Scenario Forecast of Cross-border Electric Interconnection towards Renewables in South America

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Abstract—Cross-border Electric Interconnection towards renewables is a promising solution for electric sector under the UN 2030 sustainable development goals which is widely promoted in emerging economies. This paper comprehensively investigates state of art in renewable resources and cross-border electric interconnection in South America. Based on the raw data collected from typical countries, a long-term scenario forecast methodology is applied to estimate key indicators of electric sector in target years, comparing the prospects of active promoting cross-border Interconnections Towards Renewables (ITR) scenario with Business as Usual (BAU) scenario in South America region. Key indicators including peak load, installed capacity, investment, and generation cost are forecasted and comparative analyzed by year 2035 and 2050. The comparative data analysis shows that by promoting cross-border interconnection towards renewables in South America, renewable resources can be highly utilized for energy supply, energy matrix can be optimized balanced, economics can be obviously driven and generation cost can be greatly reduced.

Keywords—electric interconnection; renewable energy; scenario forecast; energy integration; decarbonization

I. INTRODUCTION

The Cross-border Electric Interconnection is a promising solution to connect renewables bases disturbed in various countries and regions, which can be utilized to achieve independence on fossil fuel and realize a clean, low-carbon, and sustainable development. Within this trend, Global Energy Interconnection Initiative (GEI) is proposed at the 70th UN Sustainable Development Summit, which is a pioneer transmission strategy to establish a global power grid to meet global electricity demand in a clean and green way [1]. This global initiative is to promote the energy revolution, promote clean development and address climate change, and has opened a new era of sustainable energy development in the world.

The development levels of Cross-border Electric Interconnection are unbalanced in different regions of the world. According the study of [2], [3], [4], Europe, East Asia and North America feature high electric Interconnection with more complete infrastructure, high level of electrification and more obvious advantages of large-scale deployment of clean resources in the power grid. The electric interconnection levels in Oceania, Russia, Central Asia, West Asia, North Africa, and Latin America are at a global average level, characterizing by develop towards better grid structure and development degree. While Southeast Asia, South Asia and Sub-Saharan Africa, due to the insufficient electricity consumption and the low level of development of energy and power, the development level of electric interconnection is relatively low.

Considering the uneven distribution of renewable resources across the world, a promising solution to achieve the energy transition and Sustainable Development Goals of UN can be cross-border electric interconnection towards renewables [1], [5]. With the development of major energy bases, supported by Ultra High Voltage (UHV) technology and smart grid, cross-border electric interconnection can achieve the optimal allocation of energy supplies on a large scale. With cross-border electric interconnection being globally promoted, a large-scale interconnected power grids can be formed to achieve globalization of energy production, allocation, and trade. Moreover, the development of cross-border interconnection towards renewables can also bring a series of social benefits, including financing, political stability, labor employment and electricity access rate etc.

Among the different continent of world, South America is an emerging energy market consisting of developing countries with positive economies. Moreover, South America countries are in a crucial period of energy transition while facing development problems including salient deindustrialization, lagging behind infrastructure, sluggish economic growth and widening gap of economic inequality. Among countries of South America, Argentina, Brazil and Chile (abbr. ABC) are
the leading economic entities contributing more than 70% GPD of South America region [6]. The ABC countries in South America are also energy consuming centers, occupying 74% of electricity consumption of this region. Besides these, the renewable resources in ABC countries are also abundant. Fig. 1 shows rich resources as wind power in Argentina, solar power in Chile and Hydropower in Brazil etc. The positive paces of economic development, large amount the energy demand and rich renewable resources are all the driven forces for ABC countries to promote electric interconnection. Besides ABC countries, Bolivia is a positive developing country the highest GDP growth rate in this region in recent year. As a conventional resource-export country and geographical center location in South America, Bolivia is a crucial country which has the potential to become the hub of regional electric interconnection. Hence, since 2016, Bolivia government has already announced long-term plan to promote cross-border interconnections. [7]

![Fig. 1. The distribution of large-scale renewable bases in South America.](image)

Currently, due to impact of COVID-19 and political unrest from the end of 2019 to the beginning of 2020, the cross-border electric interconnections in South America are mostly paused. However, with green recovery path is more emphasized in the post-pandemic recovery of global energy sector, the cross-border electric interconnection in South America is of great prospect. Hence, this work presents a long-term forecast methodology based on renewable scenario to estimate the key energy indexes of major countries (ABC and Bolivia) in South America, which are united with cross-border electric interconnection. Firstly, the paper states scenario forecast basics by reviewing the renewable resources, major projects, and ongoing plan of cross-border interconnection in this region. The forecast model and method are applied to forecast the long-term energy characteristics of typical countries under the development trends of cross-border electric interconnection towards renewables. The various comparative forecast results of key indexes are presented to study the benefits of promoting cross-border interconnection towards renewables. Conclusions are summarized and further outlooks are made based the forecast results.

