HVDC Transmission Assessment for Expansion of Renewable Energy in La Guajira, Colombia

Task 1 – Selection of HVDC or HVAC Transmission

WORLD BANK

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Executive Summary

World Bank contracted TGS to perform the *HVDC Transmission Assessment for Expansion of Renewable Energy in La Guajira, Colombia* (reference number: 1273214).

As part of Colombia's plans to increase the generation capacity with non-conventional renewable energy sources (NCRE), a large amount of generation is planned to be integrated at La Guajira area. Collector 1, a total of 1054 MW of wind generation in La Guajira area is already planned to be integrated using 500 kV AC transmission lines to Cuestecitas. As the next step, Collector 2, about 3000 MW of NCRE sources are planned to be integrated by 2032. The objectives of the project awarded to TGS are

- to review the initial assessments undertaken by UPME (Colombia's Unit of Mining and Energy Planning), comparing HVDC technology and HVAC technology for the incorporation of the additional NCRE in the region of La Guajira; and
- to assess different options for the implementation of the HVDC technology including the specification of different associated developments, input and output nodes, voltage level, characteristics, and type of different HVDC technologies based on scenarios for the development of NCRE capacity.

The study comprises of 3 tasks:

Task 1 – Selection of HVDC or HVAC Transmission

Task 2 – Selection of HVDC Technology

Task 3 – Project Execution Considerations

This report summarizes the findings of Task-1. The Task-1 study evaluated the HVAC and HVDC transmission alternatives proposed by UPME for the interconnection of 3000 MW of renewable energy generation in La Guajira area of Colombia, Collector 2.

UPME's transmission expansion plans, and analysis were reviewed during the initial state of the study. Then, the additional studies were performed to validate the findings, using the 4 study cases representing the minimum and maximum demand scenarios for operational years 2028 and 2032. In the 2028 study cases, 2000 MW of renewable generation was interconnected. The full capacity of 3000 MW was interconnected in operational year 2032. The power system models were provided by UPME.

The outcomes of the study are summarized below.

Feasibility of 500 kV double circuit AC interconnections to Cuestecitas, Chinu, Cerromatoso or Copey

The AC interconnections were not feasible to integrate 3000 MW to the Colombian system due to the following reasons:

- *Cuestecitas*:

The Short Circuit Ratio (SCR) at Cuestecitas is as low as 1.74, which is insufficient for the proper operation of wind power plants. Therefore, many additional devices (e.g., synchronous condensers) will be required at Collector 2 to improve the AC system strength. Further, the AC network is not capable of transferring 3000 MW of generation at this location.

- *Chinu and Cerromatoso*:

The SCR at Collector 2 is as low as 1.4 in this alternative. Therefore, many additional devices (e.g., synchronous condensers) will be required at Collector 2 to improve the AC system strength.

- Copey (with Collector 1 and 2 interconnected):

The AC system strength at Collector 2 under this alternative is sufficient to connect 3000 MW of generation. However, the transmission line overloads, voltage limit violations and a large amount of reactive power requirement under some outages were identified when the Collector 2 is interconnected at its full capacity of 3000 MW.

The feasibility of the interconnection option was further studied for reduced generation levels at Collector 2. The AC contingency analysis and a preliminary dynamic simulation study showed the feasibility of interconnecting about 2000 MW using this alternative. If required, the transfer capacity may be increased to about 2500 MW by adding some reinforcements to the existing system. Further studies would be required to identify the system upgrades.

Feasibility of LCC HVDC Transmission

The LCC converters required a certain short circuit strength for the proper operation. Therefore, the LCC option was evaluated with the Collector 2 connected to the Collector 1 using a double circuit 500 kV line. However, the short circuit strength that can be achieved at the Collector 2 is still very low. The effective short circuit ratio (ESCR) is about 1.37. To achieve an ESCR of 2.0, synchronous condensers of about 650 MVA would be required at the Collector 2. Therefore, LCC option would not be a preferred solution.

Feasibility of VSC HVDC Transmission

Considering the constraints identified in the system, the VSC HVDC transmission system is the most promising technology available at present due to following key reasons:

- No additional devices such as synchronous condensers are required at La Guajira to enhance the short circuit capacity (Low SCR is not an issue for VSC HVDC technology).
- The VSC terminal at La Guajira region (Collector 2) can be operated in grid forming control (i.e., voltage and frequency regulation). In such a system, the wind farms can operate without having additional short circuit support (i.e., SCR rules are not applicable).
- Black start capability can be used to start the wind farms in the La Guajira collector system.

Recommended terminal for interconnection

When Chinu, Cerromatoso and Primavera are compared, Primavera is the closest location to the load centers. The power flow study showed that when the VSC HVDC is terminated at Chinu or Cerromatoso, the power needs to be transmitted using the AC transmission lines to the load centers in the south. Therefore, the AC transmission losses are significantly lower when the HVDC is terminated at Primavera. Although the DC transmission losses are comparatively higher at Primavera, the benefits of reduced AC transmission losses are still significant.

Primavera is proposed as the terminal location for the HVDC interconnector. However, there may be non-technical restrictions such as space limitations when constructing a HVDC terminal in a congested metropolitan area. It is recommended for UPME to evaluate the feasibility of this location.

Recommendation for grid code compliancy during a pole outage

The Colombian grid code requires the transmission system to be capable of keeping all the generation intact during all n—1 outages. The VSC HVDC pole outage will generally allow about 10% of overload of the healthy pole. Therefore, about 1350 MW of generation needs to be tripped during a pole outage if the Collector 2 is isolated. To comply with the grid code, it is proposed to interconnect the Collector 1 and Collector 2 using a single circuit 500 kV AC transmission line. This line will be mostly utilized under the contingency conditions.

Selected transmission technology–VSC HVDC

Based on outcomes summarized above, a 3000 MW bipole VSC HVDC system is proposed to be connected between the Collector 2 and Primavera or Cerromatoso. In addition, a single circuit 500 kV AC transmission line between the Collector 1 and Collector 2 is required to maintain the power transfer during a HVDC pole outage. For the HVDC system, a DC transmission voltage of 550 kV or 600 kV is recommended. The cost of losses should be evaluated over the project life to reach a proper conclusion. The half bridge converter technology with the AC breakers (the most cost-effective solution) will be first evaluated in Task 2 studies and if it is necessary based on the dynamic performance requirements, the technology will be changed to full bridge technology.

1. Introduction

World Bank contracted TGS to perform the *HVDC Transmission Assessment for Expansion of Renewable Energy in La Guajira, Colombia* (reference number: 1273214).

Since 2014, Colombia aimed to increase its electricity generation capacity with non-conventional renewable energy sources (NCRE), which is currently around 80 MW. Over the last two years, the country has embarked on the design of tailor-made public interventions, incentives, and policies, including the electricity auction schemes.

The country has recently auctioned and signed public purchase agreements (PPAs) for the construction of over 2200 MW of solar and wind generation before the end of the year 2022. Taking this into account, transmission expansion works have already been defined and awarded to enable the connection of such projects. In addition, nearly 7000 MW of mainly wind and solar potential projects have received regulatory approval in the country.

Given the above projects, high potential for additional generation and the new tenders (mainly in La Guajira, Cesar, and Magdalena) the capacity of the existing network needs to be increased. This led Colombia's Unit of Mining and Energy Planning (Unidad de Planeación Minero Energética – UPME) to analyze the alternatives for new transmission infrastructure to facilitate the interconnection of additional generation projects, particularly from La Guajira region. The expansion plan includes adding about 3000 MW of wind and solar power plants in the collectors 2 and 3 in the La Guajira region as shown in Figure 1-1. UPME is exploring AC and DC transmission options from La Guajira region (Collector 2) to the load centers close to Cerromatoso. The transmission system length would be about 650—780 km.

The objectives of the project awarded to TGS are:

- to review the initial assessments undertaken by UPME, comparing HVDC technology and HVAC technology for the incorporation of the additional NCRE in the region of La Guajira; and
- to assess different options for the implementation of the HVDC technology including the specification of different associated developments, input and output nodes, voltage level, characteristics, and type of different HVDC technologies based on scenarios for the development of NCRE capacity.

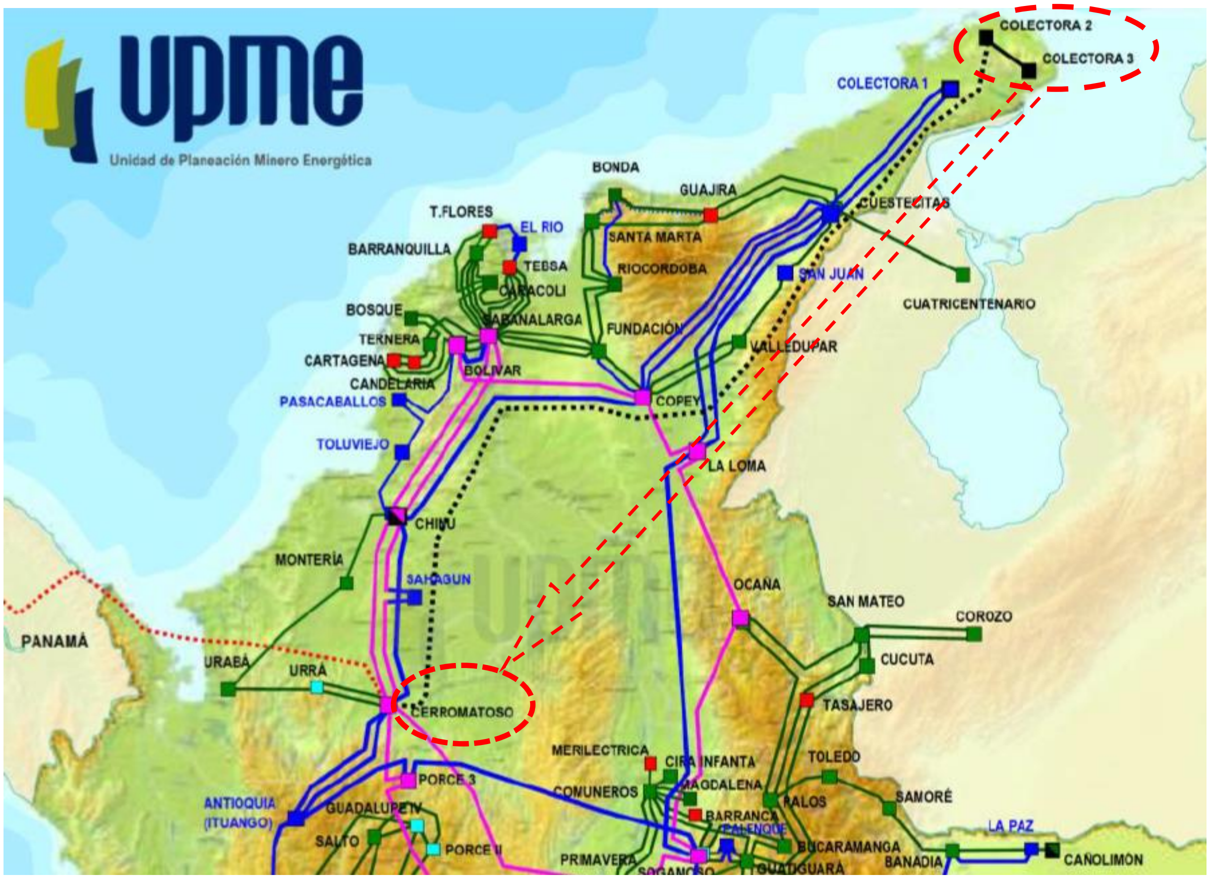

Figure 1-1: Renewable Energy Expansion Plan in Colombia [1]

The study comprised of three main tasks.

Task 1 – Selection of HVDC or HVAC Transmission

Task 2 – Selection of HVDC Technology

Task 3 – Project Execution Considerations

This report is the outcome of Task 1.

The objective of Task 1 is to review and validate UPME's finding that HVDC transmission is preferable over HVAC transmission for the integration of the large amount of renewable energy in La Guajira area into the Colombian power system.

Following two steps were performed during the study:

Step 1 – Review UPME reports and analysis

Step 2 – Additional studies to validate the selection of HVDC over HVAC

Step 3 – Selection of the HVDC technology

2. Review of Alternatives for Interconnection Proposed by UPME

UPME has identified a large potential for renewable energy generation in the La Guajira area of Colombia. A total of 1054 MW of wind generation in La Guajira area is planned to be integrated to Cuestecitas 500 kV station using about 120 km long double circuit 500 kV AC transmission line (Collector 1). This has been already integrated into the database provided by UPME. In the next expansion stage, which is evaluated in this project, UPME is planning to connect 3000 MW of renewable energy mainly from wind power plants in Collector 2 and 3 by 2032.

The interconnection alternatives studied and evaluated in the following transmission expansion plans were reviewed during this study:

- PLAN DE EXPANSIÓN DE REFERENCIA GENERACIÓN – TRANSMISIÓN 2015 – 2029
- PLAN DE EXPANSIÓN DE REFERENCIA GENERACIÓN – TRANSMISIÓN 2017 – 2031

For the additional 3000 MW of generation planned in Collector 2 and 3, three interconnection alternatives have been evaluated in the recent transmission expansion plan (PLAN DE EXPANSIÓN DE REFERENCIA GENERACIÓN – TRANSMISIÓN 2017 – 2031):

- 500 kV AC transmission lines to Cuestecitas
- 500 kV AC transmission lines to Chinu or Cerromatoso
- 550 kV VSC HVDC bipole transmission to Chinu or Cerromatoso

In addition, UPME requested to review the following interconnection option studied in PLAN DE EXPANSIÓN DE REFERENCIA GENERACIÓN – TRANSMISIÓN 2015 – 2029:

- 500 kV AC transmission lines to Copey (with Collector 1 and Collector 2 interconnected)

The studies were performed on the peak and minimum demand operational scenarios based on the projections of the June 2017 operating conditions [1].

