An Overview of the Colombian Power System

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Abstract—**The Colombian power system is facing a transition from hydro-thermal generation to a diversified mix of hydro, solar, and wind energy. This paper presents an overview of the current situation and the challenges of transitioning to a more sustainable power system. This review includes data up to June 2022 about the level of renewable power generation and the introduction of modern technologies such as hydrogen and electric vehicles.**

Keywords—**Electric vehicles, FACTS, hydropower, national grid, storage energy, wind energy.**

I. Introduction

OVER the last 20 years, the electricity demand in Colombia has grown by an average of 5% per year. By the end of 2021, the energy consumption was around 6500 GWh, with an average of 70.4% of electricity consumption for residential users and small businesses. The total generation capacity was 17.6 GW, with 67% hydroelectric, although considerable investments are expected in non-conventional renewable energies such as wind and solar. In addition, 2 GW of hydroelectric are expected with the entry into operation of Hidroituango [1].

In this context, the electricity sector in Colombia is mainly clean. However, it is heavily vulnerable to weather conditions, especially the El Niño-Southern Oscillation (ENSO), a climate pattern with unusual warming of surface waters in the eastern equatorial Pacific Ocean. This natural phenomenon produces dry seasons that drastically reduce the levels of reservoirs. Therefore, a central challenge of the system is to diversify the energy mix to reduce this vulnerability [2].

This paper presents a general overview of the current situation of the Colombian power systems and the challenges and expectations for implementing new technologies. The paper is organized as follows: Section II presents a general overview of the current situation. The system is divided into connected and non-connected zones. Each of these zones has different challenges and characteristics. Next, Section IV presents the current situation related to renewable energies. This section includes the leading technologies currently in use, although other technologies may be included in the future. After that, smart grid technologies such as energy storage and flexible AC transmission devices (a.k.a., FACTs) are presented in Section V. Electric vehicles and hydrogen are also technologies that are standing out in the future.

All the information presented here is public. Maps, tables, and figures are taken from official documents, cited in each case. The study carried out in this work is important because it exposes in a specific way the panorama of the Colombian electrical system, through the revision of the generation matrix, transmission system, and compensation technology, in addition to showing at an international level the roadmap in generation projects that show Colombia's commitment to the decarbonization of the electric power generation matrix, on the other hand, allows the global scientific community to focus attention on the development of projects that contribute to the development of technology to control and operate stably and safely electrical power systems with medium but varied diversity in the penetration of renewable energies.

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II. General overview

A. Colombian grid

The Colombia National Transmission System (NTS) includes transmission lines, compensators, substations, and interconnection equipment operating between 220 kV and 500 kV. There are more than 24000 km of transmission lines connecting the most populated areas [3]. There is also a strong interconnection with Ecuador and a weaker interconnection with Venezuela. It is expected that a new interconnection with Panama using high-voltage direct current (HVDC) technology will be created soon. Figure 1 shows the main national and international interconnections.

B. Non connected zones

Most places in Colombia have an electrical utility. However, around 1700 small towns with about 128587 inhabitants do not have 24-hour power; they usually have partial service with diesel generation that operate only 4 to 6 hours per day. These towns are distributed in a large portion of the territory, although they correspond to only 0.3% of the country's inhabitants. Despite being a small number, the development of these towns is critical for Colombia's development after signing the peace agreement. Electrification of these zones is challenging due to the large distances required to bring the interconnected power system to these places. In addition, the low number of inhabitants makes it non-viable economically to build large power stations. Therefore, microgrids are a promising solution. A growth based on diesel plants is neither economically nor environmentally viable; these remote towns are in the mountains and close to rainforests. Therefore, they have a low potential for wind energy, but a high potential for small hydropower and solar energy. Battery energy storage is also required, since solar energy's peak may differ from the peak load.

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Fig. 1. National interconnection in Colombia. Taken from Generation-transmission reference expansion plan 2015-2029 [3] (generation-transmission expansion plan).

