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Bolivia's look at 2050 with 100% hydroelectric supply towards South American electrical integration

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Abstract: This academic research work outlines an energy strategy towards 2050 and shows that Bolivia can meet 100% of its future electricity demand and with the probability of exporting surpluses to other South American countries, primarily to Brazil. The main hydroelectric generation megaprojects are "Cachuela Esperanza" (900 MW), "El Bala" (1,680 MW) and "Rositas" (680 MW) and others of smaller magnitude, including the current hydroelectric plants in operation, and projects associated with a megaproject of the three-phase transmission network of more than 3,000 km in extra high voltage (500 kV). On this occasion, this article is oriented exclusively to the electrical active power flow (MW), without this meaning that the associated electrical energy (GWh) would not be fully covered.

Key words: long-term planning; South American electrical integration; hydroelectric potential of Bolivia; active power flows; extra high voltage (EHV) transmission lines

1 Introduction

In March 2021, according to the CNDC, the Bolivian MEM had a maximum generation capacity of 3,188.27 MW, while the maximum demand registered in 2020 was 1,545.92 MW. It is observed that the surplus generation supply practically doubles the demand because ENDE-ANDINA invested on behalf of the Plurinational State of Bolivia more than 1,770 million US dollars to increase the generation capacity by 1,440 MW through combined cycle plants, with NG as the primary thermal source. The intention was to export to Argentina and Brazil, which unfortunately has not yet materialized.

It is estimated that the hydroelectric potential, technically exploitable, reaches 173,000 GWh per year in the national territory according to the studies carried out by ENDE, in cooperation with UNDP and OLADE between 1975 and 1982, and later studies. The estimated installable power is 39,857 MW, of which the current installed hydroelectric park is 476 MW, representing 1.2% of the total potential for exploitable generation, due to the lack of investments in pre-investment and investment studies for hydroelectric projects [3].

The country's hydroelectric potential must undoubtedly be exploited not only to meet its own requirements but also to generate exportable surpluses, strengthen our economy and, in turn, modify the current energy matrix towards the use of renewable primary sources, including photovoltaics, wind power and biomass. Currently, there are many power plants with these primary sources connected directly to the high-voltage grid (SIN).

2 Vision

The aim is to show a promising energy future for Bolivia, through the adoption of a strategic plan for the electricity sector, considering that the following three challenges must be addressed simultaneously:

a) the energy integration of the Isolated Systems, mainly in the whole of eastern Bolivia, through their incorporation into the SIN. Integration with neighbouring countries should also be sought, mainly with Brazil, since with this country we have the longest territorial boundaries.

b) the fulfilment of the commitments made by the country, in the international context, regarding the use of renewable energy sources, to mitigate air pollution. The reader is reminded that the author also made a suggestion to begin using wind and photovoltaic energy in Isolated Systems, see reference [2].

c) the urgent need for decarbonization of energy was widely explained by Angel Zannier in the reference [1] to comply with the commitments made by Bolivia at the international conference (Kyoto Protocol, and the Paris Accord).

Before exposing the ideas of the strategy to suggest, it is necessary to verify the important predictions on supply and demand of the electric power since 2025 to 2050.

3 Offer: 100% hydroelectric power

The most important megaprojects in the Bolivian Amazon basin are the 990 MW Cachuela Esperanza and 3,676 MW El Bala power plants. It should be noted that there are various generation technologies, however, those that produce the least ecological impact are those that use bulb-type turbines (and not Francis-type turbines), since they only require a drop height of a little more than a dozen meters, partly compensated by an immense average annual flow. In this way, although the power to be generated is reduced, the environmental impact would be mitigated.

The other future hydroelectric plants (totaling more than 7 thousand MW) each are smaller than those mentioned, and belong to other basins and have to be built: the Rositas hydroelectric complex with more than 600 MW located in the department of Santa Cruz, the Miguillas plants 196 MW in La Paz, the Ivirizu plant 164 MW in Cochabamba, Carrizal plant 347 MW between Chuquisaca and Tarija [3].

