Graphical Abstract

Integrating Climate-Driven Hydropower Variability into Long-Term Energy Planning: A Bolivian Case Study under El Niño and La Niña Scenarios

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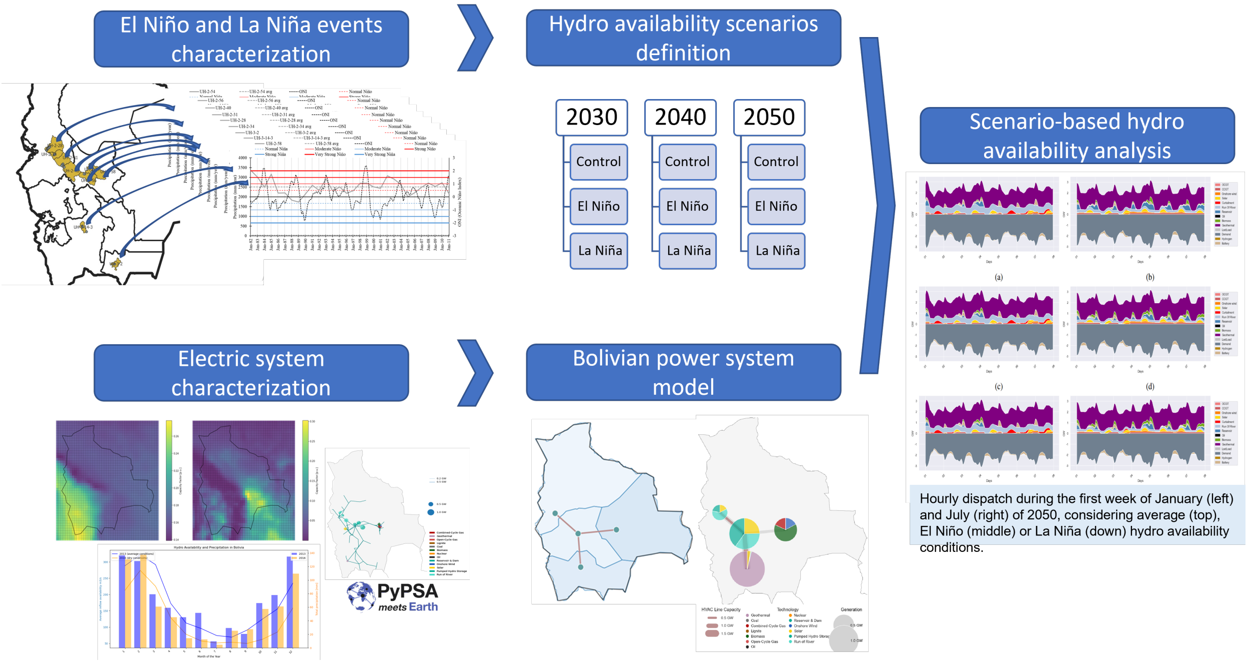

Highlights

Integrating Climate-Driven Hydropower Variability into Long-Term Energy Planning: A Bolivian Case Study under El Niño and La Niña Scenarios

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- Characterization of potential El Niño and La Niña events and their impacts on hydro resources.
- Legacy capacity can cover the effects of reduced hydro availability until 2040.
- Both El Niño and La Niña events negatively affect the potential hydropower generation in the future.
- Reduced hydro availability will affect the composition of the energy production and installed capacity mixes.
- Exploration of alternative hydro availability scenarios in the development of the Bolivian power system.

Integrating Climate-Driven Hydropower Variability into Long-Term Energy Planning: A Bolivian Case Study under El Niño and La Niña Scenarios

Carlos A. A. Fernandez Vazquez[a,b,*], Santiago Mendoza Paz[c], Adele Hannotte[b], Sergio Balderrama[a], Pedro Crespo del Granado[d] and Sylvain Quoilin[b]

[a] *Centro Universitario de Investigaciones en Energías, Universidad Mayor de San Simón (UMSS), Cochabamba, Bolivia*
[b] *Department of Aerospatial and Mechanical Engineering, Université de Liège-(ULiege), Liège, Belgium*
[c] *French National Research Institute for Sustainable Development (IRD), France*
[d] *Department of Industrial Economics and Technology Management, Faculty of Economics and Management, Norwegian University of Science and Technology (NTNU), Norway*

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ABSTRACT

As climate change effects become more evident worldwide, particularly regarding the variation of hydro resources availability, quantifying their potential impacts is critical to enable adequate adaptation strategies and facilitate planning efforts. In this sense, countries heavily reliant on hydropower must assess and integrate the implications of this variability to ensure a reliable electricity supply. Considering Bolivia as a case study, the impact of alternative hydro availability scenarios is evaluated through the analysis of extreme weather conditions associated with El Niño and La Niña events. To this end, a modeling framework is presented that combines global precipitation projections downscaled to a regional level, with which three scenarios (Control, El Niño, and La Niña) are developed for 2030, 2040, and 2050. These scenarios are later analyzed using a cost-optimization energy model tailored to Bolivia, developed with PyPSA-Earth, which allows the representation of region-specific conditions with hourly resolution, both for hydro resources availability and electrical components. Results indicate that both El Niño and La Niña events can reduce hydropower availability significantly, up to 37% compared to average years, with neither of them being strictly linked to a higher reduction of hydropower generation. Regarding the operation of the system, it is seen that Bolivia's legacy power plants can handle hydrological variability until 2040. However, the decommissioning of fossil capacity by 2050 significantly increases system vulnerability. As a result, deployment of flexible technologies such as geothermal and battery storage will play a key role in addressing both long-term capacity adequacy and short-term flexibility.

Acronyms

ENSO El Niño Southern Oscilation.

ESMs Energy System Models.

GCMs Global Climate Models.

ONI The Oceanic Niño Index.

RCP Representative Concentration Pathways.

RoR Run-of-River.

SSP Shared Socioeconomic Pathways.

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1. 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. These alterations in weather patterns (climate change) have become the world's top priority due to their influence over humanity, affecting social

*Corresponding author
caa.fernandez@uliege.be (C.A.A. Fernandez Vazquez)

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. Although the average temperature increase accelerates water evaporation, its effects in mainland and coastal regions differ. In the first case, humidity from the soil evaporates, creating drier regions. In the second case, the increment of water concentration in the atmosphere produces more intense precipitations, leading to floodings [2].

These shifts in precipitation patterns can have pronounced effects on hydropower systems, which rely on stable water availability for consistent generation. Studies from various regions have shown that climate change may either enhance or reduce hydropower potential, depending on local geography and basin-level precipitation trends. For example, while declines in hydro output are projected in western U.S. [3], increases are expected in parts of New Zealand [4]. These contrasting outcomes highlight the importance of modeling climate impacts on a regional basis and underscore the challenge of incorporating such variability into energy planning frameworks.

In addition to these changes, periodic or seasonal effects should also be considered, given their impact on water availability. In the case of South America, the El Niño Southern Oscilation (ENSO) phenomenon represents a periodical shift in the amount of warm surface seawater, its salinity, and air temperature. This process, also denominated as El Niño or La Niña events, considers the respective increment or reduction of the previously mentioned parameters, which have different registered regional impacts [5]. El Niño effects are mainly related to drought seasons in the Amazon and northeast of South America, while the coastal southeast region floodings are the most relevant effect.

Although flooding can have very harsh and immediate effects on ecosystems, human well-being, and economic activities, droughts and the systematic reduction of water availability can have more long-lasting effects at the country level. Because of this, dealing with periodical droughts requires an adaptive 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-sectoral importance of water as a resource is considered, which is used for drinking and services for the population, agricultural and livestock production, and energy production [6]. Particularly, the nexus between water and energy is a well-established research topic as hydrological-electrical frameworks have been used to analyze how the alteration of hydrological conditions (derived from climate change) would impact power generation systems [7], or energy demand behaviors and energy production of hydropower plants, particularly in regions like South Asia or Latin America [8].

Despite growing recognition of the risks posed by hydroclimatic variability and extreme events [9], most energy planning tools rely on historical data or generalized climate scenarios. This is particularly relevant as the frequency of ENSO events is expected to increase due to the effects of climate change, as reported in independent studies for El Niño [10] and La Niña [11]. In this sense, by understanding that hydro availability significantly affects energy production, the next step would be to examine how power systems could evolve under strategic conditions that may compromise their operation and expansion.

Nevertheless, currently there is a lack of integrated modeling approaches that incorporate the effects of extreme hydrological events into long-term energy system planning [12]. Furthermore, open-source frameworks that can operationalize such an integration at high spatial and temporal resolution remain limited. This study addresses these gaps by proposing a replicable methodology that combines hydro availability downscaling, ENSO-based scenario classification, and cost-optimized energy system modeling to quantify how hydrological extremes influence infrastructure planning decisions. Within this context, the Bolivian energy system represents a relevant case study: A developing country with a representative share of hydroelectric power plants in its generation mix, historically affected by both El Niño and La Niña events, and a marked regional heterogeneity.

