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University of Liege

Faculty of Applied Sciences

Contribution to the definition of long-term energy transition scenarios in Bolivia

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Master's thesis completed in order to obtain the degree of
Master in Electromechanical Engineering
By Adèle Hannotte

Academic year 2022-2023

Author:
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Academic Year 2022-2023

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Abstract

In the context of worldwide efforts to fight climate change, this master thesis addresses the need for developing countries to enhance their energy modelling capabilities for a comprehensive understanding of potential future scenarios. By using the PyPSA-Earth Modeling framework, this study focuses on Bolivia's energy transition. The goal is to bridge a research gap in energy modelling by using an open-source model that facilitates long-term, high-resolution analyses.

The thesis has two main parts. At first, it adjusts the model to Bolivia's context, with a special emphasis on hydropower, a very important energy source in the country's energy landscape. After this first step, scenarios considering factors like decommissioning of power plants, fluctuations in gas prices, and CO_2 emissions limitations are created. The research underscores the influence of current governmental policies on Bolivia's energy composition, which heavily relies on gas. Moreover, it forecasts the potential outcomes of future CO_2 restrictions, revealing opportunities in biomass and solar energy. The findings highlight that the enforcement of CO_2 limitations might lead to elevated electricity production costs, necessitating the exploration of energy storage solutions to manage the variability of sources. While these outcomes yield favorable effects on the climate, they simultaneously have the potential to result in unfavorable impacts on electricity prices. Thus, these solutions might not be financially viable without government policies that support the subsidization of renewable energy.

Furthermore, the study addresses the impact of global warming on the energy sector through a scenario analysis involving changing inflow patterns linked to decreasing global precipitation trends. This scenario underscores the need for strategic management of hydropower resources, advocating the use of Run-of-River (ROR) plants during rainy seasons and reservoir types during dry seasons. This approach optimizes energy production while mitigating the effects of reduced inflows.

Acknowledgments

I would like to express my heartfelt gratitude to all those who have contributed to the completion of this master's thesis, making this journey a truly enriching experience.

First and foremost, I would like to thank particularly Carlos Fernandez Vazquez that guided me, shared his knowledge and supported me from the beginning to the end of this thesis. Thank you also for reading this thesis and giving me your feedback so accurately.

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Finally, my deepest thanks are reserved for my family and closest friends, especially those I have met during my five years of study. Your support and motivation have been so important to my academic journey, and I am deeply appreciative of your presence in my life.

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Acronyms

BAU	Business As Usual
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CN	Carbon Neutrality
EED	Electrification of Energy Demands
EEM	Energy Efficiency Measures
ENDE	Empresa Nacional de Electricidad
FOM	Fixed Operation and Maintenance
GDP	Gross Domestic Product
HVAC	High Voltage Alternating Current
OCGT	Open Cycle Gas Turbine
OSeMOSYS	Open Source Energy Modelling System
PEEP	Plan Eléctrico del Estado Plurinacional de Bolivia
POES	Plan Optimo De Expansion Del Sistema Interconectado Nacional
PV	photovoltaics
PyPSA	Python for Power System Analysis
PyPSA-Earth	Python for Power System Analysis - Earth
RoR	Run of River
SDDP	Stochastic Dual Dynamic Programming
SIN	Sistema Interconectado Nacional
STI	Sistema Troncal Interconectado
UNFCCC	United Nations Framework Convention on Climate Change
VOM	Variable Operation and Maintenance

Chapter 1

Introduction

Global warming, driven by the increase in greenhouse gas emissions, has emerged as one of the most pressing challenges of our time. In response, countries around the world are implementing policies and strategies to mitigate and adapt to the impacts of climate change. Mitigating climate changes requires a concerted global effort, as emphasized by the Paris Agreement signed in 2015. This international accord aims to limit global warming below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 degrees Celsius. In line with this, the transition to zero-carbon solutions has accelerated significantly, particularly in sectors accounting for about 25% of global emissions. This trend is particularly marked in the electricity and transportation sectors [1].

As a developing country, Bolivia faces unique challenges in the context of climate change. Its growing population and expanding economy contribute to an increasing demand for energy, particularly for electricity, resulting in higher CO_2 emissions. From 1990 to 2021, Bolivian power production experienced significant growth, with an increase from 2.4 TWh to approximately 10.9 TWh [2]. The raising electricity demand is depicted in Figure 1.1. Analysis of the depicted data reveals that the residential sector accounted for the largest portion of the demand, with approximately 40%. Following closely behind, both the commercial and industrial sectors shared a significant portion, each representing around 25% of the total demand.

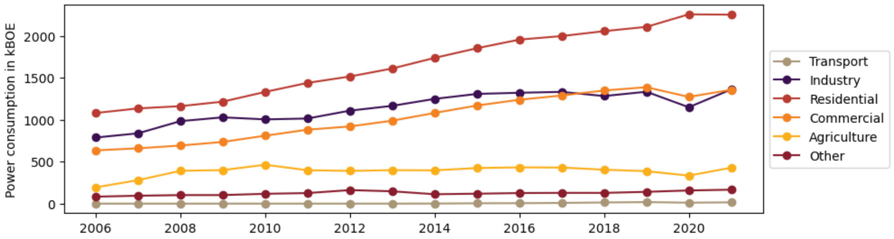


Figure 1.1: Evolution of the electricity demand per sector for the years 2006-2021.

Source: Illustration (Ritzkowsky X., 2023) based on [2].

Bolivia's electricity generation landscape

Bolivia's current electricity generation heavily relies on fossil fuels, primarily natural gas, which constituted around 63.3% of the country's electricity mix in 2020 [3]. This heavy reliance on natural gas is influenced by the government's emphasis on low gas prices (less than a quarter of the international market value of natural gas), creating a cost advantage and driving cheap energy production [4].

Despite this reliance on fossil fuels, Bolivia possesses significant untapped potential in renewable energy resources. With abundant solar radiation throughout the year, the country is well-suited for solar power generation. Additionally, Bolivia has significant hydropower potential due to its various river systems. The hydropower potential in Bolivia has the capacity to generate approximately 178 TWh of energy annually which represents about 18 times the Bolivian demand [5].

While this renewable potential holds promise for greener and more sustainable energy production, Bolivia's energy journey is a complex interplay shaped by historical trends, policy choices, and global shifts in energy dynamics. Section 2.2.1 elaborates on how hydropower potential was initially harnessed, with hydropower production accounting for about 70% of the electricity mix in 1994 and subsequently expanding through the creation of new hydropower facilities. However, the implementation of government-regulated gas opportunity prices has tempered these efforts in hydropower expansion, resulting in a proportion about 30% of the electricity mix in 2020. But more recently, Bolivia's commitment to addressing climate change has materialized through its participation in the Paris Agreement on April 22, 2016. This commitment translates into strategies aimed at mitigating greenhouse gas emissions such as the installation of new hydropower plant.

Energy modelling challenges

The oscillation between fossil fuel dominance and the potential of renewables, coupled with the intricate interplay of energy demand and supply, underscores the critical need for robust long-term energy transition scenarios. However, prevailing models designed for industrialized countries inadequately account for the unique operational nuances and data limitations encountered by developing countries like Bolivia.

Previous research on the Bolivian case has employed various models, each with distinct features and objectives (outlined in Section 3.1.2). Nevertheless, issues of transparency have at times hindered the reproducibility of these studies. Furthermore, there are gaps in predictive areas and unexplored aspects within the existing research. To bridge these gaps, this study employs the Python for Power System Analysis - Earth (PyPSA-Earth) model, offering numerous advantages (described in Section 3.2.1) and affording a comprehensive representation of Bolivia's energy system, thereby facilitating future scenario analyses.

1.1 Scope of this work and limitations

This thesis aims to simulate the Bolivian energy system on the Open Source energy modelling tool PyPSA-Earth [6]. The simulation aims to create scenarios that investigate the effects of parameter changes on future energy projections in Bolivia. Specifically, the scenarios will focus on analyzing the impact of climate change factors on hydropower production.

Before creating scenarios, the model needs to be adjusted and tested for the Bolivian case. Although PyPSA-Earth has been tested successfully in Africa and other country-specific cases, its applicability to Bolivia has not been fully explored. Therefore, a significant part of this thesis will focus on adjusting and validating the PyPSA-Earth model for the Bolivian energy system. The successful modification and validation of PyPSA-Earth for the Bolivian case will provide a robust and reliable tool for creating scenarios. The scenarios developed in this thesis will help to identify critical factors that could impact the future of the Bolivian energy system and inform policy decisions that promote a sustainable energy transition.

Overall, this thesis aims to make a significant contribution to the understanding of the potential for renewable energy in Bolivia and to the global effort to mitigate the impact of climate change through sustainable energy solutions.

Research gap

While previous researches have contributed valuable insights and guided policy decisions within the field of Bolivian energy systems, some gaps in knowledge remain. By employing the PyPSA-Earth framework, these gaps can be effectively addressed

First of all, PyPSA-Earth, as an investment model, incorporates a capacity expenditure feature that enables the study of capacity expansion across energy sources to meet future demand. This feature provides policymakers with essential information for investment decisions regarding new generation units.

Additionally, PyPSA-Earth's grid representation allows for precise spatial analysis, considering constraints such as line overloading, thereby enhancing the accuracy and realism of modelling results [7],[6]. Moreover, PyPSA-Earth combines short-term and long-term studies, using timeseries analysis to assess variations in energy generation and demand patterns, identify peak load periods, and evaluate system responsiveness to changing conditions. Furthermore, the long-term period of study enables the exploration of seasonal variations and the impact of changing climatic conditions on renewable energy generation as well as the creation of scenarios for the future years.

The advantages of PyPSA-Earth, make it a powerful tool for energy system modelling and decision-making and are further discussed in detail in Section 3.2.1.

Thesis contributions and objectives

This section outlines the key contributions made by this work, which are summarized as follows:

- **Tailoring PyPSA-Earth model to the Bolivian context:** A central aim is to enhance the representation of Bolivia's power system by adjusting the cutting-edge PyPSA-Earth model. This endeavor bridges a crucial gap in energy modelling for the country. The tailoring process involves integrating pertinent data such as generator capacity, historical hydropower inflow figures, and price adjustments. Validation against historical data and existing studies solidifies the model's accuracy and reliability for the Bolivian context.

- **Improvement of the PyPSA-Earth model:** throughout the research, various issues and challenges encountered in the PyPSA-Earth model are addressed and resolved. These adjustments will enhance the model's accuracy, reliability, and applicability to the Bolivian power system. By identifying and rectifying any existing limitations, the improved model will provide more robust and insightful results for power system analysis in Bolivia.

- **Development of an open-source model for the Bolivian power system:** using the PyPSA-Earth framework offers a unique advantage, as the resultant work is inherently open-source. This fosters enhanced accessibility and the potential for replication among fellow researchers. Through transparent sharing of the model's source code and data, collaborative opportunities are cultivated, facilitating validation and deeper investigation into Bolivia's energy landscape. The dedicated GitHub repository, accessible via `https://github.com/carlosfv92/pypsa-earth-BO`, serves as a central repository housing files, records of script modifications, and comprehensive guidelines for executing the Bolivian case.

- **Scenario construction for future projections** Following the successful adaptation of the PyPSA-Earth model to Bolivia's context, a series of scenarios are crafted to forecast the energy landscape's evolution. By considering diverse demand evolution patterns, these scenarios empower analyses of optimal scheduling and the efficient utilization of power generation units within Bolivia's grid. This analysis will provide valuable insights into efficient dispatch strategies, renewable energy penetration levels, and their economic implications. Additionally, the model's capacity expenditure feature allows for the analysis of capacity expansion across different energy sources, providing information on potential investments in new units to meet future demand. Moreover, the study explores the influence of climate change on hydroelectricity production by simulating an extreme scenario featuring reduced precipitation, this provide insight into how reduced hydropower production could influence the composition of the future energy mix.

Overall, these objectives collectively contribute to a comprehensive understanding of Bolivia's renewable energy prospects, leveraging model adaptation, refinement, power system analysis, and climate change assessment. This multifaceted research endeavor equips policymakers, researchers, and industry stakeholders with valuable tools and insights to shape a sustainable energy trajectory for Bolivia's future.

Limitations

In this research, some limitations and challenges need to be acknowledged:

- **Model Adjustment Challenges:** As the model is still relatively new, there may be issues and limitations that need to be addressed before conducting simulations, some of which cannot be done by non-developers.
- **Dynamic Nature of the Model:** Because of its recent nature, the PyPSA-Earth model and its associated repositories are continuously evolving and being updated. Keeping the model up to date may require additional time and effort.
- **Data Availability:** As for all developing countries, the availability of reliable and comprehensive data for the Bolivian power system can be a limitation. Efforts will be made to use the most accurate data sources and ensure data quality.
- **Uncertainties in Climate Change Impact Scenarios:** Predicting the behavior of natural data for future climate conditions involves inherent uncertainties. Climate change impact scenarios are subject to various factors and contains assumptions, so accurately projecting future outcomes can be challenging.

1.2 Thesis Structure

This thesis is structured into three main parts:

1. **Context Establishment:**
    - In Chapter 2, a comprehensive context is established for a thorough understanding of the thesis. This chapter delves into Bolivia's background, encompassing demographic, geographic, and socio-economic aspects. It also covers historical energy demand and production trends and explores the country's potential for renewable energy sources.
    - Chapter 3 offers an exploration of the energy modelling landscape. It covers previous attempts at modeling Bolivia's energy system and subsequently provides a detailed exposition of the PyPSA-Earth model.
2. **Modelling and Adjustment:**
    - Chapter 4 outlines the initial run of the PyPSA-Earth model for the Bolivian case, highlighting encountered issues that underscore the necessity for model customization. Specific focus is given to challenges in modelling hydropower.

  - Chapter 5 elaborates on the process of tailoring the PyPSA-Earth model to the Bolivian context, detailing the necessary adjustments made.
  - In Chapter 6, the validation of the customized model is undertaken through a comparison with historical data, validating its accuracy.

3. **Scenario Creation and Analysis:**
  - Finally, the tailored model's capabilities enable the creation and analysis of scenarios, covered in Chapter 7. These scenarios offer insights into potential future energy trajectories for Bolivia.

Overall, this thesis is meticulously structured to provide a comprehensive exploration of Bolivia's energy landscape, encompassing its context, modelling approaches, customization, validation, and consequential scenario analyses.

Chapter 2

Background

In this chapter, a comprehensive context is established, encompassing demographic, geographic, and socio-economic aspects. It also delves into historical energy demand and production trends in Bolivia, and explores the country's potential for renewable energy sources.

2.1 Demographic, geographic and socio-economic situation of Bolivia

Bolivia, situated in west-central South America, is a landlocked country known for its diverse geography and socio-economic characteristics. Bolivia covers a total area of 1,098,581 km^2, spanning approximately 35 times the land area of Belgium. Despite its vast territory, Bolivia has a population size similar to the one of Belgium, with approximately 12 million people. This striking contrast between land area and population size highlights the relatively low density of inhabitants per square kilometer in Bolivia. The sparse distribution of inhabitants in Bolivia can be attributed to various factors, notably the diverse and challenging terrains across the country. In the western region, Bolivia includes highly mountainous terrain, part of it being the vast Altiplano plateau, which contains the Andes mountain range. In contrast, the northern regions consist of more tropical areas, including parts of the Amazon rainforest. Beside this, socio-economic factors, such as limited access to essential services and infrastructure, contribute to the distribution and density of the population throughout the country [8].

