Energy transition planning in developing countries: The case of Bolivian interconnected power system

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Abstract

The transition to a more environmentally friendly energy matrix has become one of the most important goals to control the climate change. Variable renewable energy sources (VRES) are a central low-carbon alternative but their variability and lower predictability require a flexible power system capable of balancing the variations.

The aim of this paper is to determine a possible transition pathway to reach high penetrations of non-conventional renewable sources for Bolivia. To that aim, a Bolivian long-term scenario (2050 horizon) is developed based on the international targets, with the purpose to distribute economic resources optimally in the next 30 years. This is achieved by combining a unit-commitment and dispatch model with the forecast demand for the upcoming years, the already-known power system plan for the Bolivian system (5 years), and various scenarios of VRES deployment. For each scenario, the flexibility of the power generation system is evaluated in terms of energy balancing, transmission grid, system inertia, ancillary services requirement, and energy generation cost.

Results indicate a need to add 8.31 GW of transmission lines, increase storage capacity, and enhanced ancillary services up to 73.31TWh (in particular frequency containment reserve) in the next 30 years. Finally, the environmental and economic gains are evaluated with comparison to the baseline it is found that the proposed system can reduce 62% of the CO2 emissions by 2050 with high penetration of VRES. This will result into significant economic savings for the country by enhancing natural gas exportations.

Keywords:

CO2 emissions, VRES, low-carbon, power systems, Bolivia, Electricity cost, Solar energy.

1. Introduction

With the Paris Agreement countries have agreed to a common goal of maintaining the global temperature increase to well below 2 °C, by the end of the century. According to the latest UNEP Emissions Gap report, to be on track for the goal, the world needs to reduce global emissions by over 50% by 2030 and work towards carbon neutrality by 2050[1]. Based on IRENA's analysis, energy-related carbon-dioxide (CO_2) emission reductions would have to decline 70% by 2050, compared to current levels, to meet climate goals. A large-scale shift to electricity from renewables could deliver 60% of those reductions. To reduce future GHG emissions and limit global warming to less than 2°C [2], a number of countries have collectively pledged short-term and long-term policies in pursuit of efficient planned transition from predominantly conventional power systems (e.g. hydro dam and thermal) to power systems with a high penetration of Variable Renewable Energy Sources (VRES, which includes hydro-run-of-river, wind and solar)[3][4]. However, the stochasticity of these sources is highly influential in the reliability and continuity of the supply and requires flexibility in the power systems to be able to operate in its safety margins for all the equipment of the system. A power system is considered flexible if under economic limits, it is able to respond to large fluctuations in both the generation and the demand [5]. The insertion of VRES entails additional flexibility requirements, which can be achieved by:

- Dispatchable power plants (i.e. with ramp up and ramp down capabilities, reserves).
- Energy Storage systems, mainly in the form of pumped hydro storage units.
- Grid interconnections between countries.
- Demand side management (DSM) [6].

In this sense, analyzing the possible future scenarios that allow us to have an approximate idea of how electric grids could react to higher penetration of renewable sources would provide us a pathway to determine yearly objectives of VRES penetration, that could be achievable in terms of VRES integration projects to the grid within its technical safe operative margins, and with a determined pattern of economic investments.

This work proposes a methodology of energy transition planning in developing countries, with focus in the Bolivian interconnected power system. For that purpose, the present work extends a preliminary, unit-commitment, and optimal dispatch model presented at the ECOS 2018 conference [7]. The analysis carries out the possible impact of a large deployment VRES generation. The simulation is developed in terms of energy balance, transmission grid, system inertia, ancillary services requirement, and energy generation cost. All the technical input data related to power plants, load, renewable resources are collected from various sources, and used to define the base scenario for the year 2020. From that start point a percentage factor of demand growth is applied to shape the model of 2025, and the integration of different power plants planned until 2025 is considered according to the Bolivian expansion plan [12].

These scenarios are subject to different renewable penetration hypotheses. Additionally, two different natural gas prices are setted: the first one considers the price of natural gas regulated by the Bolivian government and the second one the international price of natural gas.

2. The Bolivian case study

2.1 Case study and methodology definition

The Bolivian national power grid named Nacional Interconnected System (Sistema Interconectado Nacional, SIN) is an interesting case study, since it is reporting a growing interest from the Bolivian government to integrate more renewable energy sources. We can evince that premise from the SIN expansion plan (PEEBOL2025, Plan Eléctrico del Estado Plurinacional de Bolivia 2025[8]), and from the annual reports of the different subsidiaries of the National Energy Company (Empresa Nacional de Electricidad, ENDE), were a large number of feasibility and pre-feasibility studies are listed as "currently developing" with the purpose of the construction of several run-of-river hydroelectric plants up to 2025 and beyond [8][9][10][11][12]. On the other hand, there are currently only a few wind farms, solar, or geothermal plants listed as "currently developing", and most part of them will be completed by 2021 leaving a planification gap upto 2025 and beyond. Although PEEBOL2025 has been implemented since 2014, the Bolivian electric power matrix is changing slowly. The production of VRES increased in percentage from 1.5% (120GWh) in 2014 to 11% (1046GWh) in 2020 of the total supply in each year respectively [13][14]. Nonetheless, the country still depends on natural gas as a primary energy source [7]. And apparently there are some contradictions between the policies to increase VRES deployment and the operational policies and normative of the SIN [15], while in the year 2020, the Bolivian electric power system registered 9.24% of installed power capacity of VRES, which could provide at least around 20% of the energy demanded due to the fact that the installed power capacity triples the average energy demanded. However, they still only provided 1046GWh (11%) of the 9,212GWh demanded in that year [13][14]. Thereby, in order to determine a possible transition pathway to boost the greatest possible penetration of VRES for Bolivia, and analyze the Bolivian operative policies; two structures of generation capacity of the SIN (2020 and 2025) are defined as reference to build three possible scenarios, taking into account all the projects listed in the PEEBOL 2025. The unit-commitment and optimal dispatch (UC/D) model is developed to cope with the demand for both scenarios, and thus then develop a proposal with a determined hypothetical increment of solar and wind energy power supply, expressed in MW and projected upto 2050. The Dispa-SET model has been chosen with the purpose of evaluating long-term scenarios with determined values of renewable resources penetration. This tool is characterized by using historical hourly data of demand and renewable source with specific techno-economic data of all generation units to minimize the system operational cost and the dispatch in a medium-term time horizon (refer to [16] for the detailed model description).