The remainder of the study is organized into five sections: Literature review, which presents a compilation of relevant studies linking hydropower planning and climate variability; Methods, which describes the proposed modelling framework, including the hydro-availability scenario design and the cost-optimization energy model; Case study implementation, where the framework is implemented for the Bolivian power system; Results, where a revision of simulations done for selected years is compiled; Conclusions, which highlight key findings, limitations and future work.

2. Literature review

Hydropower plays a pivotal role in energy systems, particularly in the context of climate change and sustainable development. Its flexibility and dispatchability make it a key technology for systems with high shares of variable renewable energy. However, its performance is increasingly challenged by climate-related variability and long-term hydrological shifts. This section reviews the existing literature to contextualize these challenges in energy system modeling. The review is structured into three parts: (1) the role of hydropower in energy systems and sustainable development, (2) the impacts of climate change and hydro variability, and (3) modeling approaches and key research gaps related to hydro-climate-energy interactions.

2.1. Hydropower in energy systems

Hydropower, unlike other renewable technologies, is a dispatchable and flexible technology, capable of providing hourly and seasonal flexibility to its power systems. As a result, it is often considered an integral aspect in the planning of energy systems, as hydropower plants have been found to be capable of alleviating the risk of power shortages and facilitating the introduction of other renewable technologies in country-level systems such as Spain [13] and the U.S. [14]. Nevertheless, to guarantee a reliable operation of energy systems, effective management strategies are required due to hydropower's dependence on seasonal and climatic conditions, which define water availability on daily to annual scales. [15]. Because of these intrinsic characteristics and their relevance for the development of power systems worldwide, hydro availability is a recurring topic in energy planning and climate-energy literature and events [16, 17].

While several angles can be explored around this topic, some of the most common are linked to the control strategies and optimal operation of the power plants, focusing on reservoir units [18]; incorporating different resource (water) management in different types of hydro centrals to improve their reliability [19]; or the strategic role of the hydropower plays in systems reliant on renewable energy as a technology that with balanced technical, political and economic viability [20]. Nevertheless, it is important to consider that each energy model takes the representation of the hydropower component to different levels. For example, models like ReEDS, PLEXOS, and TIMES incorporate hydropower via simplified availability characterizations or seasonal profiles, which can overlook critical dynamics like ramp rates, inter-annual hydrologic variability, or dispatch constraints [21]. In contrast, models like WEAP appeared, which focus on modeling the availability of water resources and scenario development [22].

Aside from these technical scopes, it is worth noting that recent literature also emphasizes the multifaceted role of hydropower in sustainable development, encompassing environmental, social, and governance dimensions. For instance, studies focusing on Europe have empirically assessed that there is a positive relation between hydropower production and agricultural industry growth in European Union-13 emerging economies [23], as well as pollution mitigation potentials for the continent [24]. Similarly, economic growth seems to affect hydropower growth more significantly in emerging economies [25].

2.2. Climate impacts and hydro variability

Existing literature consistently shows that climate change effects are expected to directly affect the generation potential of power systems. However, because of the region-specific implications of climate change over hydro resources, impacts will vary from region to region, and their severity will depend on local conditions [26]. A good example of these location-specific effects can be seen in the United States, where climate change effects in the power system are expected to behave differently across the country [27], and where regions with high hydropower potential like California are analyzed independently [3].

Broadly speaking, climate change impacts on hydro availability can vary widely, being mild when analyzing aggregated effects at a global scale, or severe when analyzing specific regions. At a global scale, an assessment of changes in hydropower potential for alternative climatic scenarios shows a pattern of decline in subtropical dry zones and potential increases in high-latitude basins [28]. As a result, in the long term, power systems with hydropower generation located in drier regions (particularly the global south) will be expecting reductions in their water resources availability. Conversely, wetter regions, generally the global north, may experience neutral or even positive effects, with higher resource availabilities [29]. Meta-analyses and synthesis reports, including the IPCC Sixth Assessment Report (WGII, Chapter 4) [30] and a recent global review on hydropower–climate interactions [26], support these claims mentioning that tropical and subtropical systems are disproportionately vulnerable under RCP8.5, with potential generation losses exceeding 20% in some regions; and that South America in particular is expected to be negatively influenced by climate change and periodical events like the ENSO phenomenon.

Recent basin-scale studies reinforce this heterogeneity and underline the importance of spatial granularity and regional-scale modeling in climate impact assessments. For example, in the Lower Mekong Basin, climate projections suggest dry-season discharge could decline by up to 28%, with simultaneous increases in wet-season flows intensifying flood risks [31]. Similarly, a modeling study done with OSeMOSYS for the Drin River Basin in Albania reveals a projected 15–52% drop in hydro output by mid-century, implying a need for renewable scale-up in order to mitigate the reduced hydro availability [32]. To define the hydro availability conditions in future years, these and other relevant studies make use of Global Climate Models (GCMs) to derive future precipitation series, focusing on alternative Shared Socioeconomic Pathways (SSP) scenarios. For local impact analysis, the GCM's data resolution is then usually corrected using different statistical techniques. One of these focuses on downscaling methods based on Quantile Perturbation, which establishes transfer functions between large and local-scale climate [33]. While other alternatives might exist [34], it is worth mentioning that the quantile perturbation method has already been applied for the Andean region in the past and has shown robust results [35, 36].

In addition to these implications, literature also highlights the role of hydrological extremes (such as droughts, floods, and precipitation anomalies) on dispatch reliability and long-term infrastructure adequacy [37]. This is particularly relevant in systems that are expected to be impacted in the long term by climate change variations, as is the case of Ecuador [38]. As a result, the mitigation of hydrological risks derived from these deviations in standard patterns is a key aspect for hydro generators and power systems as a whole. In this sense, accounting for key hydrological events, particularly recurrent ones like El Niño or La Niña, can improve the short-term operability of hydro systems, reduce the risk of under-performance during unfavorable conditions (prolonged droughts), and plan for future investments [39]. Despite this, ENSO-related variability remains underexplored in most national energy planning frameworks, with limited cases that explore its implications in power systems. One such study explores the case of Colombia, where the periodicity of El Niño events and their impacts on hydro availability are considered to assess the effects on its electric system, finding heterogeneous impacts across its different hydropower plants [40].

2.3. Modeling approaches and research gaps

Several case studies have attempted to incorporate climate uncertainty into Energy System Models (ESMs) to address these issues [41]. For example, a study for Ethiopia analyzed the impact of its energy system on CO2 emissions in scenarios where a reduction of the reservoir capacity could be expected due to severe droughts linked to climate change, using OSeMOSYS to model the energy system [42]. On the other hand, a study for New Zealand employed TIMES as its ESM to explore the implications of climate-induced hydro variability over investment plans and costs of decarbonization of its energy system. Unlike the previous case, this study concludes that the overall impact of climate change would be positive, as hydro resources will have a yearly increase, however, seasonality variations will increase with availability being higher in winter and lower in summer [4].

Similarly, a case study for Portugal, which also used TIMES to model the country's energy system, showcases that climate change effects could result in a representative reduction of hydropower generation in the long term, leading to an increase of electricity prices [43]. In the case of Italy, OMNI-ES is used as its ESM, evaluating the effect of hydro availability in the future, considering historical years as potential scenarios. Results conclude that even if hydro capacities are expected to be stable, the variation in hydro availability can have important effects on the investments and mix of technologies used, as with reduced hydro availability, higher shares of storage are required to provide flexibility for the dispatch of non-flexible technologies such as PV [44].

Another trend in literature is that the majority of studies regarding hydro availability and power systems are focused on developed economies that have a well-established hydro potential. Conversely, developing countries that have yet to exploit their hydro power potential [45] are the ones with fewer studies available. For example, studies in South America show that climate change is expected to have relevant impacts on the future of their energy system, affecting the overall energy-security of the system (Brazil) [46], reducing the dispatchability of power plants in the long-term (Colombia) [47] and requiring additional technologies to cover for the system's uncertain behavior in the future (Ecuador) [48].

Beyond these individual cases, a synthesis of the literature reviewed is presented in Table 1. Here, studies are grouped into three main scopes, allowing for a direct comparison of findings across contexts and approaches: the role of hydropower in energy planning, the impacts of hydro availability on power systems, and the implications of climate and weather variability for planning.

Across these studies, some patterns emerge. First, most assessments use scenario-based approaches grounded in existing global climate-change scenarios like the Representative Concentration Pathways (RCP) [54] and SSP scenarios [55], that do not necessarily focus on detailed region-specific conditions. Second, ENSO-related events are rarely integrated into these scenarios despite their recognized impacts in many regions [56]. Third, the ESMs employed for the energy systems analysis tend to focus on either dispatch optimization or long-term investments, a large share of them are not open-access, and most models often oversimplify the spatial or temporal resolution, with few examples that cover all these bases [57].

