Assessing the Impact of Hydropower Availability Variation in the Future of the Bolivian Power Generation Mix

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ABSTRACT

As climate change effects keep increasing and become more noticeable worldwide, it is of utmost importance to be able to quantify their potential effects in future scenarios. This allows adaptation processes to their effects and impacts to be more efficient, practical, and achievable. One of the most direct effects of climate is the change in the availability of resources, particularly changes in rain patterns. These subsequently affect the total availability of hydro resources across regions, reshaping the historical trends and making projections less dependable.

In this sense, countries heavily reliant on the availability of seasonal hydro resources must start analyzing and including the instability of the environmental variable in their planning efforts. This additional consideration would allow these countries to assess the impacts of hydro availability over regions, sectors, and activities. As one of these countries, Bolivia requires a scenario-based analysis to ensure how reliable hydroelectricity will be in the future to guarantee the electrical supply. Currently, over 30% of the energy produced is based on hydropower. This is even more relevant given that future development plans for the country aim to increase the

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quantity of hydropower and include additional intermittent renewable energy sources such as PV and wind projects.

To accomplish this, several scenarios are derived from historical information and atypical years where weather behaves in extreme conditions, such as years with registered “El Niño” events. The proposed scenarios are run for the years 2030, 2040, and 2050 using a Bolivian-specific energy model built upon PyPSA-Earth, a cost optimization model that considers spatial distribution of resources, power flow constraints for the electrical network, and dispatch representation of the power generation mix.

Results from the analysis show that in the long-term, as legacy capacities are decommissioned, the future power generation mix in Bolivia will require up to 10.75% additional capacities for power generation to cover lower availabilities of hydro powerplants, as well as including new storage technologies to cover demands during peak loads. These results represent a first dive into the planning of the energy sector, taking into account the uncertainty and potential effects of hydro resources and climate change in the long term.

KEYWORDS

Energy modelling; Energy planning; Hydro availability; Climate Change; Bolivia.

INTRODUCTION

Over the last century, the world has been experiencing a systematic increase in its average temperature, which in turn has been responsible for a wide array of regionalized changes in weather conditions across the world. These alterations in weather patterns (climate change) have become the world's top priority due to their influence over humanity, affecting social aspects of cultures, economic activities, environmental elements, and health security, among others [1]. One of the more pronounced effects of climate change is the alteration of rain patterns and precipitation. While the average temperature increase accelerates water's evaporation, its effects in mainland and coastal regions differ. In the first case, humidity from the soil evaporates, creating dryer regions. In the second case, the increment of water concentration in the atmosphere produces more intense precipitations, leading to floodings [2].

In addition to these changes, seasonal effects are also to be considered, given their impact on water availability. In the case of South America, the ENSO phenomenon (El Niño Southern Oscillation) represents a periodical shift in the amount of warm surface seawater, its salinity, and air temperature. This process is also denominated as El Niño or La Niña events, considering the respective increment or reduction of the previously mentioned parameters, which have different registered regional impacts [3]. El Niño effects are mainly related to droughts in the Amazon and northeast of South America, while the coastal southeast region floodings are the most relevant effect. Specifically for Bolivia, the effects are mainly represented by dry seasons due to its geographical location in the center of South America and its landlocked condition [4].

While floodings can have very harsh and immediate effects on ecosystems, human well-being, and economic activities, droughts and the systematic reduction of water availability would have more long-lasting effects at country level. Because of this, dealing with droughts requires an adaptative approach, where strategic decisions need to be considered envisioning several years in the future. This mid to long-term planning becomes even more relevant when the cross-sectorial relevance of water as a resource is considered, which is used for drinking and services for the population, agricultural and livestock production, and energy production (WEF nexus) [5]. Particularly for the energy sector, aside from effects over energy demand behaviors, the effects of reduced water availability would directly impact the potential energy production of hydropower plants [6].

Within this context, the Bolivian energy system represents an interesting case study: A developing country, heavily reliant on hydroelectric powerplants, that needs to evaluate the impacts that water availability could have in the future of its energy system. In this sense, a scenario-based assessment is conducted considering the impact that potential cases of water availability, based on historical data, would have on the energy system in the future (up to 2050). To this end, a cost-optimization model of the Bolivian electric system is developed using PyPSA-Earth, focusing on the existing and expected installed capacities and the behavior of the energy dispatch over different periods. This study builds upon previous work done for Bolivia by including future development scenarios for the electric system [7] and making use of prior experiences with the selected tool [8].

This paper is structured to include four additional sections: Method, where the tool selected and adaptations made for the modelling process are presented; Case Study, where the particularities of the Bolivian system and its resources are detailed; Results, where a revision of simulations done for 2030, 2040 and 2050 are presented; Discussion and conclusions, where some of the key findings from the simulations are summarized, and additional comments regarding limitations and future work are presented.

METHOD

This section presents the key characteristics of the modelling tool, PyPSA-Earth, and details regarding data sources and adaptations made to create a working version of the Bolivian model.

General characteristics of the model

PyPSA-Earth is an open-source energy system modelling tool that can be used to produce power system representations at global scale, derived from the PyPSA-Eur model [9] and the PyPSA modelling framework [10]. The main characteristics of the tool revolve around its capability of representing electrical systems with both a high temporal and geospatial resolution to represent the electrical network, its dispatch behavior, and optimized expansion [11].

The PyPSA-Earth model is structured as a workflow with four aggregated stages that consider 1) data gathering, downloaded from online open-source repositories; 2) data pre-processing, where information is filtered and treated to fit pre-defined format requirements, 3) base network generation, which uses processed data to create inputs to be used in the problem formulation, and 4) network optimization, where linear programming is used to solve the problem of minimizing the costs of operation of the system [12].

The objective function of the model is focused on minimizing the total aggregated costs of running the system considering investments (as annualized capital costs) and operational expenses (variable costs) associated with the electric system (generation plants and transmission network expansion) while covering an exogenously defined electrical demand. The components considered in the objective function are presented in Equation 1.

$$Objective\ function\ (Minimize):$$

$$\sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t \left[\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t} h_{n,s,t}\right] + \sum_{t} \left[suc_{n,s,t} + sdc_{n,s,t}\right]$$

Equation (1)

In the objective function, capital costs are designated as c, the dispatch of generators as g, and dispatch of storage as h, F represents the capacity of branches, w represents the snapshots considered in the model, o represents the marginal costs, suc the start-up costs, and sdc the shut-down costs. Additionally, to represent the labelling of variables considered in the model, n represents the buses, t the snapshots, l the branches, and s the generators or storage units. A more detailed representation of each component of the model and the variables considered is available in the online documentation of the PyPSA model [13].