III. Renewable energies

The planning of the generation system is the responsibility of the *Unidad de Planeamiento Minero Energetico* UPME (Energy and Mining Planning Unit), which indicates the power levels required to supply the demand for electrical energy (expected and actual) in the entire country. This task is carried out considering factors such as energy and power demand projections, the feasibility of entering new generation plants, environmental forecasts, and oil prices, among others. Possible scenarios are analyzed, including system restrictions, comprehensive information on current and future electrical infrastructure, and information on the development of projects under construction. A review of the generation transmission expansion plan 2020 – 2034 [4] provides 14 scenarios that consider the total or partial income of what will be the largest hydroelectric plant in the country, called Hidroituango. In this document, the available capacity for expansion in generation by technology is initially exposed at the end of 2019 and defined in projects that are advanced in their study stage and fixed expansion projects, see Tables I and II, respectively.

Notably, there is a high generation potential made up of diverse sources, among which the following stand out for their greater potential: solar, wind, hydraulic and thermal generation sources. On the other hand, the generation matrix in Colombia currently has an installed capacity of 17768.05 MW, made up of the plants shown in Table III. A review of each type is presented below.

TABLE I
Expansion capacities by technology defined from projects (phase 1 and 2) registered in the UPME.

Technology	Rated Capacity [MW]
Biomass	34.9
Coal	1110
Wind	2536
Gas	329.9
Geothermal	50
Hydro High	1106
Hydro Small	595.1
Solar	5122.8
Co-generation	120
Total	**11005.2**

TABLE II
Fixed expansion projects.

Name	Type	Capacity [MW]	Location
El paso solar	Solar	68	Cesar
Ituango	Hydro	1200	Antioquia
Alpha	Wind	212	La Guajira
Beta	Wind	280	La Guajira
Windpeshi	Wind	200	La Guajira
La loma	Solar	150	Cesar
Termocaribe 3	Thermal	42	Bolivar
Termocandelaria	Thermal	252	Bolivar
El tesorito	Thermal	199	Córdoba
Termoyopal G3*	Thermal	50	Casanare
Termoyopal G4*	Thermal	50	Casanare
Termoyopal G5*	Thermal	50	Casanare
Termo Jagüey	Thermal	19	Casanare
Termo Rubiales	Thermal	19	Meta
Termosolo 2	Thermal	80	Valle del Cauca
Campano	Solar	99	Córdoba
Apotolorru	Wind	75	La Guajira
Cartago	Solar	99	Valle del Cauca
San Felipe	Solar	90	Tolima
Casa eléctrica	Wind	180	La Guajira
Kuisa (Tumawind)	Wind	200	La Guajira
Chemesky(Urraichi)	Wind	100	La Guajira
Irraipa	Wind	99	La Guajira
Carrizal	Wind	195	La Guajira
Ipapure	Wind	201	La Guajira
Camelias	Wind	250	La Guajira
Acacia 2	Wind	80	La Guajira
Termosolo 1	Thermal	148	Valle del Cauca
Enr Col 1	Solar	120	La Guajira
Tayrona	Solar	76	La Guajira

A. Solar

The usable potential of solar energy is distributed throughout the national territory, ranging from 2.5 $\mathrm{kWh/m^2}$ to 6 $\mathrm{kWh/m^2}$. The areas with the greatest potential are in the north, as shown in Figure 2. So, large solar power plants are located

TABLE III
EFFECTIVE CAPACITY BY GENERATION TYPE.

Type	Net effective capacity [MW]
Co-generator	192.5
Wind	18.42
Hydro	11942.79
Solar	145.6
Thermal	5468.74
Total net effective capacity	**17768.05**

TABLE IV
CUMULATIVE CAPACITY OF CURRENT PROJECTS BY STATE, SOLAR-TYPE POWER RANGES [7].

Range [MW]	Phase 1	Phase 2	Total
0 - 1	0.76		0.76
1 - 10	211.03	574.2	785.23
10 - 20	331.74	610.59	942.33
20 - 50	80	98	178
50 - 100	987.2	2724.98	3712.18
Greater than 100	1049.30	5045.55	6094.85
Total	**2660.03**	**9053.32**	**11713.35**

in that region of the country, in addition to three plants located in the department of Meta in the center of the country which each has 19.9 MW of net effective capacity, which contributes to the 145.6 MW installed capacity for solar generation that represents 0.82% of the total installed capacity [5].