Scope	Key findings	Region	Source
Hydropower role in energy planning	Hydropower provides critical hourly and seasonal flexibility, enabling higher renewable penetration and reducing risk of shortages; its representation in energy models often omits operational constraints and variability.	Spain, USA	[13, 14, 15, 21]
Hydropower role in energy planning	Strategic hydropower management and scheduling in reservoirs and mixed hydropower plant types can enhance reliability; integration of water management approaches can improve long-term system security.	Global	[18, 49, 19, 20]
Hydropower role in energy planning	Beyond technical contributions, hydropower supports broader sustainable development goals, including agricultural productivity, pollution mitigation, and economic growth, especially in emerging economies.	Europe, EU-13	[23, 50, 25]
Climate and weather drivers of hydro variability	Climate change impacts on hydro potential are region-specific: subtropical dry zones face declines, high-latitude basins may see increases; the Global South is more exposed to negative effects.	Global	[28, 51, 29]
Climate and weather drivers of hydro variability	Basin-scale impacts reveal high seasonal differences: reduced dry-season flows, increased wet-season flood risks, and major declines in annual generation for some basins.	Lower Mekong Basin, Drin River Basin	[31, 32]
Climate and weather drivers of hydro variability	Incorporating GCMs with downscaling techniques allows localized projections; Quantile Perturbation methods have proven robust in Andean contexts.	Andean region, Ecuador	[33, 52, 35, 38]
Climate and weather drivers of hydro variability	Hydrological extremes (ENSO, droughts, floods) have substantial implications for dispatch reliability and planning, but ENSO remains underrepresented in most planning frameworks.	Ecuador, Colombia	[39, 53, 36, 40]
Hydro availability sensitivity and implications in energy systems	Climate uncertainty incorporated into ESMs can reveal divergent impacts: some systems face losses in capacity and price increases, others see seasonal shifts or positive net effects.	Ethiopia, New Zealand, Portugal, Italy	[42, 4, 43, 44]
Hydro availability sensitivity and implications in energy systems	Developing countries with high shares of hydro or untapped potential face critical vulnerabilities to climate-driven hydro variability, risking energy security, flexibility, and investment stability.	Brazil, Colombia, Ecuador	[46, 41, 47, 48]

Table 1
Summary of literature on hydropower, hydro availability, and climate implications for energy planning

Based on this review, the present study aims to address these identified gaps by 1) integrating downscaled precipitation data to enable region-specific hydrological impact analysis, 2) incorporating ENSO-event classification for extreme-event scenarios definition within planning horizons, and 3) applying an open-source, spatially differentiated cost-optimization capacity expansion model to assess energy system performance under climate uncertainty in a developing country.

3. Methods

This section is structured into three components: 1) an overview of the general methodological framework; 2) the hydro availability scenario formulation framework; 3) a presentation of the selected energy model used for the analysis.

3.1. Methodological framework

This study presents a generalizable modeling framework designed to assess the impacts of hydro resource availability linked to extreme climatic events on national energy systems. The approach combines three interconnected elements: 1) Regional catchment classification based on ENSO-event impact assessment by catchment/basins; 2) Regional assessment of future hydro availability conditions based on statistical downscaling; 3) National energy system modeling and scenario analysis based on cost-optimization (PyPSA-Earth). Figure 1 presents a simplified version of the methodological process followed, showcasing a modular structure, which is replicable and adaptable to other power systems where hydropower plays a significant role and where precipitation is sensitive to spatial distribution and climatic variation.

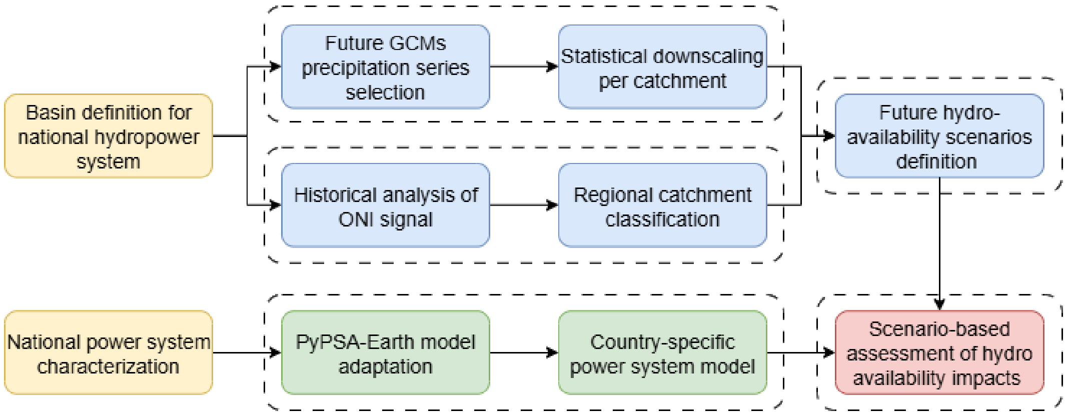


Figure 1: Proposed methodological framework for ENSO-based hydro availability impacts in power systems

3.2. Hydro-availability scenario development

To develop the potential hydro-availability scenarios, a three-stage process is followed: First, a catchment classification based on ENSO-event impacts; Second, the downscaling of future precipitation series; Third, the definition of hydro-availability resources in future scenarios

3.2.1. Regional catchment classification

To derive the connection between ENSO and energy production, the ENSO signal is analyzed together with the hydro availability conditions in each catchment where hydropower is produced. For this, a historical analysis is proposed comparing the ENSO signal, derived from The Oceanic Niño Index (ONI), obtained from the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA), with the annual precipitation expected by basin. In this way, annual precipitation values below the historical average in the basin are attributed to either El Niño/La Niña events.

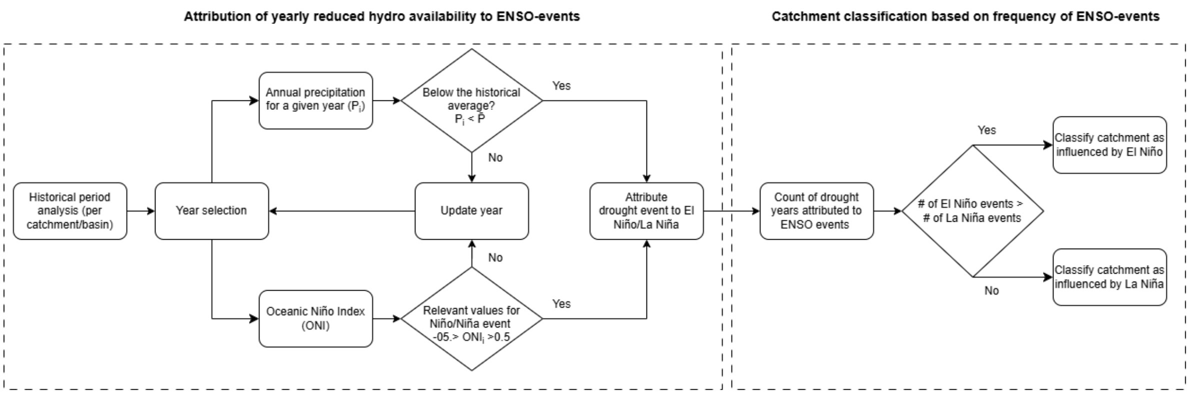


Figure 2: Flowchart analysis for the attribution of reduced precipitation availability by catchment to El Niño or La Niña events and classification based on most frequent event

Based on this attribution, considering the frequency of events that negatively affect the water availability in each catchment during the analyzed historical period and their intensity, catchments are classified as more prone to be affected by either El Niño or La Niña events. Figure 2 presents the analysis flowchart used for the ENSO-event attribution to each year and the catchment classification process based on the type of event that affects them more often.

3.2.2. Future precipitation series downscaling

To define the hydro availability conditions in future years, 13 GCMs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are used to derive future precipitation series, focusing on the SSP1-2.6 scenario [34]. For local impact analysis, the GCM's spatio-temporal resolution is corrected using the statistical downscaling method based on Quantile Perturbation, developed by Willems and Vrac [33]. This procedure is applied to the precipitation outputs of each of the GCMs series and is tailored for each of the representative basins of the region of interest.

Since the procedure delivers 13 local series for each catchment, three precipitation series with daily resolution are defined as High- (percentile 95th), Mid- (percentile 50th), and Low- (percentile 10th) availabilities, to account for the entire range of uncertainty. To select the representative series, first, different percentiles are calculated for the 13 downscaled series. Then, based on a distance minimization at a monthly scale, the downscaled series closest to the different percentiles were selected as representative.

3.2.3. ENSO-based scenarios definition

With the future precipitation availability series, reference years are defined for scenario exploration, facilitating snapshots of the evolution of the system in the long term. Each of these referential years is then represented considering the possibility of them behaving with different hydro availability conditions: As a standard year, where no El Niño or La Niña events are expected; as a year affected by an El Niño event; or as a year affected by a La Niña event.

In cases where an ENSO event is expected, basins' availabilities are affected as per their classification. To incorporate the expected precipitation differences into model-compatible inputs, historical inflows expected for each hydropower plant in the control year are adjusted proportionally, assuming a direct relation between precipitation and inflow availability.

3.3. Energy model description and adaptation

For this study, the energy system representation and capacity expansion analysis are done with PyPSA-Earth. This tool is an open-source ESM that can be used to produce power system representations at a global scale, derived from the PyPSA-Eur model [58] and the PyPSA modeling framework [59]. 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 [60].