4 Electrical energy demand

Considering historical data and estimates from reference [3], a conservative and an optimistic estimate of the future power demand (Table 1) were made based on the maximum demand recorded in 2020 (8:00 p.m. on November 24), the following was obtained:

Table 1. Forecast of maximum total demand, Pd (MW)

Year	Conservative	Optimistic
2025	1903	1903
2030	2206	2259
2035	2543	2669
2040	2921	3150
2045	3348	3726
2050	3835	4429

The estimate was made considering a growth rate of the demanded power of 4% (conservative scenario) and 6% (optimistic scenario) respectively for residential, general and public lighting consumers of urban and rural populations. Likewise, the demand of large industries, mining and transport was forecasted every five years, in addition to the interconnection of Isolated Systems, of 150 MW (conservative scenario) and 200 MW (optimistic scenario) respectively.

It should be noted that the current offer is 3,188 MW, which would last until 2040 in both scenarios, provided that the surplus is not used for another purpose before then.

A first conclusion about future supply and demand is that only with hydroelectric plants (those currently operating plus those planned), the country would be fully served, and there would even be surpluses that can be exported, comfortably meeting the challenges of decarbonizing the electricity sector, drastically reducing the air pollution. The high-voltage power grid (transmission lines) still needs to be addressed. This can not only promote the growth of SIN, but also facilitate international connectivity with neighboring countries (Brazil, Peru, Argentina, Chile).

5 Suggested planning strategy

Many times when driving a vehicle at night on the road, we have realized that the higher the focus and the more powerful the light from the high beams, the more certain we are about the obstacles we will avoid through thoughtful maneuvering in the future. On the other hand, the low beam, although necessary, only allows us to see clearly what is very close in front of the vehicle, and barely gives us time to think about the maneuvers. This is a good analogy and is essential for future decisions, that is, they are strategies for long-term planning, which will also allow us to plan future actions required by the Bolivian electric sector.

The "Medium Term Planning" that is done every six months at the CNDC is done looking eight semesters ahead, with only the results for the next semester being important and directly applicable. Well, this idea can also be applied to long-term planning. We will project ourselves to the year 2050 to see the actions necessary for the next five years immediately following the present. This will allow us to make decisions to achieve the future balance between supply and demand.

Considerations needed for simulations for the year 2050:

1) By verifying in sections 3 and 4 that only the current hydroelectric plants plus the future ones can meet the entire demand of the country for the year 2050. The contribution of existing thermal power plants is ruled out, and it is suggested that no more be installed in the future.

2) The useful life of thermal power plants is about 30 years, after which, in the worst case, only those that are strictly necessary must be replaced for reasons of reliability, not for economic reasons and certainly not for environmental reasons.

3) The vast geographical area of Bolivia and the location of the mega hydroelectric projects mean that a high voltage network of at least 500 kV is required to reach the major consumption centers. For example, the distance from Cachuela Esperanza to Santa Cruz de la Sierra via the city of Trinidad (Beni) is over 900 km. A voltage of 230 kV no longer satisfies the quality and stability of electricity.

4) Just as large hydroelectric power stations have their geographical location, so do large consumption centers and the abstract mathematical model to be proposed must be as simple as possible. Here, the important thing is the distances for planning the transmission lines.

5) The accuracy of the model does not have to be demanding, since it is only an estimation. For this reason, the reactive power flow will not be resolved. In this sense, the state of the network in permanent regime must be simulated through the "approximate active power flow", which is already a simple model.

6) On the other hand, since the transmission lines are very long, the losses cannot be ignored. In this sense, the mathematical model must allow these losses to be estimated. After obtaining the flow power per unit (which is equal to the current per unit), and knowing the resistance of the conductors of each transmission line, the calculation of the Joule effect is immediate.