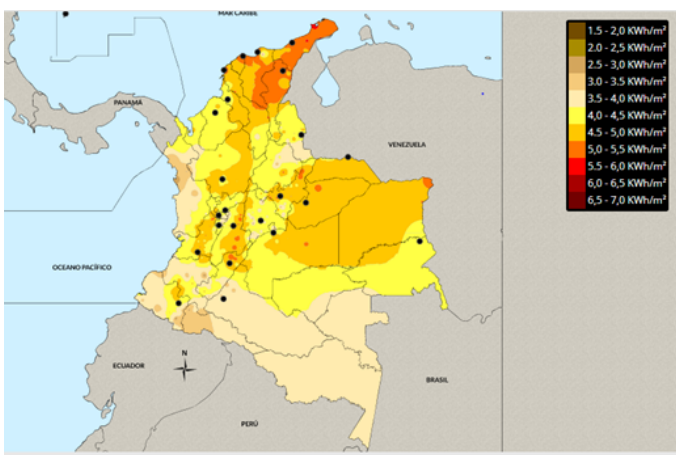

Fig. 2. Solar radiation atlas of Colombia [6].

Although this percentage is small, it is expected to increase as the expansion plan develops, which shows promising scenarios according to the latest report published on the website of the planning entity [7], see Table IV.

The phases related to the project status are described below [8]:

- Phase 1- prefeasibility study: Technical-economic analysis of investment alternatives for project development.
- Phase 2- Feasibility study: The best alternative identified in the prefeasibility stage is refined and specified, that is, the studies are deeper and more complete than the previous phase.
- Phase 3- Detail engineering study: Definition level which allows the project execution.

B. Wind

As in the case of solar generation, the *Instituto de Hidrología, Meteorología y Estudios Ambientales* IDEAM (Institute of Hydrology, Meteorology and Environmental Studies) has registered the distribution of wind potential throughout the national territory. Figure 3 shows the magnitude of the wind speed at 50 m, where the most significant potential is centered again in the northern part of the country, specifically in the departments of Atlántico and Magdalena, where wind speeds can reach values greater than 15 m/s. In this type of generation, Colombia lags behind other countries in the world [9] since it only has one wind farm with a total capacity of 18.42 MW, made up of 15 wind turbines of 1.3 MW located in the municipality of Uribia, on the Atlantic coast [5]. The installed wind generation capacity is small compared to the installed solar capacity in the same review period, representing 0.1% of the total capacity, but according to the expansion plan, it tends to rise. An example of this can be seen in the UPME generation project report application, where it is found that in the prefeasibility stage, there are 775.7 MW. In the feasibility stage, 3946.3 MW are under study, made up of 24 projects in the power ranges, as shown in Table V.

TABLE V
CUMULATIVE CAPACITY TABLE OF WIND-TYPE PROJECTS BY STATE AND POWER RANGES [7].

Range [MW]	Phase 1	Phase 2	Total
0 - 1	3		3
50 - 100	1	2	3
Greater than 100	4	14	18
Total	**8**	**16**	**24**

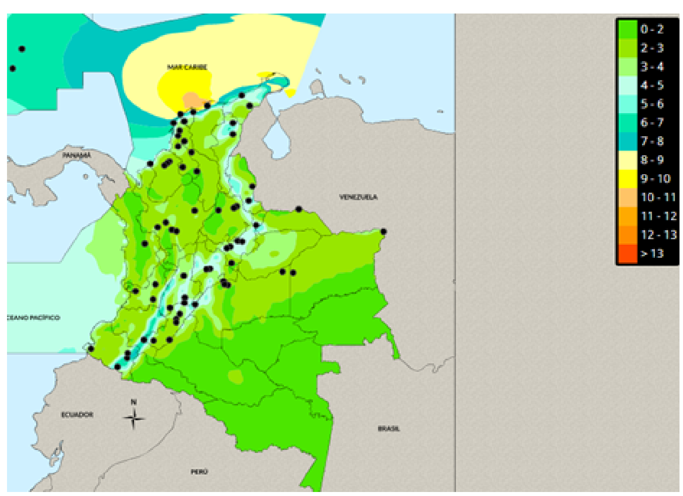

Fig. 3. Colombian wind speed atlas [6].