PyPSA-Earth 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 [61].

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

$$\sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l \quad + \sum_{t} w_t \left[\sum_{n,s} t_{n,s} g_{n,s,t} + \sum_{n,s} t_{n,s} h_{n,s,t}\right] + \sum_{t} \left[suc_{n,s,t} + sdc_{n,s,t}\right] \tag{1}$$

In the objective function, capital costs are designated as c, the dispatch of generators as g, and the 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 represents the start-up costs, and sdc represents 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 [62].

To complement the objective function, sets of equations are considered to represent operational restrictions and characteristics of technologies, physical effects like power flow constraints, and load coverage in the form of energy balances, among others. The current version of PyPSA-Earth can work 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. As a result, it can provide an optimized network and capacity expansion for the defined period.

Finally, one of the most significant contributions of PyPSA-Earth compared to other ESMs is the integration of openly available data sources into its modeling framework. Among the most relevant data sources used in the model, it's possible to mention: OpenStreetMaps [63], 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 [64], an online repository from where historical climate data is retrieved, focusing specifically on resource availability such as wind speeds, solar radiation, and precipitation values; the Shared Socioeconomic Pathways [65] database, from which alternative socio-economic development scenarios and their implications for energy demands across the world are taken.

4. Case study implementation: Bolivia

This section presents the results of the application of the proposed method to the selected case study: Bolivia. This section is divided into three subsections: the presentation of the Bolivian power and hydro context, the definition of the hydro-availability scenarios, and the presentation of adaptations made to the energy model for the capacity expansion analysis.

4.1. The Bolivian power and hydro context

Bolivia is a landlocked country in the middle of South America, whose energy system is mostly dependent on fossil fuels, with its electrical system covering only 12% of its total final energy demand. According to its national statistics [66], by the year 2024 the total effective installed capacity of the SIN (National Interconnected System) was reported to be 3,787 MW, with a peak demand registered to be 1,752 MW; For the same year the total energy demand was reported to be 11.69 TWh, of which fossil fuel-based thermal units produce 66.04%, with the rest coming from renewable technologies, mainly hydropower; Regarding its transmission system, a total length of 9,747.10 km was reported in terms of transmission lines expanded over the Bolivian territory with over a million square kilometers; Additionally, its also worth mentioning that its power system is distributed into four main regions: Northern (La Paz and Beni), Central (Cochabamba and Oruro), South (Sucre, Potosi, and Tarija) and Oriental (Santa Cruz).

Three other relevant characteristics of the country's energy system include that: 1) The Bolivian power system has a rich diversification potential, as renewable resources, particularly solar, are quite high compared to global averages. Solar and Wind potentials have been estimated to be near 40 TW and 1 TW, respectively [67], taking into consideration only technically relevant regions. For geothermal, potentials are expected to be around 1,600 MW, considering identified projects and the maximum national exploitable potential [68]. For biomass, the capacity generation potential is expected to be around 700 MW, taking into account only agroindustrial residues [69]; 2) The system is predominantly composed of thermal units as a result of a differentiated price for locally produced natural gas used in electrical generation [70]. These prices effectively act as subsidies for these plants, creating artificial competitiveness compared to renewable power plants; 3) 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 power plants in the system, consistent with its National Development Plans [71].

In the case of hydropower, the technology has played a relevant role in Bolivia in the last 25 years, with a historical minimum participation in the installed capacity of 20% [66], and 20% in energy produced [72]. This relevance is only expected to increase over time, given that national development plans aim to increase the participation of renewable power plants in the future and to abide by international commitments [73]. As of 2020, the hydro capacity composition in Bolivia has a balanced mix between Run-of-River (RoR) and reservoir power plants of 732 MW. Hydropower plants work throughout the year with seasonal variations. This is due to Bolivia's location in the tropical belt of Capricorn and its landlocked geography, both of which result in precipitation patterns over the year with clearly defined rainy and dry seasons [74]. This in turn has a major effect over the operation of hydro power plants: 1) For RoR units, their outputs follow the seasonal trend of precipitations, reducing its output during dry seasons (usually between March and October); 2) For dam or reservoir units, 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 3 presents a comparison of the total hydroelectric generation in the country by type of plant and the average seasonal precipitation across the country for 2020 as a reference year.

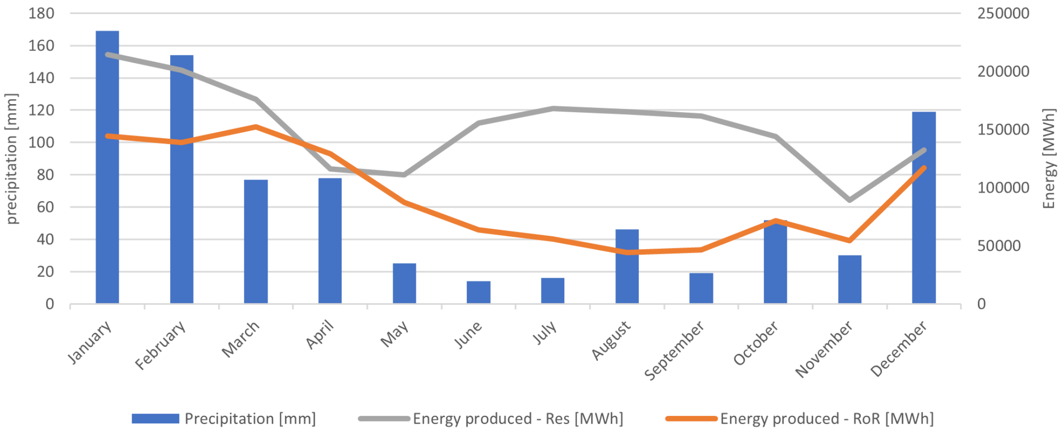


Figure 3: Average monthly precipitation and hydro energy produced in Bolivia for the referential year of 2020, based on national statistics [75]

4.2. Hydro-availability scenario formulation for the Bolivian case

While climate change impacts can be different depending on the continent and regions of study, as mentioned before, for the Bolivian case, a study from 2021 confirms that the hydro resource availability would directly and proportionally affect the system's energy production [76]. Furthermore, other studies have also linked drought impacts of El Niño events in Bolivia [77], and identified that, in Latin America, reduced runoff values and more frequent El Niño events are expected in the future [78].

Following the proposed methodology, the periodic ENSO signal is compared with the annual precipitation in each of the catchments where hydropower is produced in Bolivia. In this case, 9 catchments were identified (basins UH-2-28, UH-2-34, UH-2-31, UH-3-2, UH-2-56, UH-2-54, UH-2-58, UH-2-40, and UH-3-14-3), covering the locations of all 32 currently operating hydropower plants in the country, as shown in Figure 4.

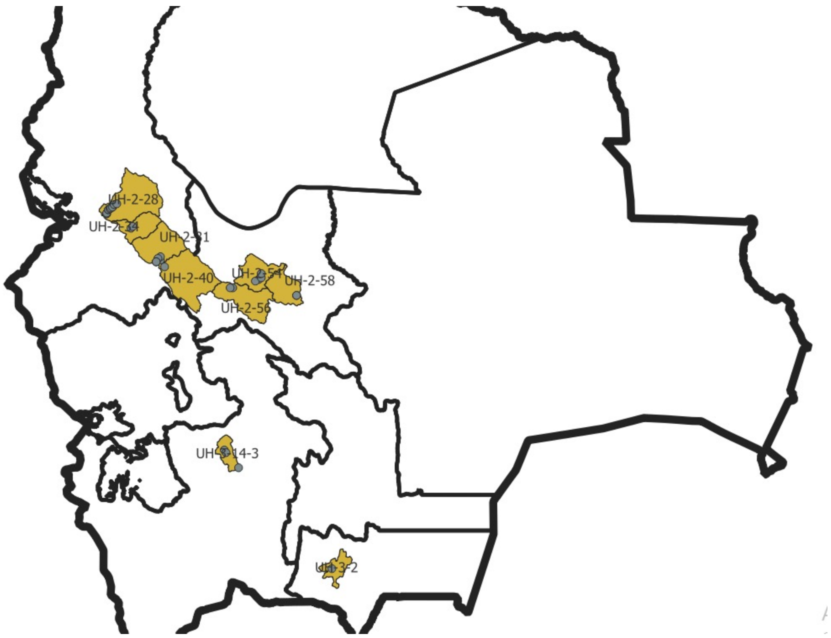


Figure 4: Distribution of currently existing hydropower plants in catchment regions in Bolivia

Scenario	1	2	3	4	5	6	7	8	9
Year	2030	2030	2030	2040	2040	2040	2050	2050	2050
Hydro availability condition	Control	El Niño	La Niña	Control	El Niño	La Niña	Control	El Niño	La Niña
Annual electric demand [TWh]	13.44	13.44	13.44	16.92	16.92	16.92	20.26	20.26	20.26
Total legacy capacity [MW][a]	2715	2715	2715	2863	2863	2863	1634	1634	1634
Planned capacity [MW][b]	350	350	350	535	535	535	–	–	–

[a] Legacy capacity values represent remaining infrastructure expected at the beginning of each year
[b] Planned capacity corresponds to planned infrastructure according to national authorities.