7) By repeating the simulation exercise with different connections of the future network, the configuration or topology is adopted in which the single or double triplet transmission lines are well used, that is, they are able to be loaded in an

acceptable manner. Consider using ACSR drivers "Ibis" and "Drake", as well as the number of each stage (HAZ), to determine the total resistance and reactance.

8) It can be verified that it is not necessary to include the current SIN network at 69, 115, and 230 kV. In the simplified model, it was deemed convenient to concentrate the demand of the northern, central, southern, and eastern systems in 3 nodes: Palca, Santivañez, and Warnes respectively. It is also necessary to mention that the total demand shown in Table 1 has been distributed in the 3 nodes mentioned, maintaining the proportions of the demand by areas of the reference [3].

6 Offer 500 kV three-phase transmission network for the year 2050

After several simulations with an "approximate active power flow" software, the network topology shown in Figure 1 was adopted, whose passive and active element data are shown in Table 2 and Table 3 respectively. The topographic profiles of the transmission lines are shown in Figure 4, obtained from the Google Earth website:

Table 2. Passive elements of the network

Nodes		Length	Number of		AWG
i	j	(km)	ternas	cond (haz)	code
1	2	483.4	2	4	drake
1	3	492,1	1	2	ibis
2	5	351,8	2	4	ibis
3	4	229,2	2	4	drake
3	5	568,9	2	4	drake
4	7	211,7	1	4	ibis
5	8	160,7	1	2	ibis
6	8	592,3	1	2	ibis
7	8	326,3	1	2	ibis

Table 3. Active elements of the network

Node	Name	Pg(MW)	Pd(MW)
1	CAE	990	120
2	TRI	0	110
3	BAL	1680	40
4	PAL	372	729
5	WAR	0	1679
6	MUT	0	200
7	SAN	756	1507
8	ROS	(Slack)	25

Table 4. State variables found

Node	Name	(°)
1	CAE	7.70
2	TRI	8.05
3	BAL	20.79
4	PAL	8.79

5	WAR	-4.27
6	MUT	-13.27
7	SAN	-5.47
8	ROS (Slack)	0.00

Clarifications: Regarding the name of nodes, in the order mentioned in Table 3 and Table 4, Cachuela Esperanza, Trinidad, Bala, Palca, Warnes, Mutún Santivañez, and Rositas. Regarding the column called "HAZ" in Table 2, the term refers to the number of conductors per phase, and the code refers to the ACSR conductors of AWG GAL in the United States.

Table 5. Flows and losses in MW

Nodes	Flow	Losses
De1a2	744.6	9.9
De1a3	125.4	2.4
De2a5	634.6	10.3
De3a4	958.4	7.8
De3a5	807	13.7
De4a7	601.4	11.1
De5a8	-237.4	2.6
De6a8	-200	6.9
De7a8	-149.6	2.1
	total	66.8

Total power (MW):	
Generated:	4476.8
Defendant:	4410.0
Losses:	66.8 1.49%
Slack Generation	678.8 (ROS)

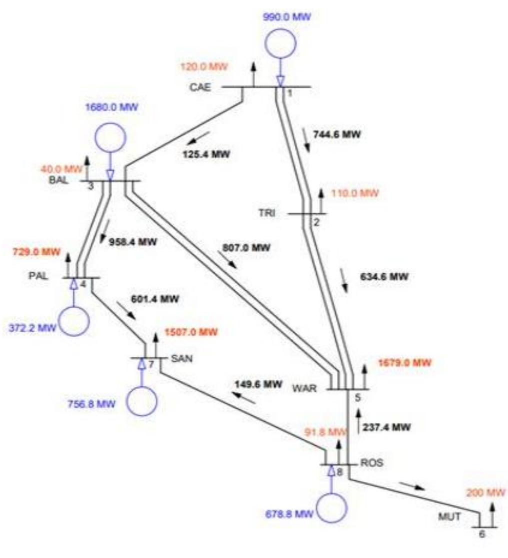


Figure 1. 500kV synthetic power grid

Considering reactive power, losses are expected to be around 3%. In this model, node 8 (ROS) added 25.0 MW to its demand, resulting in total losses of 66.8 MW.