To complement the objective function, sets of equations are considered as constraints in order to properly represent operational restrictions (technological characteristics), physical effects (power flow conditions), and load coverage (energy balances), among others. The current version of PyPSA-Earth represents problems with an hourly resolution within a timeframe of up to a year, linear power flow conditions, optimization of continuous variables, and non-elastic demand coverage and can provide an optimized network and capacity expansion for the defined period.

Data used

One of the most significant contributions of PyPSA-Earth compared to other modelling tools available is the integration of openly available data sources into its modelling framework to generate models at national and international scales. Among the most relevant data sources used in the model, it’s possible to mention:

- OpenStreetMaps [14], an online repository of maps worldwide where different layers of information can be retrieved. The model uses this source to create the network topology, considering components such as georeferenced locations of generators, substations, and transmission lines.
- Copernicus Climate Change Service [15], an online repository from where historical climate data is retrieved, focusing specifically on resource availability such as wind speeds, solar radiation, and precipitation values.
- Shared Socioeconomic Pathways [16], a database from a study done to evaluate future scenarios based on alternative socio-economic developments and their implications over energy demands across the world, among others.

While these sources provide a great starting point to create a model from scratch, it is necessary to consider that data reliability can vary depending on a case-by-case basis. In the case of developing countries or countries where information is not easily accessible, repositories can be outdated, incomplete, or inconsistent. Previous work has found that one of the critical discrepancies that can be found for the case of Bolivia is linked to the representation of transmission lines and powerplants already available in the country, which can lead to a limited or inaccurate representation of the power system in the country [8].

To tackle this issue, a set of country-specific data has been developed regarding the existing powerplants in Bolivia and their technical characteristics. Information from existing installed capacities is derived from reports of the national energy company ENDE [17], the national dispatch agency CNDC [18], and the electric regulation agency AETN [19]. Future/planned installed capacities are extracted from the webpage of the national energy company ENDE, where information from projects under development [20] and under study [21] is available. Fuel costs are extracted from past national development plans [22] and hydroelectric plant-specific inflow information are extracted from previous studies [23].

Adaptations made

While the model's structure consists of 4 main aggregated stages, to run the entirety of the workflow, it is necessary to execute over 20 different scripts which follow a chain structure in which outputs from specific tasks are used as inputs for others. While the entirety of tasks executed by the model and their relations are complex, given the open-source characteristics of the model, it is possible to review each of them individually and modify them according to the specific requirements.

As a result of this, the creation of customized versions is possible, allowing more detailed and accurate country-specific analysis. The model created for Bolivia has modified the workflow to include and replace certain predefined values obtained from repositories with customized information, as stated before. A representation of the entire workflow followed by the model to run the case of Bolivia, including the data customization actions, is presented in Figure 1.

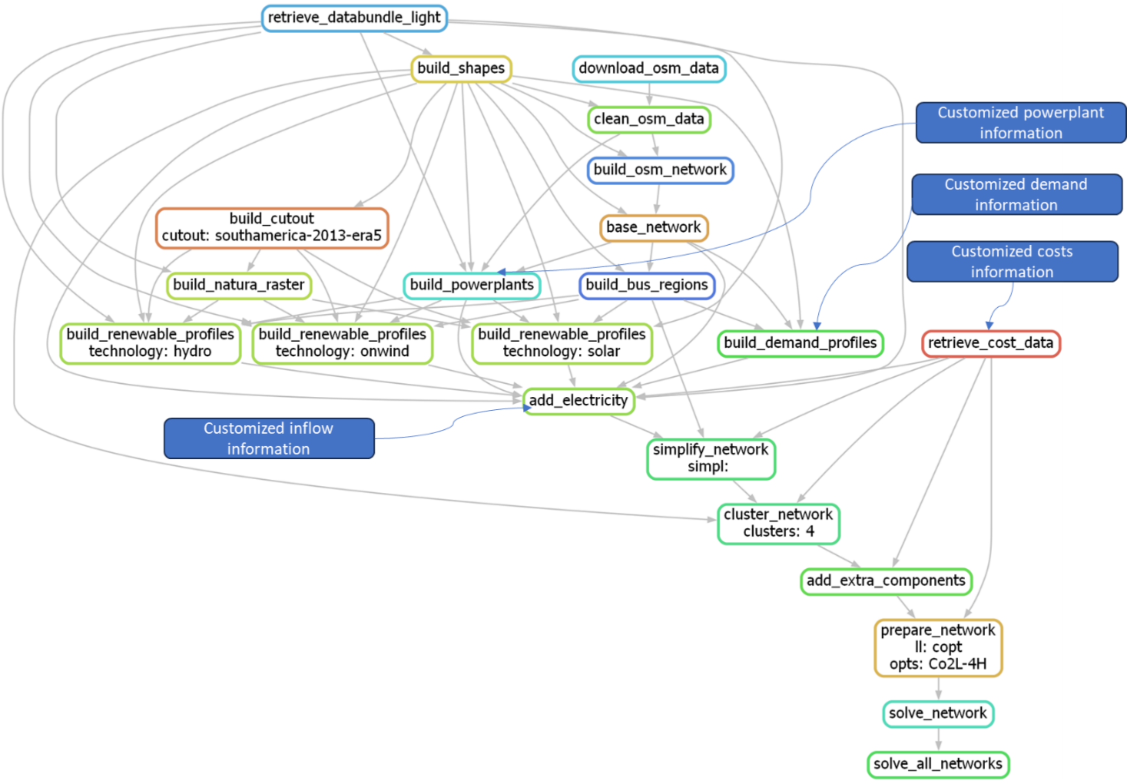

Figure 1. Adapted workflow used to simulate the Bolivian power system using PyPSA-Earth.