Table 2
Scenario characterization based on simulation considerations of the energy system in the future

The analysis for each catchment considered a comparison of historical data from 1981 to 2010. For this process, the precipitation series for each catchment is extracted from the last Bolivian Water Balance [79]. Results show that during El Niño events, basins UH-2-28, UH-2-34, UH-2-31, UH-3-2, and UH-2-56 are more likely to have drought-prone conditions. During La Niña events, basins UH-2-54 and UH-2-58 are more likely to have drought-prone conditions. Catchments UH-2-40 and UH-3-14-3 seem to not be affected by either of the events. Detailed results of the event classification for each catchment are available in the supplementary information.

To define the hydro availability conditions in future years, data from the 13 aforementioned GCMs are considered for the period 2021-2050. With these, the downscaling procedure is applied to the precipitation outputs for each of the 9 identified basins in Bolivia, and each precipitation series is assigned a percentile value based on their monthly precipitations. To better represent pessimistic cases, for each catchment, the Low-availability series (closest to the 10 percentile) is selected.

With this information, the years 2030, 2040, and 2050 are selected for scenario exploration to provide snapshots of the evolution of the system in the long term. Each of these years is then represented considering the possibility of them behaving with different hydro availability conditions: 1) as an standard year, based on the average hydro availability conditions from 2020 to work as a baseline and control year of the system's behavior; 2) as year affected by an El Niño event, where basins UH-2-28, UH-2-34, UH-2-31, UH-3-2, and UH-2-56 expect reduced hydro availability; 3) as a year affected by a La Niña event, where basins UH-2-54 and UH-2-58 expect reduced hydro availability.

For each of the referential years, the lowest annual precipitation expected in each type of event (El Niño or La Niña) within its corresponding decade is selected to represent hydro availability conditions in all hydropower plants. To incorporate the expected precipitation differences for the extreme events into model inputs, historical inflows expected for each hydropower plant in 2020 are adjusted proportionally for each scenario.

For each selected year, the annual electrical demand that needs to be covered is extracted from a country-specific study, considering Business-As-Usual (BAU) conditions for the development of the country's power system based on the historical growth trend [80]. Additionally, legacy capacities from existing power plants after their expected decommissioning and planned capacities according to national development plans are also included. Table 2 presents a compilation of the changing parameters considered for each scenario explored, including the simulated year and the type of event that will influence the hydro availability.

Regarding other characteristics, all scenarios consider most technical-economic data (i.e. investment costs, fuel prices, or efficiencies) to be constant across years in order to focus the analysis on the effects of hydro-availability conditions. Other relevant constant parameters considered throughout the scenarios are:

- A static cost structure for all technologies in the future
- A four-node configuration of the network to represent the transmission system
- Hourly resolution for data and problem formulation
- Simulations are done for the entirety of the year in each case
- Wind and solar hourly availability is kept constant in all scenarios
- No particular CO_2 emission goals are set for the power system
- Fossil-fuel-based power plants are allowed to work only until decommissioned
- Only non-emitting technologies are considered to be extendable in the future

- Only planned hydro power plants can be installed in the future

4.3. PyPSA-Earth model adaptation for the Bolivian case

While the default sources used by PyPSA-Earth provide a solid foundation to create a country-specific model, it is necessary to consider that data reliability can vary 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 identified that one of the critical discrepancies that can be found for developing countries, such as Bolivia, is linked to the representation of transmission lines and power plants already available in the country, which can lead to a limited or inaccurate representation of the power system in the country [81].

To address this issue, a set of country-specific datasets was compiled regarding the existing power plants and their technical characteristics. Information from existing installed capacities is derived from reports of the national energy company ENDE [82], the national dispatch agency CNDC [83], and the electric regulation agency AETN [66]. Future/planned installed capacities are extracted from the webpage of the national energy company ENDE, where information from projects under development [84] and under study [85] is available. Fuel costs are extracted from previous national development plans [86], and hydroelectric plant-specific inflow information is extracted from previous studies [87]. These datasets have been developed considering also previous done for the Bolivian energy system but with different modelling tools that focused on: studying the Bolivian power system and policy exploration for its decarbonization [80]; and representing the transition of its energy system in the long term with a focus on costs and dispatch adequacy [88].

To integrate these customized datasets into PyPSA-Earth, the model's base workflow, composed of over 20 different scripts that follow a complex chain structure, is modified. This is done thanks to the open-source nature of the model, which allows for a systematic review of each individual script, as well as its modification. Figure 5 illustrates a representation of the entire workflow followed by the model to run the case of Bolivia, including the data customization actions.

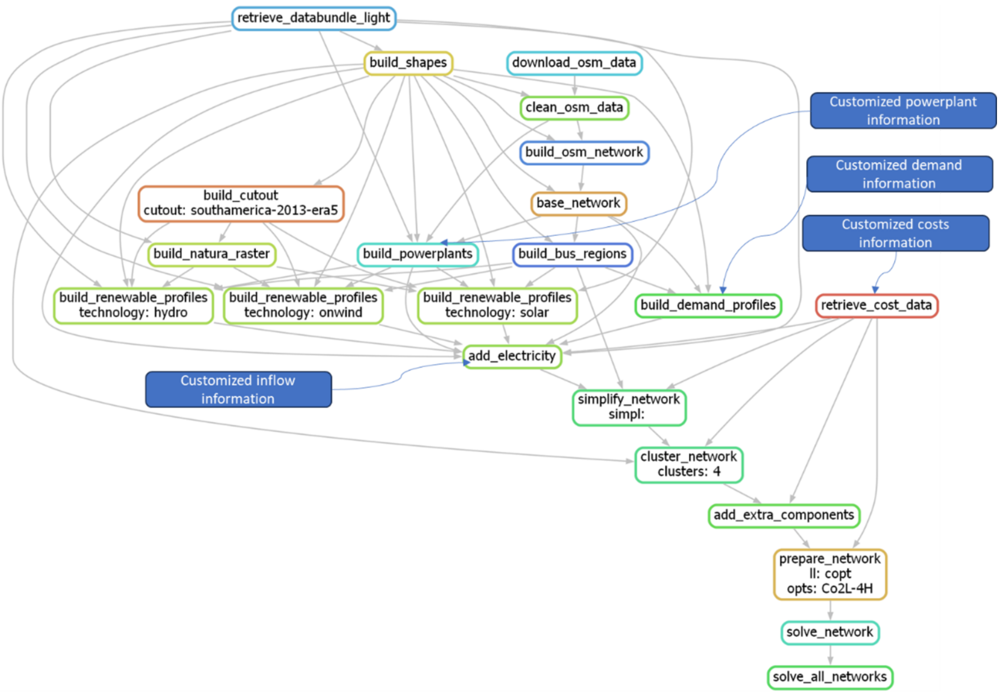
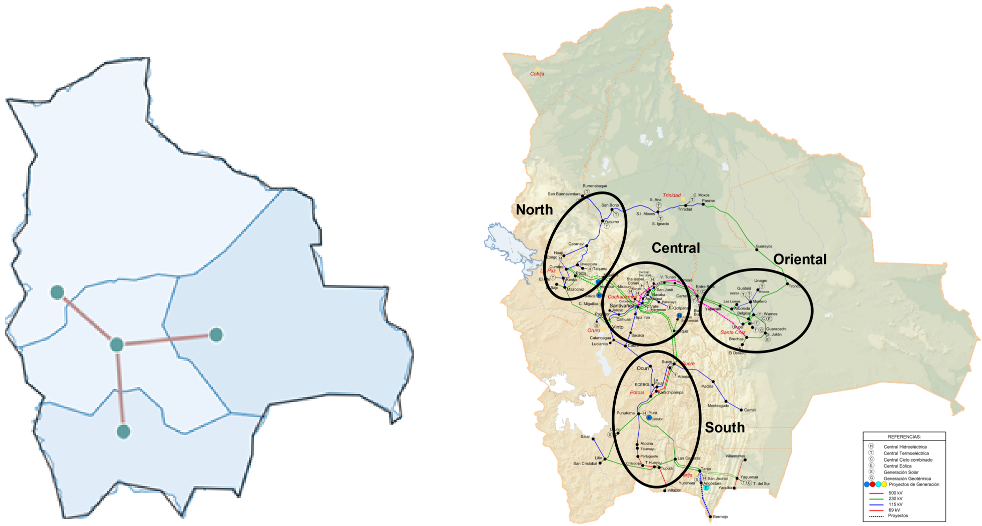


Figure 5: Adapted workflow used to simulate the Bolivian power system using PyPSA-Earth.

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. For this study, the model's four-node configuration was selected to match ENDE's four general subsystems to represent the transmission network: Northern, Central, Southern, and

Oriental subsystems. Figure 6 compares both the zones defined by the model and the aggregated sections that the energy company takes into account in the system [89].



(a) (b)

Figure 6: Aggregated zones defined by the model (left) compared to the aggregated zones considered by the transmission operators (right).