2.2 Bolivian Interconnected System

Despite the fact that some projects of generation, transmission and distribution facilities have been integrated to the SIN, and some others like Karachipampa or Kenko have been definitively taken out of service, since 2014 the SIN has not changed its structure. Thus, the energy demand of eight departments still represents 97% of the national demand in 2020 [12]. The Bolivian system is divided into four well-defined areas as shown in **figure 1**: North (La Paz and Beni), Oriental (Santa Cruz, with the future integration of Pando), Central (Oruro and Cochabamba) and Sur (Potosí, Chuquisaca and Tarija). The high voltage transmission system (STI, Sistema Troncal de Interconexión) is part of the SIN and it includes 230, 115 and 69 kV transmission lines. The SIN generation fleet is composed by:

- Hydroelectric power plants that consist of run-of-river units (HROR WAT), and reservoir plants (HDAM WAT).
- Thermal units composed of open-cycle natural gas turbines (GTUR GAS), steam turbines that operate with sugarcane bagasse (GTUR BIO), natural gas engines and Dual Fuel units that use natural gas and diesel.
- Combined cycle steam turbines that use the exhaust gases of natural gas turbines (COMC GAS).
- Diesel engines (GTUR OIL).
- Wind-onshore turbines (WTON WIN).
- Finally, there are two PV solar power plants (PHOT SUN).

2.3 SIN 2020 installed generation capacity

This is the start reference structure of the SIN where all data compiled up to 2020 is used. The power generation fleet is strongly dominated by conventional technologies (thermal and hydroelectric) with a very small percentage of wind-onshore, geothermal and solar-PV generation. The total demand reached in this year is 9212.38 GWh with a maximum peak of 1.56 GW.

SIN generation installed effective capacity during the year 2020 is presented in the **Annex A - Table 1** disaggregated by zones and technologies. It reaches a total capacity of 3,187 MW, of which 859 MW (26.95 %) correspond to hydroelectric plants, thermal generation still represented the main primary energy source with 2,186 MW (67.18 %), 27 MW (0.85 %) correspond to wind farms, the entrance of solar energy with 115 MW (3.61%), and finally 45.22 MW (1.41 %) correspond to plants that operate with biomass, all percentages of the total generation capacity of the SIN. In 2020 the energy demand was 9.2 GWh and it is estimated that it should increase 12.3 GWh by the year 2025 [12].

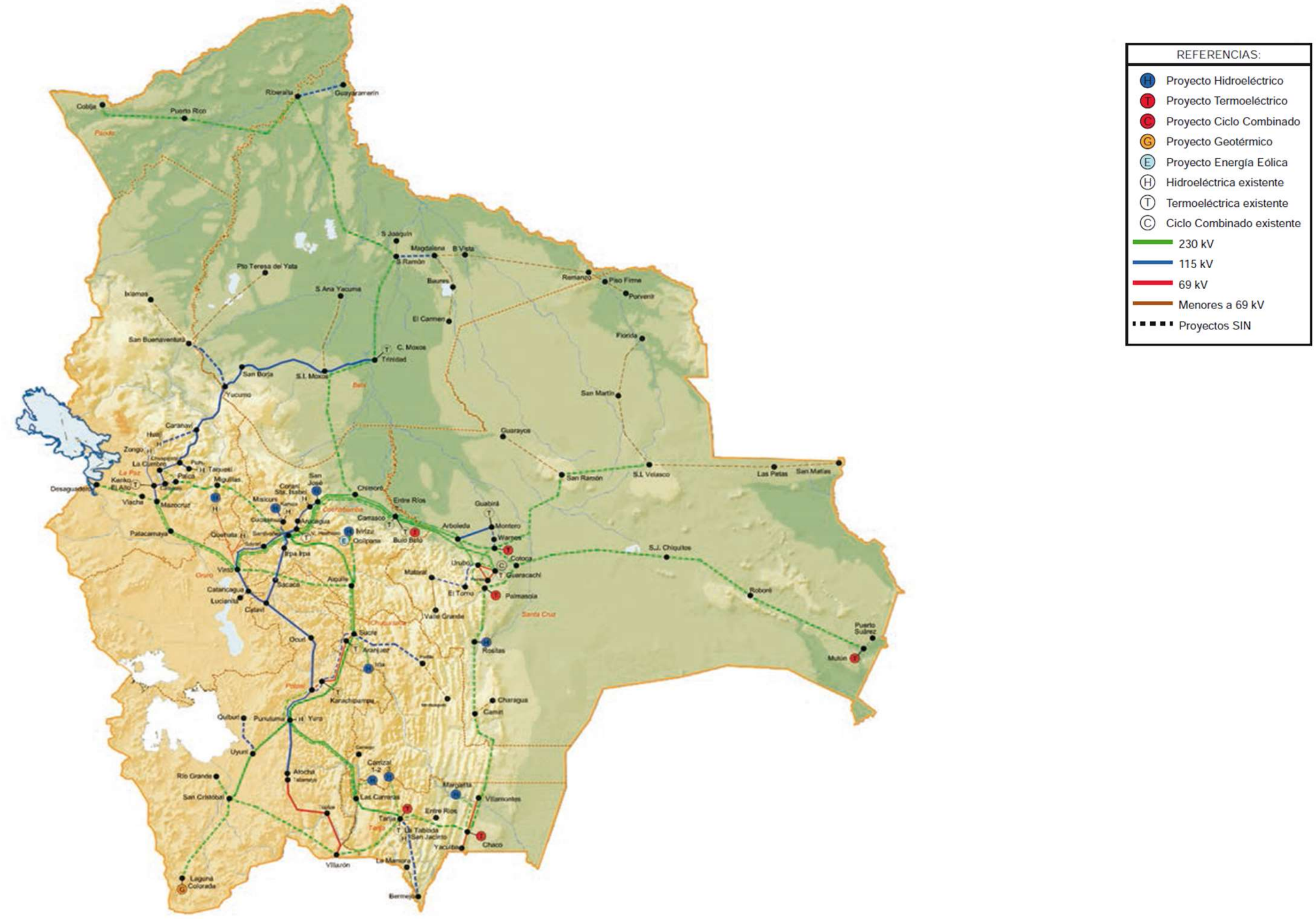

Fig.1. The SIN layout implemented and planned in the period 2020-2025 [12]