To comply with transparency standards and following the good practice of open-source modelling, a version control of the model and its adaptations for the Bolivian case can be found on a GitHub repository: https://github.com/carlosfv92/pypsa-earth-BO, where data files, details of changes made, modified scripts and output information are available.

CASE STUDY

This section presents the characteristics of the Bolivian power system, the characterization of hydro availability in the country, and the conditions to formulate the scenarios to be analyzed.

The Bolivian electric system

The Bolivian electric system characteristics have already been presented in previous studies to allow a proper representation of its energy consumption [7] and a fair comparison of historical data with modelled results [8]. However, to provide some context and a short summary of the electrical system's main characteristics, a detail of its behavior according to the latest national yearly statistical report is presented [24]:

- The total installed capacity of the SIN (National Interconnected System) was reported to be 3,778.28 MW, with a peak demand registered to be 1,658.13 MW.
- The total energy demand in 2022 was reported to be 10.59 TWh, of which fossil fuel-based thermal units produce 63.02%, and the rest comes from renewable technologies, mainly hydropower.
- The system has a total length of 9,747.10 km in terms of transmission lines expanded over the Bolivian territory with over a million square kilometers, which distribute the SIN into four main regions, aggregating demands of the departments they consider: Northern (La Paz and Beni), Central (Cochabamba and Oruro), South (Sucre, Potosi, and Tarija) and Oriental (Santa Cruz).

Coupled with these values, the following comments can be made about the energy system: 1) The system is predominantly composed of thermal units, both regarding installed capacity and energy produced. This was the result of a differentiated price for locally produced natural gas used in electrical generation, implemented in 1994 [25]. These conditions effectively acted as a subsidy for these plants and created an artificial competitiveness compared to renewable powerplants, which allowed them to constantly increase their share. 2) The Bolivian system currently has an excess of installed capacity that more than doubles the current electrical demand. This is a result of national efforts trying to include more efficient technologies in the mix (CCGT), as well as increasing the share of renewable powerplants in the system, consistent with its National Development Plans[26].

Hydro resources in Bolivia

In the case of hydroelectricity, this technology has played a relevant role in Bolivia in the last 25 years with a minimum participation in the installed capacity of over 25% [24], and 20% in energy produced [27]. This relevance is only expected to increase over time given that national development plans aim to increment the participation of renewable powerplants into the future [26] and to abide by international commitments [28]. As of 2020, the hydro capacity composition in Bolivia has a balanced mix between run-off-river powerplants (344 MW) and dam units (390 MM).

Regarding energy production, hydro powerplants work throughout the year with varying outputs throughout the year. Due to the characteristics of the country, located in the tropical belt of Capricorn and isolated to coastal regions, precipitation patterns over the year shift with clearly defined rainy and dry seasons [29]. This in turn has a major effect over the availability of hydro powerplants: 1) For run-off-river hydro, their outputs follow the seasonal trend of precipitations, reducing its output during dry seasons (usually between March and October); 2) For damn or reservoir hydro energy production across the year is still affected by the water availability, however, thanks to their capability of storing water during rainy seasons, outputs can be regulated and provide more energy during the dry months. Figure 2 presents a comparison of the total hydroelectric generation in the country by type of plant and the average seasonal precipitation across the country for the year 2020.

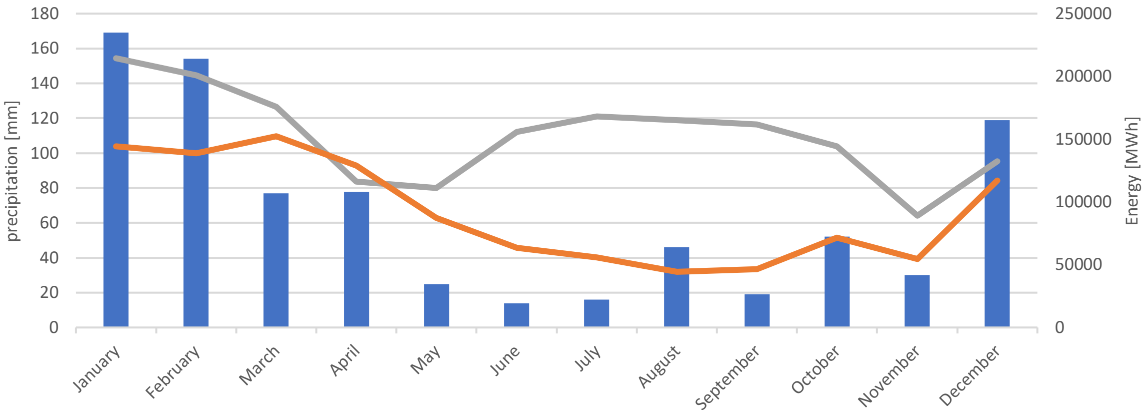

Figure 2. Average monthly precipitation and hydro energy produced in Bolivia for the year 2020, based on national statistics [30]

Scenario formulation

The nexus between water and energy presents a relevant research topic due to the issues that the energy sector will experiment because of the alteration of hydrological resources due to climate change [31]. While impacts can be different depending on the continent and regions of study, for the Bolivian case, a study from 2021 confirms that the resource availability would directly and proportionally affect the system's energy production. This study analyzed the Bolivian system of 2020 with different hydro availability scenarios and a dispatch model (Dispa-Set) [32].

In this sense, by understanding that hydro availability significantly affects the energy production in the national system, the following step would be to evaluate how it would evolve and behave under different hydro availability scenarios and answer questions such as: how the generation matrix should be composed and how the dispatch of the technologies would occur in the future. To this end, seasonal variations due to periodic events and long-term trends in rain patterns should be considered. Claim supported by studies that identified that in Latin America, and zones near Bolivia, reduced runoff values and more frequent El Niño events are expected in the future [33].

To represent the seasonal variations in the system years where El Niño events occurred are considered, assuming that years with pronounced droughts are the most relevant cases to study in the future. According to a study that assessed the drought impacts of El Niño in Bolivia, years recorded with strong impacts were 1982-1983, 1997-1998, and 2015-2016 [4]. After comparing inflow data reported for powerplants in each of these years, 2016 was selected as the referential year given its contemporary occurrence, some of the lowest historical inflows reported, and the year with the most updated information regarding existing powerplants.