To comply with transparency standards, and following the good practice of open-source modeling, a version-controlled repository of the model, including its adaptations for the Bolivian case, can be found on a GitHub repository: PyPSA-BO, where data files, details of changes made, modified scripts, and output information are available. Additional information on the characteristics and validation of the adapted version of the model for Bolivia is available in the supplementary information section.

5. Results and discussion

This section presents the simulation results of modeling the Bolivian electric system for 2030, 2040, and 2050 under hydro availability scenarios derived from El Niño, La Niña, and control conditions, as well as relevant takeaways from the results obtained from each year.

5.1. Yearly scenario simulation results

To provide a streamlined description of results obtained for each scenario, this section presents results grouped by year, including the optimized generation mixes required to cover demands, differences in the behavior of technologies during dispatch in different seasons, and a comparison of these values for each hydro-availability condition explored.

5.1.1. 2030 Scenarios

Simulations for 2030, Figure 7, show that for the most part, the power system will behave in a similar way compared to 2020, due to the system's capacity not changing significantly. While changes in dispatch can be noticed in the system based on the hydro availability conditions it considers, the biggest discrepancies are linked to the seasonal behavior of the system, where dispatch shifts significantly between months like January (rainy season) and July (dry season). This is clearly noticeable in the hydro production from RoR plants, which reduces significantly during the dry season. Other relevant changes in 2030 compared to the previous decade are that thermal plants (particularly CCGT) start to increase their share of energy production due to the expected increase of demand. Additionally, new planned capacities of renewable technologies are included in the mix, particularly wind and geothermal, which are used consistently throughout the year.

For this particular year, differences in installed capacities between the system working under average (control) or low hydro availability (El Niño or La Niña) conditions are null, as in all cases installed capacities remain equal thanks

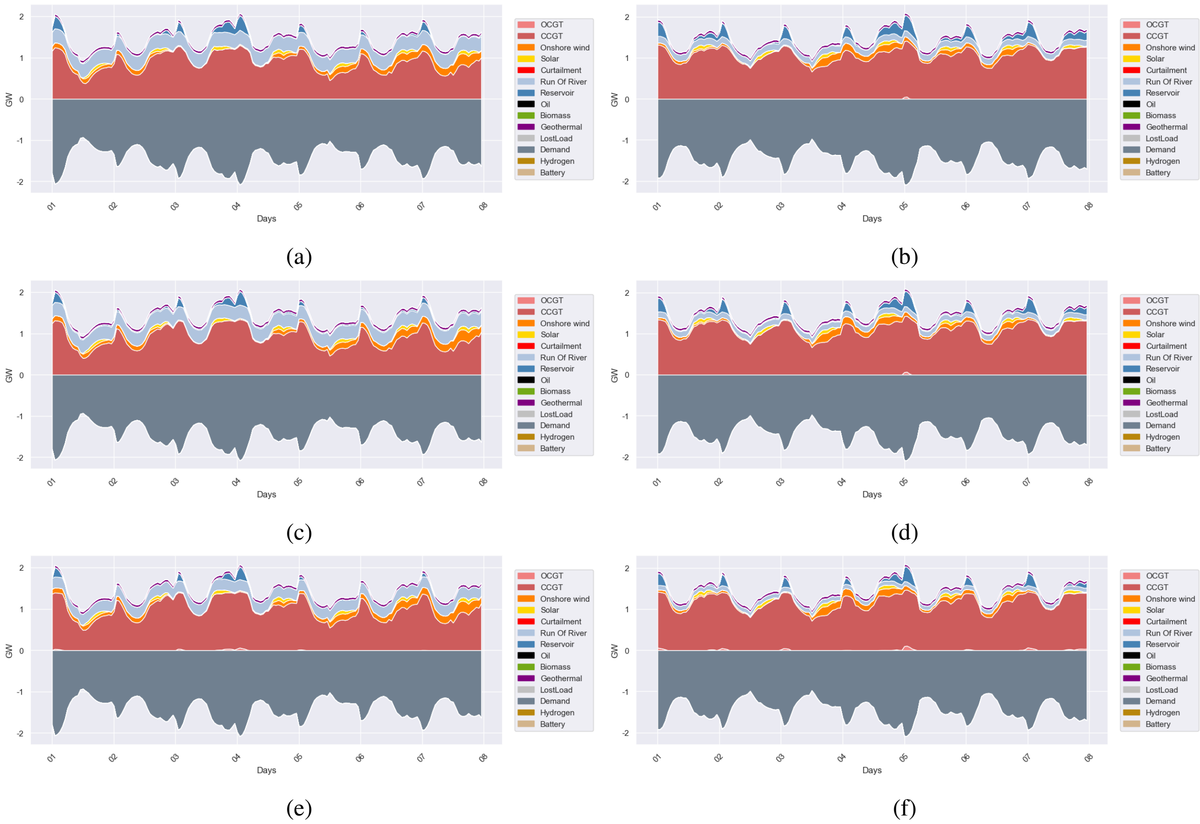


Figure 7: Hourly dispatch during the first week of January (left) and July (right) of 2030, considering average (top), El Niño (middle) or La Niña (down) hydro availability conditions.

2030	Capacity expansion [MW]			Generation share [%]		
Hydro conditions	Control	El Niño	La Niña	Control	El Niño	La Niña
CCGT	1,364.0	1,364.0	1,364.0	69.9	71.9	76.1
OCGT	461.1	461.1	461.1	–	0.1	0.2
Biomass	154.6	154.6	154.6	0.1	0.1	0.1
Oil	11.7	11.7	11.7	–	–	–
Wind	172.3	172.3	172.3	3.7	3.7	3.7
Solar	114.9	114.9	114.9	1.7	1.7	1.7
RoR	362.5	362.5	362.5	14.7	13.4	10.8
Reservoir	369.7	369.7	369.7	6.3	5.5	3.4
Geothermal	55.0	55.0	55.0	3.6	3.6	3.6
Total	3065.8	3065.8	3065.8	100	100	100

Table 3
Installed capacities and energy production shares by technology for 2030 under alternative hydro availability conditions

to overcapacity available in the system, despite the decommissioning of some OCGT power plants. Regarding dispatch, thermal units keep being the system's main energy source, with a yearly share of 69.9% under average conditions, and an increase during dry season. Compared to the potential ENSO scenarios, it can be seen that La Niña conditions would derive in more severe restrictions on the dispatch of hydro power (RoR and Reservoir), reducing its expected energy production from 21% (control) to 14.2%. Table 3 provides a more detailed comparison of the shares of energy production by technology, and the optimized installed capacities per 2030 scenario (Control, El Niño, and La Niña).

2040	Capacity expansion [MW]			Generation share [%]		
Hydro conditions	Control	El Niño	La Niña	Control	El Niño	La Niña
CCGT	1,364.0	1,364.0	1,364.0	63.0	67.1	64.3
OCGT	372.5	372.5	372.5	0.5	7.4	3.3
Biomass	133.9	133.9	133.9	0.1	0.1	0.1
Oil	7.4	7.4	7.4	–	–	–
Wind	71.5	71.5	71.5	1.1	1.1	1.1
Solar	160.1	160.1	160.1	1.9	1.9	1.9
RoR	634.7	634.7	634.7	19.8	12.4	18.4
Reservoir	549.3	549.3	549.3	8.2	4.6	5.5
Geothermal	105	105	105	5.4	5.4	5.4
Total	3398.4	3398.4	3398.4	100	100	100

Table 4
Installed capacities and energy production shares by technology for 2040 under alternative hydro availability conditions

5.1.2. 2040 Scenarios

The results of the 2040 scenarios show that the installed capacities in the system should suffice to cover projected energy consumption in all conditions, as legacy capacity and planned power plants provide a surplus of required power, similar to 2030. In 2040, the expected differences in the composition of the matrix are mostly linked to additional hydro power plants that are expected to be finalized between 2030 and 2040, and the decommissioning of several thermal units. However, while installed capacities are constant among scenarios, the differences between shares of energy produced in each case start to increase, as the system becomes more reliant on hydropower. Under average conditions, the share of hydro production increases, reaching a maximum share of 28%, compared to either of the other ENSO events. Additionally, for this year, it can be seen that El Niño is the most critical event for the system as hydro production would be the lowest in all scenarios, with 17.0% in El Niño and 23.9% with La Niña conditions. Table 4 summarizes these results.

Regarding the dispatch behavior of the system, under average hydro availability conditions, RoR becomes a much 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. For scenarios under El Niño and La Niña conditions, the dispatch behavior in the power system is similar, with the difference being that OCGT becomes more relevant to cover the reduced availability of RoR and Reservoir units, as shown in Figure 8.