### II. SCENARIO BASIS OF RENEWABLES AND INTERCONNECTIONS

In this section, the scenario forecast basics on renewables resources of major countries in South America are reviewed and summarized with ACRGIS graphics [3] and data collected in two-year field investigations in South America [8], including the distribution and characteristics of renewable resources, cost analysis of renewable energy generation, national energy development strategies and renewable energy development goals, and prospect of development trend of the base.

#### A. The distribution and characteristics of renewable resources

In South America, there exists abundant renewable energy reserves, till now there are still huge potential waiting to be explored and utilized. Moreover, as shown in Fig.1, the renewable resource distribution in South America is relatively concentrated in large areas, which is suitable to be developed as large-scale renewable bases.

For hydropower, according to data statics in [8], the total potential technical developable capacity is about 620 GW, occupying 18% of the world's total capacity, with more than 70% of the technical capacity not well developed. The largest concentrated hydropower area is in Amazonas River area, 70% of the capacity is undeveloped. The Parana River area is another large hydropower reserve in South America. The São Francisco River area is also a large-scale hydropower reserve area. For different countries, Brazil has 42% of the total potential of South America, amounting to 260 GW, with current utilization rate of about 37%. Bolivia has also 40 GW of potential technical capacity, with only 1% utilization rates of only 1%.

The solar power in South America is abundant especially in Atacama Desert region along the west coast of Chile and the northeast region of Brazil. The Atacama Desert covers a total area of 180,000 km2, with an annual average DNI of more than 3,300 kWh/m2, an annual total GHI of more than 2,600 kWh/m2. The majority of Atacama Desert region is in Chile. Hence, Chile is the most abundant country in Solar Power, with 1,200 GW technical potential capacity in PV, 500 GW technical potential in Solar thermal power, and up to 2,700 hours/year of PV utilization in its northern Chile region.

The wind power is concentrated on southern Argentina and northeastern Brazil. With an average wind speed of more than 6 m/s in 70% of its territory, Argentina is a country rich in wind resources. The technical potential capacity of wind power in Argentina can 700 million kW. In the Patagonia Plateau of southern Argentina and southwestern part of Buenos Aires, the average wind speed can reach 15 m/s, with an annual average utilization 3,000-4,500 hours, which are very suitable for the development of large-scale wind power bases. The Ceará State and Bahia State of northeastern Brazil also have relatively good wind power resources, accounting 70% of the country's total wind power technical potential capacity, which is about 150 GW. The average wind speed in these regions is 6 to 9 m/s, of which the annual average utilization hours is about 2,000 hours.
B. Cross-Border Electric Interconnection Projects

Fig. 2. The current cross-border electric interconnection plans in South America.

As shown in Fig. 2, the current cross-border electric interconnection plans in South America are illustrated. Since last two decades, several small-scale cross-border electric interconnection lines are established in South America countries, including Ecuador-Peru, Argentina-Uruguay, Argentina-Brazil, and Chile and Argentina and Itaipu lines etc. However, the current interconnection lines are mainly targeted on providing power supplies in border areas or supplement electricity supply in dry season, resulting very low utilization ratio and limited trading amount. Meanwhile, several macroscopic scale cross-border electric interconnection plans are also proposed to achieve the energy integration toward renewable development. Although the promotion paces of these plans are relatively slow due to various factors, the cross-border electric interconnection plans towards renewables still owns bright prospects.

Andean Interconnection is a cross-border electric project planned according to the desire to achieve a regional connection between the Andean Community (CAN) – comprising Bolivia, Colombia, Ecuador and Peru, with Chile as a partner. The project seeks to create a shared framework the Andean Electrical Interconnection System (SINEA), which will establish regional energy market and secure the energy supply of electrical networks in Andean countries, as well as promoting the use of renewable energy for the generation of electricity. SINEA was firstly proposed in 2011, joint declarations have been made by governamental departments, but feasible progress has been slow. Partial progress has been made to facilitate the exchange of electricity, where interconnection infrastructure already exists. [9] According the latest progress in 2020, a new road map of SINEA is planned to be released, which will characterize the development of SINEA from year 2020 to 2030.

Arco Norte Interconnection is the cross-border electric interconnection consisting of the Boa Vista substation in Brazil’s Roraima state with Guyana, Suriname, French Guyana, as well as the Brazilian state of Amapá. A preliminary study [10] conducted by Inter-American Development Bank (IDB) was carried out in 2017, in which a 1,900 kilometer high-voltage line was planned with total investment of between US$701 million and US$985 million. The Arco Norte Interconnection can exchange electricity power between countries ranging from 300MW to 4,500MW, mainly to the Brazilian market. This project is crucial due to the electricity supply problems in Roraima State of Brazil, which currently depends on a link with Venezuela with high risk of political and economic risks. The Arco Norte Interconnection draw highly attention in 2017 and 2018, however, with the new round of political changes in Brazil and neighboring countries, this project faces suspension and delay. Currently, IDB is providing bilateral studies to evaluate the project’s continuity and working on the donors committee to achieve financial resources. For next step, a new agreement with involved countries needs to be promoted to sign the achieve feasible cooperation.