To consider the long-term variation of inflows, the last 50 years of available information on average precipitation at a national scale are considered (1972-2021) [34]. While clear patterns are hard to decipher due to the fluctuating values, a linear reduction can be deduced from the data, where yearly reductions of 0.22% of the precipitation can be expected. Figure 3 shows the registered average annual precipitation for each year in the period and the linearized trend derived from these 50 years of information.

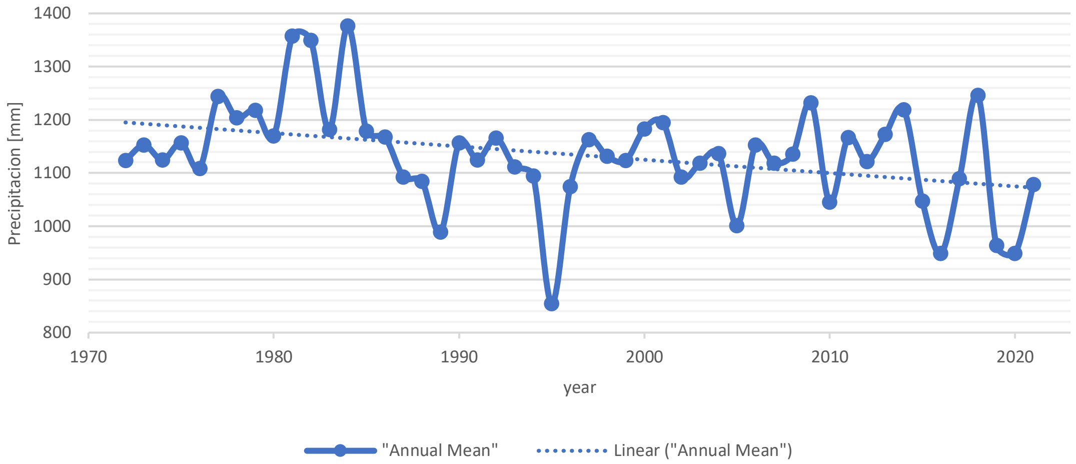

Figure 3. Average yearly precipitation registered in Bolivia for the period 1972-2021, based on data from the World Bank.

With this information, the years 2030, 2040, and 2050 are simulated, both with standard precipitation values and extreme conditions composed of more significant seasonal variations and trend-affected reductions. For the first case, 2013 has been identified as the year with the closest value to the average precipitation in the last 50 years (1133.74 mm). For the second case, historical data from 2016 is considered and then altered based on the rain availability reductions found in the regression. In both cases, aggregated demand projections under BAU conditions are considered and extracted from a previous study that analyzed future energy demands until 2050 in the country [35].

Table 1. Scenario characterization based on simulation considerations of the energy system in the future.

	2020	**2030**	**2030**	**2040**	**2040**	**2050**	**2050**	**Source**
Annual electric Demand	9.46 [TWh]	13.44 [TWh]	13.44 [TWh]	16.92 [TWh]	16.92 [TWh]	20.26 [TWh]	20.26 [TWh]	[7] [18]
Inflow data	Historical data	2013 inflows	2016 inflows	2013 inflows	2016 inflows	2013 inflows	2016 inflows	[23]
Availability reduction	None	None	3.08%	None	5.28%	None	7.48%	[34]

A compiled set of specific input data for each scenario is available in Table 1. , particularly energy demands, inflow information used, and hydro availability reductions. Constant parameters considered throughout the runs are:

- A static cost structure for future years considering a business-as-usual approach
- A four-node configuration of the network to represent the transmission system
- Isolated nodes are disregarded by the model
- Hourly resolution for data and problem formulation

- Simulations are done for the entirety of the year in each case
- Wind and solar availability information are not modified for each year
- No particular CO_2 emission goals are set
- Fossil-fuel based powerplants are allowed to work until decommissioned
- Only non-emitting technologies are considered to be extendable in the future
- Only planned hydro powerplants can be installed in the future

RESULTS

This section presents the simulation results of modelling the Bolivian electric system considering 2020 as a baseline and projections for 2030, 2040, and 2050 under different hydro availability scenarios. Results show the optimized generation mixes required to cover demands and differences in the behavior of technologies during dispatch in different seasons for each case.

Model’s considerations and results for 2020

The current version of the model can aggregate the network components of the Bolivian energy system based on the proximity of network and power infrastructure. This configuration matches ENDE's four general subsystems to represent the transmission network: Northern, Central, Southern, and Oriental subsystems. Figure 4 compares both the zones defined by the model and the aggregated sections that the energy company takes into account in the system [36]:

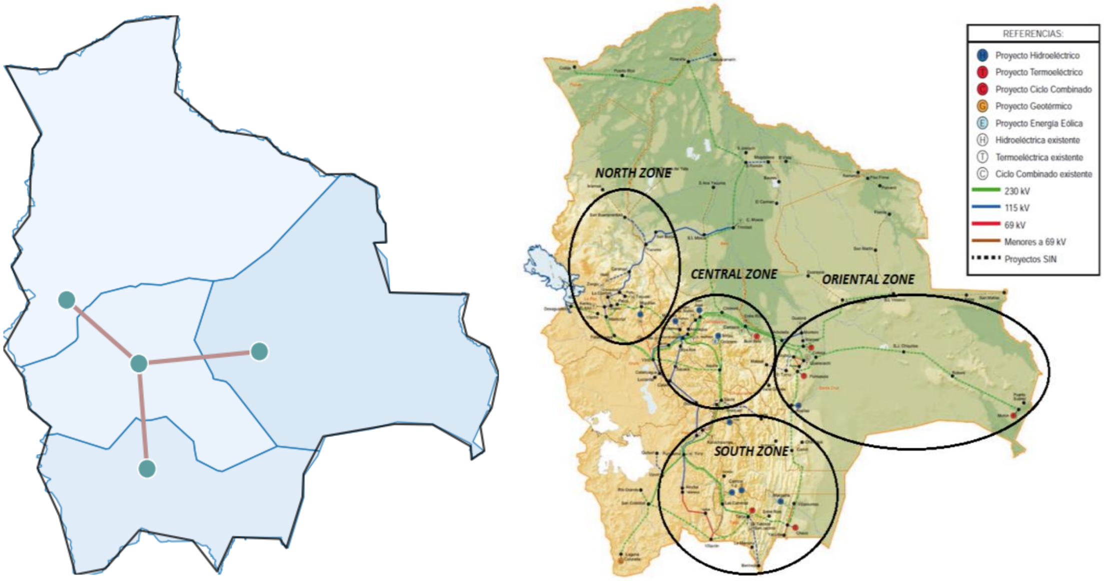

Figure 4. Aggregated zones defined by the model (left) compared to the aggregated zones considered by the transmission operators (right).