2.4. Renewable generation capacity expansion 2020-2025

The potential of VRES in Bolivia is distributed throughout the territory. Hydro-run-of-river (HROR) projects are found in all four zones of the SIN, however the main HROR projects are found in the central and south zones of the SIN. Solar energy is feasible in all regions, but mainly in the Andean highlands sector due to its high levels of radiation. Finally, wind energy predominates in the departments of Santa Cruz and Cochabamba and in some parts of the highlands. Despite the VRES expansion potential as it is shown in the **figures 2-5**, the projects planned until 2025 only represent 9.24% of the total effective capacity of the SIN by that year. For simulation purposes, and based on the regions with higher potential of expansion, a greater use of VRES will be hypothetically setted to achieve 25% 50% and 100% of primary energy supply from variable renewable energy sources.

Fig. 2. Map of renewable energy potential in Bolivia [17]

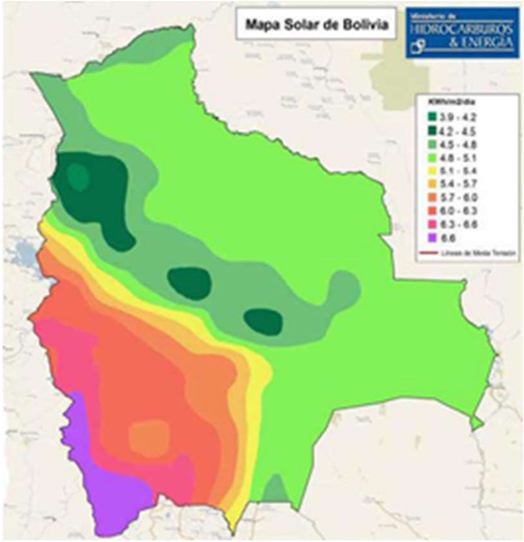

Fig. 3. Map of Solar energy potential in Bolivia [17]

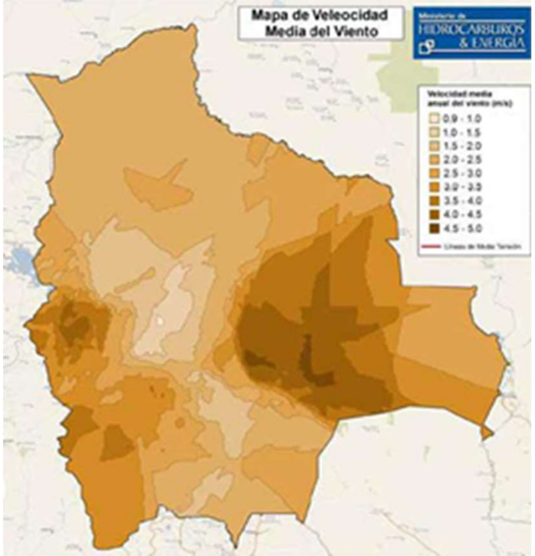

Fig. 4. Map of wind speed in Bolivia [17]

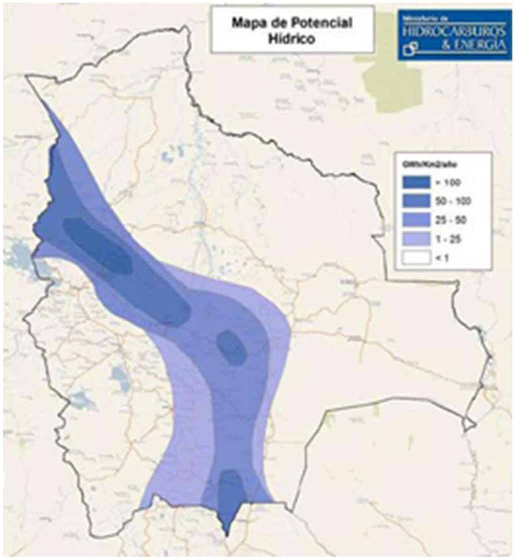

Fig.5. Map of hydroelectric energy potential in Bolivia [17]

2.4.1. Hydro resources

With the aim of increasing hydroelectric generation capacity the hydroelectric projects were chosen from the studies carried out in different stages of pre-investment, and / or pre-feasibility studies [11]. They are located in different regions of Bolivia to meet the demand and provide greater security and reliability to the system. Two important projects were completed and started operations in 2020: Misicuni with 120 MW, and San José with 120 MW, as the third stage of the waterfall of use of the upper basin of the Chapare River.

The hydroelectric generation project portfolio for 2025 includes the incorporation of: Miguillas, with Umapalca (83 MW) and Palillada (113 MW) hydroelectric plants, located in the department of La Paz, Ivirizu (164 MW) in the department of Cochabamba, Rositas (400 MW) in the department of Santa Cruz on the Rio Grande river, Icla (102 MW) in the departments of Chuquisaca and Potosí on the Pilcomayo river, the Carrizal I, II and III Project (347 MW) on the Camblaya river, located between the departments of Tarija and Chuquisaca and Margarita (150 MW), located in the “Chaco Tarijeño” on the Pilcomayo river.

These projects will contribute to the change of the energy mix with a notorious increase of the system inertia and the spinning reserve, and will supply the country's growing energy demand with 1,599 MW [8].

2.4.2. Solar resources

Almost 97% of the territory is suitable to use energy solar as primary generation source [18]. In contrast, PEEBOL2025 does not mention large-scale solar energy integration projects. Until 2020 the SIN has incorporated its three first solar energy projects: Oruro I (50MW), Uyuni_ColchaK (60MW) and Yunchara (5MW). Additionally at least three more projects are confirmed to be completed by 2025: Oruro II (50MW), Guayaramerin (3MW) and Riberalta (5.8MW) with a total solar energy capacity installed of 173.8 MW until 2025.

As shown in Figure 3 [19, 20], the southwest area of the country, has the highest radiation values (5.1–7.2 kWh/m2-day), while the north-eastern zone presents lowest values (3.9–5.1 kWh/m2-day). In addition, Bolivia comprises a strip of territory which receives the largest solar radiation in the world (the tropical zone of the South, between the parallels 11° and 22°).