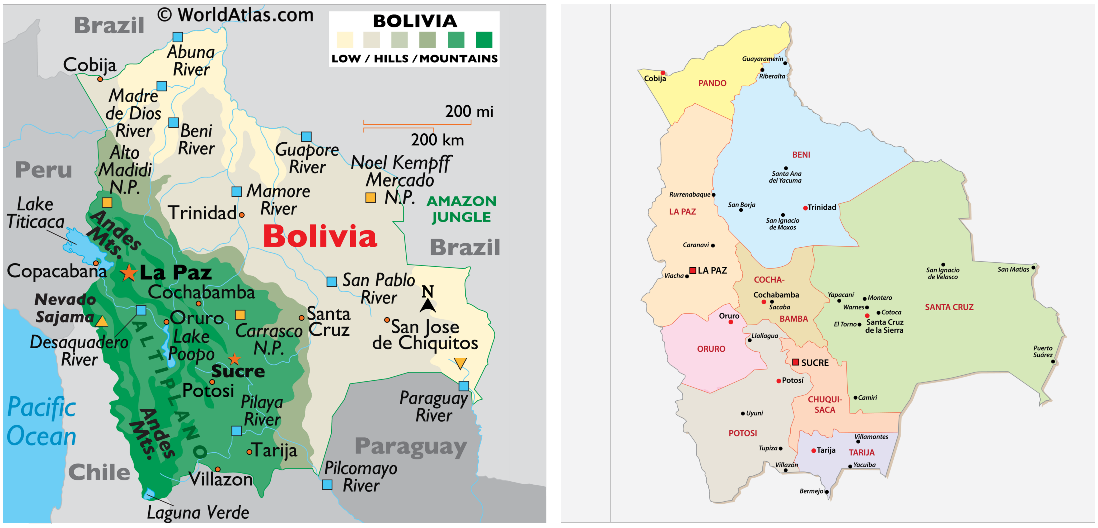


Figure 2.1: Physical (left) and political (right) maps of Bolivia [8].

When examining potential pathways for Bolivia's energy transformation, it is important to consider the country's socioeconomic situation. Bolivia is one of the poorest countries worldwide, with a Gross Domestic Product (GDP) per capita of only 3345.2 $ (compared to Belgium's GDP which is about 51 247$) [9]. This highlights the existing economic challenges and limitations that affect Bolivia's overall development, including the energy sector. However, it is important to note that Bolivia is currently experiencing a significant GDP growth, with an increase of 6.1% in 2021 (World Bank, 2023 [9]). As a developing country, this growth, coupled with a growing population and expanding economy, leads to an increasing demand for electricity [10]. This upward trend in electricity demand reflects the ongoing socioeconomic development of the country and the imperative to meet the expanding needs of its population and economy.

2.2 Energy demand and production in Bolivia

Over the past few decades, Bolivia, like many developing countries, has witnessed a remarkable growth in electricity demand, with a fivefold increase of consumption over a span of 30 years, electricity consumption currently standing at 10.9 TWh. This exponential growth in demand has compelled the installation of new power plants to meet the country's energy needs.

The selection of power plant installations has been influenced by Bolivia's historical context, particularly the challenges associated with ensuring accessible and sustainable electricity for its population. This historical evolution of the energy generation is described in the next section.

2.2.1 Historical trends in Bolivia's electricity generation

Over the years, a number of legislative measures, national policies, and evolving energy sources have had a considerable impact on Bolivia's electricity generation landscape.

The 1994 *Electricity Law Number 1604* [4] set principles for electricity pricing and tariffs, with hydroelectricity contributing to about 70% of the electricity production at that time [2].

In the same year, Bolivia ratified the United Nations Framework Convention on Climate Change (UNFCCC), emphasizing its dedication to tackling climate change impacts. Subsequently, in 1999, Bolivia further demonstrated its environmental commitment by ratifying the Kyoto Protocol.

However, subsequent changes in national policies, especially since 2006 when Evo Morales and the Movement Towards Socialism (MAS) took over the government, led to a surge in gas produced electricity. Indeed, in 2010, approximately 63% of the total electricity generation relied on gas, while hydroelectricity accounted for only 21%. This shift was facilitated by the implementation of subsidized policies with gas prices around 1.3 $/Mbtu taking advantage of the country's abundant gas resources. As a consequence, these policies have challenged the economic competitiveness of new renewable energy projects.

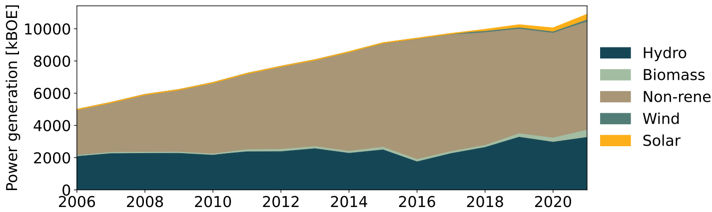


Figure 2.2: Electricity production in Bolivia - 2006-2021.

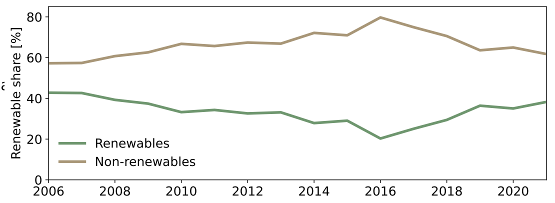


Figure 2.3: Share of renewable generation in Bolivia - 2006-2021.

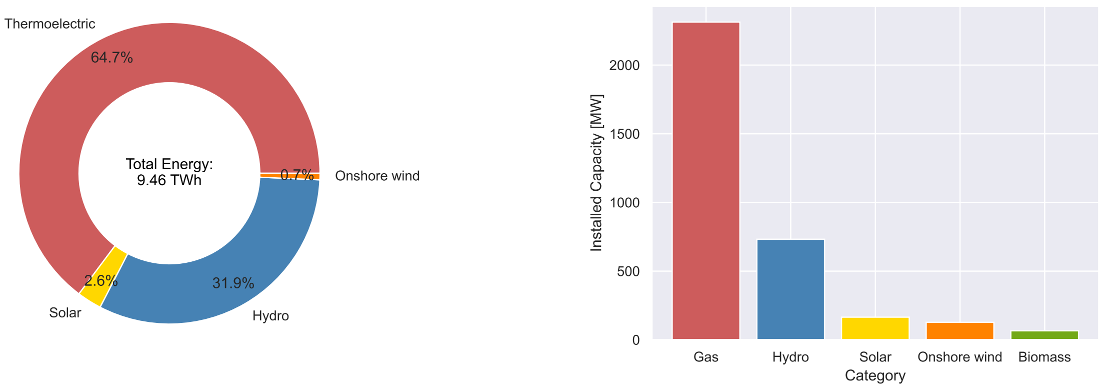
Source: Illustration (Ritzkowsky X., 2023) based on [2].

The evolution of Bolivia's electricity mix over the years is depicted in Figure 2.2, illustrating the growth in production to meet increasing electricity demand. The graph highlights the significant expansion of gas generation, which played a dominant role in the energy mix due to subsidized policies. The share of renewables, as shown in Figure 2.3, fluctuated over time. While this share was notably high in 2006, driven by hydropower plants, it declined in subsequent years due to the focus on cheap gas-based electricity generation. However, since 2016, there has been a steady increase in the renewable share, driven by policies aimed at reducing CO_2 emissions and promoting renewable energy sources.

Indeed, recognizing the need for a more sustainable energy future, Bolivia now needs to make a transition by financing renewable technologies. This transition is in phase with the objectives outlined in the Plan Optimo De Expansion Del Sistema Interconectado Nacional (POES) 2012-2022[11], aiming for a more efficient use of renewable sources and the development of hydropower projects. Additionally, in the Plan Eléctrico del Estado Plurinacional de Bolivia (PEEP) 2025 [12], Bolivia aims to become an exporter of electricity produced by clean sources and intends to meet up to 70% of its electricity demand with renewable sources.

2.2.2 Power mix and installed capacities in 2020

The base year chosen for this study is 2020, aligning with other research papers. During this period, Bolivia's total electricity production reached 9.46 TWh. Most of the electricity generation came from thermoelectric plants, contributing to 64% of the total electricity generated and primarily fueled by natural gas (Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT)), with a minor share from biomass. In the renewable energy sector, hydroelectricity played a significant role, accounting for 32% of the total energy production. Conversely, solar and wind energy accounted for a smaller proportion, representing respectively only 3% and 1% of the total energy production, respectively [13]. These proportions can be seen in Figure 2.4a.



(a) Generation of electricity [%] for 2020

(b) 2020 Installed capacity by category

Figure 2.4: 2020 Power Mix [13].

Figure 2.4b shows the installed capacity by carrier [1] in 2020 for the country. Notably, gas power plants account for approximately 68% of the total installed capacity. Considering a capacity factor of 70%, these gas plants could produce around 14 TWh for the total year, which is even more than the total energy demand in this year. This suggests that the installed gas capacity is greatly overestimated. The current abundance of gas capacity might discourage investment in new renewable energy plants, as the existing gas capacity is projected to be more than enough to meet the country's needs, even with a substantial increase in electricity demand.

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[1] In this paper, the term "carrier" design the different sources of production

2.2.3 National interconnected power system

In Bolivia, the electrical energy production system is divided into two main parts: the National Interconnected System (Sistema Interconectado Nacional (SIN)) and isolated regions that are not connected to the national grid. The SIN, operated and regulated by the Empresa Nacional de Electricidad (ENDE), ensures the reliable transmission and distribution of electricity across different regions. However, remote areas often face challenges in accessing reliable electricity due to their geographical location and limited infrastructure.

Figure 2.5: Bolivian National Interconnected System zones with the transmission lines that will be implemented by 2026 [14].

As can be seen in the figure 2.5, the Bolivian National Interconnected System is divided into 4 zones. The physical division into zones refers to how the electrical transmission network is geographically organized, each zone having its own transmission and distribution infrastructure and being managed independently. This division enables efficient management, localized operations, and better alignment with the specific needs of each zone. Each zone is separated by specific geographical boundaries, such as mountains, rivers, or other natural features that delimit the respective regions. The four zones are as following [15]:

- North (La Paz and Beni)
- Oriental (Santa Cruz)
- Central (Oruro and Cochabamba)
- South (Potosí, Chuquisaca and Tarija)

The transmission system is built upon high voltage transmission lines: 69kV, 115kV and 230kV. This transmission lines shape the main power system grid known as Sistema Troncal Interconectado (STI)

2.3 Renewable potential in Bolivia

As said previously, Bolivia is characterized by its abundant renewable resources, offering great potential for sustainable energy generation. The distribution of renewable potential throughout the country is illustrated in Figure 2.6.

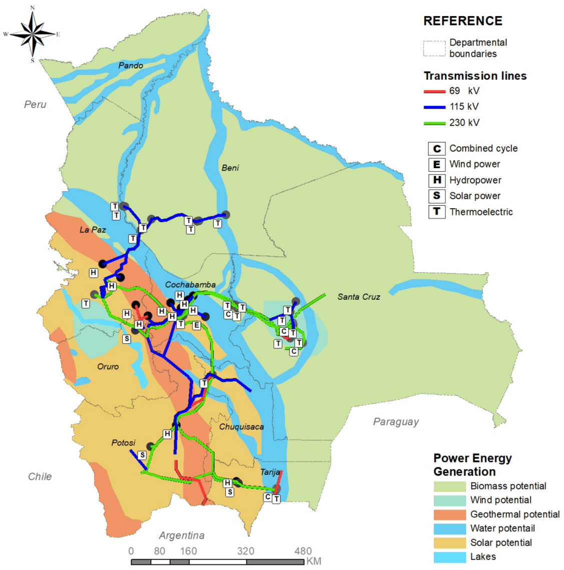

Figure 2.6: Potential for energy generation from renewable sources [16].

2.3.1 Non-hydro renewables

Solar potential

Bolivia possesses significant solar energy potential, offering a promising outlook for future energy production. The country is located in the tropical zone of the planet, south of the Equator, which experiences high and consistent solar radiation. Furthermore, due to the high altitude above sea level encountered in the two branches of the Andes mountain range and on the Altiplano plateau, solar radiation is less attenuated by the atmosphere there. The solar potential distribution can be analysed in Figure 2.7.

Compared to Belgium, Bolivia's solar potential is significantly higher. While Belgium receives an average solar irradiation of around 3.5 $\text{kWh/m}^2\text{/day}$, Bolivia experiences much higher levels, particularly in the altiplano region (La Paz, Oruro and Potosí), ranging from 6.7 to 9.5 $\text{kWh/m}^2\text{/day}$. Bolivia has a valuable opportunity to develop solar power projects and integrate them into its energy mix.

Wind potential

As Bolivia is a locked country, there is no offshore potential for the country and the average wind speed is lower compared to other coastal countries in the neighbourhood. However, there are specific regions within the country where wind speeds are quite decent, with values exceeding 8 m/s. Indeed, the data for the 10% windiest area represent a mean wind speed of 7.69 m/s corresponding to a mean

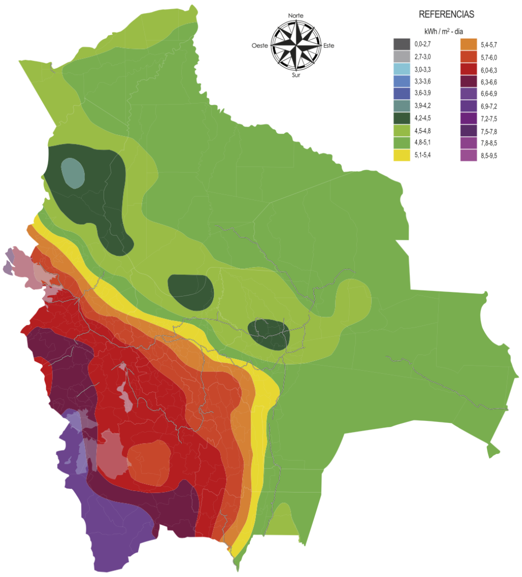

Figure 2.7: Solar energy potential in [kWh/m^2/day] [5].

power density of 463 W/m^2. While this may be considered moderate when compared to Belgium's average wind speed, these higher wind speeds in some Bolivian areas represent promising opportunities for wind energy development. Figure 2.8 provides a visual representation of the average wind speed in different regions of Bolivia at a height of 100 meters above the Earth's surface.[2]

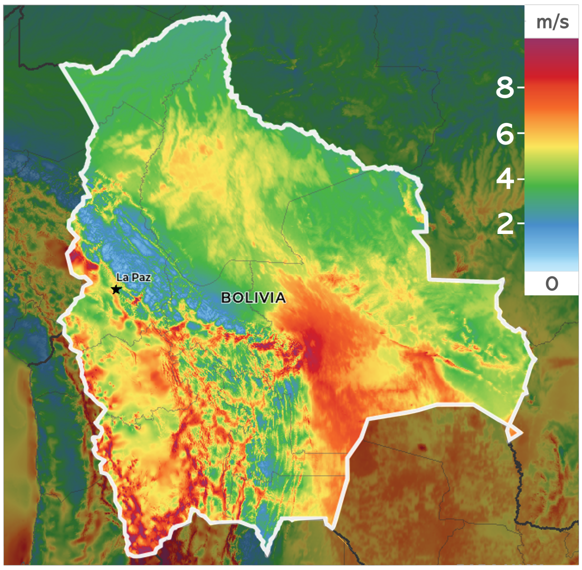

Figure 2.8: Wind energy potential in [m/s] (mean wind speed) [17].

The figure clearly shows that the most favourable regions for wind are relatively in the southern part including the South-Western tip of Bolivia, the Western and Central parts of Santa Cruz, the North-west of La Paz, and the central highlands.

According to a study [18] analysing the solar and wind potential in Bolivia, the southern regions

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[2] This 100 meters altitude is chosen to approximate the typical height of a wind turbine installation, allowing for an accurate assessment of the wind potential at the relevant elevation.

of Bolivia do not meet the minimum site requirements for wind power projects. The most promising sites for wind power development are located around the city of Santa Cruz, as well as in other smaller areas in the eastern part of the country and the highlands.

The only current installed wind turbines are located around Santa Cruz, determined by the `E` sign in Figure 2.6

Geothermal Potential

The estimated technological potential for geothermal power in Bolivia ranges from 510 to 1,260 MW, mainly located near the Chilean border where volcanoes are abundant. The Laguna Colorada near Salar de Uyuni has been identified as a promising site for large-scale power generation and a 5 MW pilot project was operational in April 2022 [19]. However, geothermal energy faces significant challenges due to high Capital Expenditure (CAPEX) costs, making it less economically viable compared to other technologies. Consequently, it is expected that geothermal energy will only have a minor role in the Bolivian power system. Nonetheless, geothermal energy remains an interesting option for renewable heat production.

Biomass potential

In Bolivia, biomass electricity production is primarily driven by the use of sugarcane residues, representing a significant opportunity for sustainable energy generation. Those residues, known as bagasse, are the by-product of sugarcane processing and can be effectively used as biomass fuel for electricity production. Currently, these sugarcane residues are provided by farmers free of charge. Moreover, these biomass power plants are strategically located directly at the sugarcane farms, which eliminates the need for transportation costs and further reduces the overall fuel expenses. Consequently, the current biomass fuel is free [20].