This chapter provides a summary of the review of the aforementioned interconnection alternatives and the conclusions based on the UPME's transmission plan expansion reports.

2.1.1 500 kV AC transmission lines to Cuestecitas

The feasibility of the interconnection of Collector 2 to 500 kV Cuestecitas, where the Collector 1 is proposed to be connected, was investigated under this alternative.

It has been concluded that the integration of over 600 MW results in transmission line overloads in CGM area even with the proposed upgrades are implemented.

2.1.2 500 kV AC transmission lines to Chinu or Cerromatoso

The possibility of interconnection using the 500 kV AC transmission lines between La Guajira and Chinu or La Guajira and Cerromatoso has been studied in terms of system strength, controllability, reactive power management and transmission line losses.

With the limited studies performed, the report has concluded that there will be operational difficulties if the long AC transmission lines are used to transmit large amount of power. Transmission line losses of about 110 MW and 70 MW have been estimated if the interconnection line is connected at Cerromatoso and Chinu respectively.

2.1.3 500 kV AC transmission lines to Copey (with Collector 1 and Collector 2 interconnected)

The feasibility of interconnecting Collector 2 to Copey has been studied along with a 500 kV single circuit interconnector between the Collector 1 and Collector 2. The study results are discussed under the Alternative 4 and 5 in *Section 6.3.1.3. Análisis Eléctricos* of [2]. Table 2-1 shows the interconnection details and the network reinforcements proposed under Alternative 4 and 5 (Note that this section reviews the outcomes of the preliminary studies as reported in UPME's generation and transmission expansion plan 2015 – 2029 [2]. Therefore, the network expansions, as shown in Figure 2-1 and Figure 2-2, represents the network state considered by UPME at the time of the study. However, the most recent network expansions, as in [3], were considered for the additional studies performed by TGS. The study results are presented in Chapter 3).

Table 2-1 HVAC alternatives and network reinforcements for interconnecting Collector 2 to Copey

Alternative 4 [2]	**Alternative 5** [2]
500 kV double circuit transmission line between Copey and Collector 2	
New 500 kV substation at Fundación and a 500 kV single circuit transmission line between Copey and Fundación.	
500kV single circuit transmission line between Fundación and Sabanalarga	
220 kV single circuit transmission line between Fundación and Copey (third circuit)	

Alternative 4 and Alternative 5 are mostly similar except for the additional network reinforcements given in Table 2-1. Figure 2-1 and Figure 2-2 show the single line diagrams of Alternative 4 and Alternative 5 respectively.

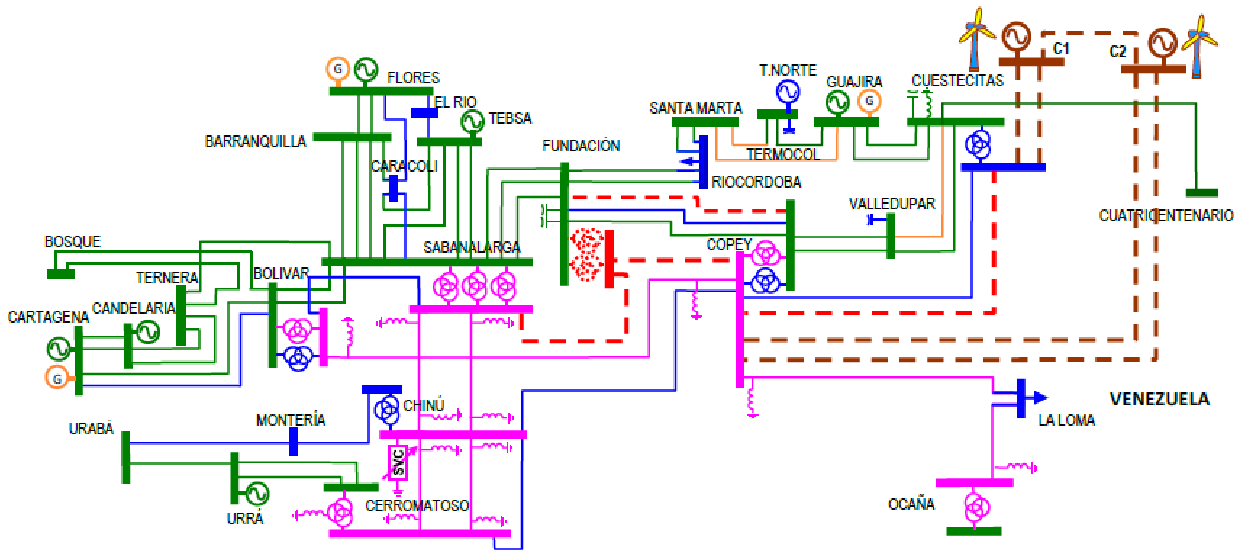

Figure 2-1 HVAC Alternative 4 [2]

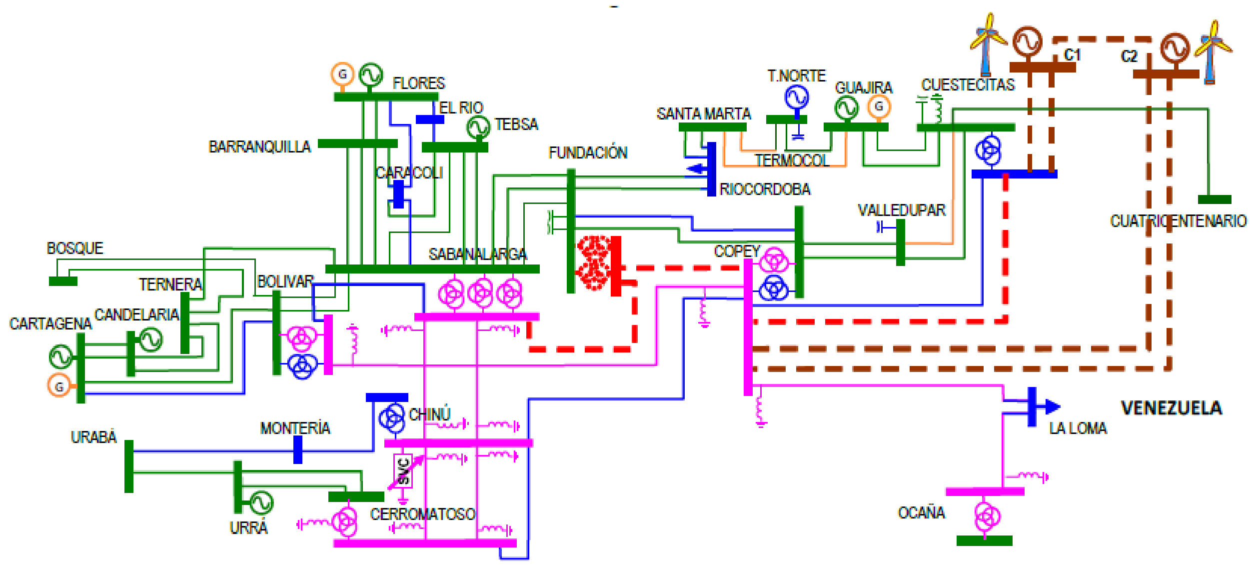

Figure 2-2 HVAC Alternative 5 [2]

Based on the preliminary investigation performed by UPME, the report has stated that the total renewable generation that can be integrated into the system from collector 1 and 2 together is 3500 MW and 3300 MW for Alternative 4 and Alternative 5 respectively. However, the total planned generation from collector 1 and 2 is about 4000 MW. Therefore, these alternatives cannot meet the expected requirement of power transfer.

2.1.4 550 kV VSC HVDC Bipole Transmission to Chinu or Cerromatoso

Considering the limitations in the previously described AC transmission alternatives, UPME report shows the VSC HVDC interconnection as a favorable solution.

Increased controllability, lower transmission losses and absence of high short circuit current contributions from the HVDC system are highlighted in the report in favor of the selection of HVDC transmission system. About 80 MW and 40 MW of HVDC transmission losses have been presented for the two proposed HVDC line termination locations Cerromatoso and Chinu respectively (Section 4.7.1.5 of [2]**)**.

In the report, the maximum possible HVDC transfer has been determined based on the short circuit strength. Considering a short circuit ratio (i.e. the ratio between short circuit strength and HVDC MW rating) of 3, the maximum possible amount of power that can be integrated is reported as 2900 MW and 3500 MW for Chinu (Figure 2-3) and Cerromatoso (Figure 2-4) respectively. Therefore, the 500 kV Cerromatoso station has been recognized as a better location.

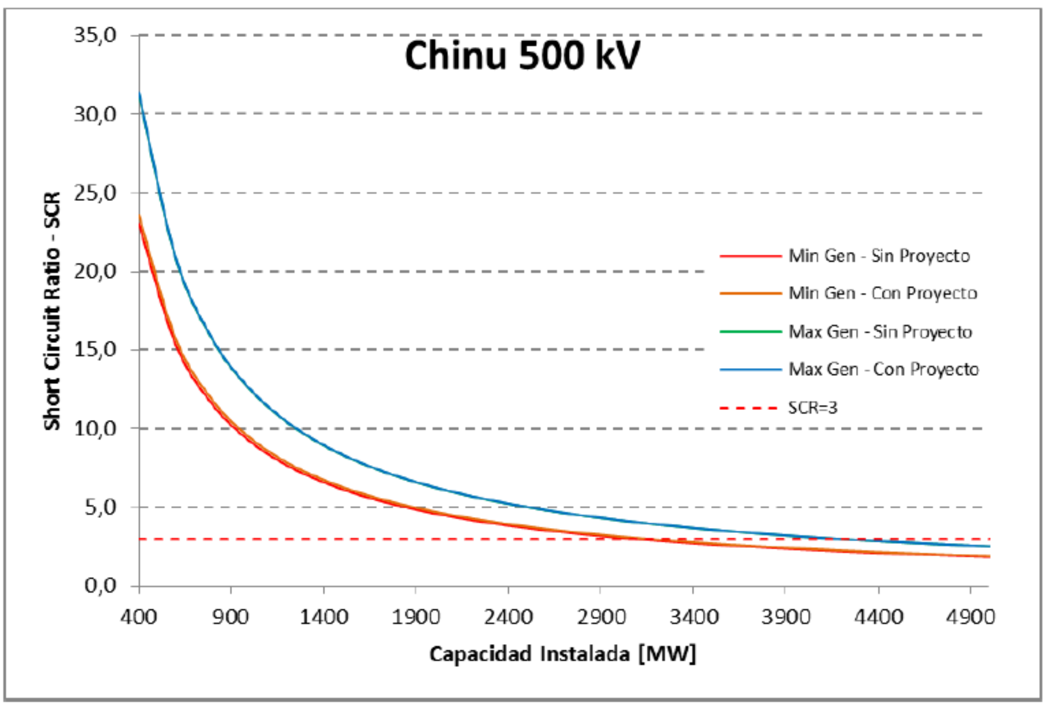

Figure 2-3 SCR relationship to connect generation in Chinú [1]

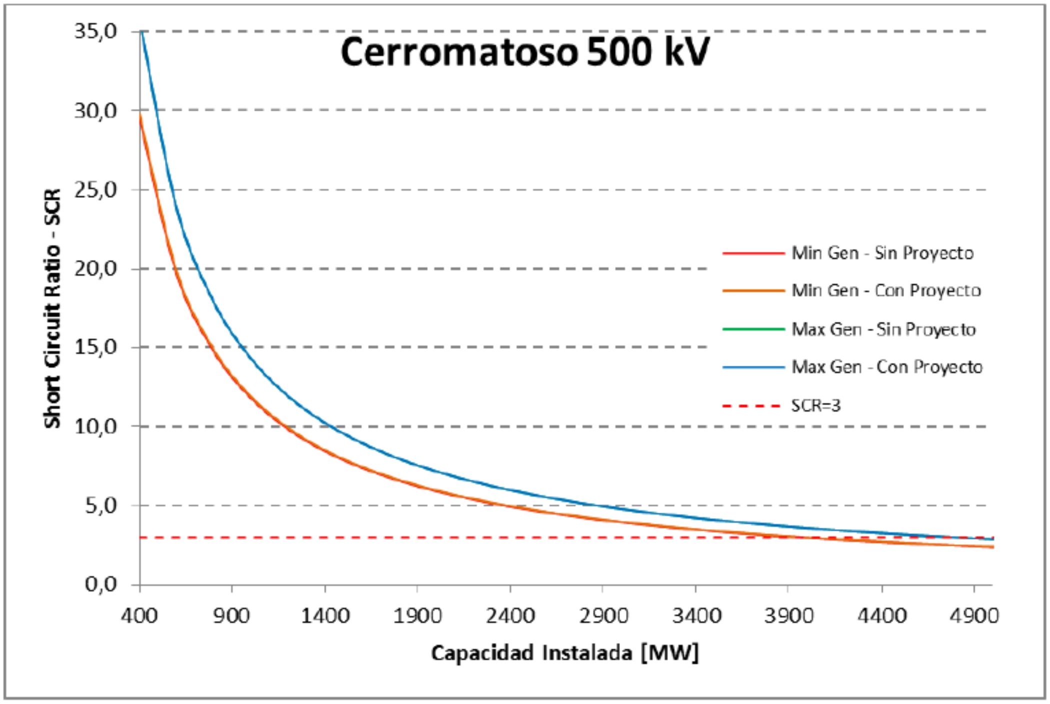

Figure 2-4 SCR relationship to connect generation in Cerromatoso [1]

3. Feasibility of the Interconnection Alternatives and Additional Studies

The feasibility of the interconnection alternatives studied by UPME are further evaluated in this chapter. TGS performed the assessment based on the previous experience, engineering judgement and the outcomes of the additional studies performed using the power system models provided by UPME. In addition, TGS evaluated the feasibility of having an LCC HVDC bipole to interconnect Collector 2.