2.4.3. Wind resources

In recent years the Bolivian wind atlas was developed [23], showing annual measurements of wind velocity at three different heights (20 m, 50 m, 80 m). The wind resource at Bolivian territory seems to be more limited than solar, stronger resource are concentrated in five sectors and the first wind farm projects are been incorporated gradually: Around Santa Cruz city, mostly south and west of urban center with the projects of “Warnes-El Dorado- San Julian”; On the corridor that goes from east to west between La Paz and Santa Cruz, passing through north of Cochabamba department with the project of “Qollpana I-Qollpana II-Qollpana III”; On the corridor between Tarija and Sucre departments that goes from north to south with the project of “La Ventolera”; Around the Titicaca Lake region in the department of La Paz with the project of “Titicaca”; Finally, at the southwest border between Chile, Argentina and Potosi department; and on the north to south corridor between Oruro and Potosi departments as possible locations for future projects [23].

2.5. SIN 2025 projected generation capacity

Based on energy policies and demand requirements, PEEBOL2025 proposes a portfolio of generation and transmission projects until 2025 for the expansion of the electrical infrastructure taking into account the availability of energy sources.

In 2025 a total power demand of 12,310 GWh is expected [12] and the generation capacities are increased: the total installed capacity raises to 5.19 GW, of which 2.14 GW (41.23%) are thermal, 2.54 GW (48.85%) are Hydroelectric, wind-onshore capacity grows up to 0.22 GW (4.28%), solar-PV with 0.17 GW (3.35%), 0.045 GW (0.87%) correspond to biomass, and geothermal appears with 0.1 GW (1.93%). The grid is also upgraded with a new 0.15 GW line between Central and North [12], a 0.16 GW line between North and Oriental, a 0.30 GW line between Central and South and a 0.30 GW lines between Oriental and South [12]. PEEBOL2025 data reveals that the following five years (2020-2025) the SIN expansion plan will integrate VRES projects in an average of 50MW per year [12].

Annex A - Table 2 summarizes the planned generation projects in each of the four regions [8][9][10][11][12].

Interconnection projects (called mega-projects), intended for energy exchange with neighboring countries were proposed and they are still on the governmental agenda. However since there is no firm schedule yet [11], the Bolivian system is considered as isolated in this work.

3. Model description

A detailed description of the open-source Dispa-SET model, its constraints and its main characteristics can be found in [25]. The model focuses on the short-term operation of large-scale energy systems by solving the unit commitment and energy dispatch problem (UC/D) solved by mixed integer linear programming (MILP) in GAMS [26][27]. The model aims to minimize the operational costs of power systems, which comprise start-up and shut-down, fixed, variable, ramping, transmission-related and load shedding costs, see the equations of the objective function **Eq.(1)** and energy balance constrains **Eq.(2).** The demand is assumed to be inelastic to the price signal [16].

$$MinSystemCost = \sum_{u,n,i} \begin{bmatrix} CostStartUp_{u,i} + CostShutDown_{u,i} + CostFixed_{u} * Committed_{u,i} \\ +CostVariable_{u,i} * Power_{u,i} + CostRampUp_{u,i} + CostRampDown_{u,i} \\ +PriceTransmission_{i,l} * Flow_{i,l} + \sum_{n}\left(CostLoadShedding_{i,n} * ShedLoad_{i,n}\right) \\ +VOLL_{Power} * \sum_{n}\left(LostLoadMaxPower_{i,n} + LostLoadMinPower_{i,n}\right) \\ +VOLL_{Reserve} * \left(LostLoadReserve2U_{i,n} + LostLoadReserve2D_{i,n}\right) \\ +VOLL_{Ramp} * \left(LostLoadRampUp_{u,i} + LostLoadRampDown_{u,i}\right) \end{bmatrix} \tag{1}$$

$$\sum_{u}(Power_{u,i} \cdot Location_{u,n}) + \sum_{l}(Flow_{l,i} \cdot LineNode_{l,n}) = \begin{bmatrix} Demand_{DA,n,h} + \sum_{r}\left(StorageInput_{s,h} \cdot Location_{s,n}\right) - ShedLoad_{n,i} \\ -LostLoadMaxPower_{n,i} + LostLoadMinPower_{n,i} \end{bmatrix} \tag{2}$$

The main characteristics of the model can be summarized as follows:

- Minimum and maximum power for each unit
- Power plant ramping limits
- Reserves up and down
- Minimum up/down times
- Load Shedding
- Curtailment
- Pumped-hydro storage
- Non-dispatchable units (e.g. wind turbines, run-of-river, etc.)
- Start-up, ramping and no-load costs
- Multi-nodes with capacity constraints on the lines (congestion)
- Constraints on the targets for renewables and/or CO2 emissions
- Yearly schedules for the outages (forced and planned) of each units.

3.1. Input data 2020-2025

The model is data-intensive and requires a number of times series, cost data and power plant data. The methodology of data acquisition and determination is the same as [7], some time series are obtained from interpolating available data. For the case of specific technical data, some information was restricted from pertinent national entities, so references data available in the bibliography are assumed. These are described in the next subsections.

3.1.1. SIN energy demand 2020-2025

The demand is divided into: regulated consumers, mostly residential, who are served by distribution companies, and non-Regulated large consumers which are large industrial enterprises that directly participate in electricity markets [12]. By 2020 the energy demand is higher in the Oriental area with 38.56%, followed by North with 23.39%, Central with 22.36% and South with 15.69% [12]. The energy demand of the country is mainly residential. In 2020 this segment demanded 38% of the required energy, followed by industrial with 27%, public services (street lighting, hospitals, public institutions, etc.) with 24% and mining sector with 11% [31].

The energy demand increased from 8,378 GWh in 2016 to 9,212 GWh in 2020. For the following years the projection of the demand was based on large consumer statements, bottom-up methods, methods based on interpolation of growth rates and methods based on the evolution of specific consumption by categories of distributors. A growth at an average of 4% per year was determined, reaching a demand of 12,310 GWh for the year 2025 and 15,128 GWh for the year 2030 [8].