In 2021, the installed capacity of biomass power plants in the country was approximately 153MW [2]. Biomass energy generation has been a part of Bolivia's power system since 2007 and has steadily increased over the years.

It is important to note that while the current business model allows for free access to biomass resources, it is uncertain whether this arrangement will persist in the future.

2.3.2 Hydropower potential in Bolivia

As said previously, many studies indicate that, from the different sources of renewable energies, the source with the greatest potential is hydropower with a potential of 39.856 GW of installed power which could generate around 178 TWh per year for the whole country [5]. This represents about 18 times more than the Bolivian demand. As can be seen in Figure 2.9, the main areas with hydropower potential are the Amazon, the La Plata, and the Cerrada basin with respectively 80 billion, 22 billion, and 1650 million m^3/year respectively.

Currently, Bolivia has a total installed capacity of 732.2 MW for the hydropower production, which allows to produce 30% of the energy mix. Hydropower plants connected to the SIN are distributed in the cities of Cochabamba, La Paz, Potosi and Tarija. Current status, ongoing projects and discussions regarding hydroelectricity development in Bolivia can be found in Appendix A.

2.3.3 Climate impact on hydropower production in Bolivia

While Bolivia has great hydropower potential, it also encounters significant challenges in hydropower production due to seasonal constraints related to its tropical climate. The country experiences distinct wet and dry seasons, which greatly influence the availability and reliability of hydropower. During the rainy season, the flow rate of rivers is abundant, allowing for increased power generation. However, in

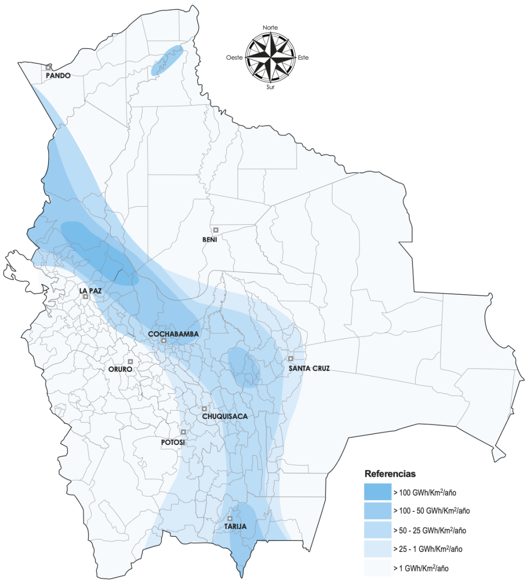

Figure 2.9: Hydropower potential distribution map for Bolivia [5].

the dry season, flow rates decrease, leading to reduced power output. These seasonal variations poses operational challenges for hydropower plants and necessitates careful management of water resources [21].

In addition to seasonal constraints, Bolivia's hydropower potential is susceptible to the impact of global warming. Changing weather patterns associated with climate change can have adverse effects on the availability and reliability of hydropower. Rising temperatures and altered precipitation patterns may lead to reduced snowfall in mountainous regions, affecting the natural water reservoirs that feed the hydropower plants. This reduction in water supply can result in decreased power generation capacity and intermittent energy production [16].

The importance and need for hydroelectricity in the Bolivian power system are well-established and widely recognized. However, the power generated from this source is subject to significant variations and uncertainties due to fluctuating climate parameters, including seasonal and inter-annual variations. These factors impact the reliability and predictability of hydropower generation.

Seasonal constraints and tropical climate

In Bolivia, the year is divided in two main seasons: the dry season and the wet seasons. During the dry season, characterized by low water availability, hydropower units operate mainly during peak demand periods. In contrast, the rainy season brings abundant water supply, allowing hydropower plants to operate at their full capacity. However, other power plants may adjust their operations to meet varying electricity demands. These seasonal variations in water availability result in discrepancies between the actual generation of hydropower and the installed capacity, as hydropower units' operational patterns change based on water availability. [16]

Impact of global warming on hydroelectricity

Climate change can have contrasting impacts on water available for hydropower in Bolivia.

On one hand, changing precipitation patterns, including more intense rainfall events, can lead to increased water availability and improve the overall water supply for hydropower generation.

However, climate change can also bring negative consequences such as prolonged droughts, increased evaporation rates, and accelerated melting of glaciers. These factors can lead to decreased water availability and reduced inflows to hydropower plants. The decline in water resources can ultimately result in decreased power generation capacity.

The dual nature of climate change impacts on water availability highlights the need for comprehensive assessment and adaptive measures to ensure the resilience and sustainability of Bolivia's hydroelectricity sector.

Inflows: particular years

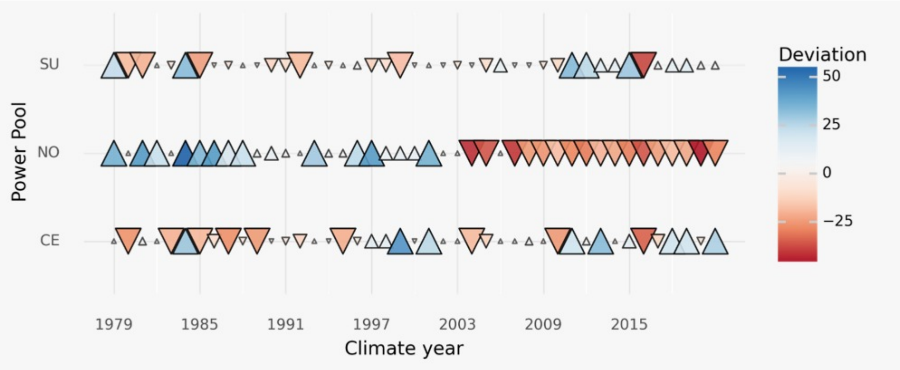

Figure 2.10: Annual variability (percentage deviation from the mean) of inflows between 1979 and 2022 [14].

Figure 2.10 illustrates a comparison of 43 simulations representing water availability for every year from 1979 to 2022. Each simulation is represented by a triangle, with the size of the triangles indicating the inter-annual variability. Larger triangles indicate higher inter-annual variability, representing greater fluctuations in water availability between years. The direction of the triangles emphasizes whether there is an increase or decrease in water availability compared to the mean. Additionally, the color of the triangles represents the intra-annual variability, indicating the variability within a year. The figure clearly shows that the wettest year was 1984 while the driest year was 2016.

Furthermore, Fernandez Vazquez's 2023 research paper [22] has also delved into this subject. Notably, an overall discernible trend is the consistent decrease in precipitations over the years. This trend is shown in Figure 2.11.

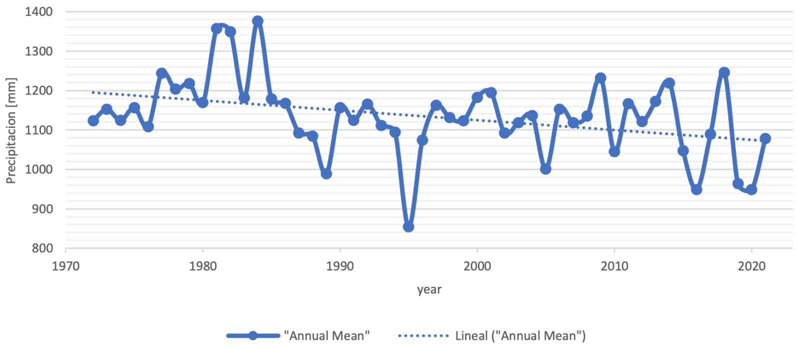

Figure 2.11: Average yearly precipitation registered in Bolivia for the timeframe 1972-2021.

Source: Illustration (Fernandez Vazquez C., 2023) based on [21].

Chapter 3

The energy model: PyPSA-Earth

This chapter offers an exploration of the energy modelling landscape. It covers previous attempts at modeling Bolivia's energy system and subsequently provides a detailed exposition of the PyPSA-Earth model.

3.1 Overview of modeling tools for energy planning

Energy modelling is a computational approach that employs specialized software to simulate the behaviour and interactions of energy systems. By making use of energy modelling, policymakers and analysts can make informed decisions about energy planning and policies. [23]

3.1.1 Characteristics of an energy model

Traditionally, policymakers and industry decision-makers have relied on closed-source energy models to shape their strategies. However, the landscape is changing with the emergence of open-source alternatives, like PyPSA-Earth, which offer distinct advantages. Open-source models provide greater customization options, enabling researchers to tailor the analysis to their specific case and to address various energy challenges. Additionally, these models promote transparency and collaboration, encouraging a collective effort in finding innovative solutions to global energy problems. [24]

Energy models can be categorized into two main approaches: "top-down" and "bottom-up." A "top-down" energy model starts with a high-level representation of the entire energy system (overall energy demand and supply for example) and breaks it down into smaller components. A "bottom-up" energy model, such as PyPSA-Earth, starts with detailed representations of individual components, such as power plants and grids, and then builds up to understand the behaviour of the entire system. In other words, it examines each element separately and considers their interactions as a whole. [23]

3.1.2 Previous work and modelling experience for Bolivia

Previous researches on energy systems in Bolivia has used a range of open-source and non-open-source models to analyse and understand the country's energy landscape. Among the open-source models, Open Source Energy Modelling System (OSeMOSYS) is a long-term model used to evaluate energy policies and investment scenarios, providing annual and seasonal data outputs. Dispa-SET, a dispatch model, analyses the short-time system behaviour and optimise the dispatch of the energy production between the different sources. Additionally, OnSSET, RAMP, and MicroGridsPy are modelling tools employed for analyzing rural electrification and microgrid settings.

On the other hand, non-open source models such as Stochastic Dual Dynamic Programming (SDDP), PowerFactory, and HOMER have been applied to study hydrothermal dispatch, transmission networks, and small hybrid power systems, respectively.

Fernandez Vazquez's paper in 2023 [25] delves further into the analysis of these models and their unique features and goals for Bolivia's energy system. While these various modelling approaches have contributed to a more comprehensive understanding of Bolivia's energy sector, some areas remain unexplored, and specific characteristics necessitate a new tool, such as PyPSA-Earth.

3.2 Description and features of PyPSA-Earth

PyPSA-Earth is an energy model system that takes open-source data as input to simulate and analyse energy systems of any country of the world. PyPSA-Earth is built upon the Python for Power System Analysis (PyPSA) framework and adds new functions to enable high-resolution modelling of the world energy system [6]. [1]

The PyPSA framework offers functional models, downloadable for practical use. Initially, a PyPSA-EUR model was created, covering the ENTSO-E region. This served as a foundation for the subsequent development of a global variant by Parzen et al. (2022). This global iteration was built upon the PyPSA-Africa version, which was modified to apply to any country's context. This global version, called PyPSA-Earth, is the model used in this paper for the adjustment to the Bolivian case.

Figure 3.1 provides an overview of the distinct model environments that are built on the PyPSA framework.

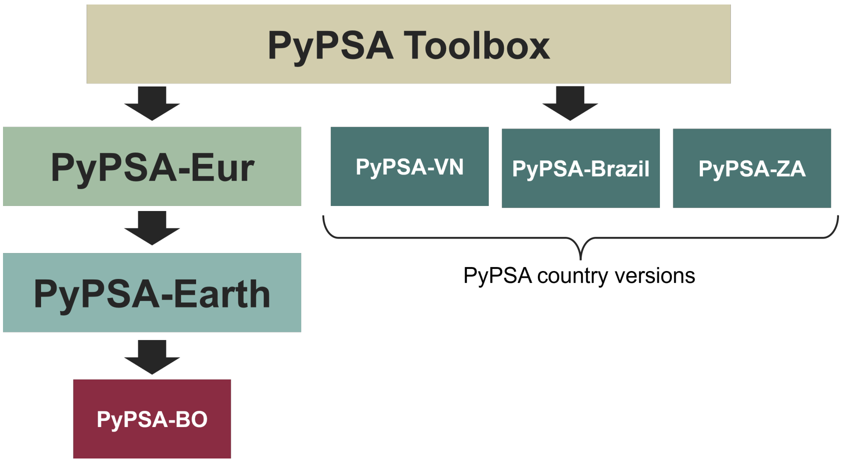

Figure 3.1: Overview of PyPSA model versions.

Source: Illustration (Ritzkowsky X., 2023).

Offering a bottom-up, open-source modelling approach, PyPSA-Earth can address the gaps and complexities in Bolivia's energy landscape, with its customizable capabilities and its good time and spatial resolution.

3.2.1 Advantages and applicability of PyPSA-Earth for Bolivian energy system modelling

As an open-source model PyPSA-Earth offers the various advantages that have been described in Section 3.1.1. One significant advantage is its unique framework with an automated workflow (explained in section 3.4), facilitated by a data management tool and Snakemake. This approach enables the model to be employed for country-specific applications with a single command, eliminating the need

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[1] The PyPSA-Earth presentation done by some members of the organization are publicly available at the following link `https://drive.google.com/drive/folders/19CV0x9VjyxHyvX3X4s2BA5MM78s6d1XW`

for extensive input data. However, it also allows for customizations to meet specific requirements while promoting sharing and collaboration among researchers.

An especially interesting feature of PyPSA-Earth is its capacity expenditure capability, which enables the assessment of potential investment in new power plants and new lines to meet demand. This feature becomes particularly significant in addressing the research gap highlighted earlier (see Section 1.1). By integrating this capability into the PyPSA optimization function, the approach considers capital costs on an annualized basis. These annualised capital costs are calculated based on the annuity which is used to spread out the initial investment cost over its expected lifetime. This helps distribute costs each year to cover both the initial investment and related expenses (like Fixed Operation and Maintenance (FOM) costs).

When modelling the Bolivian energy system, PyPSA-Earth provides an additional advantage with its high-resolution representation of the network. This feature facilitates a detailed analysis of power flows, enabling the evaluation of technical parameters such as line loading and generator power for each time step.

Moreover, PyPSA-Earth serves both short-term and long-term studies. Indeed PyPSA-Earth combines the strengths of Dispa-SET and OSeMOSYS. PyPSA-Earth offers the advantage of using time-series analysis with a short time step (such as 1 hour) and for a long period of study (e.g., 1 year). By employing this short time step, it becomes possible to assess variations in energy generation (e.g. due to renewable availabilities fluctuations) and demand patterns. This analysis helps identify peak load periods and evaluate the system's responsiveness to changing conditions. Moreover, PyPSA-Earth enables the study of the Bolivian energy system over an entire year, facilitating the exploration of seasonal variations. This capability is particularly valuable for understanding the impact of changing climate conditions on renewable energy generation.

For this reason, PyPSA-Earth's time series analysis provides specific advantages for modelling hydropower production in the Bolivian energy system. The use of hourly time series data enables a comprehensive understanding of the inflow behaviour, capturing the variations in water availability throughout the day. Furthermore, PyPSA-Earth's ability to study the Bolivian energy system over a period of one year is particularly beneficial for hydroelectricity modelling. It allows a thorough analysis of the differences between the rainy and dry seasons, which has a significant impact on water inflows and subsequently affects hydropower generation. By considering these seasonal variations, policymakers and stakeholders can make informed decisions regarding water management, reservoir operations, and overall system planning for reliable and sustainable hydropower production in Bolivia.

3.2.2 Drawbacks of PyPSA-Earth

Despite its advantages, PyPSA-Earth has some drawbacks that should be considered. First, being an open-source data-driven tool, the quality and currency of the datasets used significantly impact the accuracy of the results. This can be problematic for countries that lack access to some data or have unreliable data sources, as is often the case in developing countries like Bolivia.

Furthermore, PyPSA-Earth is still under development as an open-source project, which means multiple persons are working on it simultaneously, and new versions are frequently released. This can lead to potential instability or unexpected incompatibilities between different versions.

3.3 The Python for Power System Analysis (PyPSA) modelling framework

PyPSA is a modern open-source software toolbox written in the Python programming language. PyPSA allows the creation and analysis of power systems as well as the study of their economic and environmental implication. PyPSA is structured around nodes and edges, where nodes represent buses or network elements (such as generators, loads, and transformers) and edges represent transmission lines or cables. The network is modelled using a combination of linear and nonlinear equations, including Kirchhoff's and Ohm's laws. These equations are solved through numerical optimization methods, such as the Newton-Raphson and interior-point techniques, to determine the system's steady-state operating conditions as well as the energy production dispatching. [7]

3.3.1 PyPSA optimisation function

The goal of the optimisation is to "find the long-term cost-optimal energy system, including investments and short-term costs" [26] by minimizing the yearly total cost of the energy system. This has to be done under some constraints to assure the energy balance and grid stability.