Accordingly, the following interconnection options were evaluated:

HVAC interconnection options

- 500 kV AC transmission lines to Cuestecitas
- 500 kV AC transmission lines to Chinu
- 500 kV AC transmission lines to Cerromatoso
- 500 kV AC transmission lines to Copey (with Collector 1 and 2 interconnected)

HVDC interconnection options

- LCC HVDC bipole transmission to Cerromatoso
- VSC HVDC bipole transmission to Cerromatoso

3.1 Study Cases and Assumptions

3.1.1 Study Cases

Four study cases given in Table 3-1(for operational years 2028 and 2032) were used in the analysis. These cases were set up to integrate the generation from Collector 2 to Cerromatoso. The study cases include the transmission network upgrades defined in UPME's latest transmission expansion plan [3]. Only 2000 MW of renewable generation is expected to be connected to the collector system 2 by operational year 2028. The full capacity of 3000 MW will be reached by operational year 2032. The power flows in major 500kV network are shown in Figure 3-1 through Figure 3-4.

Table 3-1 Study case details—HVDC

Operational Year	Study Case	Collector 2 Generation (MW)	Total System Load (MW)
2028	Min Dem Min Gen	2000	7914
	Max Dem Max Gen		11934
2032	Min Dem Min Gen	3000	8315
	Max Dem Max Gen		12546

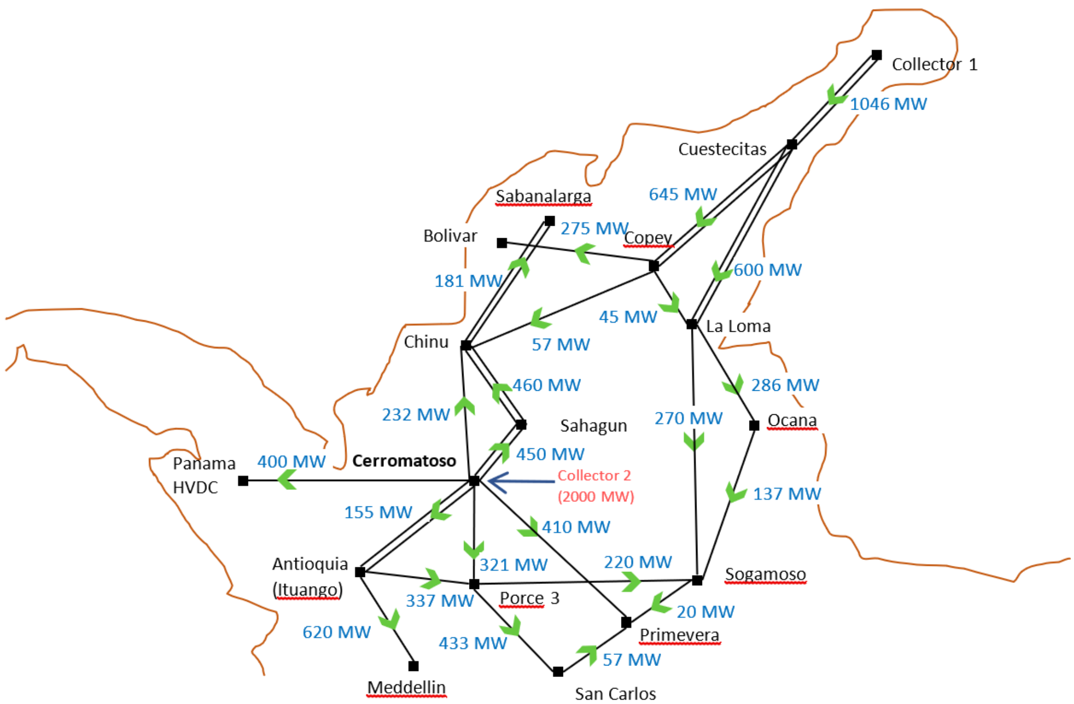

Figure 3-1 Active power flow on selected 500 kV transmission corridors - 2028 Min Dem Min Gen

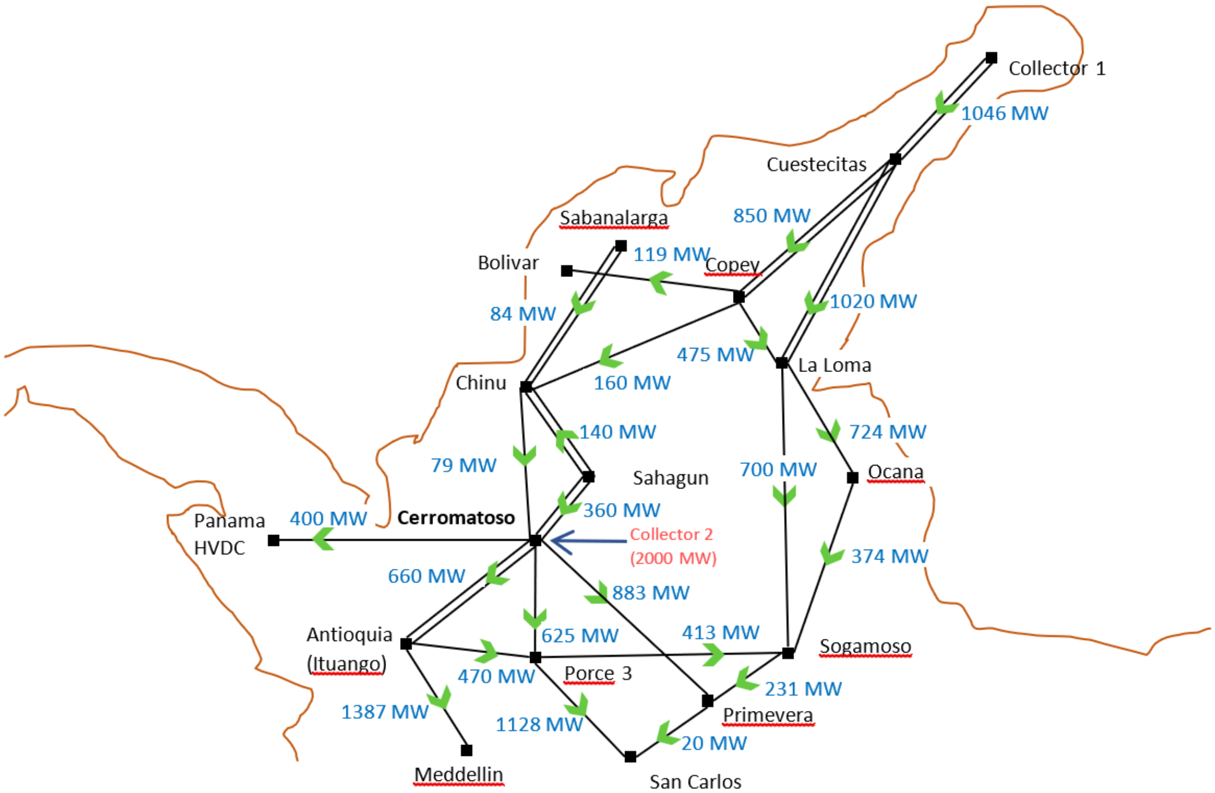

Figure 3-2 Active power flow on selected 500 kV transmission corridors - 2028 Max Dem Max Gen

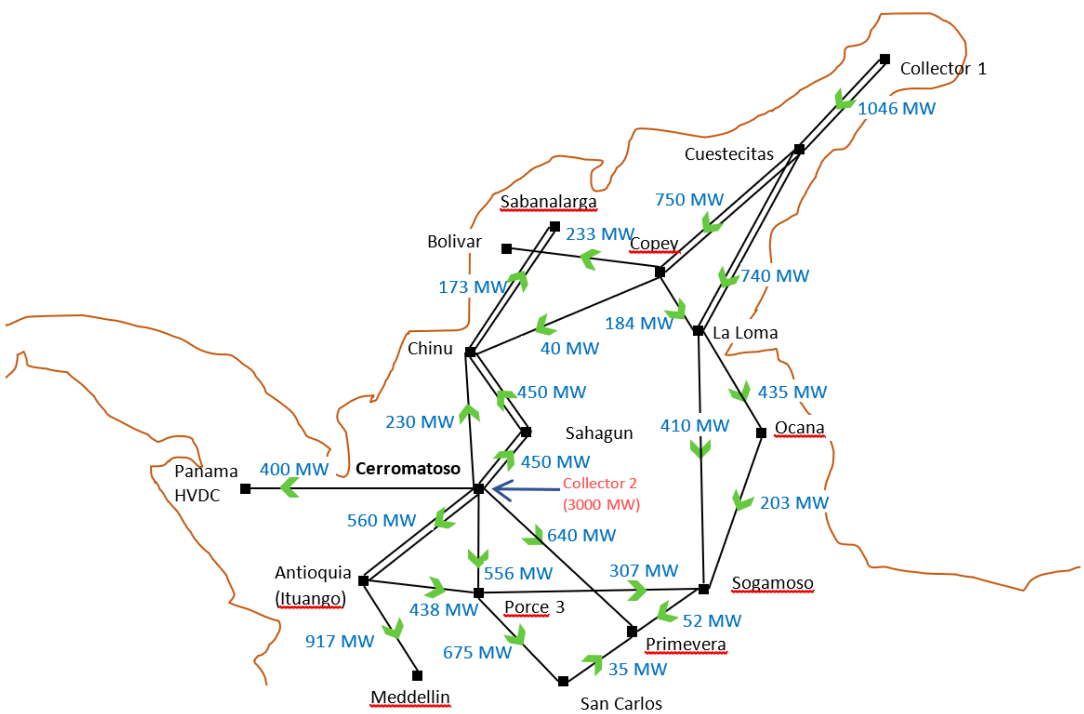

Figure 3-3 Active power flow on selected 500 kV transmission corridors – 2032 Min Dem Min Gen

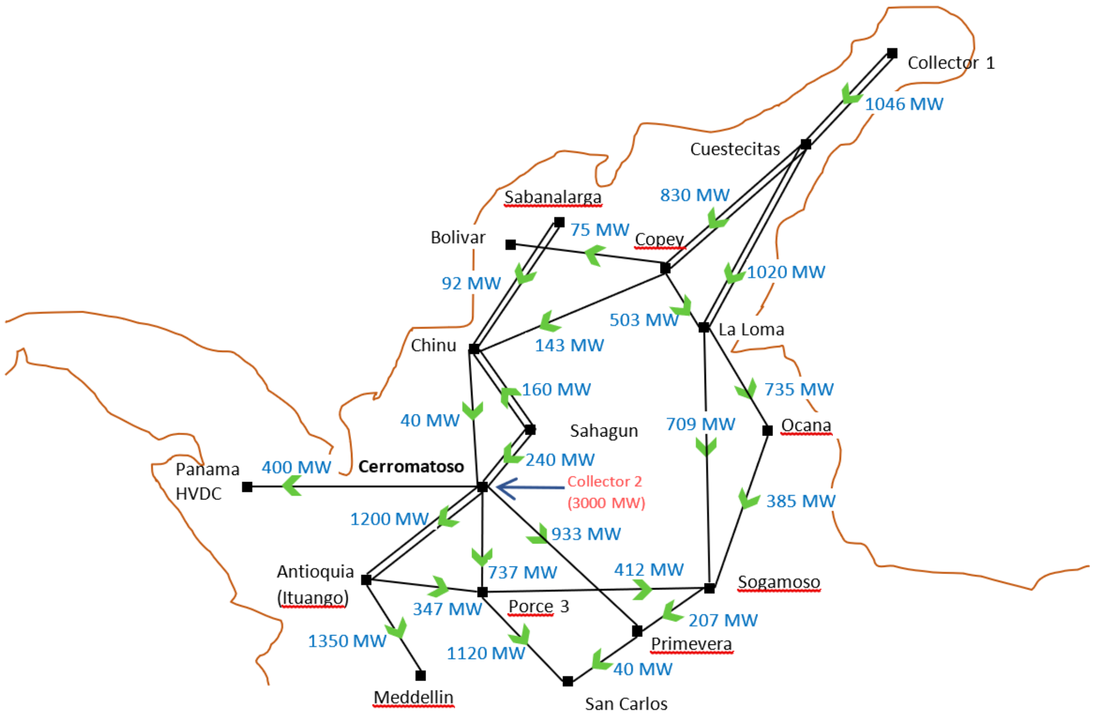

Figure 3-4 Active power flow on selected 500 kV transmission corridors – 2032 Max Dim Max Gen

In addition, the feasibility of the AC alternatives mentioned in Section 2.1.3 (500 kV AC transmission lines to Copey) were assessed using the study cases provided by UPME that were set up to integrate the Collector 2 generation to Copey using 300 km long 500 kV double circuit lines.

3.1.2 The study cases were prepared by UPME in consultation with TGS. Key considerations and assumptions

- Most of the generation in La Guajira is planned to be wind generation. The wind generators available in the market requires a minimum SCR of 3 for proper operation if they are connected to an AC interconnection. Otherwise, they should be connected to an isolated system with an HVDC in frequency control.
- No existing AC network is present in La Guajira area where the Collector 2 is planned to be located.
- The distance between Collector 1 and Collector 2 is about 50 km.
- 3000 MW of generation is available at the Collector 2 by 2032.
- For the HVDC options, the HVDC was assumed to have 3000 MW rating at the rectifier (Collector 2).
- During the Task 1 of this study, the Collector 2 generation was modelled using the same device dynamic models used for the renewable generators at the Collector 1.
- Panama HVDC was modeled as a 400 MW load connected to Cerromatoro 500 kV busbar

3.2 Feasibility of HVAC Interconnection to Cuestecitas, Copey, Chinu or Cerromatoso

The AC system strength, based on the power system models provided by UPME, at Cuestecitas, Copey, Chinu and Cerromatoso under each operational scenario is shown in Table 3-2.