3.1.2. Power plants Data 2020-2025

A revision of the following technical data was done: type of power plants (technology), the area where the unit is located (Zone) and the power capacity. This information is specified in tables 1 and 2 above.

Specific technical data sources comprise fuel type and prices, are extracted from [12][32][33]. All scenarios are evaluated into two prices of natural gas and gas oil: the subsidized prices of natural gas and gas oil by Bolivian government are 3.57 €/MWh and 13.91 respectively; the opportunity price, i.e. the monetary values at which Bolivian exports are 10.42 €/MWh and 17.19 €/MWh respectively. [12][32][33]. Sugarcane pellets prices are taken as 0 €/MWh since the bagasse of residual cane from the Bolivian sugar industry is used, efficiency [34], CO2 emission factors (CO2 intensity) [35], minimum load [1][34][36], ramp up/down [37][34][38], start up time [1][34] and minimum up/down times [34]. Specific data for storage units (storage capacity and efficiency) are found in [39]. It should be noted that the CO2 emission input does not impact the results since no CO2 pricing scheme is available in the current Bolivian regulation. A null price of CO2 emission is therefore assumed.

Economic data refers to the costs incurred by the units when they come into operation, i.e.: fixed cost (no load cost) related of operation and maintenance of units, extracted from [34][40], start-up cost (fuel cost for start-up, auxiliary electricity, chemical products, extra workforce etc.) from [34] and ramping cost (these values are in general relatively low compared to start-up values, still they can be relevant for generation technologies which are designed for baseload applications) from [41]. These two last cost parameters, also called cycling cost, turn important for thermal units [34], since the on/off number and ramping changes of these technologies increase in response to fluctuations in system load/supply requirement due to the VRES penetration [42]. A summary of the input data is presented in Annex A-Table 3.

3.1.3. Load time series 2020-2025

The time series are provided for the whole year with a time resolution of one hour. Since there are four zones in the model, four load curves are required, aggregating the demands of all sectors described above (residential, industrial, public, mining). They are extracted from [43]. **Figures 6 and 7** show these load curve and power dispatch for south zone on the week with the highest demand (March 9th-15th of 2020 and 2025). The load time series for the year 2025 is determined by applying a yearly incremental factor to 2020 load time series, taken from a demand projection study [8].

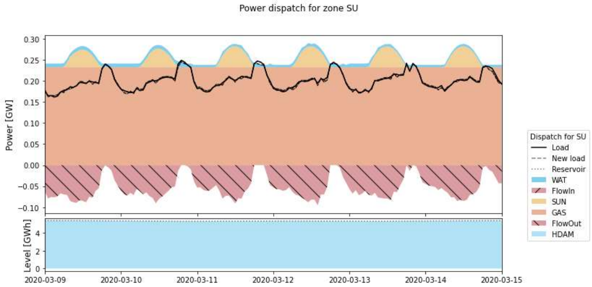

Fig.6. Load Curve and Power Dispatch for zone south (March 9th-15th of 2020)

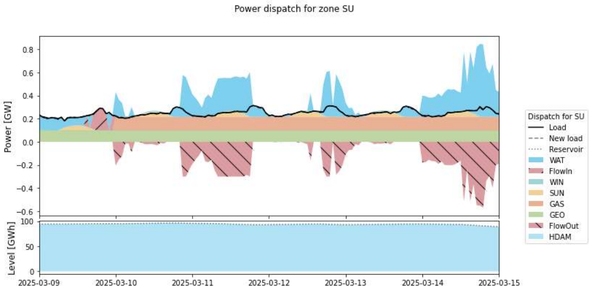

Fig. 7. Load Curve and power dispatch for zone south (March 9th-15th of 2025)

3.1.4. VRES Availability Factors 2020-2025

Availability factor is defined as the ratio between the instantaneous renewable generation and the installed nameplate capacity. Three time series are required: solar-PV, wind-onshore, and hydroelectric run-of-river [16].

Solar resources availability factor time series are obtained from global horizontal radiation models using approximate geographic location [44], environmental features [45][46], PV systems technical features [47][48][49], and monthly average solar radiation data of Bolivian solar map and data extracted from [50]. The high altitude locations (Uyuni-Colchak, Oruro I & II, Yunchará) have higher availability factors between September and April because of higher radiation levels in this season. High variability is also observed in December and January because of the rain season.

Wind resources availability factors are generated using wind hourly velocity from [50] and approximate geographic location and technical features of both installed and planned wind turbines from [23][51][52][53].. Centrals of Oriental zone have a very similar profile and present high wind resources and higher peaks in February, April, July, August and October. On the other hand, central areas of South Central zones (are less variable but they have lower wind resource.

Hydro run-of-river resources availability factors are obtained from interpolating average daily flows [54], unit technical data as nominal power, turbine type, efficiency and height of fall were taken from [55]. An individual availability factor distribution corresponding to each one of run-of-river units of the SIN is used.

3.1.5. Hydro time series 2020-2025

Hydro storage is characterized by two time series: inflows and storage level.

The “scaled inflows” are defined as exogenous time series for each energy storage unit and are expressed as a fraction of the nominal power of this unit [16]. They are obtained from [56]. Individual time series corresponding to each reservoir of the SIN is used in all simulations. Because the optimization is performed with a rolling horizon [16] of a few days, long-term storage levels must be provided as an exogenous input. In the contrary case, each optimization would tend to empty the reservoirs to their minimum value. Historical volumes accumulated in the reservoirs are therefore imposed as a lower boundary at the end of each optimization horizon. They are expressed as a fraction of the maximum energy that can be stored in the reservoir [16]. These time series are obtained based on the weekly averages collected from [39. In 2020 the main reservoir is Misicuni and, in 2025, the new Rositas hydro dam will be put into operation, adding an important reservoir capacity.

3.1.6. Outage time series 2020-2025

Outages factor refers to scheduled and unplanned interruptions of generation units and varies from 0 (no outage) to 1 (total outage). The available power is therefore given by the nominal capacity multiplied by (1 – outage factor) [16]. We used the historical outage factors available in [38].

3.1.7. Grid data 2020-2025

Because of the relative simplicity of the grid in Bolivia, the country is divided in four zones whose cross-border flows are limited by a net transfer capacity (no DC power flow is implemented in the current version of the model). The maximum capacity of transmission lines are obtained from [12].