7 Justifying the 500 kV three-phase electrical network

Regarding the probable export of electric energy to Brazil, it can be observed in Figure 2 that there is transmission infrastructure close to Bolivian territory, and there are also reinforcement projects. Specifically, we refer to the surroundings of the cities of Porto Velho, Rio Branco and Cuiabá, the first two in the North and the last one in the East of Bolivia. Therefore, the export of surpluses from the hydroelectric plants Cachuela Esperanza and El Bala may be feasible as far as the Brazilian grid is concerned. Although Brazil has many alternatives for generating electricity from natural resources and a model that allows the execution of projects at low cost, the need for firm energy and the relative local scarcity of gas can create opportunities for energy integration. See page 17 of Ref. [4]. We must not lose sight of the fact that Brazil currently has an annual growth in demand for electric power of more than 2,000 MW. In order to have an idea of the topographic profile through which the proposed 500 kV transmission lines would pass, Figure 2 is shown.

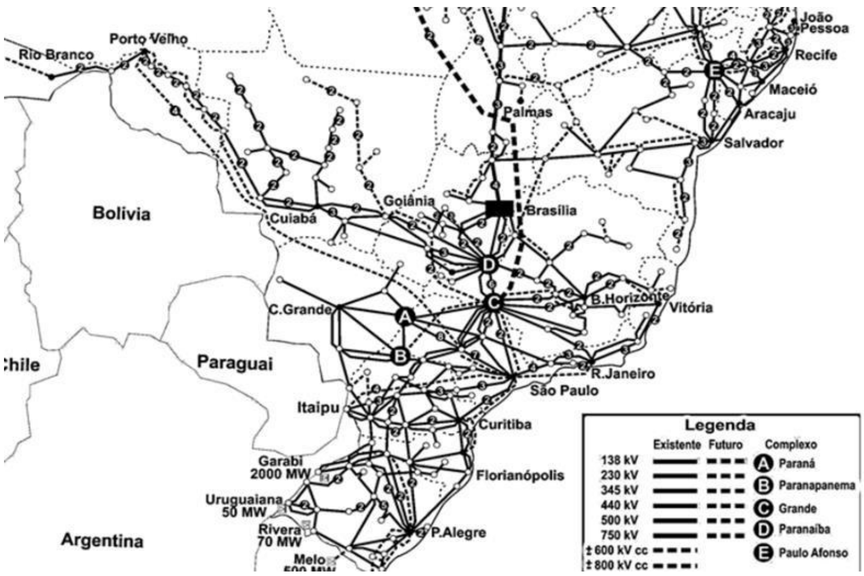


Figure 2. Brazilian interconnected system

It is worth mentioning that the eastern region of Bolivia, comprised of the departments of Pando, Beni and Santa Cruz (all bordering Brazil), covers 2/3 of the territory and ecologically contains the reserve zones for agricultural production that will provide a large part of its future economic support. The most important input for the development of this region is undoubtedly electric energy, and when this arrives on a large scale, regional progress will be accelerated and promising.

For all the above, the layout of the Bolivian transmission system for the year 2050 would be the one shown in Figure 3 (500 kV lines are shown in orange).

Regarding Peru, we can see its future 500 kV coastal network (Figure 3) to which our country could connect if a transmission line is built from the Palca region in Bolivia to the Moquegua region in Peru, which would allow integration with other Andean countries for temporary exchanges of surpluses through Peru. Once the 500 kV network is built, it will be possible to extend it in other directions, since a priori the future interconnection with other neighboring countries such as Chile, Argentina and Paraguay should not be ruled out.