Table 3-2 AC system strength at Cuestecitas, Copey, Chinu and Cerromatoso

Operational Year	Study Case	System Strength (MVA)			
		Cuestecitas	Copey	Chinu	Cerromatoso
2028	Min Dem Min Gen	6795	8371	10524	13147
	Max Dem Max Gen	8727	11170	14970	17725
2032	Min Dem Min Gen	7080	8970	11490	13951
	Max Dem Max Gen	8697	11220	14950	17730

Figure 3-4shows the AC system strength obtained for 2028 Min Dem Min Gen study case. Note that these figures include the short circuit contributions from the renewable plants as well (as in DIgSILENT models).

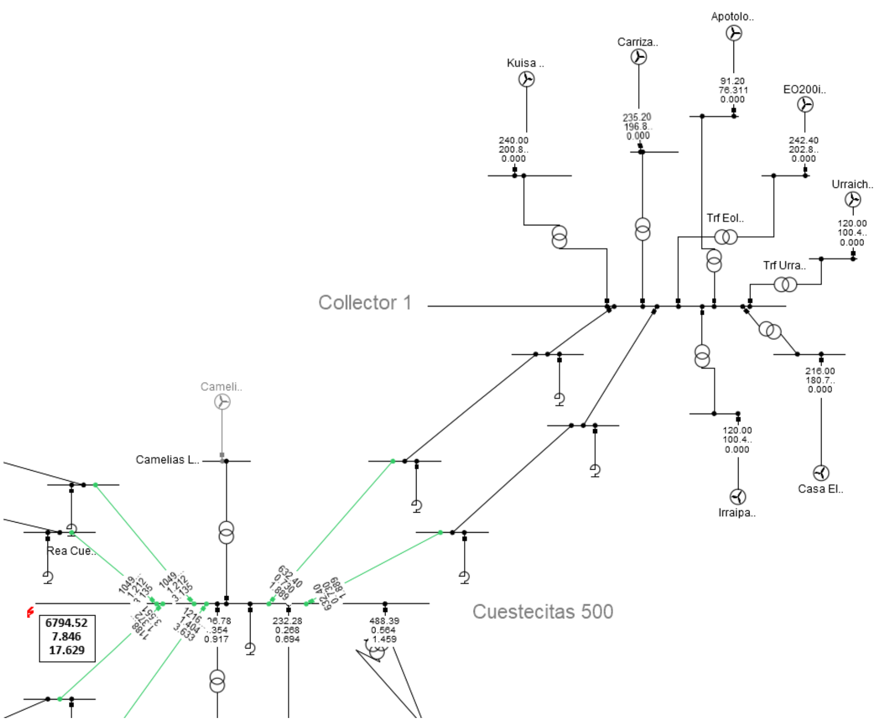

Figure 3-5 AC System strength at Cuestecitas—2028 Min Dem Min Gen

The approximate transmission line lengths from Cuestecitas, Copey, Chinu and Cerromatoso to Collector 2 are 170 km, 380 km, 510 km, and 650 km respectively.

3.2.1 Interconnection at Cuestecitas

Based on the power flow scenarios considered, the system strength at Cuestecitas is in the range of 7080 MVA to 8697 MVA by 2032. If the impedance of the interconnection circuits is ignored, the expected SCR for 3000 MW of wind generation is in the range of 2.36 to 2.9. This number will be significantly reduced when the interconnection circuit impedance is considered.

As an example, the system strength at Collector 2 was evaluated by adding a 170 km long 500 kV double circuit transmission line from Cuestecitas (Figure 3-6). This analysis was done for the *2032 Max Dem Max Gen* study case. The 500 kV interconnection circuits were assumed to have the same type as the 500 kV line from Custecitas to Collector 1. The system strength observed at Collector 2 is about 5211 MVA. The SCR for connecting about 3000 MW of generation is about 1.74. Considering the further reduction of SCR when the collector system impedances are considered, the wind farms cannot operate even with controls tuned for weak systems. Therefore, it would be required to install a large amount synchronous condensers to provide the required short circuit current for the proper operation of the wind power generators.

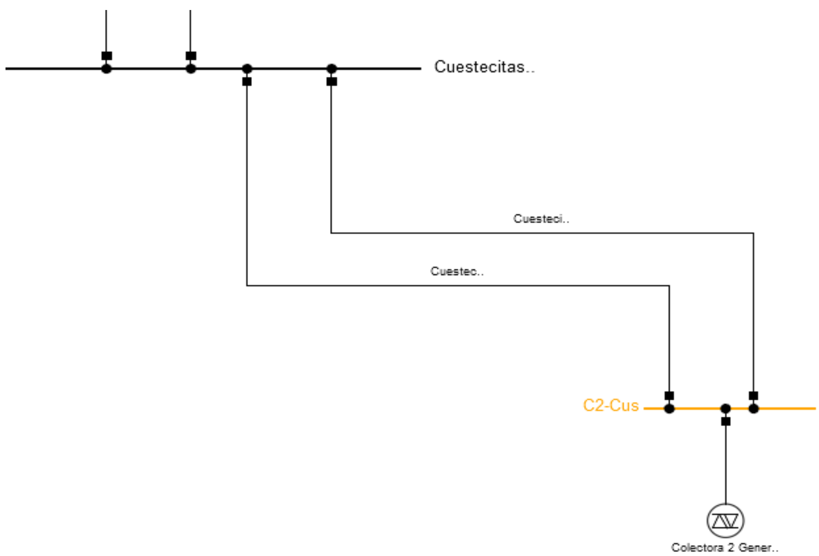

Figure 3-6 170 km long 500 kV double circuit transmission line from Collector 2 to Cuestecitas

Moreover, UPME report shows that the integration of over 600 MW at Cuestecitas will have stability issues due to the low SCR and the overload issues due to limited capacity of the 230 kV network (with the proposed AC network upgrades in service).

Therefore, there is sufficient information from the outcomes of the initial studies performed by UPME to determine that the interconnection of the Collector 2 to Custecitas is not a viable solution.

Therefore, no further studies are required on this alternative.

3.2.2 Interconnection at Chinu or Cerromatoso

The feasibility of interconnection at Chinu or Cerromatoso using 500 kV double circuit AC transmission lines were further evaluated. Cerromatoso and Chinu have much better system strength compared to Cuestecitas as shown in Table 3-2. However, the collector 2 is located about 650 km and 520 km away from Cerromatoso and Chinu respectively.

As an example, the system strength at Collector 2 was evaluated by adding a 500 kV double circuit transmission line from Cerromatoso (Figure 3-7). This analysis was done on *2032 Max Dem Max Gen* study case which has the highest system strength. The 500 kV interconnection circuits were assumed to have the same line type as the 500 kV line from *Chinu - Cerromatoso.* Considering the lengths of the interconnection lines, a 50% of series compensation was added to both circuits.

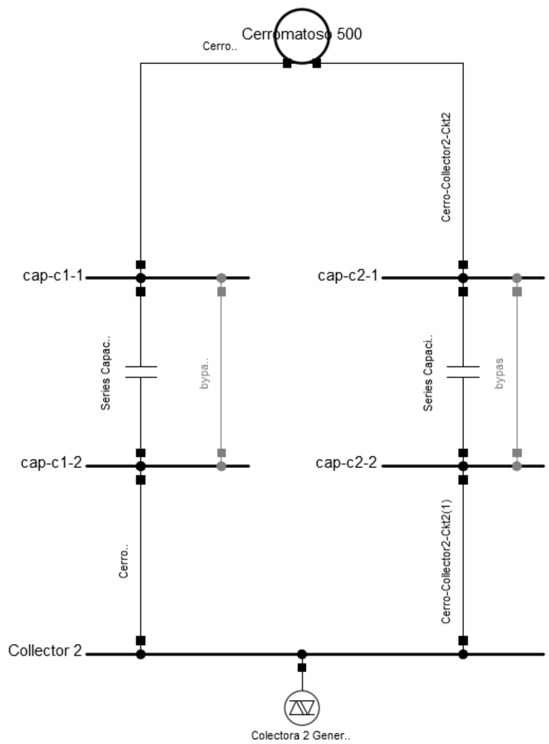

Figure 3-7 650 km long 50% compensated 500 kV double circuit transmission line from Collector 2 to Cerromatoso

Even with series compensation, the system strength observed at Collector 2 was about 4178 MVA. The SCR for connecting about 3000 MW of generation is about 1.4. Therefore, it would be required to install a large amount synchronous condensers to provide the required short circuit current for the proper operation of the wind power generators. In order to achieve an SCR of 3, a short circuit strength of about 5000 MVA needs to be provided by the synchronous condensers. If a short circuit impedance of 30% (sub transient impedance + transformer impedance) is assumed, at least 1500 MVA of synchronous condensers would be required (without considering redundancy).

In addition, the series compensated AC transmission lines connected to a large amount of wind generation may have sub synchronous resonance issues.

Considering the issues and limitations identified by previously performed studies (UPME) and the further evaluations performed by TGS, it is not recommended to have an AC interconnection between Collector 2 and Cuestecitas, Chinu or Cerromatoso.

3.2.3 Interconnection at Copey (with Collector 1 and 2 interconnected)

The interconnection feasibility of the Collector 2 at Copey as specified in Alternative 4 and Alternative 5 was further studied using the study cases provided by UPME. The interconnection configuration and the corresponding network reinforcements are discussed in Section 2.1.3. Figure 3-8 shows the Collector 2 interconnection to Copey using 500 kV double circuit AC transmission lines and the interconnection between Collector 1 and Collector 2.

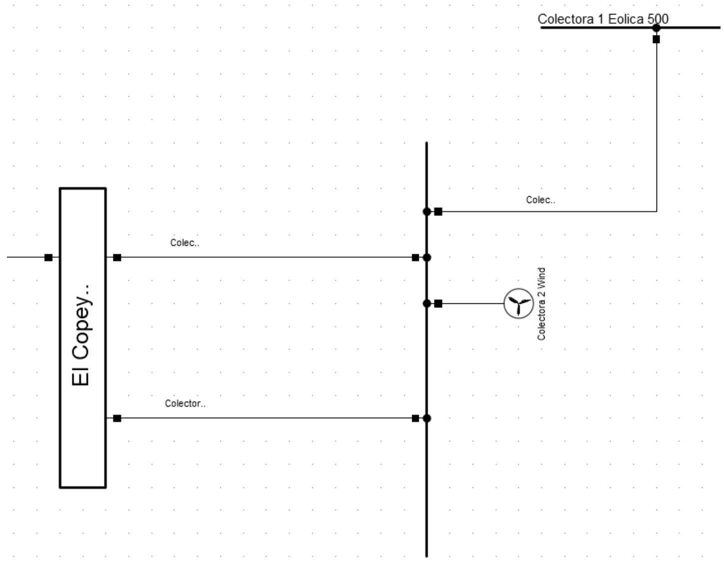

Figure 3-8 Collector 2 interconnection to Copey using 500 kV double circuit AC transmission lines

Table 3-3 shows the AC system strength at Collector 2 busbar under the Alternative 4 and Alternative 5 interconnections. Under these options the system strength at Collector 2 is sufficient to integrate the Collector 2 generation at Copey.

Table 3-3 System Strength at Collector 2 under Alternative 4 and Alternative 5

Operational Year	Study Case	System Strength (MVA) at Collector 2	
		Alternative 4	Alternative 5
2028	Min Dem Min Gen	5905	5901
	Max Dem Max Gen	6872	6864
2032	Min Dem Min Gen	5985	5982
	Max Dem Max Gen	6869	6863

3.2.3.1 *Feasibility of the interconnection of 3000 MW from Collector 2 (2032 Study Cases)*

The feasibility of interconnecting 3000 MW at Collector 2 in 2032 study cases were further studied. It was noted that a significant portion of the power generation in Collector 2 flows from Collector 2 to Collector 1 and then to the south although the Collector 2 is connected to Copey using a 500 kV double circuit transmission line. For example, in *2032 Min Dem Min Gen* study case, about 1200 MW is transferred from Collector 2 to Collector 1 and the 500 kV line between Collector 1 and Collector 2 is loaded to about 60% under system intact conditions.

