2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT LATAM)

Integration of Wind Power Plants into the Colombian Power System

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***Abstract* – The Mines and Energy Planning Unit (UPME) is responsible for establishing the energy requirements of the population according to economic, social, technical and environmental principles. UPME updates the official document entitled "Power Generation and Transmission System Expansion Plan" every year. The power generation requirements, which are proposed by the Unit, are indicatives, because most of the new power generation projects are built according to the mechanism called Reliability Charge. Additionally, UPME establishes the needs of the expansion of the transmission system in order to ensure the Colombian electrical security and the reliability of the power system. These infrastructure projects are mandatory. Considering the intention of developing new wind power plants in the north region of Colombia (La Guajira), which would add to the power system more than 470 MW, the UPME analysed the integration of these renewable facilities into the Colombian electrical system. The analysis presented in this paper are; energy analysis, electrical analysis and economic analysis.**

***Index Terms* – marginal cost, intermittency, cumulative probability function, cost benefit ratio, frequency instability and Conditioned Expected Value of Energy Rationing (VEREC).**

I. Introduction

UPME updates the official document entitled "Power Generation and Transmission System Expansion Plan" every year. In the document the short and long term projects of the electrical transmission system are defined. The projects are presented and offered in public auctions that aim at finding companies that invest on their development. Regarding the power generation system, UPME analyses different scenarios to identify indicative needs of expansion. However, the enlargement of the power generation system is mainly given by projects, which are developed under a reliability mechanism.

Several analyses are made to define the expansion requirements of the electrical system. Since the analyses demand big amount of specific information, UPME and other institutions work together on different studies to guarantee that the information is always available. In this specific case, UPME and IDEAM (Colombian national institute of hydrology, meteorology and environmental studies) elaborated and published the "Atlas of the Colombian wind and wind power" [1] in 2006. This atlas is an important reference because it presents the availability of wind in Colombia for different seasons and geographical regions. In 2013 the first wind power project was registered at UPME's information system. The project named Irraipa, would have an installed capacity of 99 MW. The information given by the company allowed UPME to do the first analysis of the integration of wind power plants into the Colombian power system. The analysis was presented in the Power Generation and Transmission System Expansion Plan 2013 – 2027 [2].

Additionally, two new wind power plants, Casa Eléctrica and Carrizal, were presented to UPME in 2014. The three projects together, would increase the capacity of the power generation system in 474 MW.

Considering the information presented by the developer of the projects and other assumptions of the Power Generation and Transmission System Expansion Plan 2014 – 2028 [3], UPME elaborated a more detailed analysis of the integration of wind power plants into the Colombian power system. The analysis considered an energetic evaluation, the study of power evacuation and the impacts of the integration of wind power plants on the marginal cost of the electricity. It was also studied the concept of complementary resource, the impacts on the reliability and the transmission requirements for implementing the new projects.

Chapter two presents the analysis of the energy impacts on the electrical system caused by connecting wind power plants. It also presents the contribution of reliability, economic benefits and the level of intermittency that this kind of facilities provides to the National Interconnected System (SIN).

The chapter number three presents the electrical analysis. The analysis aims at identifying the behaviour and performance of the subarea Guajira/Cesar/Magdalena (GCM) with and

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978-1-4673-6605-2/15/$31.00 ©2015 Crown

without the three wind power plants. Moreover, a sensitivity analysis is made in order to identify the maximum installed capacity of wind power plants that the system could resist for different configurations of the transmission system.

Finally, chapters four and five show the economic evaluation and the recommendations of the UPME regarding the interconnection of this wind power projects to the Colombian electrical system.

II. Energy Analysis

A. Methodology

First of all, different scenarios of expansion of the power generation system are defined. Some variables such as the forecast of the electrical demand, new power generation plants or the availability of the energy resources vary between the scenarios. Afterwards, the reliability energy indexes, Expected Value of Energy Rationing (VERE), Expected Conditional Value of Energy Rationing (VEREC) and Number of Occurrences (NO) are evaluated for every scenario. These indexes are estimated with the results obtained from the Stochastic Dual Dynamic Program (SDDP). All the indexes should fulfil the national regulation of electrical reliability. Nowadays the regulation defines the following conditions: i) VERE $\leq$ 1.5%; ii) VEREC $\leq$ 3.0%; and iii) NO $\leq$ 5 events in 100 cases.