Parameters and variables

Sets:	$n \in \{0, ..., \lvert N\rvert - 1\}$	buses
	$l \in \{0, ..., \lvert L\rvert - 1\}$	branches (lines, transformers and links)
	$s \in \{0, ..., \lvert S\rvert - 1\}$	technology (generator/storage) types at each bus
	$t \in \{0, ..., \lvert T\rvert - 1\}$	snapshots

Parameters:	ω_t	weighting of time t in the objective function
	$\bar{g}_{n,s}$	nominal power of generator s at bus n
	$\bar{h}_{n,s}$	storage nominal power of unit s at bus n
	$\bar{g}_{n,s,t}$	availability of generator s at bus n at time t per unit of nominal power
	$g_{n,s,t}$	dispatch of generator s at bus n at time t
	$h_{n,s,t}$	storage dispatch s at bus n at time t
	$suc_{n,s,t}$	start-up cost if generator with unit commitment is started at time t
	$sdc_{n,s,t}$	shut-down cost if generator with unit commitment is shut down at time t
	$c_{n,s}$	capital cost of extending generator nominal power by one MW
	$o_{n,s}$	marginal cost of dispatch generator for one MWh
	$f_{l,t}$	flow of power in branch l at time t
	F_l	capacity of branch l

Variables:	$g_{n,s,t}$	dispatch of generator s at bus n at time t
	$u_{n,s,t}$	binary status variable for generator with unit commitment

Time weightings factors

In PyPSA optimization process, time weighting factors (also known as weightings) are incorporated into the objective function to assign varying degrees of importance to different time periods. By adjusting these weightings, specific time periods can be given more or less weight, enabling fine-tuning of the optimization process to align with desired objectives. This allows for customization in several areas, such as prioritizing peak demand hours (where higher weightings help minimize costs or address constraints during periods of high electricity consumption) and considering factors like price variations and system characteristics.

In PyPSA, the sum of the weightings is constrained to be equal to 8760 hours per annum (h/a), as expressed by the equation:

$$\sum_t \omega_t = 8760 \tag{3.1}$$

Objective function
As mentioned earlier, the optimization function is designed to minimize the overall annual system costs. The capital costs are annualized with a discount rate r over the economic lifetime n using the annuity factor:

$$a = \frac{1-(1+r)^{-n}}{r}$$

The objective function, the mathematical representation of this minimization effort, is given by Equation 3.2:

$$\min \left[\sum_{l} c_l \cdot F_l + \sum_{n,s} c_{n,s} \cdot \bar{g}_{n,s} + \sum_{n,s} c_{n,s} \cdot \bar{h}_{n,s} + \sum_{t} (suc_{n,s,t} + sdc_{n,s,t}) + \sum_{t} \omega_t \left[\sum_{n,s} o_{n,s,t} \cdot g_{n,s,t} + \sum_{n,s} o_{n,s,t} \cdot h_{n,s,t} \right] \right] \tag{3.2}$$

One of the primary advantages of PyPSA-Earth is its dual nature as both a dispatch and an investment model. This is enabled by annualizing investment costs and distributing the initial investment expenditure over the expected lifespan of the assets.

The capital costs encompass annualized investment expenses, ensuring that when optimization is performed for a specific year, it accounts for both the operational expenses of that year and the proportion of annualized investment costs related to that particular year.

The terms of the objective functions are the following:

- The first term of the objective function $\sum_l c_l \cdot F_l$ represents the fixed cost associated with the branch installed capacity
- The subsequent terms: $\sum_{n,s} c_{n,s} \cdot \bar{g}_{n,s} + \sum_{n,s} c_{n,s} \cdot \bar{h}_{n,s}$ represents respectively the generator capacities $\bar{g}_{n,s}$ and storage power capacity $\bar{h}_{n,s}$ multiplied by their respective annualised fixed costs per capacity for each bus n and technology s.
- Then the starting up costs $suc_{n,s,t}$ and shutting down costs $sdc_{n,s,t}$ are added for every snapshot t
- And finally, operational costs are considered through the term $\sum_{n,s} o_{n,s,t} \cdot g_{n,s,t}$ multiplying the realised dispatch of every generation unit by the associated variable cost. Same for storage where $\sum_{n,s} o_{n,s,t} \cdot g_{n,s,t}$ express the fact that the positive part of the dispatched storage is multiplied by the variable storage operational cost associated.

Constraints This optimization process will involve solving the objective function while adhering to the following constraints:

- **Nodal Power Balance**: Maintain equilibrium between power generation and consumption at every network nodes to avoid energy imbalances.
- **Constraints for Generators**: Limit the time-series output of each generator based on the availability of time-series resources and generator capacities
- **Unit Commitment and Ramping Constraints**: Determine component usage and set ramp rate limits to prevent abrupt fluctuations.
- **Storage Units Constraints**: Ensure that storage nominal power and state of charge remain within their limits for effective operation.

- **Global and Emission Constraints**: Adhere to environmental goals, including CO_2 emissions reduction targets.
- **Transmission and Flow Constraints**: Address transmission limitations between nodes and use linear power flow principles for grid reliability.
- **Renewable Availability**: Consider renewable resource time series for each node and time.
- **Respect for Potentials**: Ensure that installed capacity for renewables does not exceed geographical potentials to prevent resource overuse.
- **Flexibility Integration**: Incorporate flexibility from gas turbines, battery/hydrogen storage, and High-Voltage Direct Current (HVDC) links to manage system variations.

By adhering to these constraints, the optimization process creates an energy system configuration that is economically efficient, reliable, under the desired constraints notably for the CO_2 emissions, and well-equipped to meet the diverse demands and challenges of the energy landscape.

The full formulation of the constraints is provided in the PyPSA documentation [27].

Solver PyPSA solves the mathematical optimization problem using a solver. PyPSA supports various solvers but in the case of this paper, Gurobi [2] will be used.

3.4 PyPSA-Earth Workflow

The PyPSA-Earth workflow is managed by a Snakemake file, which links together the various Python scripts used in the simulation. It enables the preprocessing of data as well as running the system optimization, making it a useful tool for energy system modelling.

The workflow can be summarized as shown in Figure 4.1.

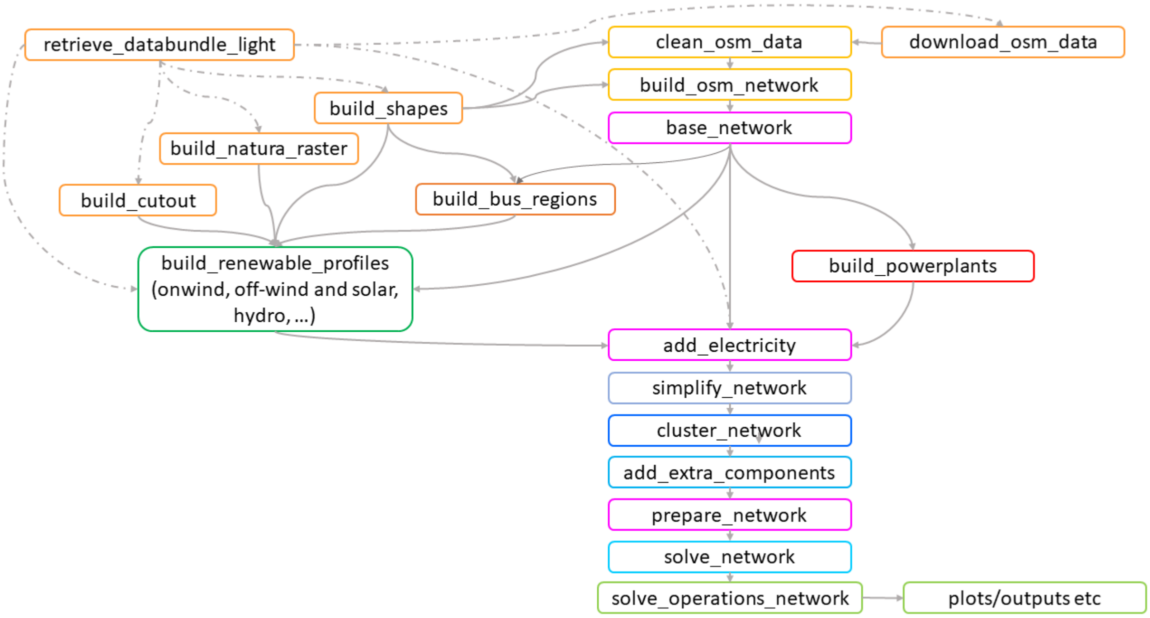

Figure 3.2: Chart of the PyPSA-Earth workflow, each block representing a snakemake rule [24].

The PyPSA-Earth workflow is structured into 5 main stages:

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[2] Gurobi Optimizer is a commercial optimization solver usually used for decision-making [28]

1. **Data download and filtering:** Raw data on energy demand, renewable energy resources, network topology, weather, and climate are downloaded. The model leverages open databases to obtain relevant data. Subsequently, data filtering is applied to remove inaccuracies, and normalization procedures are employed to ensure data consistency.
2. **Data population:** The preprocessed data is used to populate the PyPSA-Earth model, forming the basis for system representation. Each zone within the model corresponds to a specific geographical area or region of interest.
3. **Network Model Creation:** The populated data is used to construct the network model, which includes components such as power plants, transmission lines, substations, and energy demand profiles.
4. **Clustering:** Just before the network-solving stage, the data is subjected to a clustering process. The number of resulting zones can be chosen and specified in the configuration file of the model according to the needs of the user.
5. **Network Solving:** Finally, data is used by the system to express a linear optimisation problem of the system with the system constraints and optimization objectives specified in the configuration file. This optimisation function is detailed in the section 3.3.1. Once the clusters are defined, the PyPSA-Earth model is optimized using a linear programming solver. The objective is to find the optimal dispatch and allocation of energy resources within each cluster while satisfying the defined constraints and objectives. The output of the optimization stage includes the allocation of all energy resources over the simulated period, as well as various system performance indicators such as greenhouse gas emissions and total system cost.

3.5 Key functions and rules

3.5.1 Data sources and customization

To properly model any region of the Earth, PyPSA-Earth employs an array of data sources, detailed in this section. In accord with the open-source philosophy of PyPSA-Earth, the majority of these sources are open.

The main sources of data are the following:

- **Grid Topology Data:** OpenStreetMap[3] [29]
- **Environmental Data:** Copernicus [4], Eez [31], Gebco [32], HydroBASINS[33], Landcover Dataset
- **Economic Data:** WorldPop [34], GDP from DRYAD [35]
- **Costs Data:** Primary cost data is drawn from the IEA [36] database. Further insights into cost considerations within PyPSA-Earth can be found in Appendix G.
- **Technological Data:** EIA [37][5].

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[3] OpenStreetMap is an open-source database containing diverse geographic data, including road networks, geographical features, and electrical infrastructure [29].

[4] Copernicus provides access to satellite and climate data [30].

[5] The EIA (Energy Information Administration) is a U.S. government database that collects, analyses, and disseminates energy-related information. This includes data on energy production, such as the total amount of hydropower generation for a specific country during a given year. The EIA also provides insights into energy consumption, prices, statistics, forecasts and the environmental impact of various energy sources.[37] data.

For the sake of customization, PyPSA-Earth offers flexibility in input data. The main customizable inputs are:

- **Technology Costs and Details:** Users are able to fine-tune various cost-related parameters encompassing investment costs, operational costs (Variable Operation and Maintenance (VOM) and FOM), discount rates, and fuel costs. Additionally, detailed technological attributes like lifetime, efficiency, and CO_2 intensity can be adjusted.
- **Hourly Demand Load:** Within PyPSA-Earth, users can adjust many parameters for scaling the demand projections computed based on the Shared Socioeconomic Pathways (SSP2) [38]. These adjustments encompass the choice of a preferred projection year (ranging from 2030, 2040, to 2050), specification of a foundational weather year for projections (2011, 2013, or 2018), and implementation of a scaling factor. This scaling factor allows for the customization of projections, facilitating the achievement of the desired total demand over a specific time period. Notably, the SSP2 projections place a significant emphasis on GDP and population growth.
- **Legacy Capacity:** Installed power plant capacity can be personalized through adaptable files.

For detailed information about data sources, read the PyPSA-Earth documentation [24].

3.5.2 Creation of renewable profile (solar and wind)

In PyPSA-Earth, renewable energy availability is characterized by capacity factors that indicate the energy output under some conditions compared to the theoretical maximum in these conditions. These can be expressed as :

$$CP = \frac{\text{Actual output}}{\text{Maximum theoretical output}}$$

These factors are generated using the `Atlite` package, which extracts the necessary weather and climate data to produce time series data for power systems (such as wind power, solar power, hydropower, and heating demand).

The primary data source for `Atlite` is ERA-5 climate data from Copernicus. In PyPSA-Earth, the representation of renewables encapsulates this variability at a spatial resolution of, for example, 30km by 30km for ERA-5 sources. This approach provides a comprehensive insight into potential variations across diverse locations and over time.

3.5.3 Creation of power plants

Build power plants The `build power plants` function in PyPSA-Earth is responsible for constructing the hydropower plant infrastructure. It assigns a bus number to each power plant based on the bus region delimitations (using `powerplantmatching` [6] for allocating each powerplant to the closest substation). This function considers essential parameters such as capacity, efficiency, capital cost, and marginal cost of the hydropower plants. The powerplant configuration can also be customized manually in a file.

Hydropower plants caracteristics Hydropower plants are classified as Run-Of-River (`ror`), Reservoir-based plants (`hydro`), or Pumped Storage hydro plants (`PSH`). [7]

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[6] Powerplantmatching is a PyPSA "toolset for cleaning, standardizing and combining multiple power plant databases" [7]

[7] Run-of-river hydropower uses the river flow to spin a turbine, providing continuous electricity without storage. Reservoir-based hydropower stores water in a reservoir and releases it through turbines to generate electricity, offering both steady and on-demand power. Pumped storage hydropower moves water between reservoirs using surplus energy for later electricity generation, offering peak-load supply and energy storage.

3.5.4 Model of the electricity network

Creation of bus regions

First, the whole area has to be divided into bus regions. The function `build_bus_region` creates Voronoi shapes for each bus (determined by the base data from OSM [29]). For the Bolivian case, this spatial division in bus cells can be seen in the next Section (4.1.1)

Creation of the network model

The snakemake rules prepare an approximation of the real network in order to facilitate computational optimisation. The rules modelling the electricity network are the following:

- `base_network` This rule is responsible for building and storing the base network. It includes all buses, HVAC lines, and HVDC links forming the foundational structure of the electricity network model.
- `add_electricity:` This rule focuses on adding generators and demand to the network model. It integrates renewable and conventional power plants, as well as load time-series data, creating a comprehensive representation of energy generation and consumption. The `add_electricity` function serves the purpose of incorporating electrical generators, load, and existing hydro storage units into a foundational network structure (created previously in `base_network` rule). This function facilitates the connection of hydroelectric generators to the network while defining various essential characteristics, including the generator's bus, maximum power output, and efficiency.
- `simplify_network:` This rule transforms the transmission grid into a simplified version, featuring a 380 kV-only equivalent network. This simplification helps improve computational efficiency while retaining essential network characteristics.
- `cluster_network:` Using a clustering approach (e.g., k-means), this rule partitions the network into a predetermined number of zones. It then reduces the network to a representation with one bus per zone. This clustering enhances the model's manageability and computational performance.
- `add_extra_components:` This rule is responsible for adding extra components to the model beyond the core network structure. Examples of such components include storage systems, which contribute to a more accurate representation of the real-world energy system.
- `prepare_network:` This rule introduces optional constraints and requirements into the modelling process. These can include CO2 emissions constraints, security margins, and other specifications that enhance the realism and reliability of the model's results.

These rules create a detailed electricity network stored including transmission network topology, today's thermal and hydropower generation capacities as well as today's load time-series. Moreover, it creates generators with zero capacity for renewable (solar, wind) containing locational and hourly wind and solar capacity factors as well as additional gas power plants listed in the extendable carrier list of the configuration file.