Similarly, the model’s wind and solar resources availability has proven to be consistent and adequately distributed by comparing average availability factors with published data from the Ministry of Energy and Hydrocarbons [37]. When comparing specific locations from these datasets and transforming them into average capacity factors, values provide similar results to the ones observed in existing powerplants, like is the case of San Julian (wind) and Uyuni (Solar), located in the regions with the highest potential in the country of their respective technologies. Results from plotting average capacity factors for wind and solar technologies across Bolivia are available in Figure 5.

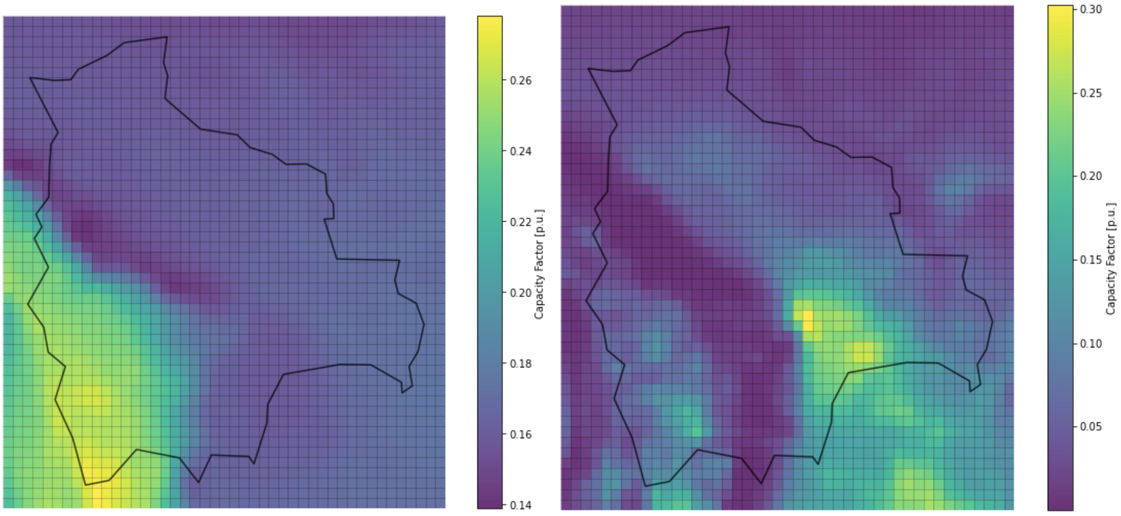

Figure 5. Standardized solar (left) and wind (right) capacity factors in Bolivia calculated based on data from Copernicus Climate Change Service.

For the case of hydro resources, due to the simplified approach used by the model to transform runoff data into operational inflows for the powerplants, results show higher discrepancies. Because of this, the registered inflows in the hydro powerplants have been obtained from previous studies [23] and processed to be fed directly into the model.

Simulation results for the year 2020 show that installed capacities are now included and coincide with historical values thanks to the adaptations made to the workflow. However, due to the optimization premises of the model and the simplification of the system, slightly different behaviors can be noticed when reviewing the energy produced by type of technology. The biggest difference is linked to the operation of thermal plants, for which Combined Cycle Gas Turbines (CCGT) are used exclusively in the model, compared to reality, where small fractions of the thermal generation are covered by Open Cycle Gas Turbines (OCGT) and Diesel (Oil) powerplants. The use of these technologies can be linked to national regulation that allows the use of cost-suboptimal technologies when operators consider that performance on areas (at distribution level) could be hindered [38].

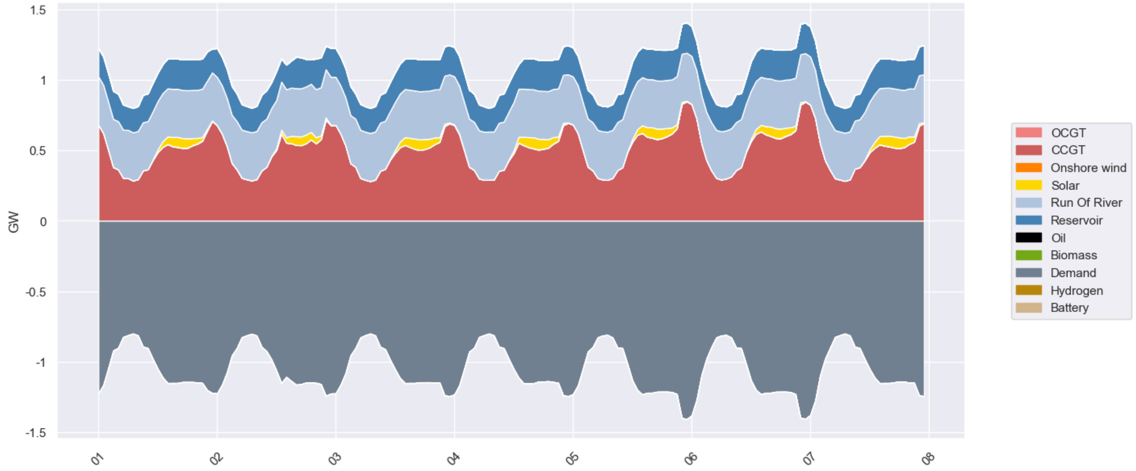

Figure 6. Hourly dispatch during the first week of 2020 according to the model.

Figure 6 shows the hourly production by technology, simulated by the model for the first week of the year. In this figure the dispatch shows that renewable technologies such as solar, wind, and hydro, both Run-off-River (RoR) and Reservoir, are used at their maximum capacities and that CCGT works as the main regulation technology in the system. This behavior is consistent with the cost characterization in the model, given that renewable technologies (aside from biomass) do not incur variable expenses linked to their operation, which is the case for fuel-based technologies.