The preliminary AC contingency analysis indicated that it is difficult to interconnect 3000 MW of generation due to the following reasons:

- Base case low voltage violations observed in 2032 Max Gen Max Dem in El Banco, Gaira and Santa Marta areas
- Equipment overloads were observed including several 500 kV transmission lines (Table 3-4 lists the equipment overloads)

Table 3-4 Equipment overloads when the Collector 2 is integrated with 3000 MW of generation using Alternative 4 and 5

Monitored Element	Study Case	Contingency	Loading (%)
Santa Marta 1 220/110	2032 Max Dem Max Gen A4	Santa Marta 9 220/110	187
Norte 500/230	2032 Max Dem Max Gen A4	Norte - ReaNva Espe 1 500	134
Chinu - Since 1 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	127
La Loma - Ocaña 1 500 T2	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	122
Copey 220/110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	120
Chinu - San Marcos 1 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	118
Nva Esperanza 2 500/120/11	2032 Max Dem Max Gen A4	Nva Esperanza 1 500/120/11.4	115
Nueva Esperanza - Río 115 kV	2032 Max Dem Max Gen A4	Nva Esperanza 1 500/230/13.8	114
Sabana de Torres - San Alberto 1 115	2032 Max Dem Max Gen A5	Ocaña - Sogamoso T1 500	114
Magangue - Since 1 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	113
Chinu 1 500/110	2032 Max Dem Max Gen A4	Chinu 2 500/110	112
Cuestecitas(TRC) - San Juan 1 220	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	112
Chinu 3 500/110	2032 Max Dem Max Gen A4	Chinu 2 500/110	112
Ocaña 1 500/230	2032 Max Dem Max Gen A5	Ocaña 4 500/230	109
Ocaña 4 500/230	2032 Max Dem Max Gen A5	Ocaña 1 500/230	108
Lizama - Sabana de Torres 1 115	2032 Max Dem Max Gen A5	Ocaña - Sogamoso T1 500	108

Monitored Element	Study Case	Contingency	Loading (%)
Cuestecitas 500/230	2032 Min Dem Min Gen A5	Colectora 2 - Copey 500 kV	106
Nva Esperanza 1 500/120/11.4	2032 Max Dem Max Gen A4	Nva Esperanza 2 500/120/11.4	105
NMonteria 1 230/110	2032 Max Dem Max Gen A5	NMonteria 2 230/110	105
Cuestecitas - Colectora1 1 500 T2	2032 Max Dem Max Gen A4	Cuestecitas - Colectora1 2 500 T1	104
Cuestecitas - Colectora1 2 500 T2	2032 Max Dem Max Gen A4	Cuestecitas - Colectora1 2 500 T1	104
El Banco - El Paso 1 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	103

- Severe low voltages at several busbars were observed (Table 3-5 lists the bus voltage less than 0.85pu)

Table 3-5 Low voltages at busbars when the Collector 2 is integrated with 3000 MW of generation using Alternative 4 and 5

Monitored Element	Study Case	Contingency	Voltage (pu)
El Banco 110\El Banco 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.59
Mompox 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.62
Magangue 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.65
La Jagua 110\La Jagua 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.72
Libertad 110\Libertad 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.73
Manzanares 110\Manzanares 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.73
Codazzi GCM 110\Codazzi GCM 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.73
Gaira 110\Gaira 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
La Mojana 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
Santa Marta 110\PT Sta Marta 110 LIB	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
El Paso 110\Barra1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
Since 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
La Cuna 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.74
Cienaga 110\Cienaga 110	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.76
La Loma 110	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.76
Ocaña 500\Barra1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.76

Monitored Element	Study Case	Contingency	Voltage (pu)
T Puerto Nuevo	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.76
Puerto Nuevo	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.76
El Carmen 110\El Carmen 110	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.77
Rio Cordoba 110\PT RCR 110 ATR1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.77
Rio Sinu 110\PT Rio Sinu 110-TierraAlta	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.77
San Marcos 110	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.77
Valledupar 220\Barra Capacitores Valledupar 220	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.78
Monteria 110	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.78
La Loma 500\Barra 1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.78
Nva Monteria 110\Barra 1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.78
San Juan 110\San Juan 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.78
Nva San Juan 110.4	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.78
Coveñas 110\PT Sierraflor 110-TF1.4	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.79
Aguachica 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.79
Fundacion 110\PT Fun110-Tr3 2	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.79
Buturama 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.79
Guatapurí 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.79
Valledupar 110\PT Vlldpar T11 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.79
Ayacucho 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.79
San Juan 220	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.79
San Alberto 115\San Alberto 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.80
Santa Marta 220\Sta Marta 220 - Barra 1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.80
Cerete 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.80
R Cordoba 220\Rio Cordoba 220 - Barra 1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.80
El Copey 500\Copey500_B1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.80
Sierra Flor 110\PT Sierraflor 110-TF1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.81

Monitored Element	Study Case	Contingency	Voltage (pu)
Maicao 110\Maicao 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.81
Convencion 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.81
Ocaña 115\Barra1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.81
Toluviejo 110\PT Tolu CVS 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T3	0.81
Termocol 220\Termocol 220 - Barra 1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.81
Boston 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.82
Bolivar 500\Barra 1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.82
Boston - Chinu 1 110\Boston - Chinu 2 en Boston	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.82
Copey 110\Copey 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.82
Fundación 500 kV	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.82
Fundacion 220\PT Fun220-Tr3 2	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.82
Tibu 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.83
Carreto 500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.83
Sabanalarga 500\SAB_B1_500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.83
Guayepo 500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.83
Atlantico Photo 500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.83
Riohacha 110\Riohacha 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Chinu 500\CHN_B1_500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Copey 220\Barra1	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Toluviejo 220	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Ocaña 220\Barra1	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.84
Sabana de Torres 115\Sabana de Torres 115	2032 Max Dem Max Gen A5	La Loma - Sogamoso 1 500 T2	0.84
Planeta 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Cuestecitas 500	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.84
Monteria 220\Monteria_B1_220	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.85
Tierralta 110	2032 Max Dem Max Gen A4	La Loma - Ocaña 1 500 T1	0.85

- Large amount of reactive power is required to obtain a feasible operating point under some outages (e.g.: about over 1200 Mvar is required at Collector 2 under the outage of Collector 1—Collector 2 AC transmission line in *2032 Max Dem Max* Gen study case)

3.2.3.2 Feasibility of the interconnection of 2500 MW from Collector 2 (2032 Study Cases)

The feasibility of interconnecting 2500 MW at Collector 2 in 2032 study cases were further studied for Alternative 4 and Alternative 5. The preliminary AC contingency analysis identified the following issues:

- Several minor equipment overloads (>100%)
- Low voltages at few bus bars around 0.85pu

3.2.3.3 Feasibility of the interconnection of 2000 MW from Collector 2 (2028 and 2032 Study Cases)

The AC contingency analysis indicated the feasibility of integrating about 2000 MW of generation at Collector 2 using the HVAC Alternative 4 and Alternative 5. Several minor equipment overloads and voltage limit violations were identified; however, those are local issues and are not a result of this project.

Considering the outcome of the steady state analysis of 3000 MW, 2500 MW and 2000 MW cases, it was decided to further analyze the 2000 MW option for dynamic performance.

Dynamic simulations were performed for a selected set of contingencies to check if the system can withstand disturbance close to the Collector 1 and Collector 2. For transient stability simulations, the Collector 2 generation was modelled using the same dynamic models used to model the Collector 1 generation.

The following is the list of contingencies simulated using the transient stability simulation. A 100 ms long 3ph-g fault was applied in all contingencies.

Contingency 1: Fault on 500 kV Colector 1—Colector 2 interconnection, cleared by tripping the faulted transmission line

Contingency 2: Fault on circuit 1 of 500 kV Copey—Collector 2 transmission line, cleared by tripping the faulted transmission line

Contingency 3: Fault on 500 kV Cuestecitas – Collector 1 transmission line, cleared by tripping the faulted transmission line

Contingency 4: Fault on 500 kV Copey - Cuestecitas 1 transmission line, cleared by tripping the faulted transmission line

Contingency 5: Fault on 500 kV Cuestecitas - La Loma 1 transmission line, cleared by tripping the faulted transmission line

The system was capable of maintaining the transient stability under the above list of contingencies for all study cases when the Collector 2 is interconnected under Alternative 4 and Alternative 5.

Figure 3-9, Figure 3-10 and Figure 3-11 show the active power flow, bus voltage and the active power generation at renewable generators at Collector 1 and 2 under the contingency 1 for the study case *2032 Min Dem Min Gen* with the Alternative 4.

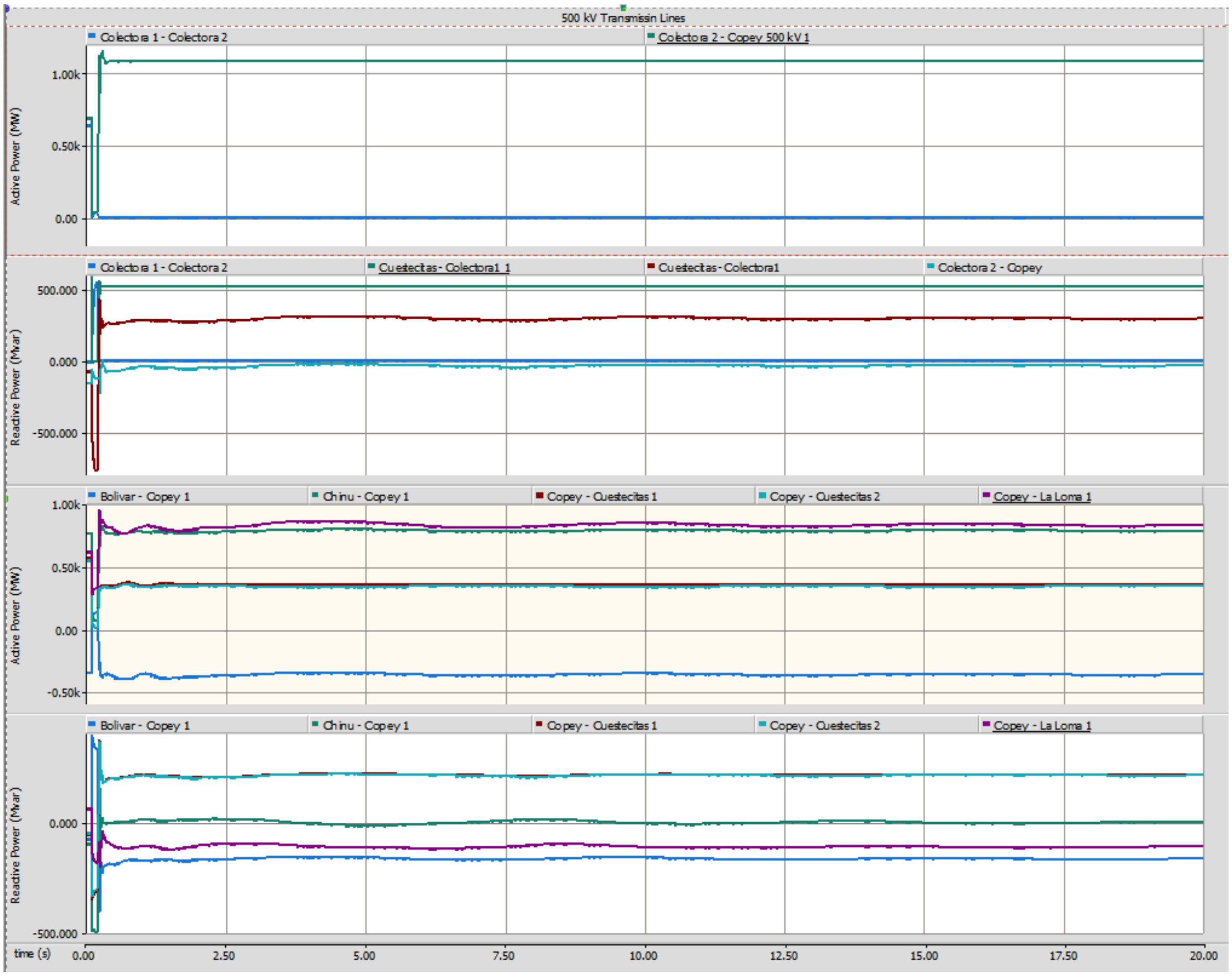

Figure 3-9 Active power flow on selected 500 kV transmission lines (Contingency 1, 2032 Max Dem Max Gen—Alternative 4)

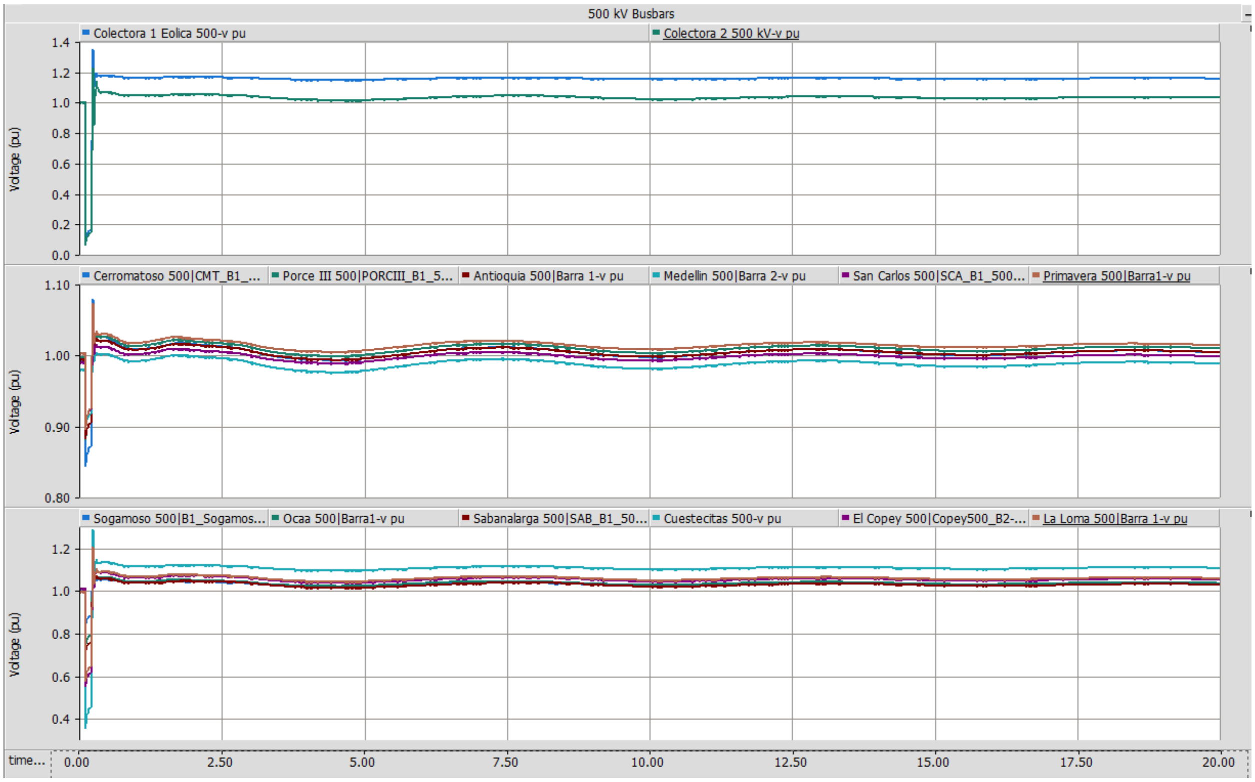

Figure 3-10 Selected 500 kV bus voltages (Contingency 1, 2032 Max Dem Max Gen—Alternative 4)