All the conditions should be fulfilled in order to include the scenarios as an option for expanding the power generation system. If the any of the conditions is not satisfied, new expansion projects should be considered. The projects should avoid an overexpansion while assuring the fulfilling of the indexes during the period of the analysis.

B. Assumptions

The following variables and assumptions were considered as the most relevant: i) stochastic availability of the resources; ii) development of power generation projects; iii) fuel prices; iv) forecast of the demand of energy and power; v) starting date of the new power generation plants; and vi) new technologies for power generation.

C. Results

Considering the aforementioned assumptions, an initial energy analysis, which includes only the existing power generation plants and the projects that are under construction, is made in order to set a scenario of reference. This analysis allows identifying the moments when new power plants are required to supply the demand of electricity. The results obtained from the simulation software shows that in 2025 the conditioned expected value of energy rationing is greater than 3%, which means that the electrical system is in risk.

Several scenarios are considered for the expansion of the power generation system, however for the present study the scenarios 5 and 7 from the document of reference are chosen [3]. These scenarios are analysed because in the scenario 5 the power generation expansion is made by conventional technologies, and in the scenario 7, the expansion of installed capacity includes wind power plants (the projects Irraipa, Casa Eléctrica and Carrizal).

Table I shows the schedule of the expansion of the power generation system in Colombia. The expansion in the scenario 5 is made by conventional power plants which includes the second stage of the hydropower plant Itaungo and four coal fired power plants. In contrast the expansion in the scenario 7 includes the three wind power plants, three coal fired power plants and the second stage of the hydropower plant Itaungo. The scenarios 5 and 7 are simulated with the software SDDP in order to find the energy behaviour of the system. The simulation allows identifying the reliability of the SIN, the evolution of the marginal cost, and generation by technology among others. The results show that the reliability index for both scenarios fulfil the requirements established by the national regulation. Regarding the marginal cost, it is possible to conclude that:

- The expected value of the marginal cost would be 59.8 US$/MWh from 2015 to 2018 for the scenarios 5 and 7, because the power generation system is similar in both cases. This value would decrease during the period 2018 - 2020, to about 56.0 US$/MWh for the scenario 5 and to about 54.8 US$/MWh for the scenario 7. The value falls because of the expansion of the generation system. In both cases the system is expanded with new hydroelectric plants.
- The average of the marginal cost would be 50.9 US$/MWh and 48.5 US$/MWh for the scenarios 5 and 7 respectively during 2020 and 2022. This lower cost corresponds to the enlargement of the hydro power plant Ituango and the implementation of the wind power plants in the scenario 7. Afterwards, from 2022 to 2028, the average of the marginal cost would be 54.5 US$/MWh for the scenario 5 and 53.6 US$/MWh for the scenario 7.
- Comparing the results of marginal cost of the scenario 5 and the scenario 7, allows us to conclude that the wind power plants reduce the marginal costs in about 1.2 US$/MWh during the period 2019 – 2028.

The expected value of power generation by technology is computed for both scenarios. Comparing the production of electricity from hydro power plants and wind power plants allowed us to identify that there is complementarity of the two energy sources. The Figure 1 shows how the wind in La Guajira is an energy complement of the hydroelectricity in Colombia, this phenomena increases the reliability of the system. It is important to mention that the previous analysis considered all the hydro power plants together. Since individual cases were not studied, it could be possible to find better or worse correlations for specific power plants.

TABLE I
EXPANSION SCHEDULE

Power Plant	Date	Scenario 5 [MW]	Scenario 7 [MW]	Resource
Sogamoso	nov-14	800	800	Hydro
Gecelca 3	oct-14	164	164	Coal
Cucuana	dic-14	55	55	Hydro
Quimbo	jun-15	396	396	Hydro
Tasajero II	nov-15	160	160	Coal
Carlos lleras Restrepo	dic-15	78.1	78.1	Hydro
San Miguel	dic-15	42	42	Hydro
Gecelca 3.2	dic-15	250	250	Coal
Termonorte	dic-17	88	88	Liquid fuels
Porvenir II	nov-18	352	352	Hydro
Ituango	jun-22	2,400	2400	Hydro
Exp.Carb. 1	dic-20	200	200	Coal
Exp.Carb. 2	dic-21	300	300	Coal
Exp.Carb. 3	jul-23	250	N/A	Coal
Exp.Carb. 4	dic-23	300	300	Coal
Irraipa	ene-19	N/A	99	Wind
Carrizal	ene-20	N/A	195	Wind
Casa Eléctrica	ene-21	N/A	180	Wind
Small Plants	According to projected growth			

Two benefits of integrating 474 MW of wind power plants to the electrical system have been identified. The first one is the reduction of the marginal cost and the second is the increase of reliability during the periods of low availability of the hydro power plants. However, it is necessary to evaluate the intermittency of the resource and the possible troubles it may cause to the operation of the SIN.