TABLE VI
TOTAL SUPPLY BY HYDROGRAPHIC AREA [10].

Hydrographic area	Total supply [Mm^3]	Average flow[m^3/s]
Caribe	200280	6350.8
Magdalena Cauca	273338	8667.4
Orinoco	533843	16928
Amazonas	728247	23092.5
Pacífico	287405	9113.5

TABLE VII
ACCUMULATED CAPACITY TABLE OF CURRENT PROJECTS BY STATE, POWER RANGES OF HYDRAULIC TYPE [7].

Range [MW]	Phase 1	Phase 2	Total
1 - 10	82.42	33.89	116.31
10 - 20	87.99	33.60	121.59
20 - 50	146	45	191.89
50 - 100	98	66	164
Greater than 100	460		460
Total	**875.3**	**178.49**	**1053.79**

C. Hydroelectric

Colombia is a country rich in water. Five large hydrographic areas make it up, and each of these areas offers very different volumes and flows, according to the national water study (ENA) carried out in 2018, where the most extensive offer in volume with 728247 Mm^3 can be found in the Amazon area where the average flows add up to 23092.5 m^3/s as can be seen in Table VI. From the above, the high use of water resources for electricity generation in Colombia is justified. 67.2% of the net capacity is obtained from around 150 small, medium and large-scale hydroelectric plants [5].

The use of this resource and the construction of hydroelectric power plants in the country continues to grow at all scales, since it is expected that around 1053.79 MW will enter the planning period as a result of 34 projects according to what is reported in the UPME report exposed in Table VII. This is an advantage for the electricity sector, but it could represent a challenge in terms of the operation and stability of the system, particularly if the aforementioned El Niño phenomenon were to occur.

D. Geothermal

Regarding geothermal resources, the geographical position of Colombia plays an important role since a part of the territory is located on the Pacific Ring of Fire, where the natural temperature gradients of the subsoil present high values, an example of this is current volcanic activity. Studies carried out show that the geothermal potential in Colombia is found in areas close to the volcanoes: Chiles, Cerro Negro, Cumbal, Azufral, Galeras, Doña Juana, Sotará, Puracé, Nevado del Huila, Nevado del Ruiz and Nevado del Tolima. As of 2014, Colombia did not have any power plant that took advantage of this resource for the production of electrical energy, it only had the study of 2 projects located in the Ruiz volcanic massif and in the volcanic influence near Ecuador [11].

TABLE VIII
ACCUMULATED CAPACITY TABLE OF CURRENT PROJECTS BY STATE, POWER RANGES OF BIOMASS TYPE [7].

Range [MW]	Phase 1	Phase 2	Total
1 - 10	1.06	4.8	5.86
20 - 50		25	25
Total	**1.06**	**29.8**	**30.86**

Today, given Colombia's commitment to the Paris Agreement, an energy transition plan has been developed that motivates the use of geothermal generation plants. This has begun with the start-up of a pilot plant in the department of Casanare with 100 kW of installed capacity, that will generate up to 72000 kWh of electrical energy, equivalent to the average consumption of 480 families in a month, and will allow an additional reduction of up to 550 tons of CO2e per year, the entry of two projects developed in the departments of Casanare and Meta by the companies is also expected. Parex and Ecopetrol, where hot water derived from oil drilling is used to produce electricity [12].