3.5.5 Solving the Network

Once the network is modelled with its constituent components, constraints, and component-specific details (such as costs), the final step involves the application of the `solve_network` rule. At this stage, all accumulated data is used to formulate an optimization problem within the PyPSA framework.

As explained in Section 3.3.1, the optimization task is undertaken by a solver, aiming to minimize the total annualized costs. This entails determining the most efficient allocation of energy resources throughout the simulated timeframe and for each time step. This optimization process includes the potential creation of new power plants to address capacity extension requirements.

The result of this optimization procedure provides valuable insights across multiple dimensions, encompassing the allocation of energy resources, assessment of capacity extension requirements, determination of the total system costs, and quantification of CO_2 emissions. This outcome is materialized through the creation of a comprehensive `network` database that consolidates all network-related information. Additionally, a time-series data frame is generated, detailing the production of each carrier within every cluster and for each individual time step.

Chapter 4

Bolivia energy modelling

In this chapter, the use of PyPSA-Earth for the specific Bolivian case will be studied. As hydroelectricity production has special importance in the Bolivian case, the modelisation of hydroelectricity in PyPSA-Earth will also be studied more in detail in this chapter.

4.1 First run of the model for Bolivia

In the context of PyPSA-Earth, various essential parameters are defined within a configuration file. However, it's important to note that the default configuration has been tailored primarily for the African continent. The default settings incorporate data that in phase with the characteristics of the African energy landscape. It serves as a starting point for the model's functionality, but due to the adaptable nature of PyPSA-Earth, these parameters can be customized to fit the Bolivian context more accurately.

Parameters The configuration of the model in the default PyPSA-Earth configuration includes the following parameters:

- Country Configuration (Nigeria and Benin): The choice of Nigeria and Benin as the default country configuration ["NG", "BJ"] highlights the starting point for the model's geographic focus. This selection allows for swift customization to fit the energy context of other countries.
- Cutout Region (African Landcover Maps): The cutout region determines the geographical area from which weather data and renewable energy potential estimations (such as solar and wind) are derived. It's crucial to tailor it to ensure accurate representations and estimations.
- Environmental and Demand Data (2013 to 2014 and Projection for 2030): The temporal scope of data selection shows the model's capacity to accommodate various time frames. The use of 2013 as a default year for accurate and verified data underscores its reliability. Moreover, projecting demand data into 2030 acknowledges the model's ability to anticipate future energy needs.
- Population and GDP Information (The year 2020): Including population and GDP data for the year 2020 acknowledges the socioeconomic dimensions in energy planning.
- Renewable Capacity Data (IRENA Website, Year 2020): Sourcing renewable capacity data from the IRENA website for the year 2020 ensures that the model uses the latest and most reliable information for accurate simulations.
- Cost Data (The year 2020): Incorporating cost data from the year 2020 ensures the model reflects recent price values.

- Extendable Carriers (Solar, Wind, OCGT, CCGT): In the default file, the expansion capability is allowed only for some carriers but the model allows for the addition of a wide range of energy sources like geothermal, biomass, hydro,...
- Clustering Approach (10 Nodes): The use of a 10-node clustering approach in the default configuration showcases the model's strategy for grouping regions, thus enabling efficient and effective analysis.

Adjustments for the initial run To initiate the model's execution for the Bolivian case, several adjustments were implemented to enable the model to run. These adjustments do not yet address the full adaptations needed to represent accurately the Bolivian energy system. The following adjustments were implemented:

- Adjustment of cutout region: The predefined data bundle was manually replaced with South America landcover maps, as Bolivia is part of the South American region. These maps were sourced from Protected Planet [39].
- Integration of New Climate Data: To enable the acquisition of precise weather data for the Bolivian case, PyPSA-earth has been configured to support the download of additional climate data. Specifically, the model allows the retrieval of new climate data specific to Bolivia from Copernicus [30].
- Removal of offshore wind options: Considering Bolivia does not have a coastline, all offshore wind options were removed from the model to prevent conflicts during the creation of renewable availability.
- 4-nodes configuration: to simplify the use of the model, a 4-nodes clustering process has been preferred.

Other changes and adjustments will be done later for the representation of the Bolivian case and are described in sections 5.1 5.2, 5.3 and 5.4 for the specific hydroelectricity case.

Workflow for the Bolivian case

To perform the first run of PyPSA-Earth for the Bolivian case, the workflow can be summarized as shown in Figure 4.1.

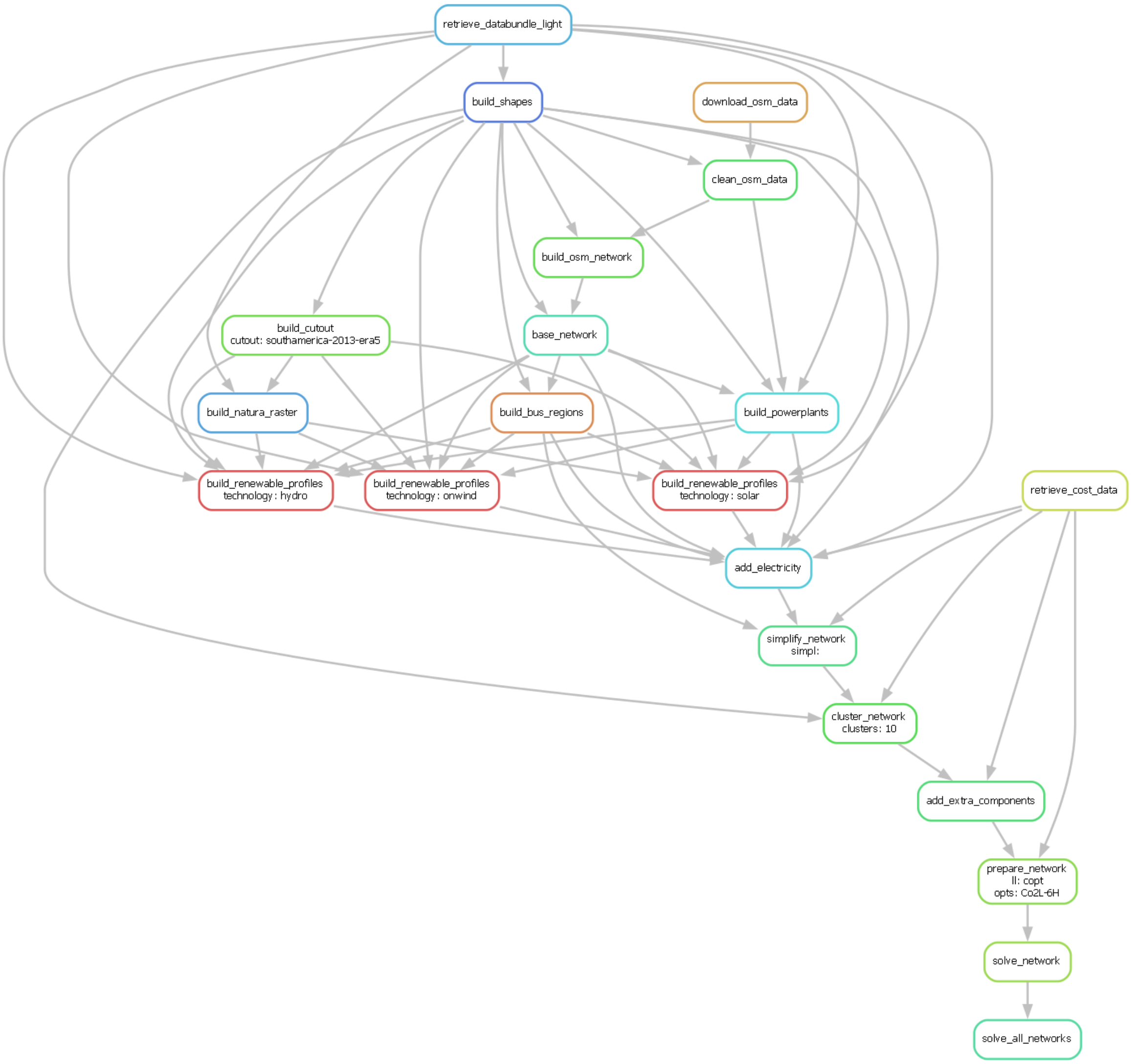


Figure 4.1: Workflow for a first run of PyPSA-Earth with adjustment to the Bolivian case.

4.1.1 Base network representation

In Figure 4.2, the base network created by the model after downloading and filtering the default data from the OSM data was compared with the available data from online repositories (the year 2012 has been chosen as the reference to match available OSM data), and it was found that most of the network's elements were taken into account, including the connection rings in the south and central parts of the system, as well as most of its 69, 115, and 230 kV lines.

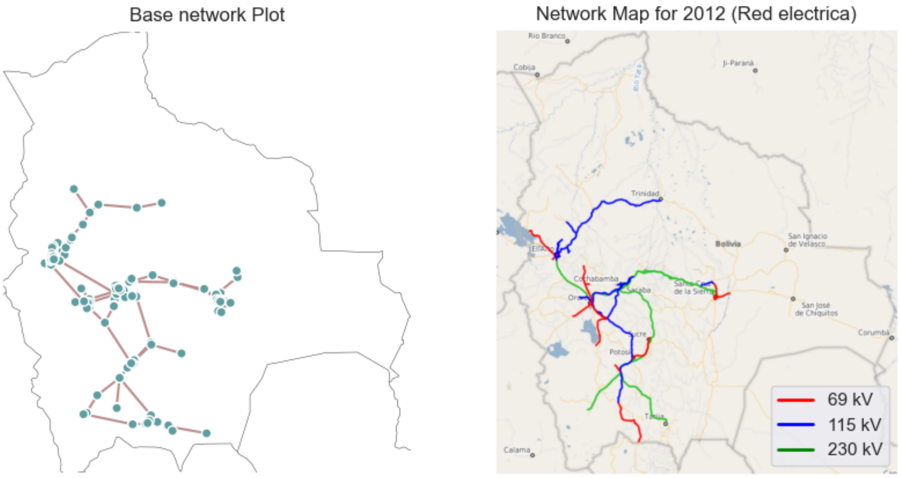


Figure 4.2: Comparison between the base network of the model and historical data (2012).

The `build_bus` function led to a country division into 81 regions as it is represented in Figure 4.3

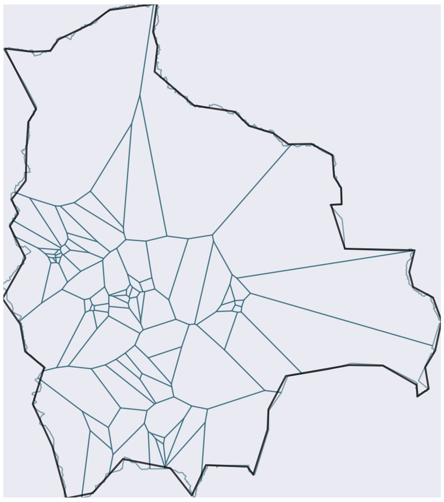


Figure 4.3: Spatial limits division in bus cells.

4.1.2 Analysis of energy demand and production distribution

The first run of PyPSA-Earth for Bolivia shows the following results:

The initial model run resulted in an electrical network consisting of 131 buses and 115 lines. It included 238 generators and 112 loads.

However, the initial clustering method resulted in an isolated node in the solved network, which is not representative of the actual Bolivian energy system. The clustering process grouped all the isolated nodes, based on a certain voltage level, into one big node disconnected from the rest of the network. This clustering process adaptation is explained more in detail in Section 5.1. The resulting clustered network for a 4-zone configuration is represented in Figure 4.4, which includes four connected nodes and one isolated node that requires further investigation.

Figure 4.4: Representation of the solved network before adjusting the model.

In the initial run of the PyPSA-Earth model for the Bolivian energy system, the yearly results are the following:

- Total demand: 11.31 million MWh
- Total production: 17.20 million MWh
- Total production with reservoir-type hydropower plant: 0.29 million MWh
- Total energy stored (battery + hydrogen): 1.496 million MWh

These results revealed an interesting phenomenon in the Bolivian energy system: there is a significant surplus of production compared to the total demand. This surplus production primarily comes from the isolated node within the network.

Due to this isolation, the energy produced in other nodes cannot be used by the isolated node. This led to very large production in the isolated node. Consequently, two main options arise for the energy supply to meet the demand:

- **Installation of a large number of power plant in the isolated node:** By increasing the power generation capacity within the isolated node, it becomes feasible to satisfy the energy demand independently.

- **Load shedding:** Consider a load shedding technology, represented by the `load` carrier, to balance the lack of production. Load shedding involves strategically reducing the power supply to some consumers during peak demand periods or when the supply cannot meet the demand.

In the results for the first simulation, the demand of the isolated node is covered, as explained in the second option with a `load` carrier which has a value of 5.3 million MWh, which represents the difference between the demand and the production.

Figure 4.5 shows the load and the production per zone:

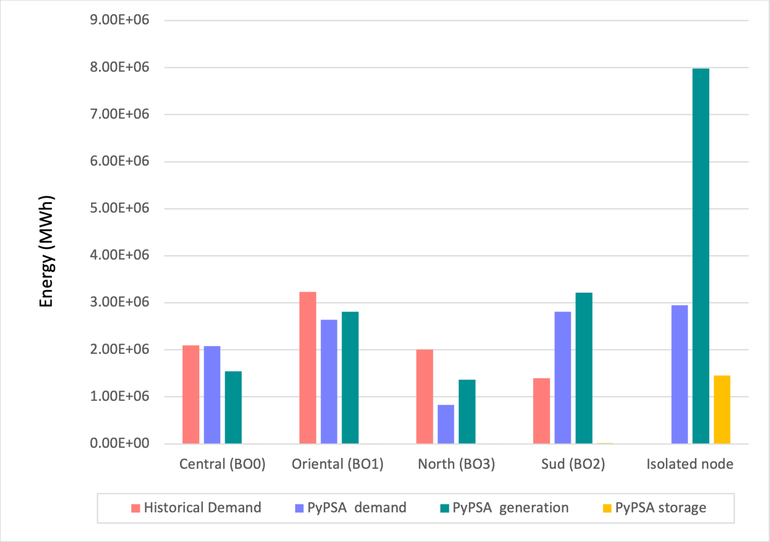


Figure 4.5: Demand and production per bus before adjusting the model.

It can be observed that the production in the isolated bus is considerably higher than the production in the other buses. Furthermore, the isolated bus exhibits a significant imbalance between production and demand (with production almost 3 times higher than the demand). This phenomenon can be attributed to the fact that the isolated bus actually is an aggregation of many smaller isolated buses. This results in inefficient generation and a higher need for generation capacity to cover the demand. Additionally, some storage capability is used, but only in the isolated bus, indicating an attempt to address this imbalance.

4.1.3 Power plant installed capacity

Figure 4.6 shows the installed capacity of every type of power plant in the first configuration of the model

This configuration has several issues:

- Solar stations are spread all around the system when in reality they are only installed in the south
- There is not enough capacity to cover the demand
- Gas power plant are only considered as OCGT, not CCGT which is also very important part of the Bolivian production
- Some reservoir-type hydropower plant are considered as Run of River (RoR)
- The generator configuration is generally not up to date (no date after 2002)

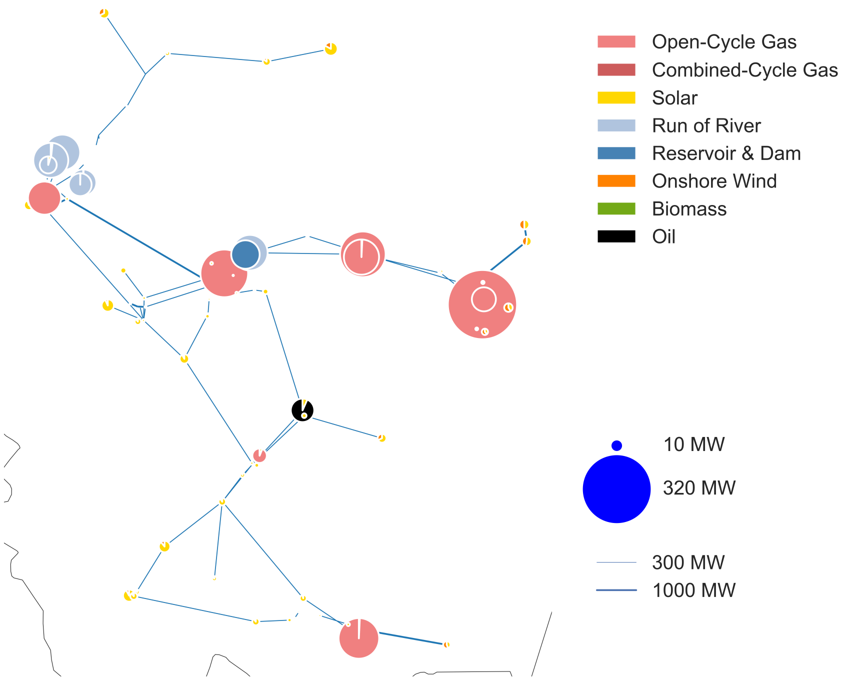


Figure 4.6: Map of power plant installed capacity before adjusting the model.