The Figure 2 presents the estimated cumulative probability function of the hourly power variation for wind power plants. Likewise, the Figure 3 shows the estimated cumulative probability function of the power produced by the wind power plants. The figures were built with information provided by the project's developer, which includes data of a specific type of wind turbines. This information includes data from in-situ measurements.

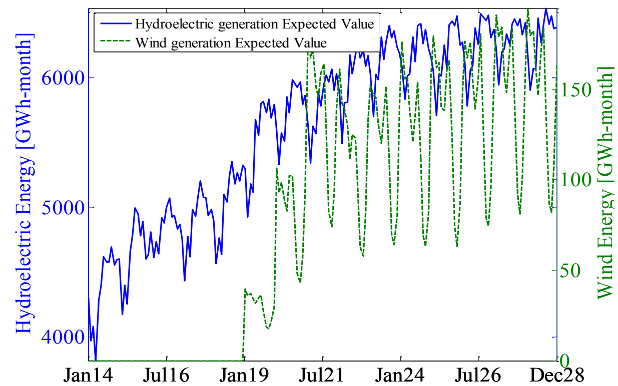

Figure 1. Expected value of the power generation from wind and hydraulic power plants. Complementarity.

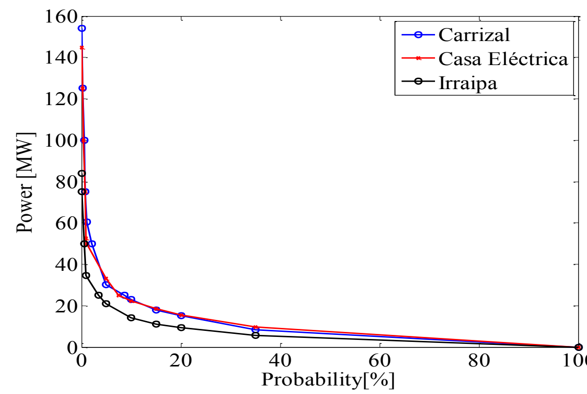

Figure 2. Cumulative probability function of the hourly power variation of the three wind power plants.

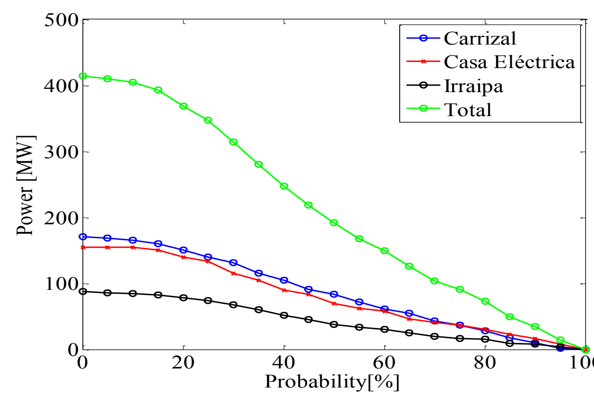

Figure 3. Cumulative probability function of the power produced by the three wind power plants in one hour.

With respect to the Figure 2 and Figure 3, the probability of having an hourly power variation greater than 240 MW, 268 MW and 300 MW, considering the total power generation of the three projects, is less than 0.1%. These values are considered as a reference because are related to the biggest power generation units in Colombia (Guavio, Sogamoso and Ituango), which are referring to set the trigger levels of the Load

Automatic Disconnection scheme for low frequency - EDAC. Also, the probability of having a wind power generation greater than 100 MW, when the three wind power plants are included, is 74.0%. This is possible due to the characteristics of the wind in La Guajira, which is relatively constant compared to the wind in other geographical regions.

III. ELECTRICAL ANALYSIS

This chapter presents the electrical analysis of the integration of the three wind power plants, Casa Eléctrica, Irraipa and Carrizal.