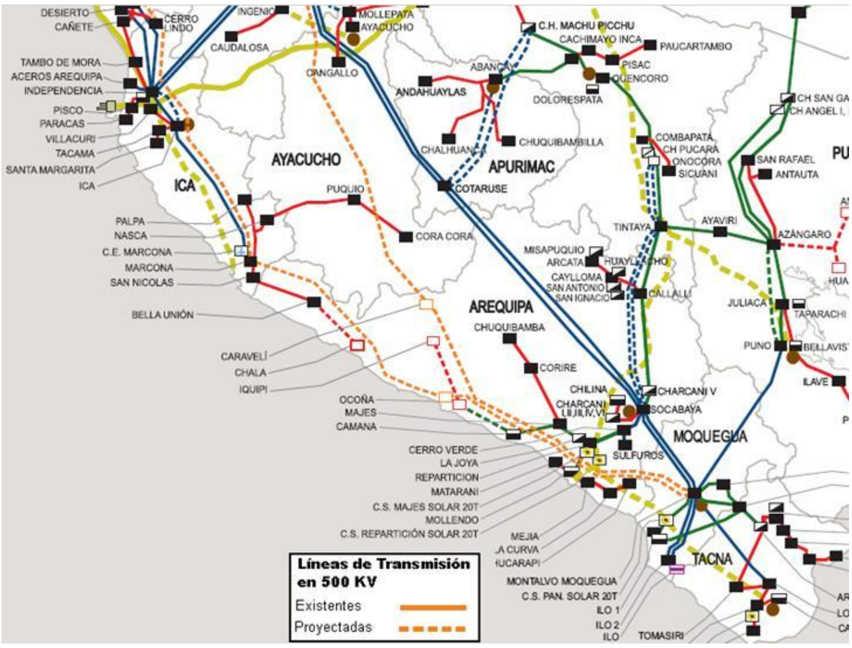


Figure 3. Peru's interconnected system

8 What will happen before 2050?

Once the simulations for 2050 have been carried out, some conclusions can be drawn that will help plan the preceding decades, i.e. 2040 and 2030, considering the estimated duration of the construction of mega hydroelectric power plant projects and transmission lines.

The ideal situation would be to build the Cachuela Esperanza power plant (900 MW) before 2030 and integrate it into the SIN through 500 kV lines, and also into the Brazilian System (no more than 100 km away), because there will be an oversupply on the Bolivian side, and even more so when the El Bala power plant (1,680 MW) is completed. Something similar can be foreseen with the Rio Grande hydroelectric complex (with its main Rositas power plant of more than 650 MW) which, through an electrical interconnection substation in the border region of Puerto Suarez (Bolivia), could meet the demand of the Cuiabá region (Brazil) for several decades or years.

Bolivia's energy strategy with Brazil must contemplate the gradual reduction of NG exports to this country, and replace it with the export of electric energy through the 500 kV network. Another aspect that must not be lost sight of is that once exports are consolidated, they cannot be prolonged indefinitely, because, as Bolivia's own energy needs grow, the magnitude of export power must decrease, until it is eliminated in some future year close to 2050. Ultimately, it will be necessary for both countries to formalize a serious diplomatic agreement with mutual benefits that includes economic aspects from the construction of the Cachuela Esperanza, El Bala, and Rositas power plants, and the respective transmission lines, followed by the purchase of electric energy from Bolivia for a long period to be defined, until the cessation of exports based on the growth of Bolivian demand.