4.1.4 Solar and wind potentials

In Figure 4.7 and 4.8, the potential for solar and wind that are computed by PyPSA-Earth can be seen.

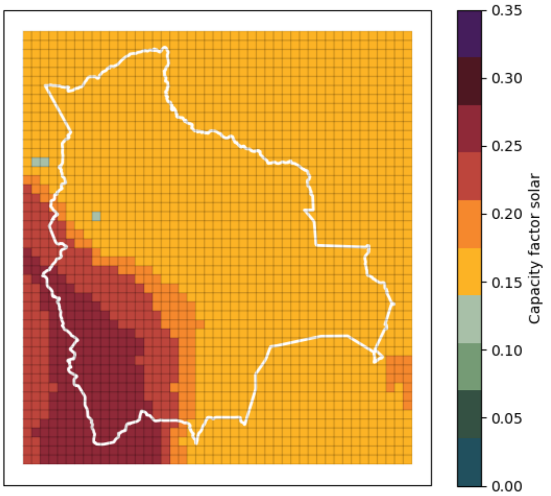


Figure 4.7: Map of the average capacity factor in PyPSA for solar PV in Bolivia.

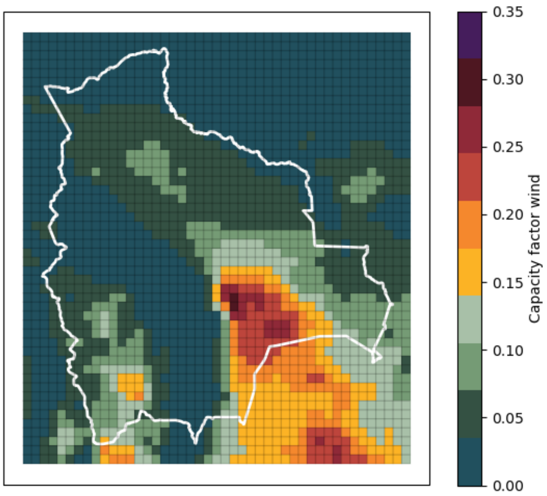


Figure 4.8: Map of the average capacity factor in PyPSA for a 3 MW wind turbine in Bolivia.

As described in Section 3.5.2, the main measure used by the PyPSA model is the average capacity factor. For the calculation of these capacity factors, specific technologies are assumed such as Vestas V112 3MW wind turbine for representing wind potential and CSi photovoltaics (PV) panels with latitude-optimal orientation for solar.

By comparison with the meteorological data presented in section 2.3 the use of `Atlite` can be confirmed as a good source for determining the capacity factors since the same zones are considered to have a good potential for solar and wind.

4.1.5 Hydropower potential

During the initial execution of the PyPSA-Earth simulation, complications arose from an intern problem within the `Atlite` library resulted in unreasonably high estimates of hydropower potential. As a consequence, the final results returned by the model did not account for hydropower generation. However, it's worth noting that this issue has been addressed and resolved in subsequent versions of PyPSA-Earth.

These computed inflow potentials were then used to determine the actual inflow of the power plants.

A comparative breakdown of the yearly inflow, which is effectively used by the installed power plants for the year 2013, is presented in Table 4.1. This table contrasts historical data obtained from the EIA with the PyPSA computations before and after the initial adaptation.

Table 4.1: Total yearly used inflow (2013).

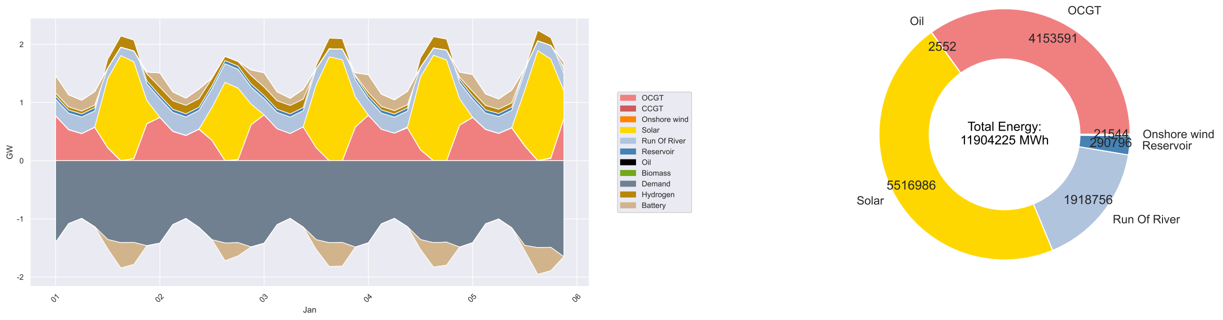
PyPSA Computation (First run)	**PyPSA Computation** (After first adjustments)	**Historical data (EIA[37])**
–	8.317 TWh	2.761 TWh

It can be seen that the inflow computation is nearly four times greater than the historical data. This overestimation of hydro potential will be further elaborated upon in the subsequent section. This problem is particularly acute in the case of a country with a large number of hydropower plants located very close to each other, which is the case in Bolivia.

4.1.6 Energy dispatch analysis

Figure 4.9 provides insights into the composition of the energy mix within the system's predictions for the year 2030, using weather data from 2013.

In Figure 4.9.**A**, the hourly energy dispatch for the period from January 1, 2020, to January 6, 2020, is depicted. This graph illustrates the allocation of energy sources during each hour and showcases the behavior of hydro storage in this specific timeframe. Figure 4.9.**B** on the other hand represents the cumulative total energy production for the entire year.



A - Hourly energy dispatch for January 2020 period

B - Yearly total prediction for 2020

Figure 4.9: Energy Dispatch before the model adjustment.

The analysis of these figures highlights a discrepancy between the predicted power mix and the historical power mix described in Section 2.2.2. More specifically, the contributions from solar energy and energy storage do not accurately represent the actual energy mix. This discrepancy is attributed to the model's treatment of solar power as an expandable element, leading to a substantial increase in installed solar capacity from 118 MW to 4205 MW during system optimization.

This expansion of solar capacity indicates that the initial model run fails to capture the true dynamics of the system. This inadequacy is linked to various parameters discussed in the previous section, such as inconsistent installed capacities and issues with network representation resulting in an isolated bus. Nonetheless, this observation underscores the great potential of solar energy generation within the Bolivian energy framework, particularly in remote regions where localized energy production addresses specific local demands.

4.2 Modelling of hydroelectricity in PyPSA-Earth

As can be seen in the previous section, the initial version of the PyPSA-Earth for the Bolivian case had a lot of issues, and many of them are related to the hydro representation in the model. In this section the focus will be on understanding the hydro modelling in PyPSA-Earth, how the inflows are computed and used by the model to be changed into hydropower plant power production.

4.2.1 Challenges in representing hydroelectricity

Bolivia's electricity generation mix has historically relied heavily on hydropower, and this trend is expected to continue, or even increase, in future predictions. Consequently, the accurate representation of hydro potential holds paramount importance for the model. However, the default version of PyPSA-Earth encountered a series of challenges when dealing with hydropower production. In light of these challenges, this section is dedicated to unravelling the methodology employed for computing inflows and their subsequent integration within the model, allowing for a more accurate simulation of hydropower generation.

4.2.2 Hydroelectricity modeling framework

A visual representation of the data scheme used in the hydroelectricity modeling process in PyPSA-Earth is represented in Figure 4.10.

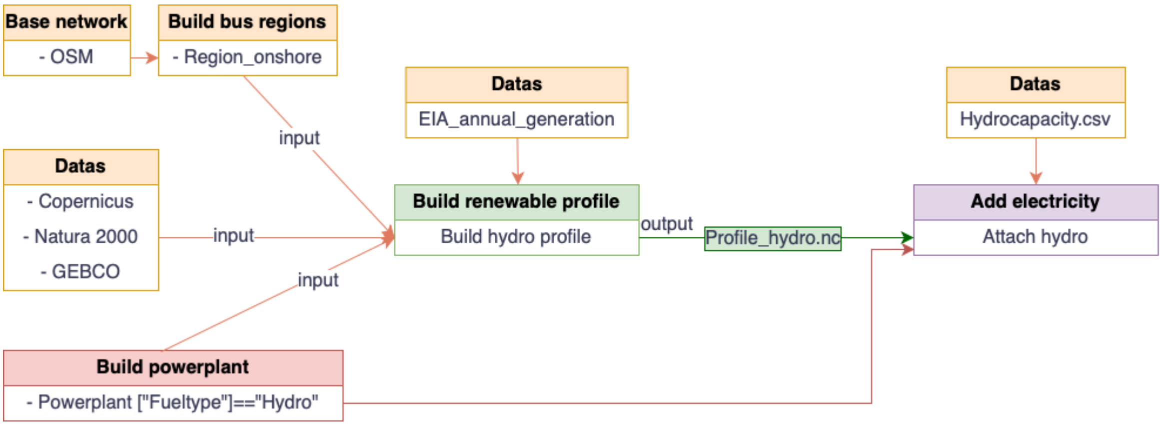


Figure 4.10: Data Scheme for PyPSA-Earth Hydroelectricity Modelling.

The hydroelectricity modelling in PyPSA-Earth entails generating a `hydro profile` file. This file encapsulates inflow availability in MW for each time step and across the 81 distinct spatial divisions in the Bolivian context. The spatial divisions are based on the country's geographical demarcation using the `build bus regions` function (results shown in Section 4.1.1). Inflow data is computed using cutout data, such as runoff and hydrobasins, data sourced from GEBCO. The hydro profile is created using the `hydro` method within the `atlite.Cutout` module.

The hydro profile is then normalized, incorporating yearly data from the EIA to represent the country's overall hydro characteristics. Subsequently, the `add_electricity` function uses the normalized hydro profile file to attach a timeseries availability to every power plant.

PyPSA-Earth integrates multiple data sources for hydroelectricity modelling:

Copernicus Data: Copernicus provides climate data including wind speed, solar influx, and temperature [30]. Of particular significance in hydroelectricity modelling is the runoff variable, which quantifies the volume of water flow over the ground surface, measured in meters.

Natura 2000 Data: Information from Natura 2000 is used for natural reserve data [40].

GEBCO Data: GEBCO (General Bathymetric Chart of the Oceans) provides a grid dataset that helps interpret and analyse bathymetric data. This dataset classifies the source data for each grid cell.

4.2.3 Computation of the inflows

In PyPSA-Earth, inflows are computed by the `Build Renewable` function

The inflows for each of the 81 regions are calculated by considering the resource availability for every timestep in each region. The hydro resource data is prepared using the `hydrobasins` feature and the `runoff` data from Copernicus with a fixed speed approximation of 1 m/s. The `atlite.cutout()` function with the `"hydro"` method is used to estimate the water availability for hydropower generation. More details about the computation of these inflows can be found in Appendix B

To compute the resources for each spatial division, the hydro basins data are first intersected with the bus regions for the country. Then, for each spatial division, the resource is computed by summing the run-off data that contains that spatial division.

$$Resource_z(t) = \frac{\sum_{(i,j)\in I_z} R_h(i,j,t)}{10^6} \times v_z$$

With

- $R_h(i,j,t)$ the runoff at coordinates (i,j) and time t. The summation $\sum_{(i,j)\in I_z}$ indicates that we consider all the coordinates within the spatial division z when computing the total runoff.
- v_z represents the speed of water flow within the spatial division z. In the model, this one is fixed for every zone at $1 m/s$ by default.

Normalization To ensure that the sum of inflows in the bus regions where hydropower plants are located matches the yearly hydropower generation reported in historical databases, a normalization factor is applied. The specific value of this factor depends on the chosen normalization method.

If the normalization parameter is set to `EIA`, the normalization factor is computed based on the yearly data obtained from the Energy Information Administration `EIA` database.

In this case, the normalization factor ensures that the total hydropower production from the zones with hydropower plants aligns with the reported hydropower generation for the country as a whole. By dividing the country's annual hydropower generation by the sum of hydro production from the relevant zones, the normalization factor scales the inflow values in those zones accordingly.

$$\texttt{EIA\_annual\_energy} = \frac{1}{multiplier} N_{normalization} \times \sum_{zone} \sum_{t}^{365*24} inflow_{zone}(t)$$

- With multiplier that can be fitted, equal to 1.1 by default
- The `zone` parameter considers only the zones that contain hydropower plants, that are the zones represented in the Figure 4.11

NB: The normalization process based on zones does not consider the fact that multiple power plants could exist within a single zone. This issue is addressed in more details in Section 4.3.

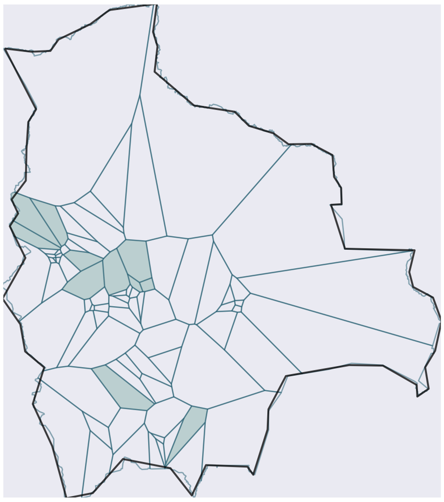


Figure 4.11: Zones containing hydropower plants in Bolivia.

4.2.4 Adding inflows to the power plants

Once the inflows are computed by zone, hydroelectricity is integrated into the network by attributing these inflows per powerplant. This is done by the `add_electricity` rule. The computed inflow values are then assigned to the respective power plants using different variables, depending on the specific type of hydropower plant enabling the future computation of the maximum power output for each hydropower plant. These inflow values are essential for determining the power generation capacity of each hydro generator, taking into account the available water inflows.

Since the `hydro profile` file contains data for 81 zones instead of individual power plants, the `add_electricity` function creates a new variable called `"inflow_t"` to store the inflow time series specifically for zones that contain hydro power plants (zones showed in Figure 4.11)

Adding hydropower plants to the network

As can be seen in figure B.1, the 27 power plants introduced in the `powerplant` CSV file are distributed around the zones determined previously, as represented in Figure B.1. The inflow has to be considered for each of these power plants according to the region they are in.

When adding hydropower plants to the network, the `add_electricity` function handles the inflows differently based on the type of power plant.

The run-of-river (RoR) For run-of-river power plants, the function computes the `p_max_pu` variable, representing the maximum power output, by using the inflow data and the nominal capacity of the plant. This computation ensures that the power output is limited by the plant's rated capacity and the available water inflows. The process is depicted in Figure 4.13.

For each run-of-river power plant, the corresponding inflow time series is selected using the plant's bus ID and divided by the nominal power of the generator. This division yields the maximum available power output as a function of time. The `p_max_pu` attribute of the generator is set to this corrected maximum power output. If the ratio of the maximum power output to the rated capacity exceeds 1, the code limits it to 1 since the generator cannot produce more power than its rated capacity.

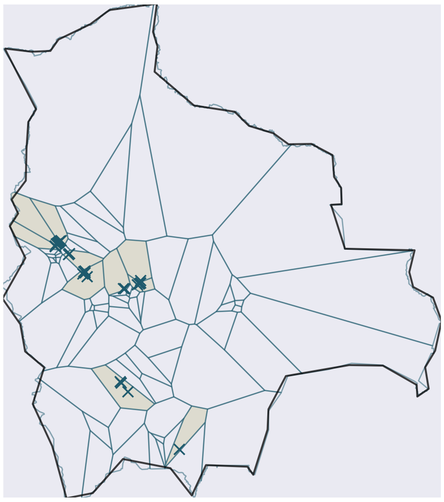


Figure 4.12: Hydropower plants location and zones.