3.2 Transition proposal 2050 horizon

Based on the context of the period 2020-2025 this work proposes three possible planning scenarios with different levels of VRES penetration defined on the following targets:

- **Low penetration scenario**: VRES are increased 50MW per year, reaching 25% of the projected demand in 2050.
- **Moderate penetration scenario:** VRES are increased 100MW per year, reaching 50% of the projected demand in 2050.
- **High penetration scenario:** VRES are increased 200MW per year, reaching 100% of the projected demand in 2050.

Finally, combined increment of solar-PV/wind-onshore penetration scenarios were simulated, increasing the power of both technologies proportionally to the PEEBOL2025 data up to 2025, so that the VRES capacity reaches 25%, 50%, 100% of the total projected demand. Total power values of solar-PV and wind-onshore technologies for all scenarios are specified in Annex A-Table 4. The capacities of other technologies are kept unchanged. The current location of VRES units is conserved. The time series of 2020 scenario is conserved for the 2025 simulations and are up scaled when necessary.

4. Results

For a simpler analysis and manageable presentation, the results of the different scenarios are summarized in Annex A-Table 4. We can observe the following:

- High penetration levels of VRES could reduce the average electricity cost from 17.07€/MWh to 8.56 €/MWh by 2050. It is however important to note that these cost is only operational. For a more accurate result we should take into account the investments costs according to [33]. This clearly shows that solar energy could be more competitive if the governmental subsidy gas prices is withdrawn.
- Solar energy peak energy supply is produced during the radiation peak hours (12:00 and 15:00) which helps to reduce the cost due to the reduction of supply with thermal energy in that period of time. However, the transmission lines get congested up to 2848 hours with flow-in of energy to the areas with less penetration of VRES. Thus, by 2050 the following increment of power for the transmission lines is needed: {'CE -> NO': 2.8GW, 'CE -> OR': 1.1GW, 'CE -> SU': 0, 'NO -> OR': 0, 'OR -> CE': 0.051GW, 'OR -> NO': 2.1GW, 'OR -> SU': 0.030GW, 'SU -> CE': 0.175GW, 'SU -> OR': 2.1GW}
- All three scenarios show that the system is flexible enough to integrate a significant percentage of VRES until 2030. However, from 2031 and onwards it is necessary to increment up to 106TWh (8 times the reservoir installed in 2020) and up to 1.5GW of capacity of Hydro power units to meet the minimum performance conditions [57] stated by the CNDC, which indicates that: "the minimum total reserve of the system will be equal to 30% of the effective capacity of the generating units assigned with firm power."
- The main limitation is the energy curtailment principally in the north area of the SIN by 2050, mainly because this region has the lowest penetration of renewable energy projected, with a generation capacity of 47 % under the demand. Thus flow-in of energy is needed to cover the demand in the north area. However, with higher percentage of VRES installed the curtailment decreases considerably up to: 16.24 TWh for 50MW/Year; 7.29 TWh for 100MW/Year; and 1.07 TWh for 200MW/Year penetration by 2050.
- The percentage of load that is covered with VRES translates into displaced thermal generation. Reaching up to: 2.32 TWh for 50MW/Year; 4 TWh for 100MW/Year; and 8.32 TWh for 200MW/Year penetration by 2050. Bolivian consumption i.e. 8.32 TWh from natural gas turbines could be avoided, corresponding to almost 73.31 million of TCO2 in the high penetration of VRES scenario.
- The consumption and generation curves also show certain compatibility between the Bolivian load and the solar generation. Peak solar generation is produced around 12:00 and 15:00 PM, this is useful to cover an increase in the load that begins precisely at that time principally at oriental zone, although the peak load is around 19:00 and 21:00 hours. Between October to December and January to March this trend is accentuated and beneficial for the system. The opposite happens between May and September months, where hydraulic storage levels increase as well as high levels of radiation occur, during this period, higher curtailment levels are also stated.
- **Figure 8** shows the evolution of the energy storage levels of the hydro dam reservoirs throughout the year. It should be note at winter months of Bolivia (June, July and August) hydraulic reservoirs level decreases for that reason the participation of hydraulic units in the energy balance is less in this months as can be seen in **Figure 9**.

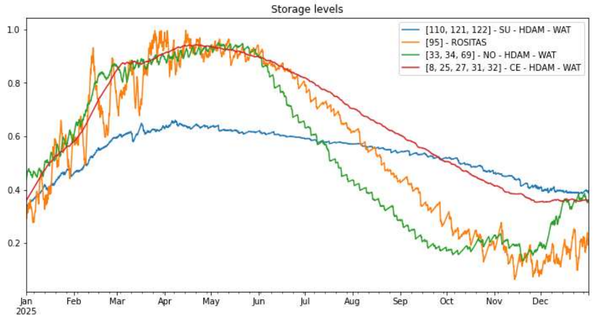

Fig.8. Storage Levels Curves for 2025

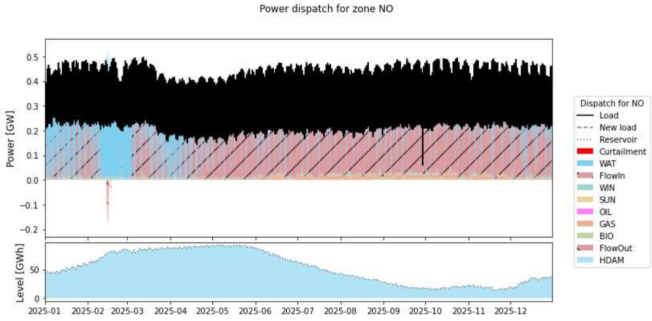

Fig.9. Energy Balance Curves for 2025

5. Conclusions

A comprehensive model of the Bolivian power system has been developed and is released as open-source together with its input date, thus ensuring a proper reproducibility and re-usability of this work.

Simulation results for 2020-2030 show that the system has enough flexibility to accept between 25-30 % penetrations of VRES without the need for additional flexible or storage units. At least 2000 MW of VRES could be introduced without any issue, which largely covers the projects considered in the PEEBOL 2025. It is also worthwhile to that the plans for new hydro dam capacities (e.g. “El bala”, “Cuenca Amazonica”, “Cuenca del Plata” and “Cachuela esperanza”) favor greater participation of VRES, providing the system with enough flexibility to install another 3000 MW of power from VRES.