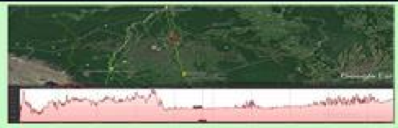
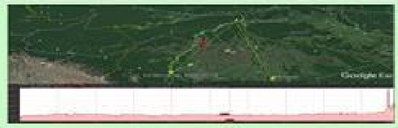
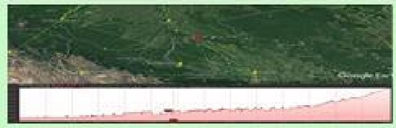
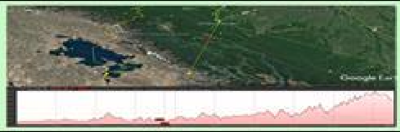
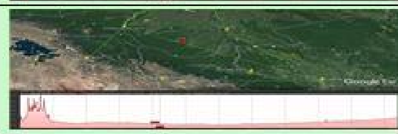
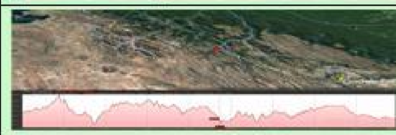
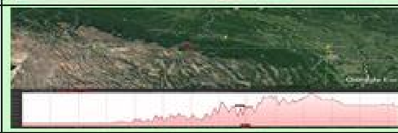
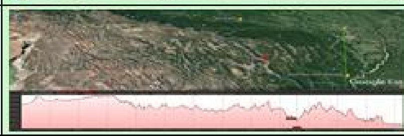
Nodos		RUTA	Longitud [Km] (trazo directo)	Perfíl topográfico
CAE	TRI	Cachuela - Trinidad	481	
CAE	BAL	Cachuela - Bala	490	
TRI	WAR	Trinidad - Warnes	351	
BAL	PAL	Bala - Palca	228	
BAL	WAR	Bala - Warnes	568	
PAL	SAN	Palca - Santivañez	212	
WAR	SAN	Warnes - Santivañ	327	
WAR	ROS	Warnes - Rositas	160	
MUT	ROS	Mutun - Rositas	593	
SAN	ROS	Santivañez - Rosita	326	

Figure 4. Topographic profile of the proposed 500 kV three-phase transmission lines

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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Annexes

Abbreviations:

CNDC: National Load Dispatch Committee, coordinating entity of the wholesale market;

MEM: wholesale electricity market; ENDE: National Electricity Company, state-owned;

UNDP: United Nations Development Program; OLADE: Latin American Energy Organization

GN: natural gas; SIN: National Interconnected System

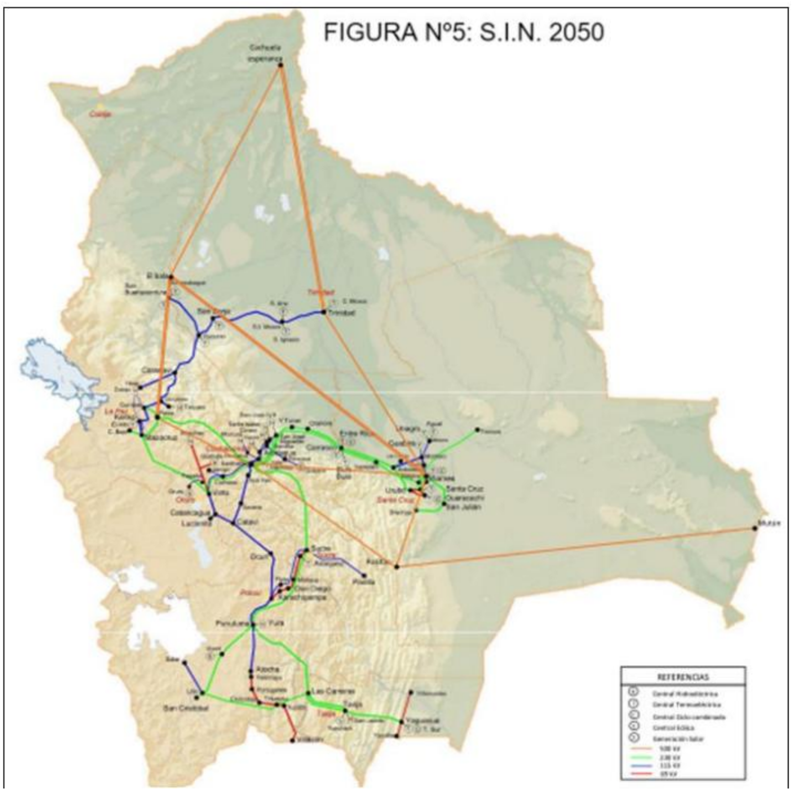

Figure 5. National internet system by 2025