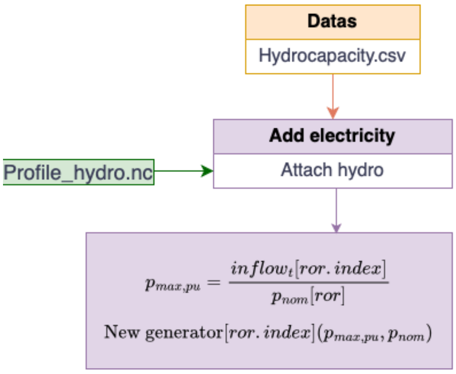


Figure 4.13: Data scheme for the allocation of Run-of-River power plants within the model.

The reservoir-based hydropower plants Unlike run-of-river power plants, reservoir-based hydropower plants are able to store energy for later use, allowing for more flexible and optimized usage of hydro resources. However, in the context of the `add_electricity` function, determining the `p_max_pu` variable for reservoir-based power plants is not possible since it depends on the optimization process of the model, which determines the optimal energy storage.

To account for the influence of inflows on reservoir-based hydropower plants, the `add_electricity` function introduces an `inflow` parameter. This parameter represents the inflow data, which indicates the water inflows into the reservoirs over time. However, it does not directly determine the power output. Instead, it serves as an input to the optimization model, allowing it to determine the most efficient way to store and use the available energy within the hydro reservoirs.

The method used for assigning power plants of the reservoir type is illustrated in Figure B.2.

Storage units are added to the network and their nominal power is assigned based on the `p_nom` values from the hydropower plant information. The `max_hours` parameter determines the number of hours the reservoir can sustain power generation at its maximum capacity. It represents the energy-to-nominal power ratio and is typically calculated based on the volumes indicated in the power plant CSV file for each power plant, scaled to match historical data at the national level. However, in this

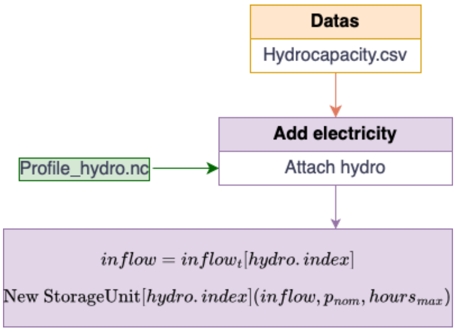


Figure 4.14: Data scheme for the allocation of Reservoir power plants within the model.

implementation, the default value of 6 hours is used for all reservoir-based power plants, this value will have to be changed and this issue is discussed in section 4.3

Furthermore, the corresponding inflow data for the hydropower plants is selected using the `inflow_t` variable. This inflow data will be used in later stages to compute the maximum power output, taking into account the efficient use of the storage functionality.

4.2.5 Distribution per clustered zone

In the `solve_network` function, the hydropower plants are considered by clustering them into three zones: BO0, BO2, and BO3 as can be seen in figure B.3. The clustering is based on the geographical location of the power plants and aims to group them together for the purpose of analysis and computation.

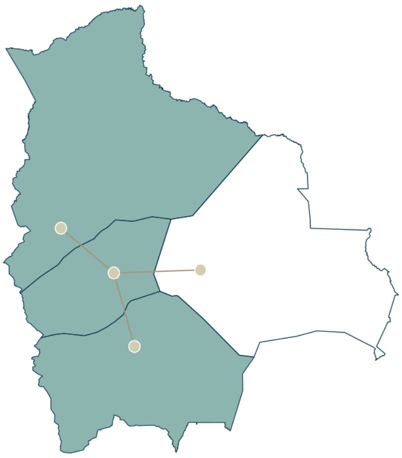


Figure 4.15: Clustered zones containing hydropower plants.

After the `solve network` rule is executed, the results include new time-series values for each zone. These values provide important information about the hydropower plants, such as:

- **p :** The power output of the hydropower plants in each zone every timestep
- **p dispatch :** The dispatched power from the hydropower plants, taking into account the network constraints and optimization objectives (refers to the optimal power flow)
- **state of charge:** The state of charge of the storage units associated with the hydropower plants.

4.3 Problems regarding the modelling of inflows in Pypsa-Earth

1. **Assumption of a single hydropower plant per zone and Normalization**

   In the context of normalized inflows in PyPSA-Earth, the assumption is made that each zone contains only one power plant. This simplification facilitates the representation and management of the power system, streamlining the modelling process.

   However, a potential challenge arises when dealing with multiple power plants within a single zone. In such cases, the sum of the inflow values from each individual plant can significantly exceed the national inflow data used for normalization. This discrepancy arises because the normalization process is performed at the zone level (in the build renewable function), considering the aggregated inflow values, rather than at the individual power plant level.

   By consequence, when there are numerous power plants within a zone, the total inflow calculated based on individual plant data may not match the national-level inflow data used for normalization purposes. This inconsistency can introduce inaccuracies in the modelling results and affect the reliability of the normalized inflow values.

   It is important to be aware of this issue and carefully consider the implications when modelling systems with multiple power plants per zone. Adjustments or alternative approaches may be necessary to address this challenge.

   In this thesis, the identified solution to address this significant problem is to use historical data for inflows, bypassing the PyPSA inflow computation. Further details on this approach are provided in the model adjustment section, more specifically in subsection 5.4.

Issue request on the GitHub repository

The problem of multiple power plants per zone and its impact on the normalization process was detected in the modelling of inflows using PyPSA-Earth. After discussing the issue with the developers of the model, it was confirmed that this is a challenge that needs to be addressed. To track and resolve this problem, alternatives were discussed with the developers. However, to keep consistency with the functions used in the rest of the modelling, they will address the issue themselves
Link to the GitHub issue request: `https://github.com/pypsa-meets-earth/pypsa-earth/issues/759`

2. **Storage consideration in reservoir-type plant:**

   As explained in section 4.2.4, reservoir-type power plants in PyPSA-Earth are represented by storage units with a parameter called `hour_max`, which indicates the number of hours the reservoir can sustain power generation at maximum capacity (energy-to-nominal power ratio). Ideally, this parameter should be determined based on the volumes specified in the power plant CSV file for each plant, scaled to match historical data at the national level.

   However, the current implementation of the model does not consider the input data (volumes) provided by the power plant file. Instead, a default value (6 hours by default) is assigned to all reservoir-type plants, which is determined in the `add_electricity` rule. This default value does not account for the varying storage capabilities of different power plants, leading to inaccurate modelling results.

   To address this issue, it is essential to modify the model to consider the volume data provided in the power plant file for each reservoir-type plant.

Issue request on the GitHub repository

To track and resolve this problem, we have discussed the issue with the developers and other collaborators of PyPSA-Earth, who agreed that this is indeed a bug in the model. An issue request on the GitHub repository of PyPSA-Earth has been initiated and this feature has been planned to be added.
Link to the GitHub issue request: `https://github.com/pypsa-meets-earth/pypsa-earth/issues/760`

3. **Limited data resolution:** Since the inflow time series is selected based on the power plant bus ID, the method assumes that all generators connected to the same bus will experience the same inflow. This can lead to inaccuracies in situations where the inflow changes significantly within the same zone or sub-zone, or where multiple hydropower plants are connected to the same bus but experience different inflow conditions.

4. **Ignoring upstream water use:** The method does not account for upstream water use, which can significantly impact the inflow at downstream hydropower plants. This can be particularly problematic in areas where there are multiple generators in cascade in a hydroelectric system, such as in Bolivia. Upstream water use by other generators or water users can reduce the available inflow for downstream generators, leading to inaccurate estimates of available hydropower.

Chapter 5

Model adjustment to the Bolivian case

As described in Section 4.1, the initial application of the default PyPSA-Earth model to simulate the Bolivian energy system revealed obvious disparities between the model's outcomes and historical data. To ensure an accurate representation of the Bolivian energy system, further changes are essential. This section delves into the specific adjustments made to the original PyPSA-Earth model to better match with historical results for Bolivia.

5.1 Adjusting the clustering process for accurate spatial representation

Among the issues highlighted by the initial model run, the clustering process was of significant concern. When configured to cluster into more than four zones, the process resulted in a single isolated node created. This phenomenon led to a substantial portion of the demand having to be met solely by the isolated node, causing a significant imbalance between demand and production. Various enhancement strategies were explored (detailed in Appendix C), including adjusting the bus group tolerance or enforcing the connection of lines. However, the ultimate decision was to work with a 4-cluster version of the model which is shown in Figure 5.1

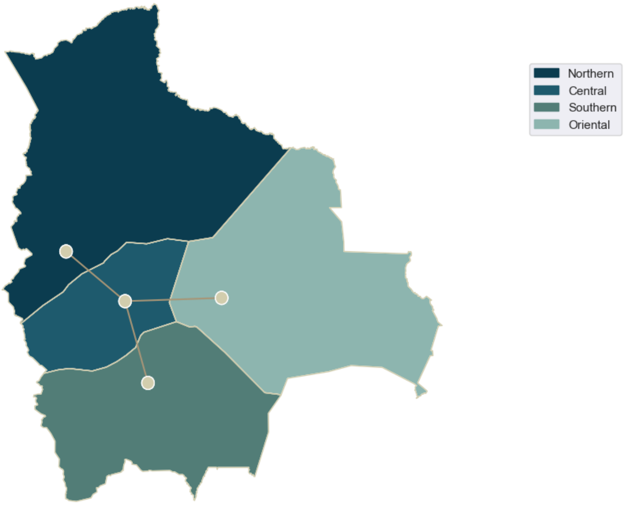


Figure 5.1: Representation of the 4 buses division of Bolivia returned by PyPSA-Earth.

This 4-cluster representation effectively matches with Bolivia's four main geographical zones. This design choice accurately captures regional diversity and leverages existing research in Bolivia. Using this 4-node representation, the clustering process can account for the unique attributes of each zone, leading to a more accurate analysis and modelling of the energy system. This approach considers the specific demands, resources, and limitations of each region, and aids in identifying tailored challenges and opportunities. These insights are crucial for devising sustainable energy strategies and promoting focused development.

5.2 Generator configuration

Custom Power Plant File Creation To align the specifications of installed power plants in PyPSA-Earth with available literature, a `custom power plant` file must be created. This file allows for the modification of power plant data, enabling adjustments that overwrite default values sourced from OpenStreetMap (OSM).

The existing hydro powerplants, both installed and planned, along with their categorization as RoR (Run-of-River) and Reservoirs, are outlined in Table A.2 in the Appendix.

The distribution per carrier is shown in Figure 5.2, providing a comparison between the results before and after the adjustment process. This comparison highlights a total installed power capacity of 3.24 GW across 263 generators. Through this comprehensive modification, the power plant representation has been successfully aligned with the actual data, resulting in a significant improvement.

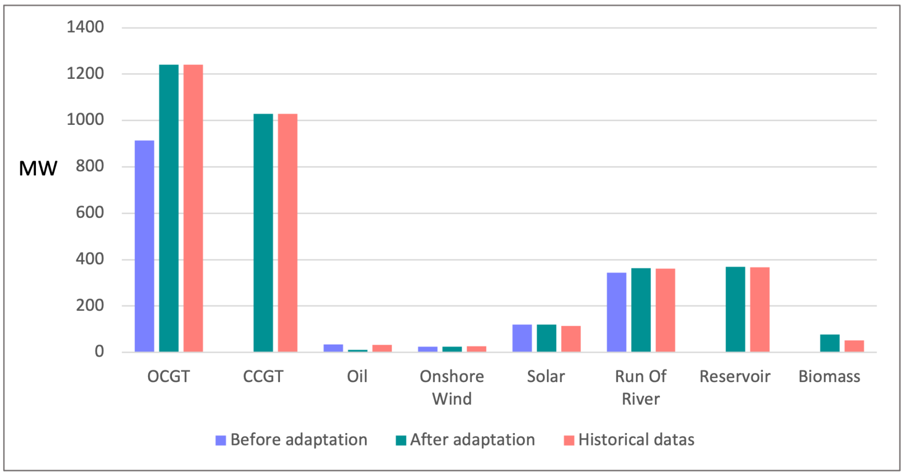


Figure 5.2: Installed capacity validation.

To visualize the impact of these changes, Figure 5.3 displays the spatial distribution of the adapted installed powerplants. This depiction can be compared to Figure 4.6 to observe the notable improvement resulting from the adjustment process.

5.3 Demand projection

Demand projection for 2020

In PyPSA-Earth, the demand profile time-series is determined through projections that incorporate GDP, weather, and population data. These projections are developed within the framework of a specific Shared Socio-economic Pathway (SSP) scenario, specifically set to SSP2. [1]. These demand projections

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[1] The Shared Socio-economic Pathway (SSP) framework is employed in climate change research to explore possible future societal and economic conditions. SSP2 represents a middle-of-the-road scenario characterized by moderate population growth and balanced economic development. It avoids extreme shifts toward rapid growth or decline in both population and GDP [38]

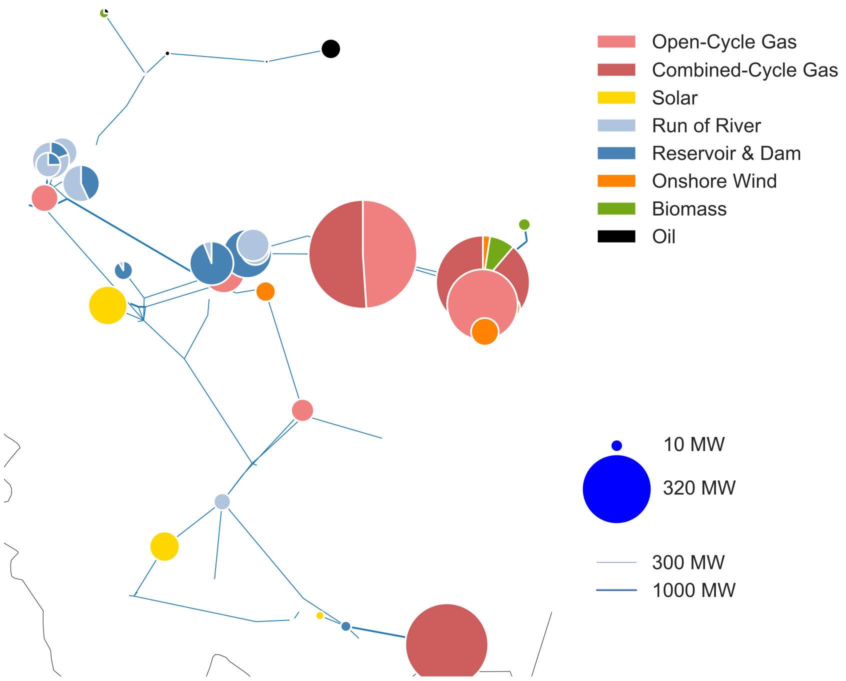

Figure 5.3: Map of power plant installed capacity after adjusting the model.

span the years 2030, 2040, 2050, and 2100 and are formulated based on the typical characteristics of available meteorological data from specific weather years (2011, 2013, or 2018). Table 5.1 illustrates the load predictions for different years, each associated with the respective weather year.

Table 5.1: Demand predictions for different forecasts years and weather years.

Prediction Year	**Weather Year 2011**	**Weather Year 2013**	**Weather Year 2018**
2030	10.959 TWh	11.338 TWh	11.269 TWh
2040	14.156 TWh	14.655 TWh	14.558 TWh
2050	19.545 TWh	20.184 TWh	20.051 TWh

The choice of weather year has an impact on the results, as the total yearly demand for the same prediction year can increase up to 3.5% when a different weather year is used. Such variations in demand could have a substantial impact on the total system cost if additional demand requires investments in more expensive technologies. Furthermore, the demand values are consistently higher for the weather year 2013, which is used for all the scenarios.

To estimate the demand for past years, such as the base scenario we are considering in 2020, the demand projection needs to be scaled using a scaling factor. According to the CNDC database [3], the total demand for 2020 is reported as 9.212 TWh. Consequently, the demand must be scaled down to the desired level, which can be achieved by adjusting the scaling factor in the configuration. In order to reach a demand of 9.212 TWh using the weather year 2013 and the prediction year 2030, a scaling factor of 0.84 is applied.