2030 Scenarios

Simulations for 2030 include an updated customized file where powerplants are added if they are planned to be installed between 2020 and 2030 or removed if they are expected to be decommissioned before 2030. Results considering an average inflow show a similar behavior compared to 2020. However, due to the increase in demand over time, thermal plants start to increase their share of production of energy. In addition to that, new planned capacities of renewable technologies are included in the mix, particularly wind and geothermal, which are used consistently throughout the year. Finally, hydro production remains consistent throughout the year; however, due to the seasonal availability of hydro resources, RoR production reduces during the dry season.

Considering reduced inflow availabilities for the simulation of 2030, installed capacities remain equal thanks to overcapacities available in the system, despite the decommissioning of some OCGT powerplants. However, changes in the dispatch are noticeable due to the reduction of hydro resources. While RoR powerplants still work at their available capacities across the year, a substantial reduction of their available capacities is appreciated during the dry season. In the case of Reservoir units, they reduce their output during the rainy season to store water and provide more consistent support during the dry season (consistent with the system's operation in past years). Finally, while thermal units keep being the system's main energy source, their share increases during low hydro availability conditions, even making marginal use of OCGT and Biomass during peak hours.

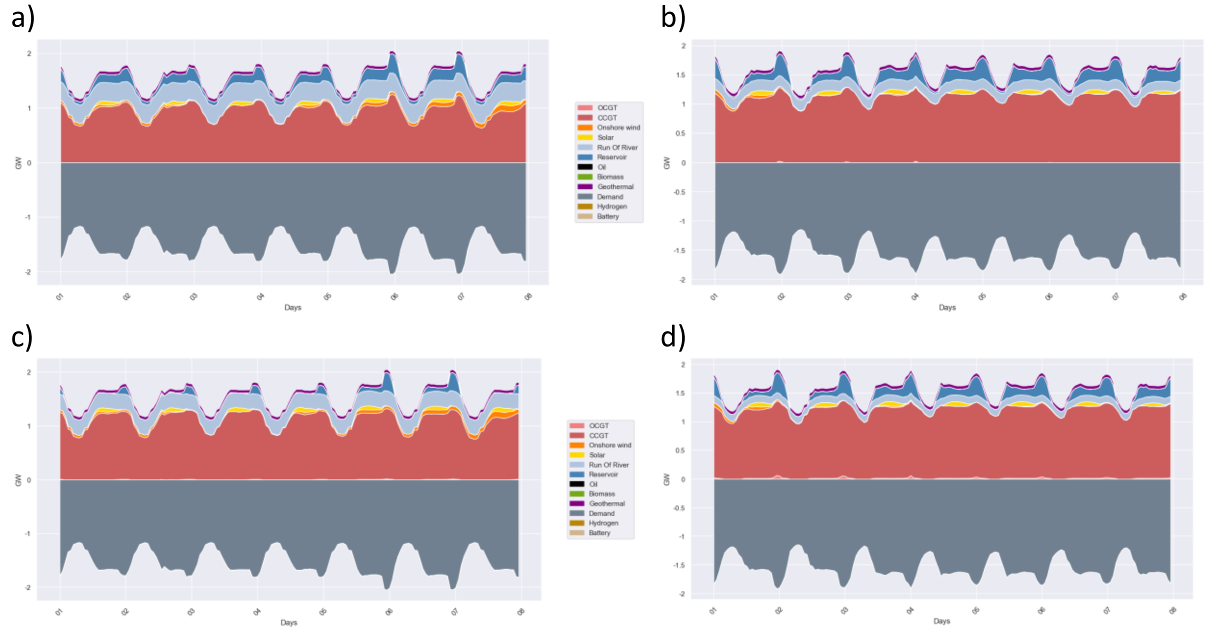

Figure 7. Hourly dispatch during the first week of January (left) and July (right) of 2030, considering average (top) and reduced (down) inflow availability.

Figure 7 shows these behaviors for 2030, both for average and low hydro availabilities, by presenting the simulated dispatch of the first week of January (rainy season) and July (dry season). Table 2. shows the brownfield capacities considered for the year (legacy powerplants), the shares of energy production by technology, and the optimized installed capacities per scenario (Average and Reduced inflows).

Table 2. Simulated installed capacities and energy production share by technology for 2030.

2030	Installed capacity (Legacy plants) [MW]	Installed capacity (Average inflows) [MW]	Installed capacity (Reduced inflows) [MW]	Energy produced (Average inflows) [%]	Energy produced (Reduced inflows) [%]
CCGT	1,363.99	1,363.99	1,363.99	68.10	75.53
OCGT	461.08	461.08	461.08	0.12	0.51
Biomass	154.58	154.58	154.58	0.01	0.01
Oil	11.74	11.74	11.74	--	--
Wind	172.34	172.34	172.34	1.51	1.51
Solar	114.90	114.90	114.90	1.47	1.46
RoR	362.53	362.53	362.53	15.48	11.66
Geothermal	55.00	55.00	55.00	3.62	3.61
Res	369.67	369.67	369.67	9.69	5.71
Total	3,065.83	3,065.83	3,065.83	100.00	100.00

2040 Scenarios

Results from 2040 scenarios show that installed capacities in the system should suffice to cover the projected energy consumption, similar to 2030. In 2040 the expected differences in the composition of the matrix are linked to additional hydro powerplants that should be finalized between 2030 and 2040 and the decommissioning of several thermal units. However, it's worth noting that while installed capacities are constant among scenarios, the differences between shares of energy produced across the year start to increase. Table 3. summarizes these results.

Table 3. Simulated installed capacities and energy production share by technology for 2040.