Renewable sources tend to lower the prices of electricity generation, but in the Bolivian case, this is only marginally noticeable due to the government subsidy for natural gas. This makes renewable solar energy less competitive in the Bolivian context. The simulation results using a higher price for gas, such as the international price, show a greater potential for price reduction. For future simulations the price of gas should be updated.

It should be noted that, historical radiation data from years 2020-2025 have been used in the different proposed scenarios in a deterministic way, to obtain more accurate results, uncertainty and forecasting should be taken into account. This will be the object of future work. Finally generic techno-economic values were used, e.g. to understand the effect of gas prices. More accurate scenarios with specific data will be carried out in future works.

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ANNEX A: TABLES

Table 1. Power generation fleet in the SIN in 2020 [12]

Area	*Central Name*	*Technology*	*Number of Units*	*Total Power (MW)*
Central	Miguillas System	HDAM WAT	9	21.11
	Corani System		10	280.35
	Misicuni System		3	120
	San Jose I_San Jose II	HROR WAT	4	124
	Kanata		1	7.54
	Valle Hermoso	GTUR GAS	8	107.65
	Carrasco		3	122.94
	Bulo Bulo		3	135.41
	Entre Rios		4	105.21
	Entre Rios	COMC GAS	3	376.98
	Oruro I	PHOT SUN		50.01
	Qollpana I & II	WTON WIN	10	27
North	Taquesi System	HDAM WAT	2	89.19
	Zongo System		21	188.04
	Quehata	HROR WAT	2	1.97
	Kenko	GTUR GAS	2	-
	El Alto		2	46.19
	Trinidad	GTUR OIL	19	25.28
	Rurrenabaque		1	1.8
	Yucumo		1	0.35
	San Borja		2	1.8
	Say		2	1.62
	San Ignacio de Moxos		2	0.73
	San Buenaventura	GTUR BIO	1	5
Oriental	Guaracachi	COMC GAS	3	192.92
	Warnes		2	248.1
	Guaracachi	GTUR GAS	5	126.72
	Santa Cruz		2	38.07
	Warnes		5	195.56
	Unagro	GTUR BIO	1	14.22
	Guabira		1	21
	IAG		1	5
South	Yura System	HROR WAT	7	19.04
	San Jacinto	HDAM WAT	2	7.6
	Aranjuez	GTUR GAS	10	33.76
	Karachipampa		1	-
	Del Sur		4	147.55
	Del Sur	COMC GAS	2	232.32
	Uyuni_ColchaK	PHOT SUN	21	60.06
	Yunchara		2	5
SIN	*All Centrals*	*All Technologies*	*184*	*3187.09*

ANNEX A: TABLES

Table 2. Conventional and renewable generation projects planned for the period 2020-2025

Area	*Central*	*Technology*	*Situation*	*Total*
Central	Oruro II	PHOT SUN	Projected up to 2021	50.01
	Qollpana III	WTON WIN	Projected up to 2023	21
	Sehuencas_juntas	HDAM WAT	Projected up to 2025	279.88
	Banda Azul		Projected up to 2025	133.7
North	Guayaramerin	PHOT SUN	Projected up to 2025	3
	Riberalta		Projected up to 2025	5.8
	Umapalca_Palillada	HDAM WAT	Projected up to 2025	203
	SanCristobal_Anazani_SantaRosa	HROR WAT	Projected up to 2025	45
	Titicaca	WTON WIN	Projected up to 2025	21
Oriental	San Julian	WTON WIN	Projected up to 2021	39.6
	WARNES I		Projected up to 2021	14.4
	El Dorado		Projected up to 2021	54
	Rositas	HDAM WAT	Projected up to 2025	400
	Warnes II	WTON WIN	Projected up to 2025	21
South	La Ventolera	WTON WIN	Projected up to 2025	24
	Laguna Colorada	STUR	Projected up to 2025	100
	CarrizalI_CarrizalII_CarrizalIII	HDAM WAT	Projected up to 2025	346.5
	Icla_Margarita		Projected up to 2025	270

Table 3. Power plants data

Technology	*Installed capacity, MW*		*Efficiency, %*	*Subsidized Fuel cost, €/MWh*	*Non subsidized Fuel cost, €/MWh*	*Total CO2 emissions, TCO2/MWh*	*Ramp up/down rate, %/min*	*Average Ramping costs, €/MW*	*Average start-up costs, €/MW*	*Average Start-up/down time, h*
	2020	*2025*								
Natural gas turbine	1059.06	1059.06	35.74	3.57	10.42	0.64	15.42	4.03	67.97	0.33
Diesel gas turbine	31.58	31.58	33.82	13.91	17.19	0.25	15.42	0.92	18.44	0.33
Combined cycle turbine	1050.32	1050.32	55.92	3.57	10.42	0.31	6.42	9.47	1028.3	2.33
Biomass turbine	45.22	45.22	29.7	0	0	0	15.42	0.16	0.98	0.3
Hydro DAM	706.29	2339.37	90	0	0	0	3.33	0.28	1.4	0.08
Hydro ROR	152.55	197.55	90	0	0	0	3.33	0.28	1.4	0.08
Wind on shore	27	222	53	0	0	0	3.33	1	1	0.02
Photovoltaic	115.07	173.88	20	0	0	0	3.33	0	0	0.02
Geothermal	0	100	10	0	0	0	3.33	0	0	0.02

Table 4.1. Results for Low, Moderate and High VRES scenarios

Year	*Total Installed Capacity Until 2020 MW*	*Projected Energy Demand GWh*	*Projected Power Demand MW*	*Scenarios Of VRES Increment*			*Projected Installed Capacity, MW*		
				Low. Sce. 50 MW/YEAR	*Mod Sce. 100 MW/YEAR*	*Adv. Sce. +200MW MW/YEAR*	*Low. Sce. 50 MW/YEAR*	*Mod Sce. 100 MW/YEAR*	*Adv. Sce. 200 MW/YEAR*
2020 (Ref. year)	3187.09	9212	1566	142.07	142.07	142.07	3329	3329	3329
2025	3187.09	12310	2052	395.88	642.07	1142.07	3583	3829	4329
2030	3187.09	15128	2499	645.88	1142.07	2142.07	3833	4329	5329
2035	3187.09	19308	3189	895.88	1642.07	3142.07	4083	4829	6329
2040	3187.09	24642	4071	1145.88	2142.07	4142.07	4333	5329	7329
2045	3187.09	31450	5195	1395.88	2642.07	5142.07	4583	5829	8329
2050	3187.09	40139	6631	1645.88	3142.07	6142.07	4833	6329	9329