A. Methodology

First of all, the electrical behaviour of the subarea Guajira/Cesar/Magdalena (see Figure 4) without the wind power plants is established. The analysis allows identifying the needs for expanding the transmission system. Second, the behaviour of the subarea Guajira / Cesar / Magdalena including the three wind power plants is evaluated, determining also their connection to the grid. Finally, different possibilities for expanding the transmission system are evaluated, it for the connection of more wind power capacity (greater than 474 MW).

B. Assumptions

The following assumptions are considered for the electrical analysis: i) the forecast of power energy demand, which considers large power consumption; ii) power generation and transmission expansion, defined in the Table I and Table III. Also, the power system operation scenarios defined in the Table II; and iii) the maximum transmission capacity between Colombia and Venezuela is considered, also the overload limits in the fault state for each element of the power system (actual and future).

TABLE II.
POWER SYSTEM OPERATION SCENARIOS.

Scenario	Generation in GCM	Demand in GCM	Power importation from Venezuela
1	Max.	Max.	Inactive
2	Max.	Max.	Active (150 MW)
3	Max.	Min.	Inactive
4	Max.	Min.	Active (150 MW)

C. GCM Subarea behaviour with the integration of 474 MW of wind power plants:

The network behaviour is presented, considering 474 MW in the 500 kV bus bar Cuestecitas substation (it is not considered a 220 kV connection in Cuestecitas substation due to space limitations. According to the report “Connections Opportunities” by TRANSELCA, there is only space for connecting the second transformer Copey 500/220 kV – 450 MVA.), and the transmission expansion defined in the Table III (2018 and 2022). Clearly the Cuestecitas – Copey 500 kV failure limits the wind power integration. Under this contingency this new power is injected from Cuestecitas 500 kV to the 220 kV grid in GCM, causing an overload higher than the load limit in the Cuestecitas 500/220 kV transformer and the Cuestecitas – Valledupar 220 kV line, situation it becomes more critical importing power from Venezuela. In this sense, Table IV presents the maximum capacity that can be incorporated, depending on the scenario under study.

TABLE III
TRANSMISSION SYSTEM EXPANSION INCLUDING IN GCM.

Project	Starting date
Capacitive compensations in the substations Termocol 220 kV and Valledupar 220 kV.	2015
Second transformer Copey 500/220 kV – 450 MVA.	2015
Río Córdoba substation 220/110 kV	2016
La Loma substation 500/110 kV	2016
New substation Cuestecitas 500 kV with a new link of 500 kV Cerromatoso – Chinú – Copey – Cuestecitas, and a second circuit Copey – Fundación 220 kV.	2018

TABLE IV
MAXIMUM CAPACITY OF WIND POWER INTEGRATION. HORIZON 2018 – 2022.

Scenarios	Limiting factor	Maximum capacity [MW]
1.	N -1 Cuestecitas – Copey 500 kV	440
2.		290
3.		360
4.		210

D. Subarea behaviour whit the integration of 474 MW of wind power plants, and two reinforcing network alternatives.

The network behaviour is presented, considering 474 MW and two reinforcing alternatives, they are: i) Alt 1: second Cuestecitas 500/220 kV transformer and second Cuestecitas – Valledupar 220 kV link; ii) Alt 2: second Copey – Cuestecitas 500 kV link.

In the Table V the electrical behaviour of the GCM subarea is presented for the two reinforcing network options. Respect to alternative 1, the contingency that limits the integration of power wind is the loss of the Cuestecitas – Copey 500 kV line. Under this topology, even though there are already two Cuestecitas 500/220 kV transformers and two Valledupar – Cuestecitas 220 kV line, all the power is again injected to the 220 kV grids in GCM from Cuestecitas 500 kV, causing the overhead of the two referenced links. Considering the alternative 2, the second line Cuestecitas – Copey 500 kV ensure the integration of 1,200 MW (even more of that).

The maximum capacity of wind power that is possible to connect in the grid, under different topologies, must be validated with stability analysis. In this sense, a double link at 500 kV level between the “Colectora” substation, that adds all the wind parks, and Cuestecitas substation it's considered. The option of a single link between these substations was discarded, because a single event on this line could activate the EDAC by frequency instability problems. Is observed that under the unavailability of a link and the parallel element failure, the frequency may be below of the EDAC set activation and subsequently, load shedding, this to safeguard the security of the system. However, there are no violations under normal conditions of the grid, when one circuit fails. Regarding voltage stability, there are no risky conditions under several contingencies of the interconnection between GCM and the rest of the system, this for the transmission expansion (see Table III).