5.1.3. 2050 Scenarios

Unlike results from previous years, simulations run for the year 2050 show that, due to the decommissioning of power plants in the long term, the remaining installed capacity does not suffice to cover the expected demand. By 2050, it is expected that most of the CCGT and all OCGT power plants will be taken out of the system and that the large majority of the legacy capacity in that year will be composed of 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, consistent with the narrative proposed in the SSP1-2.6 scenarios, the model opts to increase the capacities of mainly Geothermal units to cover most of the baseload, as well as making use of Biomass for peak demands. This composition provides a flexible technology mix that can replace the previous over-reliance of the system on thermal units. Additionally, in all 2050 scenarios, battery storage capacities are included to help regulate dispatch during peak hours of the future demands, with similar storage capacities ranging from 1946 MWh in La Niña conditions to 1877 MWh in average conditions. Finally, unlike previous years, in 2050, both ENSO events behave similarly, with very close hydro availability reductions expected. Between both conditions, La Niña is expected to have a slightly lower generation share (17%), which still represents a significant reduction compared to the control conditions where hydropower generation provides 22.6% of the total energy produced by the power system. The specific installed capacities and energy produced for each technology and scenario are available in Table 5.

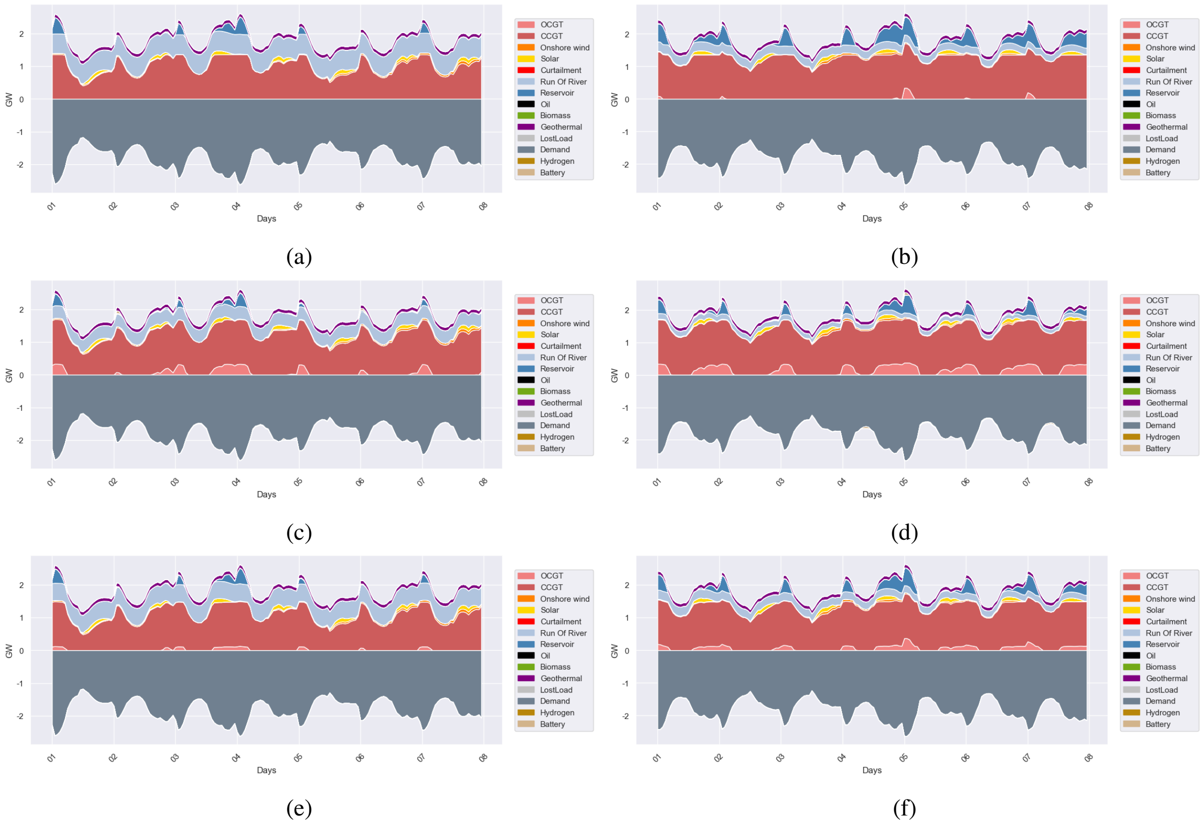


Figure 8: Hourly dispatch during the first week of January (left) and July (right) of 2040, considering average (top), El Niño (middle) or La Niña (down) hydro availability conditions.

2050	Capacity expansion [MW]			Generation share [%]		
Hydro conditions	Control	El Niño	La Niña	Control	El Niño	La Niña
CCGT	123.6	123.6	123.6	4.2	4.2	4.2
OCGT	–	–	–	–	–	–
Biomass	440.4	391.9	392.5	2.4	4.2	4.4
Oil	–	–	–	–	–	–
Wind	117.4	125.7	125.5	1.8	1.8	1.8
Solar	390.9	369.6	370.8	3.4	3.2	3.1
RoR	611.7	611.7	611.7	15.8	12.7	12.7
Reservoir	549.3	549.3	549.3	6.8	4.6	4.3
Geothermal	1536.3	1624.4	1624.1	65.6	69.3	69.5
Total	3769.6	3796.2	3797.5	100	100	100

Table 5
Installed capacities and energy production shares by technology for 2050 under alternative hydro availability conditions

Regarding seasonal variations, in the scenario with average hydro conditions, it is expected that during rainy seasons, 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 contribute to the baseload generation, and batteries to cover peak loads on a daily basis. For the ENSO-related scenarios, the behavior of the system remains consistent. However, to cover the reduced availability of RoR and Reservoir units, the system increases the dispatch of flexible technologies such as Biomass and Geothermal, and reduces the production of non-flexible technologies such as Solar and Wind. Visual representations of the seasonal behavior for each scenario are exemplified in Figure 9.

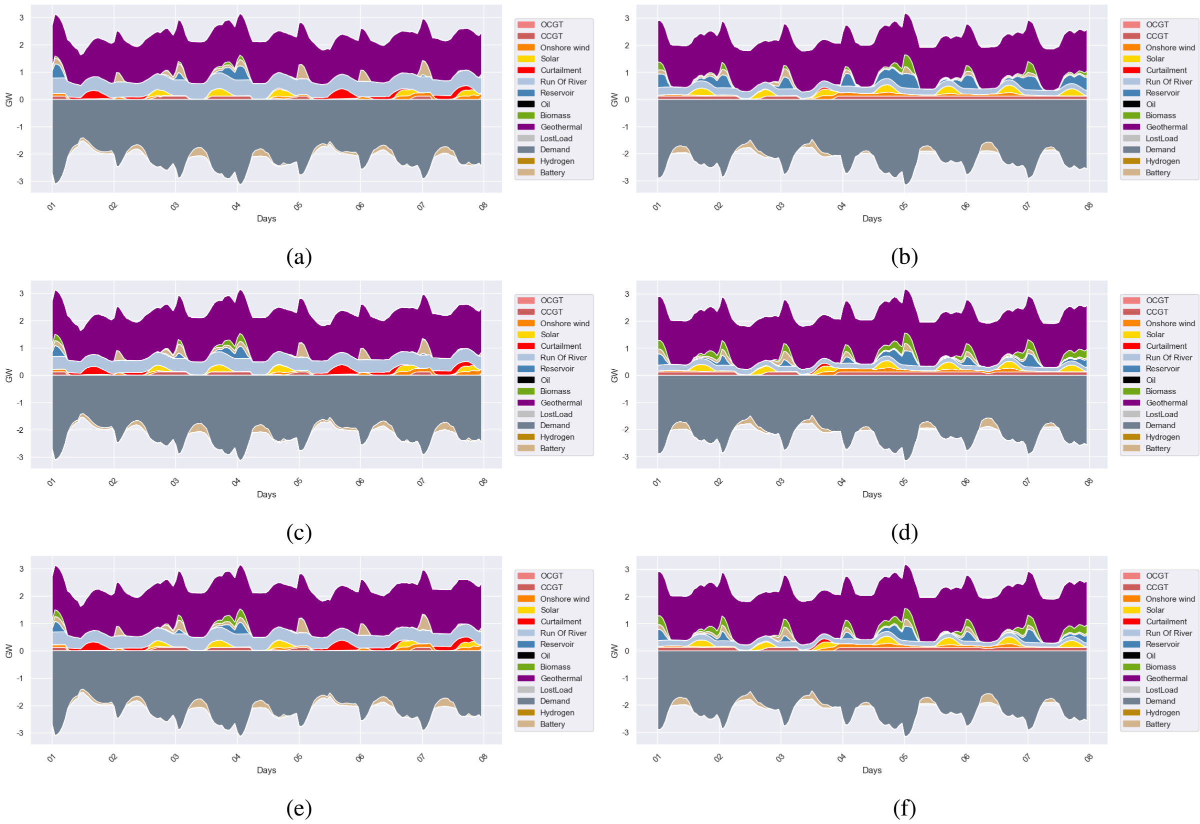


Figure 9: Hourly dispatch during the first week of January (left) and July (right) of 2050, considering average (top), El Niño (middle) or La Niña (down) hydro availability conditions.

Although the total installed capacities found in 2050 are consistent compared to the expected demands, the increase in Geothermal capacity in particular is a big outlier. Nevertheless, the proposed capacities are within the range of the highest geothermal potential resources estimated for Bolivia [68] and are consistent with results from previous studies that analyzed the Bolivian system under similar conditions [88], which stated the need for a large investment in flexible technologies in scenarios where fossil-based units cannot be expanded.