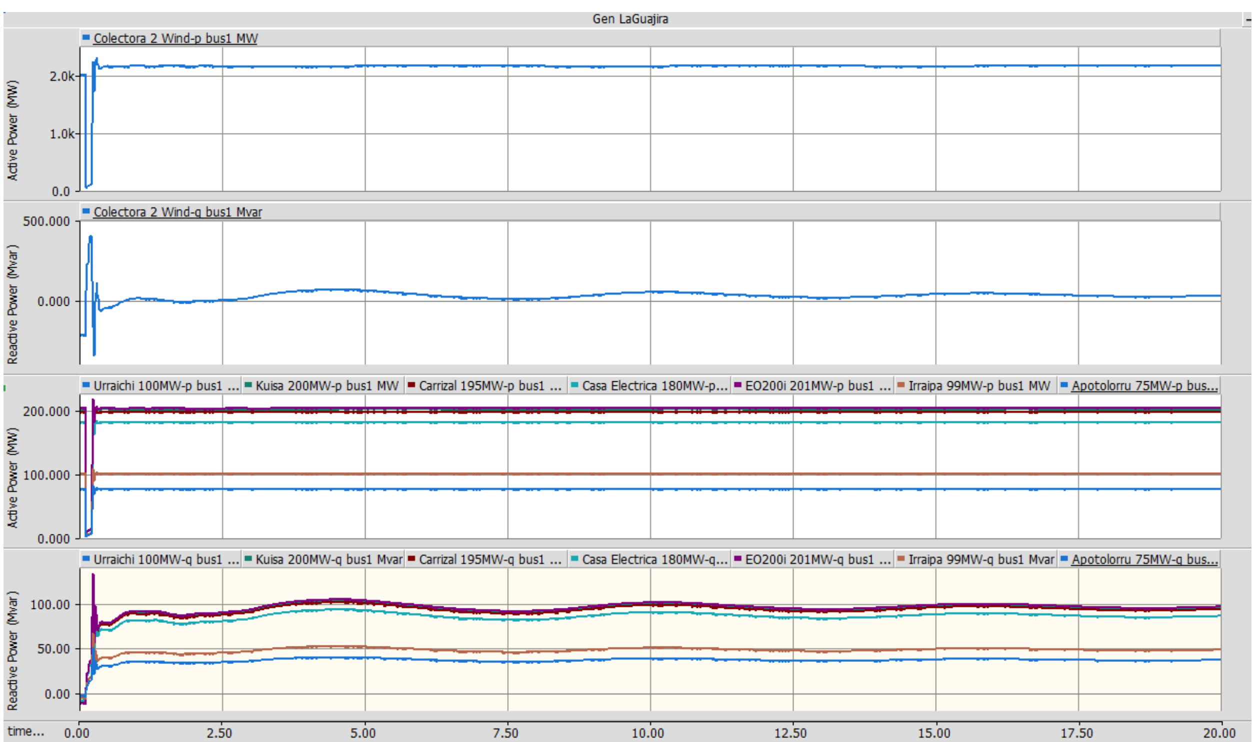

Figure 3-11 Renewable generation at Collector 2 and Collector 1 (Contingency 1, 2032 Max Dem Max Gen—Alternative 4)

The preliminary dynamic simulation study indicated the feasibility of integrating about 2000 MW of generation from Collector 2 as proposed in Alternative 4 or Alternative 5.

From the preliminary studies performed, it was concluded that the AC alternative 4 or 5 with 2000 MW of renewable generation at Collector 2 are feasible solutions. The transfer limit can be increased to about 2500 MW with additional reinforcements which need to be identified from a detailed study.

Note that the preliminary dynamic simulation results presented in this section should only be considered to identify the feasibility of the solution. The overall system dynamic performance was not assessed during this study. Additional network reinforcements, tuning of device dynamic models would be required to meet the system performance criteria. The system studies planned in Task 2 will consider the system performance in detail.

3.3 Feasibility of LCC HVDC Transmission

LCC HVDC is the most matured type of HVDC transmission technology which has been in operation since 1960s. The technical capabilities, economic advantages, and low operating losses, make the line commutated converter (LCC) HVDC an attractive solution for power system interconnections. However, the thyristor based LCC converters needs support from the AC terminals for the proper operation.

- The short circuit ratio at the connection point should be 2 or greater for the proper operation of LCC HVDC. For the inverter terminal the SCR should be even bigger considering the commutation performance of the thyristor valves.
- The line commutated converters absorb reactive power in both rectifier and inverter operation. Typically, 50 to 60% of the converter rating.

Collector 2 is expected to be an isolated collector system connected to 3000 MW of wind power generated in La Guajira area. Therefore, there is not enough short circuit capacity in such system to connect an LCC converter to Collector 2. An alternative solution is to connect the Collector 2 to Collector 1 with a 500 kV double circuit AC line. The expected short circuit capacity with the connection of the double circuit 500 kV AC line between systems 1 and 2 was investigated.

The maximum short circuit capacity at Collector 2 was found to be about 5600 MVA (*2032 Max Dem Max Gen* study case).

Short Circuit Ratio: ***SCR = (Short circuit MVA at AC bus)/Rated DC power***

For a 3000 MW HVDC link, maximum SCR = 1.86

In the LCC HVDC systems, AC filters are used and the dynamic performance in weak systems is deteriorated by the AC filters. By considering the impact of the filters, the Effective short Circuit Ratio (ESCR) is defined as

ESCR = (Short circuit MVA at AC bus – MVA rating of filters)/Rated DC power

For a 3000 MW HVDC link with 50% filters, maximum ESCR = 1.37

The CIGRE Guide for Planning DC Links Terminating at AC System Locations Having Low Short Circuit Capacities identifies the following categories of ESCR:

High	ESCR > 2.5
Low	2.5 >= ESCR >= 1.5
Very Low	ESCR <1.5

The ESCR value at Collector 2 is much lower than the values defined in the CIGRE guidelines. The short circuit capacity can be increased by adding synchronous condensers. In order to achieve an ESCR of 2, an additional short circuit strength about 2000 MVA would be required. If a short circuit impedance of 30% (sub transient impedance + transformer impedance) is assumed, at least 650 MVA of synchronous condensers would be required (without considering any n-1 contingency for machine availability). Therefore, LCC HVDC option is not a preferred solution.

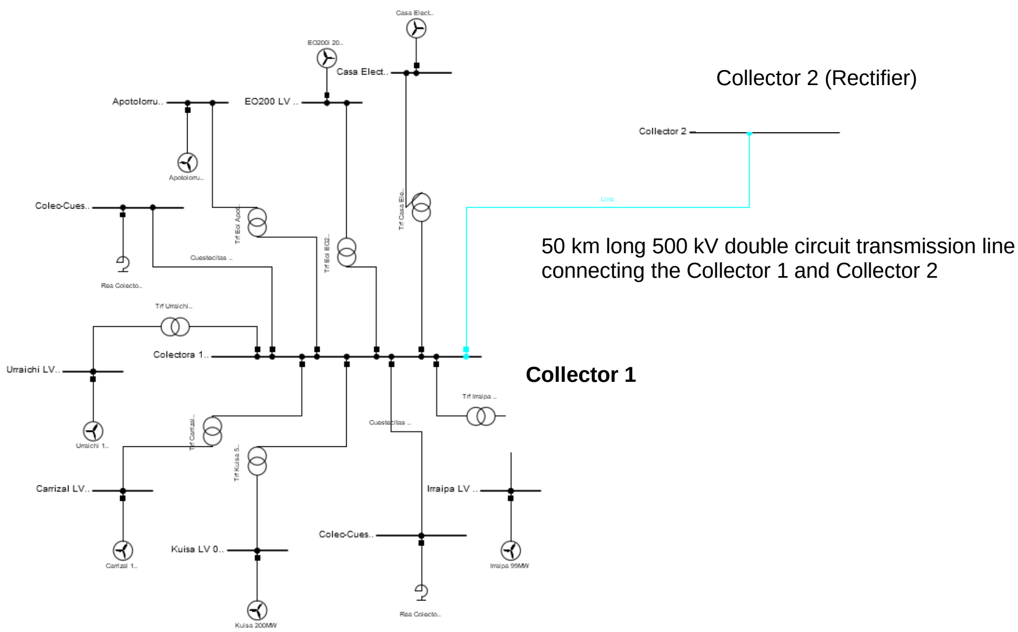

Figure 3-12 LCC HVDC transmission system rectifier at the Collector 2

3.4 Feasibility of VSC HVDC bipole transmission to Cerromotoso

The voltage source converter (VSC) was introduced in the 1990s. The VSC valves utilize the insulated gate bipolar transistor. (IGBT). Unlike thyristor valves where only the turn on can be controlled, IGBT valves can be controlled in both turn on and turn off. Therefore, a VSC HVDC is capable of operating in an isolated AC system. Further, VSC converters can control their reactive power in both directions. This is a distinct advantage over the LCC technology.

Another advantage of the VSC HVDC systems is that it can provide the black-start capability. VSC HVDC system are gaining popularity around the world for interconnecting large amounts of renewable energy to the AC networks. Current HVDC converter ratings are up to 3000 MW and voltages up to 600 kV. VSC can be applied in bipolar, symmetrical monopoles, and back-to-back HVDC systems [4].

Considering the AC system conditions discussed in Section 4.2, VSC HVDC would be the preferred solution due to the following reasons:

- No additional devices such as synchronous condensers are required at La Guajira to enhance the short circuit capacity (Low SCR is not a critical issue)
- The VSC terminal at La Guajira region (Collector 2) can be operated in frequency control (i.e., isolated operation or grid forming control). In such a system, the wind farms can operate without having additional short circuit support (i.e., SCR rules are not applicable)
- Black start capability can be used to start the wind farms in the La Guajira collector system
- SSR issues are not expected (as with series compensated AC transmission lines)

The following table provides a complete technical comparison of VSC HVDC and LCC HVDC technologies. The table is reproduced from [4] for the further understanding of the reader on the selection of VSC HVDC over LCC HVDC system.

Function	LCC	VSC
Semi-conductor device	Presently thyristors devices are of sizes 4, 5, and 6 inches which has a rating of 8.5 kV and up to 6300 Amps.	IGBTs with anti-parallel free-wheeling diode, with controlled turn-off capability. Device ratings of 4.5 kV and 2500 A are available
DC transmission voltage	± 1100 kV with an overhead transmission line and up to ± 600 kV with an PPL-MI cable	Up to ±600 kV with an overhead transmission line and +/- 525 kV with a cable
DC power	Up to 12000 MW on a single bipole and DC voltage of ±1100 kV	Typical ratings of 1200 MW in a symmetrical monopole and as high as 3000 MW utilizing either parallel devices or converters
Reactive power requirements	Consumes reactive power between 50% and 60% (depending on the design) of its rating at each terminal.	Does not consume any reactive power and each terminal can independently control its reactive power. The converter can supply reactive power to the system.
Filtering	Requires large filter banks	Requires moderate size filter banks or no filters at all
Black start	Limited capability	Capable of black start and feeding passive loads
AC system short circuit level	Critical in the design	Not as critical
Commutation failure performance	Fails commutation in the event of AC disturbances and DC disturbances	Does not fail commutation
Load rejection over voltage	Large and has to be mitigated	Not large
Footprint	Large because of the size of filtering and reactive power support equipment	40-50% of the size of a similar rating of an LCC
Power losses	Approximately 0.65-0.7 % of the station rating	Approximately 0.85-0.9 % of the station rating

Function	LCC	VSC
Electromagnetic interference	No difference in requirements between the LCC and VSC. The high dv/dt due to the commutation (commutation overshoot) process is critical for the design of the converter building	No difference in requirements between the LCC and VSC. In VSC based on MMC, there is no fast switching of the IGBTs, therefore no steep dv/dt

Considering the major limitations identified with AC options and LCC HVDC options, the most feasible solution to transmit 3000 MW from the Collector 2 is a VSC HVDC system. The details of the proposed VSC option are discussed in the next chapter.

4. Proposed Solution—VSC HVDC Bipole

Preliminary studies were performed to determine:

- Most suitable location for VSC interconnection
- VSC configuration
- DC voltage levels and
- Requirements for handing HVDC pole outages.

The results are summarized in the following sections. Note that the proposed solution will be studied in detail in Task-2.

4.1 Review of the Recommended Terminals: Chinu, Cerromatoso and Primavera

From the outcome of the studies performed by UPME [1] and TGS, Chinu and Cerromatoso 500 kV stations are the most appropriate locations for the interconnection terminal.