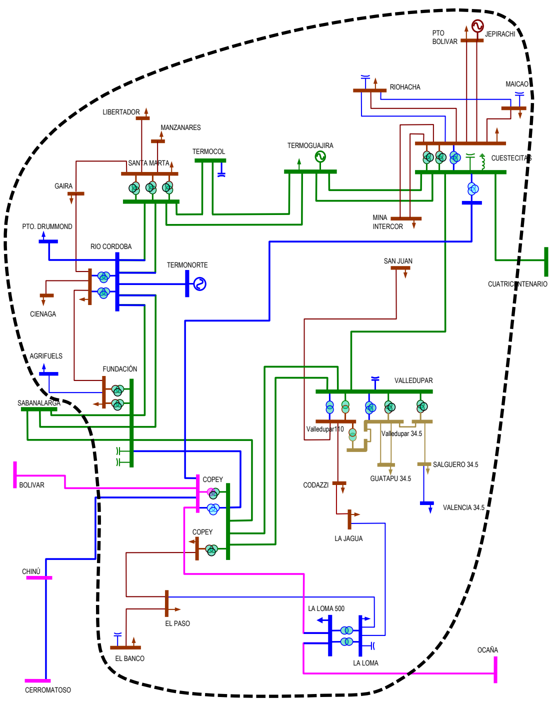

Figure 4. One line Diagram of GCM. Magenta color 500 kV, green color 220 kV, brown color 115 kV and blue color future transmission expansion.

IV. Economic evaluation

In the chapter two the analysis of two long-term scenarios were presented. One of the scenarios (scenario 7) includes wind power plants into the SIN. From the results it is possible to conclude that; by installing the wind power plants (474 MW) it would be possible to avoid installing 250 MW of coal fired power plants that are required in the scenario 5. The results also show that the reliability of the SIN could be achieved with wind power plants. Additionally, it was shown that the wind in the northern part of La Guajira is a complementary energy resource to the hydro energy in Colombia (See Figure I). These results together with the reduction of the marginal costs, allow concluding that wind power plants bring several benefits to the SIN. However, this kind of projects have not been developed in Colombia mainly because of the limitations of the transmission system in the area where the resource is available, as it is shown in the chapter three. This is the reason for study and analyse some reinforcement alternatives. Such reinforcements allow integrating the 474 MW from the wind power plants into the SIN. Therefore, it is necessary to evaluate the economic benefits of integrating the three wind power plants into the Colombian electrical system.

This chapter presents the economic evaluation of integrating the wind power plants. The evaluation is focused on the cost – benefit analysis. Additionally, a sensitivity study was made in order to quantify the maximum capacity of wind power plants that the proposed infrastructure to expand the power system would resist.

TABLE V
SYSTEM´S BEHAVIOUR WHIT THE INTEGRATION OF 474 MW OF WIND POWER PLANTS. HORIZON 2018 – 2022.

Case	Alternative1		Alternative 2	
	Limiting factor	Max capacity [MW]	Limiting factor	Max capacity [MW]
1.	Cuestecitas – Copey 500 kV	440	None	1,200
2.		290	None	1,200
3.		360	None	1,200
4.		210	None	1,200

A. Benefits of integrating power plants into the SIN.

The three wind power plants of the analysis do not have Firm Energy Obligations (OEF), neither reduce considerably the expected restriction costs, this for the defined transmission expansion (Table III), and given the distance between the Colectora substation and Cuestecitas, increase the system losses. The estimation of the costs and the benefits consider the previous simplifications. In this sense, the only benefit to be considered is the reduction of marginal cost. In contrast, the costs are related to the interconnection to the grid, transmission reinforcements and the increase in system losses.

B. Economic evaluation of connecting the 474 MW of the wind power plants

The evaluation of the reduction of the spot price produced by the integration of the 474 MW from the wind power plants considers the expected evolution of the marginal cost for the expansion alternatives presented in the Table I. Regarding the costs, the reinforcements of the transmission system and the physical connection of the three wind power plants are evaluated according to the policy CREG 011 issued in 2009. Such policy describes the Constructive Units. The estimation of the rising in the losses of the system considers the evolution of the marginal cost of the scenario 7 (Table I).