Bolivia Energy Heart Interconnection is proposed by Bolivia Government in 2016 [7], which is included in Bolivia 2025 Energy Plan. Bolivia is geographically located in the heart of South America, bordering the three major South American Countries. To reduce the economic, rely on Nature Gas Export and stimulate the modernize development, Bolivia Government plans to become the regional energy export hub with its abundant hydropower resources through promoting cross-border electric interconnection with neighboring countries, including Argentina, Brazil, Peru, and Paraguay. The plans is also named as Energy Heart Plan, which plans to achieve 8,000MW annual power export to neighboring countries with adding 5,552 MW hydropower capacity and upgrade the power grid from 230kV to 500kV. Due to demand of economic development, Bolivia has been the country in South America with the highest level of driven force for promoting cross-border electric interconnection. The interconnections between Peru and Bolivia, Argentina and Bolivia have been in a relative fast pace that the 230kV lines are being in construction. An interconnection study contract is also jointly signed by ENDE (Bolivia), IDB and Electrobras (Brazil) [11]. However, after the political turbulence happened in 2019 and pandemic, the previous pace has all been in paused.

South Cone Interconnection is the cross-border interconnection plan between South Cone Countries (Argentina, Chile, Uruguay, Paraguay) and Brazil [12]. The South Cone Interconnection has the best basics among all the cross-border electric interconnection plans being developing in South America. There already exists 3 Binational Hydro Plants with 19,090 MW installed capacity and 10 interconnections with 4,966 MW power transmission capacity. Moreover, the ABC countries involved in South Cone Interconnection have relative stable politic environment and better economic basement to achieve regional electricity trade market and large-scale cross-border electric interconnection towards renewables. Although the basics are good, obstacles still remain in the way of success including the unequal sized systems between Brazil and neighboring countries, different regulatory frameworks between countries, currency devaluation in trading, political risks in long term agreement and impact of COVID-19 etc.
III. SCENARIO FORECAST METHODOLOGY AND MODELS

In this section, in order to show the comprehensive benefits of promoting cross-border electric interconnection towards renewables, a scenario forecast methodology proposed in [8] is applied to obtain the long-term estimation of comparative results on key indicators between Interconnection Towards Renewables (ITR) scenario and Business as Usual (BAU) scenario. This methodology is illustrated in Fig. 3.

The first procedure methodology is to collect important present data from target countries in different categories, including Economy (GDP, Import, Export), Society (Electricity Access Rate, Employment Rate), Renewable Resources (Hydro, Solar, Wind), Ecology and Environment (Carbon Emission, Forrest Area), Energy and Power (Production, Consumption). After setting up the target estimation year, the next step is to forecast the energy & power demand in target year for target countries, which is the comparison standard for both ITR scenario and BAU scenario. Then, various scenario constraints of renewable energy development and cross-border electric interconnection are applied. Finally, the forecast output is calculated and obtained.

For the energy and power demand forecast, based on the complexity of energy and power system and multi-objective orientation of energy and power transition, energy and power demand forecast model is formed by combining simulation with optimization according to the idea of top-down and bottom-up complementing each other, as shown in Fig 4.

The forecast model structure analyzes the influence of economic development on energy demand from macro to micro; bottom-up quantifies the influence of technology progress, efficiency improvement, environmental constraints, and the energy policies on energy demand from micro to macro, then predicts energy consumption intensity and overall energy structure. According to the forecast of energy demand and energy consumption intensity, the simulation methods, including regression analysis [13], trend extrapolation [14] and growth curve [15], are used to achieve the final energy power demand forecast combining with multi-objective or single-objective optimization model. Finally, considering the efficiency of power generation, heating, oil refining and other conversion processes, the global/regional primary energy demand by sector and variety is calculated.