Cerromatoso and Chinu are about 135 km apart. The network power flow for 2032 study cases were compared with the HVDC connected to Cerromatoso and Chinu. The left and right figures in Figure 4-1 and Figure 4-2 show the network power flow when the HVDC (3000 MW) is interconnected at Chinu and Cerromatoso respectively.

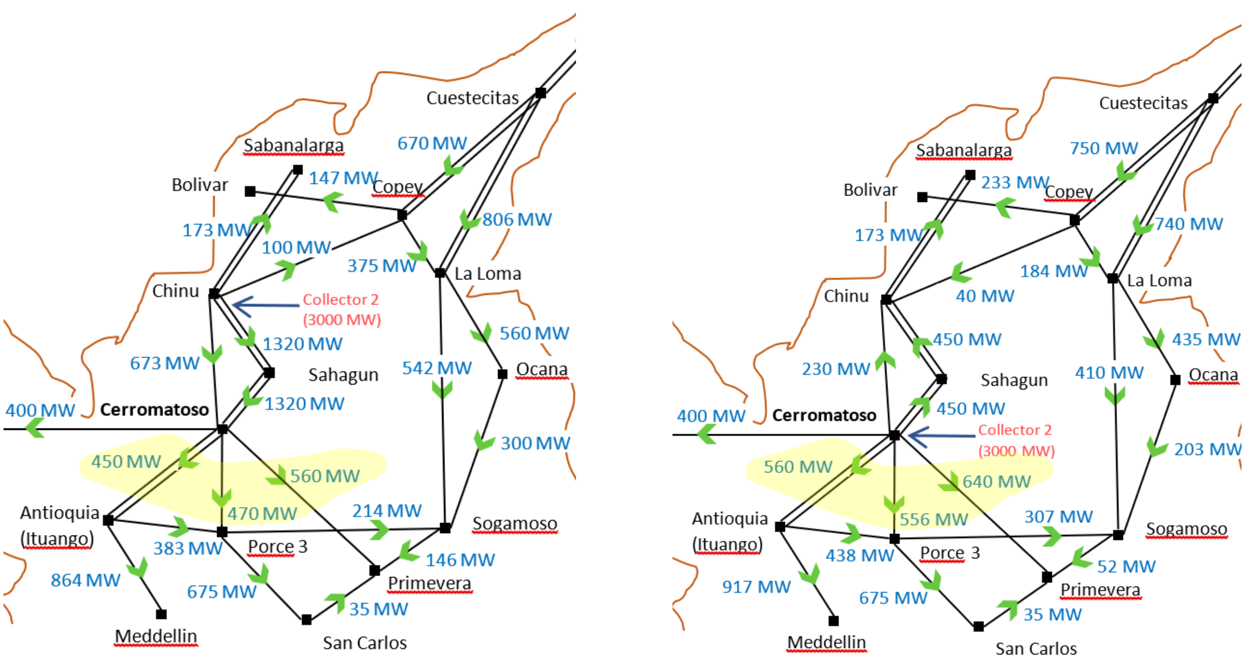

Figure 4-1 Network power flow based on the Collector 2 interconnection location in *2032 Min Dem Min Gen* study case (Left: at Chinu, right: at Cerromatoso)

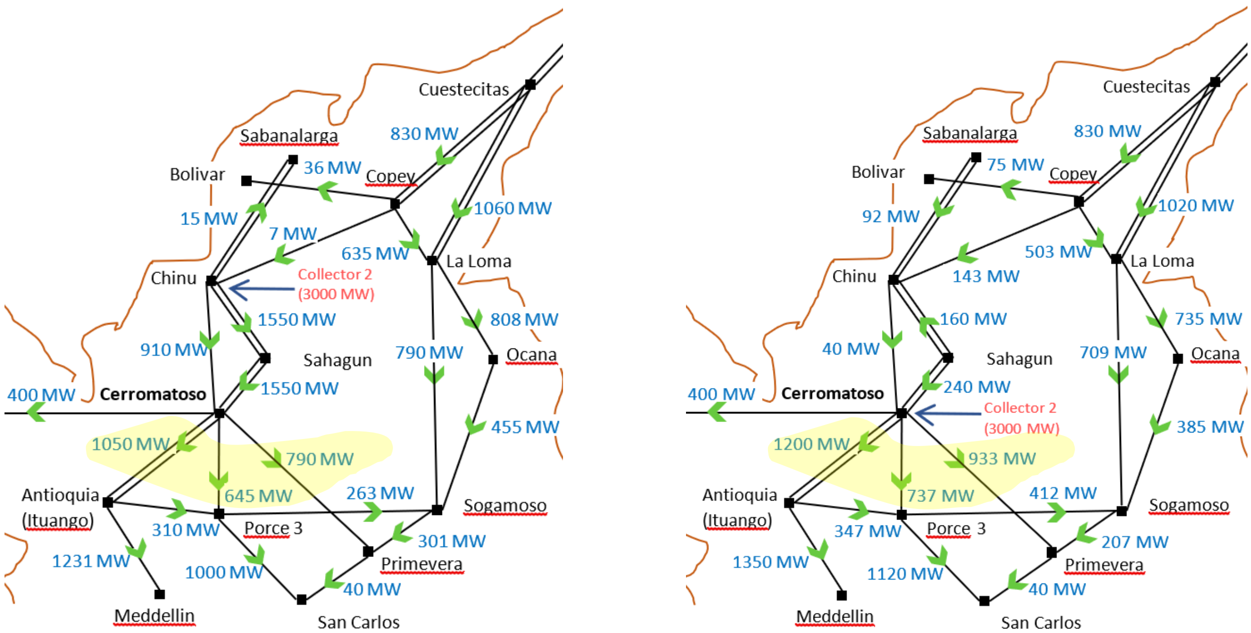

Figure 4-2 Network power flow based on the Collector 2 interconnection location in *2032 Max Dem Max Gen* study case (Left: at Chinu, Right: at Cerromatoso)

The following observations were made:

- The load centers are further down to Cerromatoso. Therefore, when interconnected at Chinu, the power needs to be transmitted for about 135 kms to Cerromatoso using the 500 kV AC transmission lines. The highlighted power flows in Figure 4-1 and Figure 4-2 show the similarity of the power flow from Cerromatoso to south (Antiuquia, Porce and Primevera) irrespective of the interconnection location. Accordingly, the selection of Cerromatoso will result in lower transmission losses.
- The system strength at Cerromatoso is higher than Chinu in all operational scenarios (Table 3-2) and will be a better location for interconnection in terms of the overall system stability.

Based on the above observations, when Chinu and Cerromatoso stations are compared, it is recommended to select Cerromatoso 500 kV station as the terminating station for the proposed VSC HVDC interconnector for the Collector 2.

The feasibility of selecting 500 kV Primavera substation as the terminating station for the proposed VSC HVDC interconnector was studied based on a request from UPME. The benefits of Primavera and Cerromatoso were compared during this analysis.

Table 4-1 shows the AC system strength and losses (without HVDC transmission system losses) when the Collector 2 is interconnected at Cerromatoso and Primavera. Note that for 2028 scenarios only 2000 MW of generation from the Collector 2 was considered.

Table 4-1 AC system strength and losses (without HVDC) when the Collector 2 is interconnected at Cerromatoso and Primavera

Year	Study Case	System Strength (MVA)		Losses without HVDC (MW)		
		Cerromatoso	Primavera	Cerromatoso	Primavera	Δ Losses
2028	Min Dem Min Gen	13147	12989	158	153	5
	Max Dem Max Gen	17725	14188	420	363	57
2032	Min Dem Min Gen	13951	12697	206	187	19
	Max Dem Max Gen	17730	15083	428	365	63

The AC system strength at Primavera is sufficient to absorb the VSC HVDC power transfer. Moreover, the AC system losses are considerably lower when the interconnection is at Primavera. The HVDC transmission line to Primavera will be about 780 km long (about 150 km longer than to connect at Cerromatoso). Therefore, the HVDC transmission losses will be more when the interconnection is at Primavera than at Cerromatoso. The additional DC transmission losses are expected to be about 15 MW and this amount is still lower than most of the loss differences shown in Table 4-1.

Figure 4-3 shows the comparison of power flow when the Collector 2 is connected at Cerromatoso and Primavera for the *2032 Max Dem Max Gen* scenario which has the largest difference in AC system transmission losses (refer Table 4-1). The highlighted power flows in major transmission lines south to Cerromatoso show the less loading on long transmission lines which is the main reason for the reduced AC transmission losses.

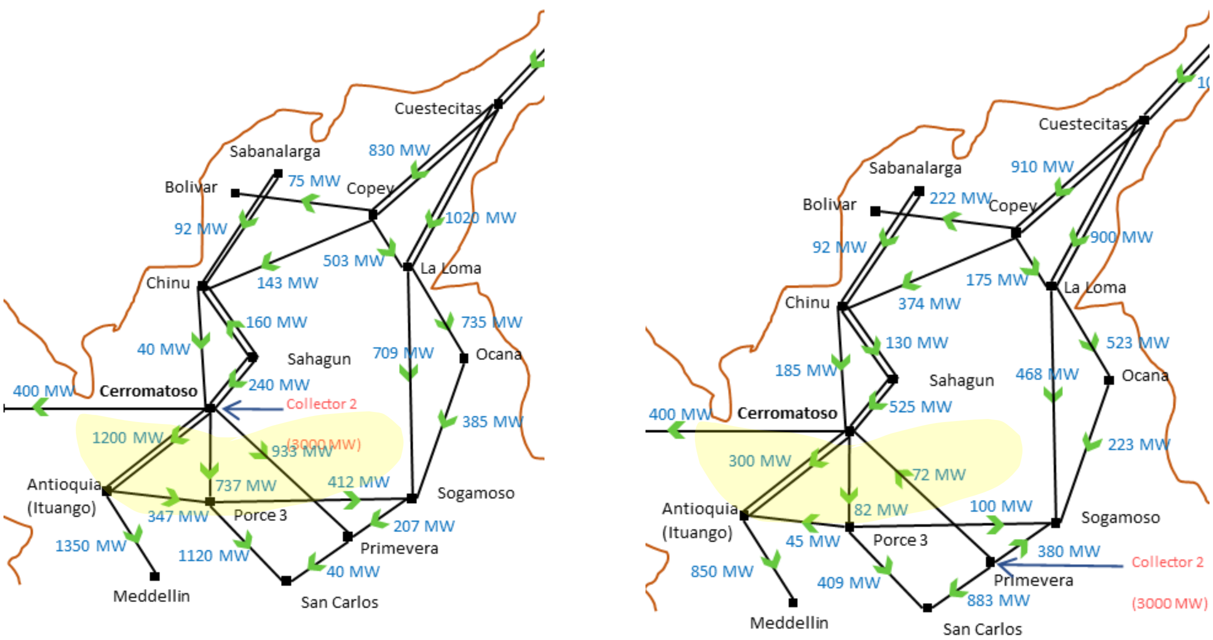

Figure 4-3 Power flow comparison-Collector 2 interconnected at Cerromatoso vs Primavera (2032 Max Dem Max Gen)

Based on this analysis, when Cerromatoso and Primavera stations are compared, it is recommended to select Primavera 500 kV station as the terminating station for the proposed VSC HVDC interconnector.

Primavera is expected to be a congested area as it is located very close to Bogotá. There may be non-technical constraints for constructing a converter station such as space limitations. It is recommended for UPME to further evaluate the selection of Primavera as the HVDC converter station.

4.1 VSC Topology

As already mentioned in Section 4.3, the VSC HVDC (bipole can be used to interconnect the Collector 2 to the Colombian AC system at Cerromatoso. Figure 4-4 shows a simplified diagram of VSC HVDC bipole system.

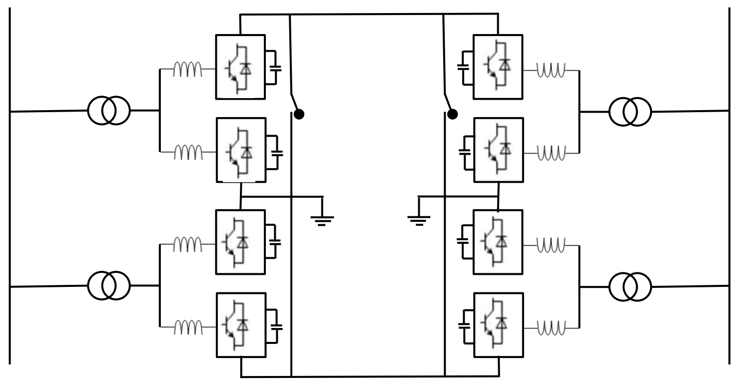

Figure 4-4 Simplified diagram of a VSC HVDC bipole system

The HVDC transmission utilizes an overhead line. HVDC overhead lines are subject to DC line faults for a variety of reasons. DC line faults are typically non-permanent. One of the major advantages of HVDC is the ability to restart following DC line faults, further, the ability to restart at reduced dc voltage in the range of 80% of nominal dc voltage to overcome pollution related dc line faults. Basically, following a dc line fault, a fault deionization period is initiated by setting both the dc voltage and the dc current to zero. Following a preset period, the transmission can be restarted either at full voltage or reduced voltage. The performance of the VSC systems under DC line faults depends on the converter topology. The following options are available:

- Half bridge multi-level converter (MMC) VSC:

  The half bridge converters do not have the ability to clear dc line faults without tripping of the converter AC breakers. For a DC line fault, the converter is blocked as soon as the fault is detected, however, the AC system will feed the DC fault through the free-wheeling diodes (looks like an AC fault from the AC side). The fault current has to be extinguished by tripping the converter AC breakers. However, the opening of the AC breakers, followed by a fault deionization period, followed by re-energization and deblock of the converter can be as long as 1 second. Such a long time can have an impact on the connected AC system. If high speed fault clearing is required, the alternative is a high-speed DC breaker (ultra-fast electronic switch). The fast DC breakers can be used to quickly extinguish the DC fault current in the range of 10ms. However, there are costs associated with the breaker that should be considered

- Full bridge modular multi-level converter (MMC) VSC:

  The full bridge MMC converter is capable of extinguishing DC line faults. The fault current can be controlled to zero without blocking the converter (controlled DC fault current control logic). In terms of the controllability, the full bridge options would be the best option. The power transfer can be quickly restarted, and any number of restart attempts can be programed easily. However, the cost of the converters is higher than half bridge converters and the losses are also higher than a half bridge solution.

