Guo X, Guo X. China's photovoltaic power development under policy incentives: a system dynamics analysis. Energy 2015;93:589–98.

[6] Zhang MM, Zhou DQ, Zhou P, Liu GQ. Optimal feed-in tariff for solar photovoltaic power generation in China: a real options analysis. Energy Policy 2016;97:181–92.

[7] Ahmed S, Mahmood A, Hasan A, Sidhu GAS, Butt MFU. A comparative review of China, India and Pakistan renewable energy sectors and sharing opportunities. Renew Sustain Energy Rev 2016;57:216–25.

[8] Sahoo SK. Renewable and sustainable energy reviews solar photovoltaic energy progress in India: a review. Renew Sustain Energy Rev 2016;59:927–39.

[9] Manju S, Sagar N. Progressing towards the development of sustainable energy: a critical review on the current status, applications, developmental barriers and prospects of solar photovoltaic systems in India. Renew Sustain Energy Rev 2017;70:298–313.

[10] Aliyu AK, Modu B, Tan CW. A review of renewable energy development in Africa: a focus in South Africa, Egypt and Nigeria. Renew Sustain Energy Rev 2017:1–17. http://dx.doi.org/10.1016/j.rser.2017.06.055. [February 2016].

[11] Ferreira A, Kunh SS, Fagnani KC, Souza TA De, Tonezer C, Rodrigues G, et al. Economic overview of the use and production of photovoltaic solar energy in brazil. Renew Sustain Energy Rev 2018;81:181–91. http://dx.doi.org/10.1016/j.rser.2017.06.102. [April 2016].

[12] Morales S, Álvarez C, Acevedo C, Diaz C, Rodriguez M, Pacheco L. An overview of small hydropower plants in Colombia: status, potential, barriers and perspectives. Renew Sustain Energy Rev 2015;50:1650–7.

[13] Hernandez JA, Velasco D, Trujillo CL. Analysis of the effect of the implementation of photovoltaic systems like option of distributed generation in Colombia. Renew Sustain Energy Rev 2011;15(5):2290–8.

[14] DANE. DANE; 2017. [Online]. Available: 〈http://www.dane.gov.co/〉.

[15] Vides-Prado A, Ojeda E, Vides-Prado C, Herrera I, Chenlo F, Candelo J, et al. Techno-economic feasibility analysis of photovoltaic systems in remote areas for indigenous communities in the Colombian Guajira. Renew Sustain Energy Rev 2017. http://dx.doi.org/10.1016/j.rser.2017.05.101.

[16] Haghighat A, Alberto S, Escandon A, Naja B, Shirazi A, Rinaldi F. Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. Renew Energy 2016;97. http://dx.doi.org/10.1016/j.renene.2016.05.086.

[17] Jimenez M, Franco CJ, Dyner I. Diffusion of renewable energy technologies: the need for policy in Colombia. Energy 2016;111:818–29. http://dx.doi.org/10.1016/j.energy.2016.06.051.
[18] Aguirre-mendoza AM, Díaz-mendoza C, Pasqualino J. Renewable energy potential analysis in non-interconnected islands. case study: Isla Grande, Corales del Rosario Archipelago, Colombia. Ecol Eng 2017:0–1. http://dx.doi.org/10.1016/j.ecoleng.2017.08.020. [December 2016].
[19]. Acto Legislativo 005 de 2011. Proyecto de Acto Legislativo N° 155 de 2017 Cámara.
[20] MdEyMd Colombia. Atlas de Radiacion Solar de Colombia; 2005.
[21] IDEAM, SOLAR ATLAS; 2017. [Online]. Available: ⟨http://atlas.ideam.gov.co/visorAtlasRadiacion.html⟩.
[22] Radomes AA, Arango S. Renewable energy technology diffusion: an analysis of photovoltaic-system support schemes in Medellín, Colombia. J Clean Prod 2015:2009. http://dx.doi.org/10.1016/j.jclepro.2014.12.090.
[23] World energy council. World Energy Trilemma Index|2017; 2017.
[24] UPME and Ministerio de Minas y Energía. Plan Energetico Nacional – Colombia: Ideario Energético 2050; 2015.
[25] Congreso de Colombia. LEY 629 DE 2000; 2000, p. 85.
[26] Congreso de Colombia. LEY 697 DE 2001; 2001.
[27] Congreso de Colombia. Ley 855 de 2003; 2003.
[28]. Congreso de Colombia. Ley N° 1715 del 13 de mayo de 2014, no. May. Upme; 2014, p. 26.
[29] Ministerio de Minas y Energía. Decreto 348. Bogotá; 2017.
[30] Ministerio de Minas y Energía. Resolution 030 CREG; 2018. [Online]. Available: ⟨http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/83b41035c2c4474f05258243005a1191?OpenDocument⟩, [Accessed 07 March 2018].
[31] UPME and BID. Integración de las energías renovables no convencionales en Colombia; 2015.
[32] Gonçalves P, Sampaio V, Orestes M, González A. Photovoltaic solar energy: conceptual framework. Renew Sustain Energy Rev 2017;74:590–601. http://dx.doi.org/10.1016/j.rser.2017.02.081. [December 2016].
[33] UPME. Panasonic Project; 2016. [Online]. Available: ⟨http://www1.upme.gov.co/sgic/?q=content/panasonic-lanzó-uno-de-los-proyectos-más-importantes-de-energía-limpia-en-bogotá⟩.
[34] Tadeo University Project; 2014. [Online]. Available: ⟨http://www.utadeo.edu.co/es/noticia/destacadas/home/1/la-energia-limpia-activa-la-tadeo⟩.
[35] Portafolio; EAN University Project; 2016. [Online]. Available: ⟨http://www.portafolio.co/negocios/empresas/lg-colombia-trae-paneles-solares-alta-eficiencia-494129⟩.
[36] Codensa MA. Memoria Anual Codensa 2014; 2014.
[37] UPME. Éxito Project; 2016. [Online]. Available: ⟨http://www1.upme.gov.co/sgic/?q=content/grupo-%C3%A9xito-invirti%C3%B3-2000-millones-en-su-primera-planta-fotovoltaica⟩.
[38] University UAO. UAO Project; 2015. [Online]. Available: ⟨http://www.uao.edu.co/noticias/sistema-solar-fotovoltaico-uao⟩.
[39] CELSIA-EPSA. Laboratory EPSA; 2017. [Online]. Available: ⟨http://portal.epsa.com.co/nosotros/sala-de-prensa/notas-especiales/epsa-puso-en-operación-el-laboratorio-solar-más-grande-de-colombia⟩.
[40] Rodríguez-Urrego L, Valencia-Llanos J, Rodríguez-Urrego D, Martínez-García A. Design, implementation and operation of a solar hybrid system in a remote area in the Colombian Guajira desert. WIT Trans Ecol Environ 2015;195(31):427–38.
[41] Ministerio De Minas y Energía. Velocidad del viento en superficie. Atlas Viento y Energía Eólica Colombia. 2006;32:19–34.