The scenario forecast optimization model mainly aims at minimizing the total social and economic cost including construction, operation and maintenance and fuel costs during the planning period, and constructing problems on optimization based on energy policies, environmental constraints, energy resources, and power balance and to solve the planned annual generation capacity, various types of installed components, timing of development, carbon emissions, etc., as shown in Fig 5. The optimization target in scenario forecast is to achieve minimum total social and economic cost. The optimization equation can be characterized as

$$\text{min } PV C_f = \sum_{i=1}^{T} (T_f - T_{f,i} + F_{f,i} + M_{f,i} + O_{f,i})$$

where $i$ is the construction cost, $S$ is the subsidy in energy policy, $F$ is the fuel cost, $O$ is the operation cost, $j$ is the power unit identification, $T$ is the planning period, $t$ is the specific planning year, and $M$ is the land acquisition difference between two cases.
IV. COMPARATIVE SCENARIO FORECAST RESULT ANALYSIS

In this section, typical countries in South America are selected in the scenario forecast of cross-border electric interconnection towards renewables. Comparative results are derived to have a thorough comparison of key indicators in energy and power sector between Interconnection Towards Renewables (ITR) scenario and Business as Usual (BAU) scenario. The specific parameters are defined to set the target condition for a fair comparation.

The target year of forecast is set on 2035 and 2050. The reason for these selections is to match the UN 2030 sustainable development agenda and long-term planning goals set for many countries. The target countries are selected to represent the typical development situation in South America, which are Argentina, Brazil, Chile and Bolivia. Case 1 is the Interconnection Towards Renewables (ITR) scenario, in which the cross-border electric interconnection plans are all well achieved and renewable energy (Solar, Hydro, Wind) is well developed for energy supply. Case 2 is the Business as Usual (BAU) scenario, in which the current development track with no interconnection is applied. Finally, Peak Load, Installed Capacity, Carbon Emission Investments and Benefits in target years are selected as key indicators for the comparative analysis for both cases.

A. Peak Load Analysis

The peak loads of electricity systems in the typical countries are firstly forecasted and analyzed. Typical annual and daily load characteristics are forecasted and shown in Fig. 6 and Fig. 7. Comparatively, the load characteristics after interconnection is also shown to present the benefits in Interconnection Towards Renewables (ITR) scenario. Except for Chile, the daily load fluctuations are relatively small, the daily peak load is concentrated between 14 pm and 22 pm, and the minimum load appears at night, due to the large total load in Brazil, the overall daily load characteristics of Brazil, Bolivia, Argentina and Chile are basically the same as the Brazilian daily load characteristics, however the minimum daily load rate has increased by 4%. From the perspective of the whole year, taking Brazil and Argentina as an example, the annual peak load of Brazil occurs from February to April, which is the load trough of Argentina. When the annual peak load of Brazil appears in July, the annual peak load of Argentina occurs. So, the load characteristics of Brazil and Argentina are complementary.

![Fig. 6. Typical annual load characteristics forecast.](image1)

![Fig. 7. Typical daily load characteristics forecast.](image2)

The peak load of countries in BAU scenario are calculated for year 2035 and 2050, shown in Table 1. The total peak load in case 2, where the cross-border electric interconnections are all achieved, is also shown in Table 1. In 2035 and 2050, the total seasonal unbalance coefficient of maximum load (seasonal unbalance coefficient = average monthly maximum load/annual maximum load) can reach 0.95 after power grids in the four countries interconnecting. The total peak load of the four countries can be reduced by 8.4 GW in 2035 and 11.6 GW in 2050 in Interconnection Towards Renewables (ITR) scenario.

| Country                  | Year 2035 | Year 2050 |
|--------------------------|-----------|-----------|
| Argentina in BAU scenario| 52.0      | 70.5      |
| Brazil in BAU scenario   | 193.0     | 270.0     |
| Chile in BAU scenario    | 28.0      | 37.5      |
| Bolivia in BAU scenario  | 6.0       | 10.0      |
| Total Peak load in BAU scenario | 279.0 | 388.0 |
| Total Peak load in ITR scenario | 270.6 | 376.4 |
| Peak load reduced after Interconnection | 8.4 | 11.6 |

*Unit: GW

B. Installed Capacity Analysis

The installed capacity of power generation of countries is analyzed. The installed capacity matrix of countries is forecasted for year 2035 and 2050 in Fig. 8 and Fig. 9. The share of different types of energy sources are shown. Through comparison, it is obvious that in ITR scenario, the share of renewables in installed capacity is greatly improved by 7% and more balanced for energy security.

![Fig. 8. Installed capacity matrix forecast in 2035.](image3)
applied to the raw data of typical South America countries to forecast the prospect of actively promoting cross-border interconnections towards renewables in South America region. The peak load, installed capacity, investment, and generation cost are forecasted and comparative analyzed by year 2035 and 2050. The comparative results show that by promoting cross-border interconnection in South America, the renewable resources can be highly developed for energy supply, the energy matrix can be optimized, and economies can be obviously driven and generation cost can be greatly reduced. The total peak load of integrated power systems of typical countries can be significant reduced by 11.6 GW in year 2050. By year 2050, the typical countries by promoting cross-border electric interconnections towards renewables can save annual generation cost as much to 5.5 billion USD/year while 35% of annual carbon emission in this region can be reduced.

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