Considering the options:

- Half bridge converter and AC breaker trip
- Half bridge converter and fast DC breaker
- Full bridge converter

The studies in Task 2 will be started with the half bridge converters with AC breakers which is the most cost-effective solution. The converter technology will be changed to full bridge technology if the dynamic studies (for DC faults) show that it is necessary.

4.2 Considerations Related to HVDC Pole Outage

The system operating conditions under a HVDC pole outage play a key role in the design of a new HVDC system. Usually, in AC transmission lines, the thermal rating is much higher than the actual power transfer under system intact conditions. Therefore, during a circuit outage a double circuit AC transmission line, the healthy circuit is capable of temporarily transmitting most of the power. In contrast, due to the cost of equipment and technical limitations, the HVDC systems are usually designed to be operated at the rated power transfer in normal conditions. Therefore, during a pole outage, overloading the other pole to carry a large amount of excess power is not possible. The HVDC systems typically have about a 10% of overloading capacity. if additional overloading capability is required, the ratings of the equipment should be increased (technology permitting) at the design stage and this will add an additional cost. Usually, it is expensive to have addition overload capabilities in a VSC HVDC system.

The pole outage is an n—1 operating condition. Usually, the grid codes do not allow load shedding under n—1 operating condition. The systems are designed to withstand the outage by having sufficient spinning reserve and optionally the additional HVDC overload capability.

4.2.1 Compliance to the Colombian Grid Code During the Pole Outage

Colombian grid code states that the system should be capable of transmitting the generation to the loads under all n—1 operating condition. The only path to transmit the Collector 2 generation to the Colombian grid is the VSC HVDC. Under a HVDC pole outage, some of the renewable generation connected to the Collector 2 will have to be tripped due to the power transfer limitation of the healthy HVDC pole. However, the generator tripping under an n—1 contingency violates the Colombian grid code. Therefore, the generation tripping should be avoided. It is also not feasible to consider a 100% overload capability for the VSC HVDC system. Therefore, an additional AC path was considered by interconnecting the Collector 1 and Collector 2.

4.2.2 Interconnection of Collector 1 and Collector 2

The studies were performed to assess the feasibility of transmitting the excess power, during an HVDC pole outage, to the AC system via a 500 kV single circuit interconnection between the Collector 1 and Collector 2 (note that the Collector 1 and Collector 2 interconnection was also considered under the AC alternatives in Section 3.2.3 and the feasibility study for LCC HVDC in Section 3.3).

During a pole outage, the healthy pole is capable of transmitting about 1650 MW to south (with a 10% overload capability). The generation tripping can be avoided if the remaining 1350 MW can be transferred to the AC system via the connection from Collector 1 to 2. Figure 4-5 shows the network power flow between the Collector 2 and Collector 1 during the pole outage in the *2032 Max Dem Max Gen* study case.

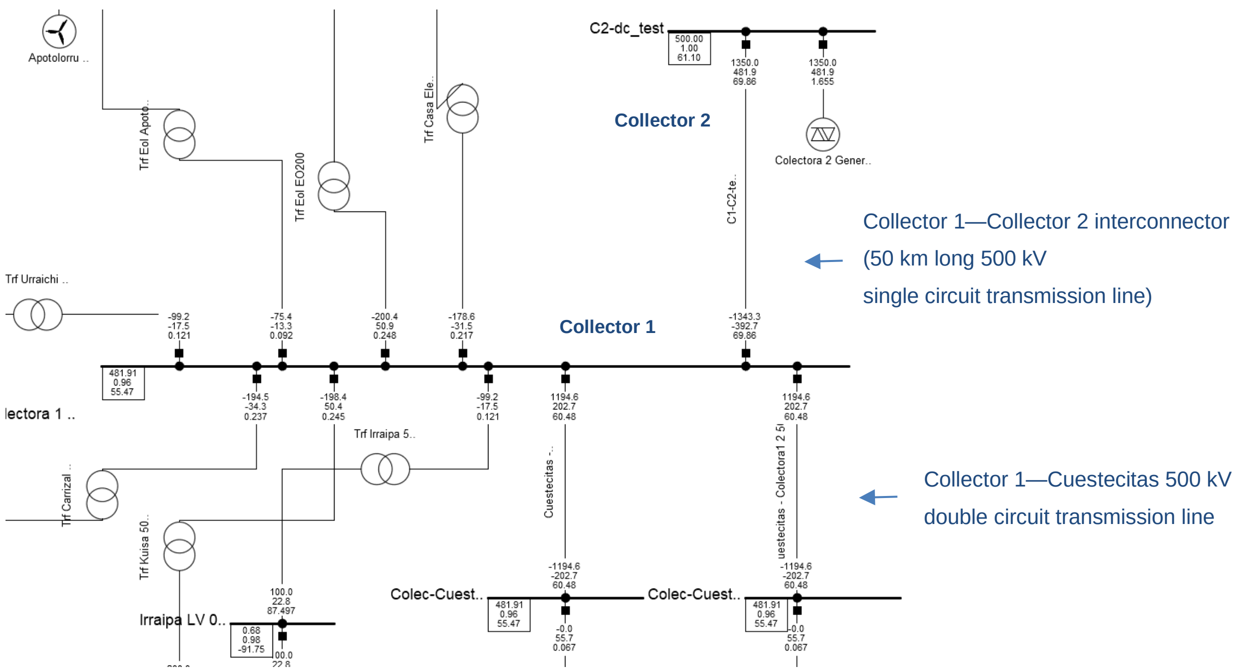

Figure 4-5 Collector 2 to Collector 1 Power flow during a HVDC pole outage (2032 Max Dem Max Gen)

The steady state analysis showed that the system is capable of transmitting the power to the south without overloading the major transmission lines and equipment. For example, under these conditions, the double circuit 500 kV transmission lines from Collector 1 to Cuestecitas is only loaded to about 61% of its thermal rating.

At the pole outage in 2028 study cases, only 350 MW need to be transmitted via the proposed Collector 1—Collector 2 interconnector (the healthy pole is capable of transmitting 1650 MW). The analysis showed that the system is capable of transmitting the power to the south without thermal limit violations of major transmission lines and equipment.

The study results presented in this section show that the generation tripping due to the HVDC pole outage can be avoided if the Collector 1 and Collector 2 are connected using a 500 kV single circuit transmission line. This line will be lightly loaded during the normal operating conditions and will be loaded up to about 70% of its thermal rating during an outage of a HVDC pole.

Therefore, it is recommended to consider a VSC bipole system with a 3000 MW rating and a 500 kV single circuit AC interconnection between the Collector 1 and 2 together for this project. The VSC terminal at the Collector 2 needs to be operated in grid forming control mode.

4.3 Review of Recommended HVDC Voltage Levels

The HVDC power rating is 3000 MW. Considering the present state of the VSC valve ratings, it is clear the DC voltage cannot be any lower than 500kV bipolar system. If +/- 500 kV is considered the DC current is 3 kA. This rating is available only from certain manufacturers. To reach 3000MW rating at 500 kV, obviously one can utilize parallel valves, or converters or IGBTs. However, this would be a complicated and expensive solution. In our opinion a better alternative is to increase the DC voltage above 500 kV. UPME proposed 550 kV, this results in a DC current of 2.7 kA. Considering that the project is to be realized within 5 years, the indication in the industry is that a 2.8 kA current rating will be available. Therefore 550 kV is a viable option. If we consider a bipole at +/- 600 kV the DC current is 2.5 kA. Certainly, this is available considering the present converter ratings. Increased DC voltage will reduce the DC line losses. Obviously, there may be increase in the cost of the DC line and the converter at 600 kV compared to 550 kV. The cost of losses should be evaluated over the project life to reach a proper conclusion.

5. Conclusions

As part of Colombia's plans to increase the generation capacity with non-conventional renewable energy sources (NCRE), a large amount of generation is planned to be integrated at La Guajira area. Collector 1, a total of 1054 MW of wind generation in La Guajira area is already planned to be integrated using 500 kV AC transmission lines to Cuestecitas. As the next step, Collector 2, about 3000 MW of NCRE sources are planned to be integrated by 2032.

This study evaluated the HVAC and HVDC transmission alternatives proposed by UPME for the interconnection of 3000 MW of renewable energy generation in La Guajira area of Colombia, Collector 2.

UPME's transmission expansion plans, and analysis were reviewed during the initial state of the study. Then, the additional studies were performed to validate the findings, using the 4 study cases representing the minimum and maximum demand scenarios for operational years 2028 and 2032. In the 2028 study cases, 2000 MW of renewable generation was interconnected. The full capacity of 3000 MW was interconnected in operational year 2032. The power system models were provided by UPME.

The outcomes of the study are summarized below.

Feasibility of 500 kV double circuit AC interconnections to Cuestecitas, Chinu, Cerromatoso or Copey

The AC interconnections were not feasible to integrate 3000 MW to the Colombian system due to the following reasons:

- *Cuestecitas*:

  The Short Circuit Ratio (SCR) at Cuestecitas is as low as 1.74, which is insufficient for the proper operation of wind power plants. Therefore, many additional devices (e.g., synchronous condensers) will be required at Collector 2 to improve the AC system strength. Further, the AC network is not capable of transferring 3000 MW of generation at this location.

- *Chinu and Cerromatoso*:

  The SCR at Collector 2 is as low as 1.4 in this alternative. Therefore, many additional devices (e.g., synchronous condensers) will be required at Collector 2 to improve the AC system strength.

- Copey (with Collector 1 and 2 interconnected):

  The AC system strength at Collector 2 under this alternative is sufficient to connect 3000 MW of generation. However, the transmission line overloads, voltage limit violations and a large amount of reactive power requirement under some outages were identified when the Collector 2 is interconnected at its full capacity of 3000 MW.

  The feasibility of the interconnection option was further studied for reduced generation levels at Collector 2. The AC contingency analysis and a preliminary dynamic simulation study showed the feasibility of interconnecting about 2000 MW using this alternative. If required, the transfer capacity may be increased to about 2500 MW by adding some reinforcements to the existing system. Further studies would be required to identify the system upgrades.

Feasibility of LCC HVDC Transmission

The LCC converters required a certain short circuit strength for the proper operation. Therefore, the LCC option was evaluated with the Collector 2 connected to the Collector 1 using a double circuit 500 kV line. However, the short circuit strength that can be achieved at the Collector 2 is still very low. The effective short circuit ratio (ESCR) is about 1.37. To achieve an ESCR of 2.0, synchronous condensers of about 650 MVA would be required at the Collector 2. Therefore, LCC option would not be a preferred solution.

Feasibility of VSC HVDC Transmission

Considering the constraints identified in the system, the VSC HVDC transmission system is the most promising technology available at present due to following key reasons:

- No additional devices such as synchronous condensers are required at La Guajira to enhance the short circuit capacity (Low SCR is not an issue for VSC HVDC technology).
- The VSC terminal at La Guajira region (Collector 2) can be operated in grid forming control (i.e., voltage and frequency regulation). In such a system, the wind farms can operate without having additional short circuit support (i.e., SCR rules are not applicable).
- Black start capability can be used to start the wind farms in the La Guajira collector system.

Recommended terminal for interconnection

When Chinu, Cerromatoso and Primavera are compared, Primavera is the closest location to the load centers. The power flow study showed that when the VSC HVDC is terminated at Chinu or Cerromatoso, the power needs to be transmitted using the AC transmission lines to the load centers in the south. Therefore, the AC transmission losses are significantly lower when the HVDC is terminated at Primavera. Although the DC transmission losses are comparatively higher at Primavera, the benefits of reduced AC transmission losses are still significant.

Primavera is proposed as the terminal location for the HVDC interconnector. However, there may be non-technical restrictions such as space limitations when constructing a HVDC terminal in a congested metropolitan area. It is recommended for UPME to evaluate the feasibility of this location.

Recommendation for grid code compliancy during a pole outage

The Colombian grid code requires the transmission system to be capable of keeping all the generation intact during all n—1 outages. The VSC HVDC pole outage will generally allow about 10% of overload of the healthy pole. Therefore, about 1350 MW of generation needs to be tripped during a pole outage if the Collector 2 is isolated. To comply with the grid code, it is proposed to interconnect the Collector 1 and Collector 2 using a single circuit 500 kV AC transmission line. This line will be mostly utilized under the contingency conditions.

Selected transmission technology–VSC HVDC

Based on outcomes summarized above, a 3000 MW bipole VSC HVDC system is proposed to be connected between the Collector 2 and Primavera or Cerromatoso. In addition, a single circuit 500 kV AC transmission line between the Collector 1 and Collector 2 is required to maintain the power transfer during a HVDC pole outage. For the HVDC system, a DC transmission voltage of 550 kV or 600 kV is recommended. The cost of losses should be evaluated over the project life to reach a proper conclusion. The half bridge converter technology with the AC breakers (the most cost-effective solution) will be first evaluated in Task 2 studies and if it is necessary based on the dynamic performance requirements, the technology will be changed to full bridge technology.

6. References

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