E. Biomass

Colombia has the potential for a diverse generation matrix in terms of generation type. Another renewable energy source used for energy use is biomass, derived from agricultural residues, livestock, methane sources, pruning residues, collection centers, and marketplaces [3]. In previous year, the participation of biomass in electricity production, according to reports from the Colombian electricity system operator [13], was 792.6 GWh, while in 2020, the contributions were 724.4 GWh, representing a growth of 9.4%, in the last two years. In the future scenario in Colombia, the generation of electricity using biomass as a primary resource expects the inclusion of 3 new projects in the short term that would add 30.86 MW of installed capacity to the generation matrix, according to the project report in Table VIII.

IV. SMART TECHNOLOGIES

A. Storage and FACTs Devices

Currently, the Colombian electrical system has 3 FACTS devices: an SVC (Static Var Compensators), a STATCOM (Static Synchronous Compensator), and a Series Compensator. The SVC is installed in the Chinú Electrical Substation is connected in parallel to generate or absorb reactive power in the northwestern zone of Colombia. It can absorb up to 150 MVA and generate 250 MVA and has 2 TSC (Thyristors switched capacitor), 2 TCR (Thyristors controlled reactor), and a group of filters as shown in Figure 4. This SVC was put into service in 1999, and to date, it has had two critical upgrades. By 2023 the complete renovation of its entire control system is expected.

In the San Marcos Substation in the southwest region, there are two TCSC (Thyristors switched capacitor) for the transmission lines Esmeralda-Yumbo 2 and Esmeralda Yumbo 3 at 230 kV. These circuits connect the Esmeralda and Yumbo Substations with a length of 130 km and a capacity of 350A,

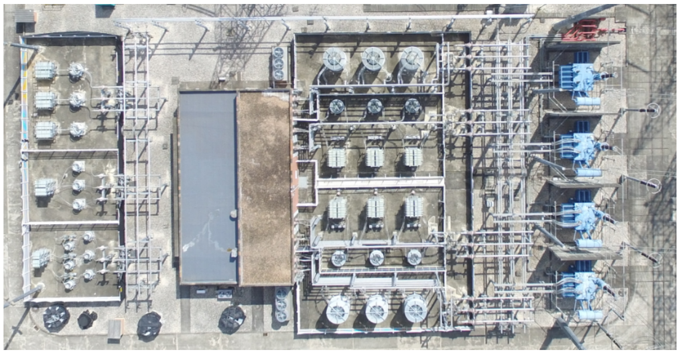

Fig. 4. SVC installed in Chinu electrical substation.

with series compensation. The power transmission capacity increased to 700 A since the series compensation reduces the impedance of the line by half. The TCSC was put into service in 1996 and updated in July 2015. Currently, UPME's expansion plan contemplates the incorporation of 3 more offsets to the north of the country.

In the center region of Colombia, the STATCOM (Static Synchronous Compensator), is at the Bacatá Electric Substation. This equipment operates at 500 kV and can absorb from 200 MVA and generate up to 200 MVA, this equipment is the most modern in the entire country, and its operation is primarily a reactive power source made up of converters, better known as VSC, STATCOM was put into service in 2015. In terms of energy storage, today in Colombia, there are a few projects of no conventional energy that involve using batteries to save energy and use it in cases of a contingency N-1. An example of this is the public call UPME-STR- 01-2022, which aims to connect a bank of batteries in a solar farm located in Barranquilla to an electrical substation (Oasis, Silencio, and Union) to guarantee a minimum an hour of service [14].

B. Hydrogen

Colombia is a country that is beginning the energy transition process, where it is committed to exploiting primary resources from non-conventional renewable sources for the production of electrical energy. One of them is hydrogen, which provides two types of production: hydrogen blue and green, according to what is established by the hydrogen roadmap in Colombia to 2050 [15]. This commitment is reaffirmed with the issuance of Law 2099 of July 10, 2021, or energy transition law, where are dictated measures for the promotion and use of hydrogen, including tax benefits, resources to finance the execution of production projects, as well as support for research in any of the action fronts related to technology for storing, conditioning and distributing hydrogen. [16]. In that order of ideas, this process began in March 2022 with a pilot project owned by the Ecopetrol company located in the Cartagena refinery, with the entry of a 50 kW PEM (Proton Exchange Membrane) technology electrolyzer and 270 solar panels, which uses industrial water from the refinery to produce 20 kg of high-purity green hydrogen per day [17].