Table 4.2. Results for Low, Moderate and High VRES scenarios

ANNEX A: TABLES

Year	*Covered Load by VRES, %*			*Load Shedding, %*			*Total load, TWh*		
	Low. Sce. 50 %	*Mod Sce. 100 %*	*Adv. Sce. 200 %*	*Low. Sce. 50 %*	*Mod Sce. 100 %*	*Adv. Sce. 200 %*	*Low. Sce. 50 TWh*	*Mod Sce. 100 TWh*	*Adv. Sce. 200 TWh*
2020 (Ref. year)	9.07	9.07	9.07	0	0	0	9.36	9.36	9.36
2025	19.29	31.29	55.66	0	0	0	11.77	11.77	11.77
2030	25.85	45.70	85.72	24.77	7.17	4.11	14.36	14.36	14.36
2035	28.09	51.48	98.52	37.78	20.11	3.89	18.25	18.25	18.25
2040	28.15	52.62	101.76	39.96	19.68	3.56	23.32	23.32	23.32
2045	26.87	50.86	98.98	40.54	19.94	3.19	29.79	29.79	29.79
2050	24.82	47.39	92.63	42.72	19.17	2.81	38.02	38.02	38.02

Table 4.3. Results for Low, Moderate and High VRES scenarios

Year	*Curtailment, TWh*						*Thermal generation displaced, TWh*		
	Low. Sce. 50		*Mod Sce. 100*		*Adv. Sce. 200*		*Low. Sce. 50*	*Mod Sce. 100*	*Adv. Sce. 200*
	Zone	*Energy curtailed*	*Zone*	*Energy curtailed*	*Zone*	*Energy curtailed*	*TWh*	*TWh*	*TWh*
2020 (Ref. Year)	-	0	-	0	-	0	0	0	0
2025	-	0	NO, SU	0.97	NO, SU	0.47	1.22	1.88	3.24
2030	CE, NO, OR, SU	3.56	CE, NO, OR, SU	1.03	CE, NO, OR, SU	0.59	1.36	2.48	4.24
2035	CE, NO, OR, SU	6.9	CE, NO, OR, SU	3.67	CE, NO, OR, SU	0.71	1.64	2.83	5.24
2040	CE, NO, OR, SU	9.32	CE, NO, OR, SU	4.59	CE, NO, OR, SU	0.83	1.8	3.47	6.24
2045	CE, NO, OR, SU	12.08	CE, NO, OR, SU	5.94	CE, NO, OR, SU	0.95	2.06	3.49	7.24
2050	CE, NO, OR, SU	16.24	CE, NO, OR, SU	7.29	CE, NO, OR, SU	1.07	2.32	4	8.24

Table 4.4. Results for Low, Moderate and High VRES scenarios

Year	*Average electricity cost, €/MWh*						*Projected Reservoir needed, MWh*			*Transmission Lines with Congestion*
	Low. Sce. 50		*Mod Sce. 100*		*Adv. Sce. 200*		*Low. Sce. 50*	*Mod Sce. 100*	*Adv. Sce. 200*	
	Subsid. Nat. gas	*Intern. Nat. gas*	*Subsid. Nat. gas*	*Intern. Nat. gas*	*Subsid. Nat. gas*	*Intern. Nat. gas*	*MWh*	*MWh*	*MWh*	
2020 (Ref. Year)	6.28	17.07	6.28	17.07	6.28	17.07	1239106	1239106	1239105.95	{'CE -> NO': 0, 'CE -> OR': 0, 'CE -> SU': 0, 'NO -> CE': 0, 'OR -> CE': 0, 'SU -> CE': 0}
2025	3.89	12.82	3.1	8.16	1.72	10.11	1239106	1239106	1239105.95	{'CE -> NO': 0, 'CE -> OR': 0, 'CE -> SU': 0, 'NO -> OR': 3, 'OR -> NO': 1394, 'OR -> SU': 0, 'SU -> CE': 28, 'SU -> OR': 124}
2030	2.95	11.74	2.09	5.96	0.51	10	1301061.3	1424971.8	1920614.22	{'CE -> NO': 0, 'CE -> OR': 1, 'CE -> SU': 0, 'OR -> CE': 0, 'OR -> NO': 1872, 'OR -> SU': 0, 'SU -> CE': 33, 'SU -> OR': 344}
2035	2.51	11.02	1.66	4.95	0.48	9.83	1366114.3	1638717.6	2976952.04	{'CE -> NO': 368, 'CE -> OR': 0, 'CE -> SU': 0, 'OR -> CE': 0, 'OR -> NO': 2004, 'OR -> SU': 0, 'SU -> CE': 73, 'SU -> OR': 911}
2040	2.23	10.47	1.41	4.51	0.42	9.52	1475403.5	2130332.9	3418693.32	{'CE -> NO': 834, 'CE -> OR': 87, 'NO -> OR': 0, 'OR -> CE': 26, 'OR -> NO': 2032, 'OR -> SU': 0, 'SU -> CE': 124, 'SU -> OR': 1237}
2045	2.16	9.98	1.28	4.65	0.23	9.11	1593435.7	2812039.4	6222021.84	{'CE -> NO': 1353, 'CE -> OR': 486, 'NO -> OR': 0, 'OR -> CE': 34, 'OR -> NO': 2036, 'OR -> SU': 6, 'SU -> CE': 153, 'SU -> OR': 1435}
2050	2.1	9.76	1.23	4.91	0.16	8.56	1657173.2	3374447.3	10639657.3	{'CE -> NO': 2848, 'CE -> OR': 1151, 'CE -> SU': 0, 'NO -> OR': 0, 'OR -> CE': 51, 'OR -> NO': 2045, 'OR -> SU': 30, 'SU -> CE': 175, 'SU -> OR': 2135}