2040	Installed capacity (Legacy plants) [MW]	Installed capacity (Average inflows) [MW]	Installed capacity (Reduced inflows) [MW]	Energy produced (Average inflows) [%]	Energy produced (Reduced inflows) [%]
CCGT	1,363.99	1,363.99	1,363.99	61.35	67.87
OCGT	372.49	372.49	372.49	0.27	5.79
Biomass	133.94	133.94	133.94	0.01	0.01
Oil	7.44	7.44	7.44	--	--
Wind	71.54	71.54	71.54	0.44	0.44
Solar	160.10	160.10	160.10	1.64	1.64
RoR	634.74	634.74	634.74	20.86	14.65
Geothermal	55.00	55.00	55.00	2.84	2.84
Res	549.32	549.32	549.32	12.59	6.76
Total	3,348.56	3,348.56	3,348.56	100.00	100.00

Considering average hydro availability, RoR becomes a more prominent source of generation during rainy season and, while reduced, together with Reservoir units, they still provide relevant shares of energy during dry seasons. While CCGT units still represent the bigger share of energy production, their role as regulators shifts during dry seasons. During dry season CCGT units work mostly as baseloads, and the system makes use of Reservoir units and trace amounts of OCGT for regulating the system during peak hours. This behavior is similar in the cases with reduced hydro availability, with the difference being that OCGT becomes more relevant to cover for the reduced availability of RoR and Reservoir units, as shown in Figure 8.

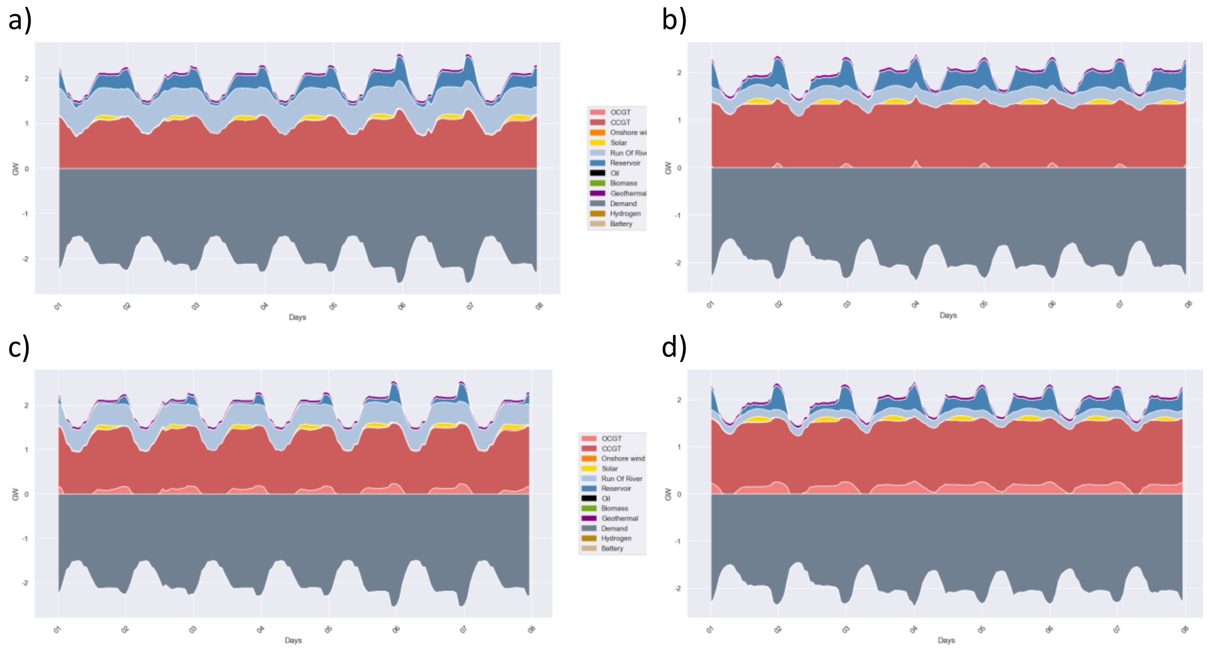

Figure 8. Hourly dispatch during the first week of January (left) and July (right) of 2040, considering average (top) and reduced (down) inflow availability.

2050 Scenarios

Unlike results from previous years, simulations run for the year 2050 show that, due to decommissioning of powerplants in the long term, the remaining installed capacity in that year shouldn't suffice to cover the expected demand. For 2050 it is expected that most of the CCGT and all OCGT powerplants will be taken out of the system and that the large majority of the legacy capacity will be composed by hydro units, with smaller shares of other technologies such as Solar, CCGT, Wind and Geothermal.

Because of this and considering the limitation on the model to expand new fossil fuel-based units, the model opts to increase the capacities of mainly Geothermal and Solar units to cover most of the baseload, as well as making use of Biomass, which was previously disregarded. Additionally, new technologies such as batteries and hydrogen are also included to help regulate dispatch during peak hours. The specific installed capacities and energy produced for each technology and scenario are available in Table 4.

Table 4. Simulated installed capacities and energy production share by technology for 2050.

2050	Installed capacity (Legacy plants) [MW]	Installed capacity (Average inflows) [MW]	Installed capacity (Reduced inflows) [MW]	Energy produced (Average inflows) [%]	Energy produced (Reduced inflows) [%]
CCGT	123.60	123.60	123.60	3.78	4.52
OCGT	--	--	--	--	--
Biomass	99.00	165.09	99.03	3.45	2.63
Oil	--	--	--	--	--
Wind	45.00	45.09	45.02	0.29	0.29
Solar	104.00	495.69	711.10	4.15	5.82
RoR	611.77	611.77	611.77	16.75	11.25
Geothermal	55.00	1,425.81	1,644.05	61.16	70.03
Res	549.32	549.32	549.32	10.42	5.46
Total generation	1,587.69	3416.37	3,783.89	100.00	100.00
Batteries	--	146.92	96.85	--	--
H2 fuel cells	--	405.37	426.42	--	--
Total storage	--	552.29	523.27	--	--

Regarding seasonal variations, in the scenario with average hydro conditions, it is expected that, for the most part, a mix of hydro, Solar, and Geothermal units should suffice to cover the energy demands in the system. However, during the dry season, the mix makes use of Biomass and CCGT to cover baseloads and a more intensive use of batteries and hydrogen to cover peak loads on a daily basis. For the scenario with reduced inflows, the behavior of using Geothermal units remains consistent, and together with RoR units, they are capable of covering most of the baseload, using storage technologies consistently across the season to cover peak loads. During dry season Reservoir and Solar capacities are used consistently in tandem to provide the demand increments during working hours and rely on storage units to cover peaks. These behaviors are exemplified in Figure 9.