C. Electric Vehicles

In 2019, the ministries of environment and sustainable development, mines and energy, transport, and the UPME delivered the national mobility strategy that includes the period 2018-2022, where the political will to promote a transition toward electric mobility is shown, there are four challenges that this transition requires [18]:

- Regulatory and political.
- Economic and market.
- Technical and technological.
- Infrastructure and land use planning.

Knowing the above scenario, Colombia currently has policies that allow access to incentives for using zero and low-emission vehicles, such as discounts on mandatory traffic accident insurance, discounts on mechanical and technical inspections, and exceptions to beak and plate for mobility [19]. Achieving that, as of September 2021, there are 4928 electric vehicles and 18366 hybrid vehicles in the unique national transit registry (RUNT) [20], which are understood to be residential charging stations and 188 charging stations distributed throughout the country, see Figure 5.

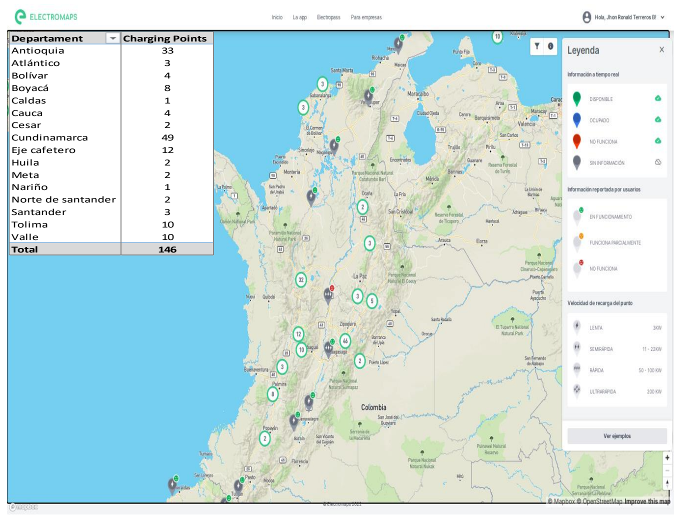

Fig. 5. Electric vehicle charging points in Colombia [21].

V. Conclusion

In this paper, an overview of the Colombian electricity system was made, where it was possible to conclude that the system is composed of the National Transmission Network and Conventional Generation Systems; this system is divided into connected and unconnected zones; For the connected areas, the National Transmission System (STN) is made up of numerous transmission lines, compensators, substations and interconnected equipment that operate between 220 kV and 500 kV in addition to using backup interconnections with Ecuador, Venezuela, and Panama to interconnect the most populated areas of the country. For non-interconnected areas, solutions based on diesel plants have been implemented, being economically and environmentally non-viable; Therefore, the most promising solution is the implementation of microgrids by taking advantage of the high potential of small hydroelectric plants and solar energy on a low number of inhabitants. Regarding Generation, it can be concluded that the system has an effective net generation capacity of 17.6 GW, and a mainly clean energy matrix made up of renewable resources such as: Hydraulic (67.21%), Thermal (30.78%), Cogenerators (1.08%), solar (0.82%), wind (0.10%) according to Table III, and due to their vulnerability with respect to climate changes (El Niño phenomenon, greenhouse effect, and surface water heating) it is necessary to diversify the energy matrix with non-conventional energy sources. Finally, it was also possible to conclude that although there are few technology implementation projects (FACTs Devices, VSC, STATCOM, SC and TCSC), energy storage and energy transition; The country, through the expansion plan carried out by UPME, has begun to establish recommendations that promote the implementation of these technologies, the exploitation of resources from non-conventional renewable sources such as hydrogen, and the implementation of policies that encourage the use of electrical vehicles.

Acknowledgment

This paper is part of the project CLIMAT-AmSud (22-CLIMAT-04) between France, Argentina, Chile, Colombia, and Paraguay that search for the mitigation of climate change through research in power electronics and smart technologies and Fondecyt Regular 1220556 Research Project.

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