While it could be argued that a mix of solar PV and utility-scale batteries could be comparable in terms of dispatchability, the system's cost would be much higher in this case as: First, the installed capacity of solar needed would be several times the equivalent of geothermal to generate the same amount of energy in a day due to the intermittency of the solar resource; Second, the battery system would have to be large enough to provide uninterrupted dispatch during hours where no solar is available, which can be particularly challenging in periods with consecutive days with reduced solar (during rainy season for example). Given that this paper primarily focuses on the large-scale implications of hydro resources availability, a more detailed exploration of this outcome falls outside its scope. However, targeted sensitivity analyses could offer valuable insights into the underlying drivers of this resulting mix, the extent to which dispatchability and costs may become constraints, and potential strategies to address these challenges.

5.2. Hydro availability implications on the power system

The comparative analysis across scenarios in 2030, 2040, and 2050 highlights how varying levels of hydro availability resources affect both system expansion and dispatch behavior. For Bolivia in particular, during the first two decades, results from 2030 and 2040 show that fluctuations in hydro resources availability, while significant for the operation of hydropower plants, do not have a major effect over the system expansion, as dispatch is covered with the existing overcapacity of thermal units in the system (mostly CCGT and OCGT). Notably, reservoir units adjust their output in all scenarios to preserve capacity availability for peak periods, while CCGT units act as baseload generators.

However, by 2050, structural changes in the system, including the widespread decommissioning of legacy thermal units and the limitation of new deployment of these units, aligned with the SSP1-2.6 narrative, result in greater sensitivity to hydro availability. For 2050, results show that an installed capacity of 3.8 GW should suffice to cover the expected demand increases in the future of the Bolivian system under BAU expansion conditions. While capacity is not expected to increase much compared to other years, the energy mix will vary significantly as decommissioned thermal power plants are replaced using mostly planned Hydro plants and expanding Geothermal to cover base loads.

Regarding the expanded capacity composition, differences can be expected depending on the future hydro availability conditions, something consistent with results obtained for Europe, where climate change-induced conditions affect the behavior and expansion of the power system in the future [90]. For instance, comparing the 2050 Control and La Niña scenarios shows that ENSO-related conditions would prompt a 30 MW increase in total capacity. In addition to this, when hydro units are less available to complement and regulate the hourly dispatch, the main flexible technology (Geothermal) increases its capacity by 6%, and the cheapest generation technology (Solar) reduces its capacity by 5%. These discrepancies are expected to increase in the long term as the frequency and intensity of extreme events in the region grow [91], and as hydropower continues to be included in development plans, following global trends [92].

It is also worth mentioning that in this study, the expansion of geothermal is derived from its cost-effective nature (high flexibility and null fuel costs), the particular constraints considered for the scenarios analyzed (no new fossil units can be expanded), and the inability of planned RoR and reservoir plants to provide consistent seasonal regulation during low-inflow periods. However, while results can provide an idea of the growth and change magnitudes in the power generation mix, because Bolivia has limited domestic experience with geothermal power generation, the specific technology mix should be taken cautiously, as this result highlights a potential modeling–reality gap.

Consequently, these observations highlight the need to complement future modeling efforts with studies that: 1) broaden the scope of impacts of climate change in the energy system, as presented in a study for United States that implies the impact of climate in several other key areas such as demand, transmission, or other renewable sources, on top of the power system [27]; include the relations of the hydropower with other socio-economic parameters that could affect its development, such as governance indicators or economic growth [93] and; 2) consider additional scenarios that explore alternative development conditions, as it has been identified that, in cases like the European system, some divergent power system scenarios can have more substantial impacts compared to climate projections [94]. This is particularly relevant as alternative transition pathways for countries can lead to structural changes in their size and composition, with key aspects to consider being emission reduction targets, electrification rates, reductions in costs of generation technologies, etc., as shown in a study conducted for Bolivia [88].

Regarding hydro resources, it is also possible to see that RoR and Reservoir units are heavily affected by seasonality and reduced inflow availabilities expected from ENSO events. This is consistent with similar studies that also used RCP projections to simulate water availability to be later integrated in their energy models [32]. In the case of RoR units, while resource availability reductions will affect the total yearly production, the most significant factor affecting their dispatch is the seasonal variation. For example, for the year 2040, the generation shares for the Control and El Niño conditions would be 19.8% compared to 12.4% (an overall 37% reduction between scenarios). Nevertheless, when comparing the dispatch of RoR units between the dry (July) and rainy season (January), generation can be expected to be 49.40% lower (in the Control year). This same difference increases up to 68.22% in years where pronounced droughts are expected (such as El Niño in 2040). Reservoir units, while also affected by hydro availability, exhibit a more strategic behavior under alternative conditions. When average hydro availabilities are expected, these units produce similar amounts across the year. However, when reduced availabilities are expected, reservoir units reduce the amount of energy produced during the rainy season in order to store water and provide higher yields during the dry season.

Finally, while some studies have attributed El Niño events to droughts in the western part of Bolivia [77] and reduced runoff values in Latin America [78], the size of the country, its location in the middle of South America, and the distribution of its power plants make it difficult to assign a direct impact to these events. In fact, the results from this study confirm that either event (El Niño or La Niña) can result in reduced hydro resources for power generation in the country. Particularly, in 2030, conditions from La Niña would represent the largest generation losses compared to El Niño. In 2040, El Niño is expected to have the biggest reduction potential compared to La Niña. In 2050, both events would have similar negative impacts on the hydropower system.

6. Conclusions

This study highlights the critical importance of understanding the interplay between water availability and energy systems, particularly the effects driven by the ENSO phenomenon. It proposes a modular and replicable approach to integrate climate-driven hydrological variability into energy system planning, combining future downscaled precipitation data, ENSO-based scenario formulation, and energy system modeling. This methodology is then demonstrated through a national-level case study focused on Bolivia, a developing country with a hydropower-reliant generation mix and high exposure to interannual climate variability. The scenario-based assessment is conducted for 2030, 2040, and 2050, focusing on the impacts of potential variations in water availability associated with El Niño and La Niña events. To simulate the Bolivian power system, an open-source cost-optimization energy model (PyPSA-Earth) is adapted and calibrated for the country (PyPSA-BO).

Findings show that, in the short and medium term (2030–2040), Bolivia's energy system appears robust enough to handle reduced inflows thanks to its current overcapacity from thermal units. However, by 2050, the system becomes increasingly sensitive to hydrological variability. Model results suggest that the system's capacity may need strategic changes in its composition when comparing the expansion of a year under control or reduced hydro-availability conditions. Particularly, the capacity is expected to increase significantly through flexible generation and storage technologies, to buffer the effects of hydropower variability, especially considering that a large share of the generation fleet will be decommissioned by this decade. These findings also highlight the need to complement future modeling efforts with feasibility and sensitivity assessments, particularly when future investments depend on technologies with limited domestic experience, such as geothermal in Bolivia. This can be further expanded with the inclusion of complementary scenarios that explore alternative transition pathways, cost-reduction trends, changes in efficiency of technologies, fuel availability constraints, or more strict expansion limits for specific technologies, alongside climate-induced variability.

In terms of hydro dispatch, the analysis confirms that Run-of-River units are most affected by seasonal droughts, while reservoir-based generation becomes increasingly strategic under constrained inflow conditions in extreme events. Additionally, the analysis of the hydro availability scenarios also shows that, while either El Niño or La Niña events can negatively impact hydro-availability, no single ENSO event consistently leads to the worst-case scenario across decades. Instead, their impact is regionally distributed and varies over time, reinforcing the need for high-resolution spatial and temporal modeling when planning hydropower-dependent systems.

Finally, while this study is limited to the analysis of 3 referential years per decade under BAU development conditions, results offer a first step toward integrating extreme event analysis into mainstream energy modeling and planning. While uncertainties remain, particularly regarding inflow projections, cost structures, and future transition pathways, this framework enables a precautionary approach to long-term planning efforts and serves as a basis to further explore the behavior of hydrological resources. In this sense, future work should focus on exploring the accumulated effect of several ENSO-events in the development pathways of a country instead of only focusing on referential years per decade; developing multi-scenario comparisons to assess how and to what extent different modeling choices can affect energy system planning under climate uncertainty; and integrating socio-economic variables in energy models to better represent the complexity of impacts of hydropower availability in national-level energy systems.

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CRediT authorship contribution statement

Carlos A. A. Fernandez Vazquez: Conceptualization, Methodology, Software, Visualization, Data Curation, Formal analysis, Investigation, Writing- Original draft preparation. **Santiago Mendoza Paz:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing- Original draft preparation. **Adele Hannotte:** Software, Data curation, Validation, Writing- Original draft preparation. **Sergio Balderrama:** Validation, Writing- Original draft preparation. **Pedro Crespo del Granado:** Methodology, Software, Supervision, Funding acquisition, Writing- Original draft preparation. **Sylvain Quoilin:** Methodology, Software, Supervision, Funding acquisition, Writing- Original draft preparation.

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