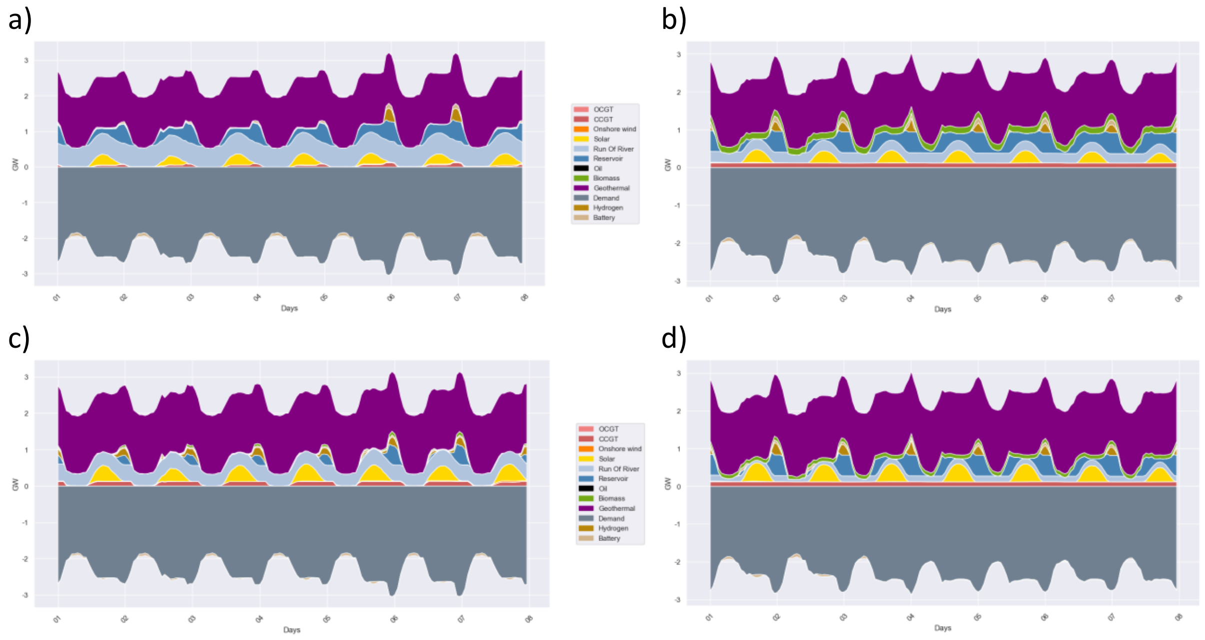

Figure 9. Hourly dispatch during the first week of January (left) and July (right) of 2050, considering average (top) and reduced (down) inflow availability.

DISCUSSION AND CONCLUSIONS

As results from scenarios run for 2030, 2040, and 2050 show, an installed capacity in the order of 3.5 GW should suffice to cover the expected increases of demand in the future of the Bolivian system under BAU conditions. While the composition of the installed capacities in the system would remain stable until 2040, it is expected that in a longer term (2050) the energy mix would vary due to the decommissioning of older powerplants that need to be replaced, using mostly Solar and Geothermal technologies to cover baseloads.

While the increase in Geothermal capacity until 2050 is extreme, the proposed capacities are relatively similar to the higher end of the geothermal potential resources estimated for Bolivia, around 1.260MW [39]. In addition to this, the proposed expansion is consistent with results from previous studies that analyzed the Bolivian system under similar conditions [7]. However, it is worth nothing that in both cases restrictive conditions are given to the models, where no more fossil fuel-based technologies are allowed to be installed and where hydro production is kept constant. Nevertheless, results should be taken cautiously due to the region's lack of experience with this technology. Complementary studies should be done to better assess the technical and economic feasibility of this scenario.

Regarding the use of hydro resources, it is possible to see that the modelled RoR and Reservoir units are heavily affected due to seasonality and long-term availability reduction, consistent with results from previous studies [32]. For the case of RoR units, while long-term reduction trends can reduce the total yearly outputs between each decade modelled, the most significant factor affecting generation is the seasonal variation. During average conditions, outputs in the dry season (July) are expected to be 49.40% lower compared to the ones in the rainy season (January), where power output values are closest to the installed capacity; This same difference increases to 68.22% in years where pronounced droughts are expected due to strong El Niño effects.

For Reservoir units, behavior becomes more complex due to the strategic nature of the technology. In years where average availability is expected, dam hydro units produce similar amounts across the year. However, when reduced availabilities are expected, Reservoir units shift their behavior and reduce the amount of energy produced during the rainy season in order to store water and provide higher yields during the dry season. During the rainy season, energy production is registered to become as low as 27.21% of the generation expected during the dry season, where power output is the highest.

During the first two decades modelled, these fluctuations are covered with the overcapacity in the system and its capability to compensate for both seasonal and long-term fluctuations. However, during 2050, the effects of the reduced availabilities of RoR and Reservoir units would derive in a system that requires additional powerplants in the order of 10.75% of the total installed capacities during average conditions to cover both base and peak loads. This additional capacity could become even higher if technologies with higher intermittence are considered to cover the base load, such as wind and solar, which in turn would require additional storage capacities to provide flexibility to the system [40]. Further studies should be done on this topic, considering the effects of using alternative mixes of renewable technologies to provide higher shares of the baseloads.

Results from this study provide a benchmark for Bolivia's future energy planning and development scenarios, simulating a security margin linked to the availability of hydrological resources. Although the scenarios presented are simple and intertwined with uncertainties due to the characteristics of climate and hydrological systems [41], these are worked around expected changes in hydro availability due to climate change in the region [33]. Additionally, results provide a precautionary approach towards planning efforts and serve as a basis to further explore the behavior of hydrological resources with complementary modelling tools.

Finally, when analyzing the evolution of the system, it is important to consider that the renewal of installed capacities must be done gradually to avoid sudden shifts of installed capacities, which would result in high investments required in short periods. To this end, transition pathways must be designed to reduce technical, economic, and logistical problems that could arise from the change of the matrix [7]. To tackle this issue, it is suggested that future studies consider additional constraints in the model in the form of limits for the maximum yearly installed capacities by technologies.

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