The Table VI presents the VAN of the connections cost of the wind power plants. The Table VII shows the cost – benefits analysis to each scenario in two different ways: i) the first one considers the connection cost of integrating the wind power plants to the grid; ii) the second only assumes the investments related to the reinforcements of the grid (the connection is in charge of the project developer).

TABLE VI
VAN OF THE CONNECTIONS COST OF THE WIND POWER PLANTS.

Item	Alt 1	Alt 2	Power plant connection	Losses
VAN USD$	38,442,910	76,446,072	118,328,802	2,000,000

TABLE VII
BENEFIT - COST ANALYSIS FOR THE ALTERNATIVES

Topic	Result
Benefit [MUSD$]	229
B/C focus 1: Alternative 1 including the connection	1.4
B/C focus 2: Alternative 1 excluding the connection	5.7
B/C focus 1: Alternative 2 including the connection	1.2
B/C focus 2: Alternative 2 excluding the connection	2.9

The results show that for every alternative the benefit - cost analysis is greater than 1.

C. Sensitivity analysis of the economic evaluation

Even though the results show that integrating 474 MW of wind power plants is feasible from the technical and economic point of view, the region of La Guajira has the capacity (availability of the resource) for hosting more than 10,000 MW of wind power plants. However, UPME only has information of some wind power projects, which may add up to 1,200 MW.

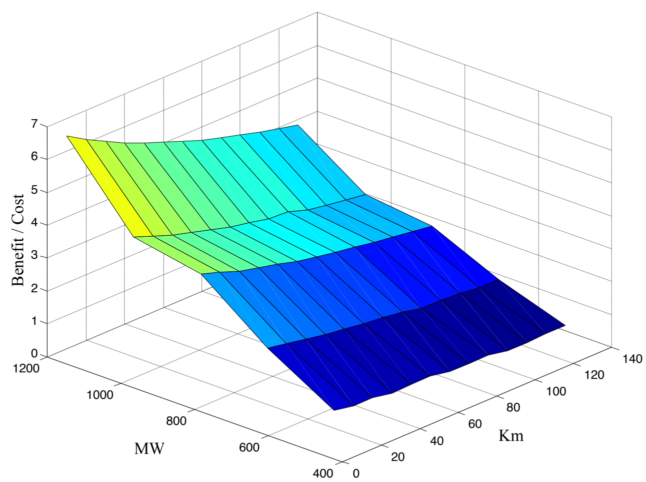

Figure 5. Sensitivity of cost – benefit analysis.

Previously, it was suggest that a reinforcement of the grid in 500kV, would allow the integration of more than 1,200 MW. This is the reason why the Cost / Benefits ratio is analysed for the integration of several wind power plants. The Figure 5 presents the way the cost-benefits relation changes according to the integration of wind power plants and the costs of the double circuit Cuestecitas – Colectora 500 kV, which at the same time is proportional to the location of the last substation (Colectora 500 kV). It is important to mention that the valuation includes the reinforcement costs and a double circuit between the substations Colectora and Cuestecitas 500kV.

The Figure 5 shows that the larger the renewable installed capacity, the greater the benefits / cost ratio. On the other hand, the larger the distance between the substations Cuestecitas and Colectora, the lower the benefits obtained from the reduction of the marginal cost.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of the analyses showed that the integration of the 474 MW from wind power plants is feasible from the technical and economic point of view. Additionally, the data from the atlas shows that the potential for installing wind power plants in La Guajira is greater than the capacity of the three projects of the analysis. Therefore, the UPME recommends developing a second transmission circuit Cuestecitas – Copey 500 kV and a double link Cuestecitas – Colectora 500 kV, only if new wind capacity (more than 1,200 MW), which contributes to reach the benefits identified in the analysis, is built in the subarea La Guajira. It is also important to mention that developing the wind power projects will help to build new infrastructure that allow to achieve the optimal benefits. Such benefits would be shared between national demand and the developers of new projects.

This work focuses mainly on the impacts in terms of transmission and generation expansion, by incorporating large-scale of wind power in the Colombian system. Although the probability of frequency variations greater than the threshold activation of the EDAC by the intermittency of the wind resource is determined in the document (which are less than 0.1%), and is establish under different contingencies in the transmission grid, that involving the sudden loss of wind power, that no problems of frequency and voltage instability are noted, the focus of the study is not to analyse in detail the expected operation of the system. Future work will examine this issue in conjunction with the Colombian System Operator, XM.

VI. REFERENCES

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