Future demand projections

Future demand predictions depend on numerous parameters, which fluctuate according to different scenarios. Fernandez Vasquez's paper in 2022 [41] studied Bolivian demand projections for 2050. This study considered various scenarios, encompassing a Business-As-Usual (Business As Usual (BAU)) scenario as well as scenarios influenced by other parameters. Within this paper, future demand projections will be done by scaling these established demand values.

Typical future projections values from CNDC can be found in Appendix F

5.4 Change of the inflows input data

As discussed in Section 4.2, the inflow computation in PyPSA-Earth currently has several bugs and issues, particularly with the normalization process (for which the model improvements are depicted in Appendix D and an issue request have been made). Therefore, it was decided to bypass the inflow computation in PyPSA-Earth and directly provide the available inflow data for the power plants in Bolivia.

Inflows input datas

Previous studies (referenced in Section 3.1.2) have extensively analysed the hydroelectricity data, including inflow measurements, in great details. For example, the SDDP system has been extensively employed in various studies and assessments [14], establishing a robust and validated dataset for inflow computations per power plant. It accurately captures the raw measurement data from ENDE [2]. In order to improve the accuracy and reliability of the inflow data used in the `add_electricity` rule (discussed in Section 4.2), the original inflow data will be replaced with measurements derived from the SDDP system.

The SDDP system provides inflow data at the power plant level, enabling a benchmarking process to compare the names of power plants in the SDDP dataset with those in the PyPSA model.

Figure 5.4 illustrates the inflow values obtained from SDDP. On the left side, the graph displays the data for each power plant in Bolivia, while the right side shows the mean per unit values for the entire country.

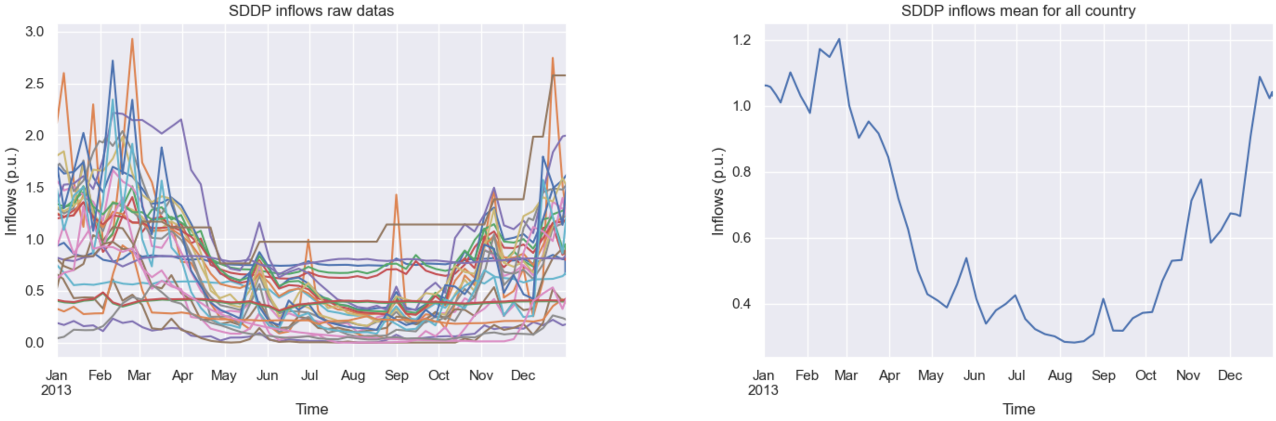

Figure 5.4: SDDP hourly inflows values: raw data.

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[2] ENDE is the national electricity company of Bolivia [15] It is a state-owned company responsible for the generation, transmission, and distribution of electricity throughout the country.

As it can be seen, the provided SDDP inflow values are expressed in per-unit format and normalized between 0 and 1. It is important to note that some values may exceed 1, indicating either a potential shortage for RoR type power plants or the presence of reservoir-type power plants with storage capabilities. In the case of inflows greater than 1, an evaluation is required to determine the feasibility of storing the excess inflow to mitigate hydropower production variability. This process is explained in the paragraph about the behaviour of hydro storage.

The per unit value is later adapted to the capacity of every power plant as it is represented in Figure 5.5. These results lead to a total yearly production of 4.13 million MWh.

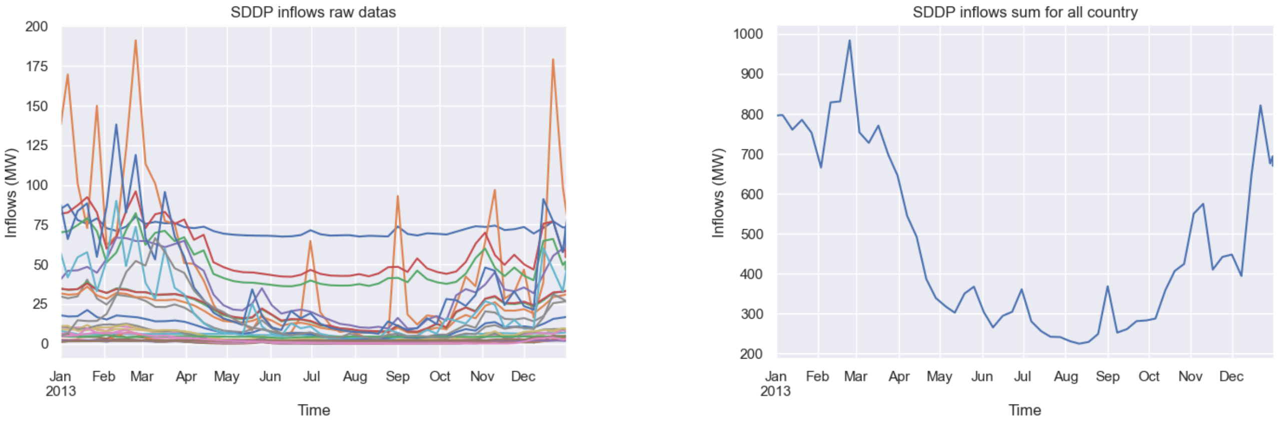

Figure 5.5: SDDP hourly inflows values: data scaled with capacities

Processing of the inflow data by the system

The inflow data obtained from the SDDP system is processed by the PyPSA-Earth model to estimate the power production of hydroelectric plants in Bolivia. Figure 5.6 analyses how these input data are processed and show the results generated by the model. It compares the raw inflow data from the SDDP system, scaled in MW (as shown in Figure 5.5), with the power production computed by the model considering two scenarios: one where all power plants are treated as reservoir-type plants and another where all power plants are considered as run-of-river plants. It is important to note that the storage capability is currently set to 6 hours, although a more detailed analysis of storage will be discussed in a future section.

Figure 5.6 provides a daily sampling of the storage power results for more visibility. These fluctuations will be subjected to a detailed exploration in the subsequent section on energy storage (referenced in Figure B.4 in the appendix for an hourly representation).

During the dry season, the power production curve for RoR plants closely follows the pattern of the SDDP data, indicating that the RoR plants effectively use the available inflows.

This disparity could stem from differences in how power plants are accounted for in the two sources. The SDDP database treats power plants as individual entities, measuring the output power of each distinct power plant. In contrast, the Pypsa-earth model groups all the power plants together within a clustering zone, resulting in a combined power output for that zone. This aggregation approach in Pypsa-earth might lead to less precise predictions compared to the detailed individual plant approach in SDDP. This discrepancy becomes particularly significant during the rainy season when inflow levels tend to be higher.

Additionally, during the dry season, the power production from the storage-type hydropower plants remains slightly lower than the RoR power production throughout the period. This can be attributed

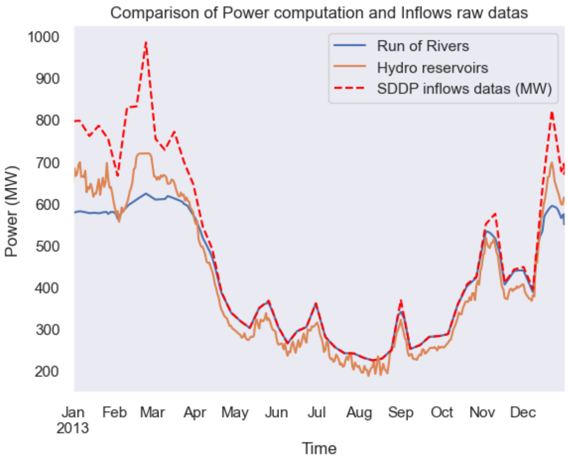

Figure 5.6: Computed hydropower with SDDP data: comparison of Run-Of-River and Reservoir.

to the effective use of the storage capacity by the storage-type plants, which strategically store the excess inflows to ensure a steady power output during periods of low inflow.

One notable observation is that the total power production result does not exceed the total installed capacity of the country, which is 732.2 MW. This suggests that the model is effectively predicting power generation within the boundaries of the installed capacity limits.

Results for a mix of ROR and Reservoir type

In order to reflect the real power system in Bolivia, a mix of run-of-river (ROR) and hydropower plants was considered in the model (it has been explained in Appendix A). This approach considers the different inflow patterns and storage capabilities of these power plants, resulting in a more comprehensive assessment of the power system's performance.

Figure 5.7 illustrates the results for the total hydropower generation (mix of reservoir and ROR power plants) in Bolivia computed by the model.

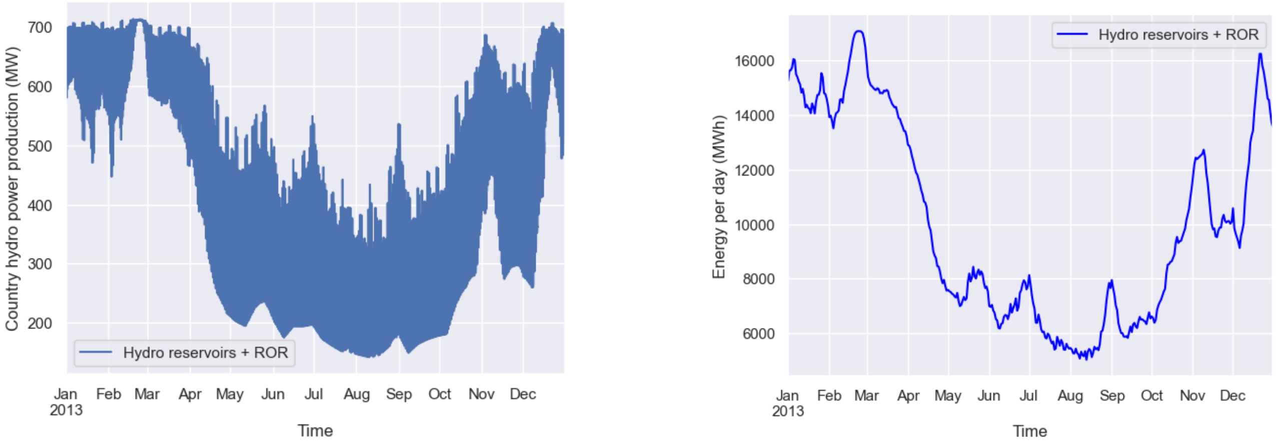

Figure 5.7: Results of hourly hydropower production computed, with SDDP data, considering reservoir and RoR type power plants

On the left side of the figure, the hourly power generation data is displayed, while the right side shows the same data aggregated on a daily basis to determine the daily energy production. The total yearly power production for this mix of the reservoir and ROR power plants amounts to 3.65 million MWh.

Verification of total yearly production with CNDC data

To validate the results, they have been compared with the CNDC (National Dispatch Center for the Unified National Electricity System) data [13]. As shown in Figure 5.8, we observe that the power generation calculated using the SDDP data in PyPSA-Earth is significantly higher than the historical data provided by CNDC, which indicates a total yearly energy production of 2.507 million MWh.

This discrepancy can be attributed to the fact that the power plant efficiency is not taken into account and a fixed multiplier, as explained in the normalization section (Section 4.2.3), is set to 1.1. Additionally, the difference between the dry and wet seasons is more marked in the PyPSA-Earth results compared to the CNDC data, suggesting a potential mismatch in the representation of storage, which will be further discussed in the subsequent storage section.

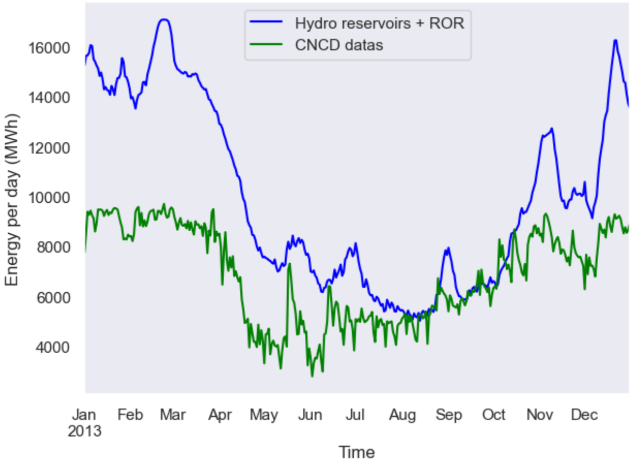

Figure 5.8: Hydropower computation compared with CNDC data.

Note that once again, in the graph, the results for the power produced by storage devices are sampled and summed by day to enhance visibility and analysis.

Behaviour of hydro storage

To accurately represent the inflow behaviour in our model, we need to consider the hour of storage for the reservoir-type power plants. Currently, the model has a limitation where it only allows one same value of the parameter `max_hour`, for all the reservoirs. Therefore, we will determine the hour of storage [3] by dividing the total storage capacity (which is approximately 500,000 MWh) of all the reservoirs in the country by their total nominal power.

$$\texttt{max\_hour} = \frac{500000[MWh]}{369.67[MW]} = 1352[h]$$

This calculation yields a value of 1352 hours as the hour of storage this study will use for etablish a constrant on every reservoir-type hydropower plant in the PyPSA-Earth Bolivian model.

Figure 5.9 illustrates how the results change when the maximum storage hours of the hydropower plants are increased from 6 to 1352 hours. The graph presents the sampled results aggregated on a daily basis.

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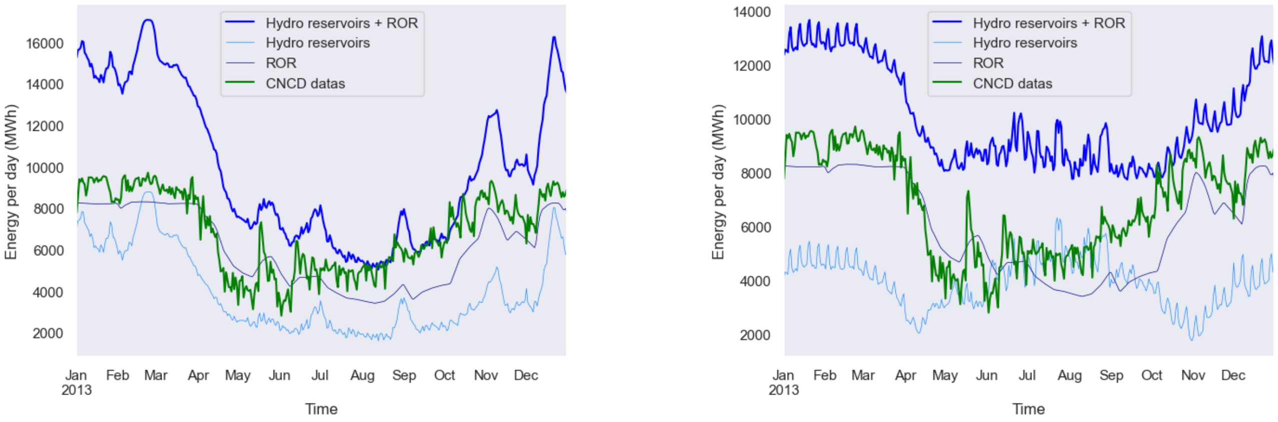
[3] It represents the number of hours that the hydropower plant can continuously generate electricity at its maximum rated capacity without the need for inflow from the river or other water sources



A - Max hour=6 h

B - Max hour= 1352

Figure 5.9: Effects of adjusting maximum storage hours on hydropower computation.

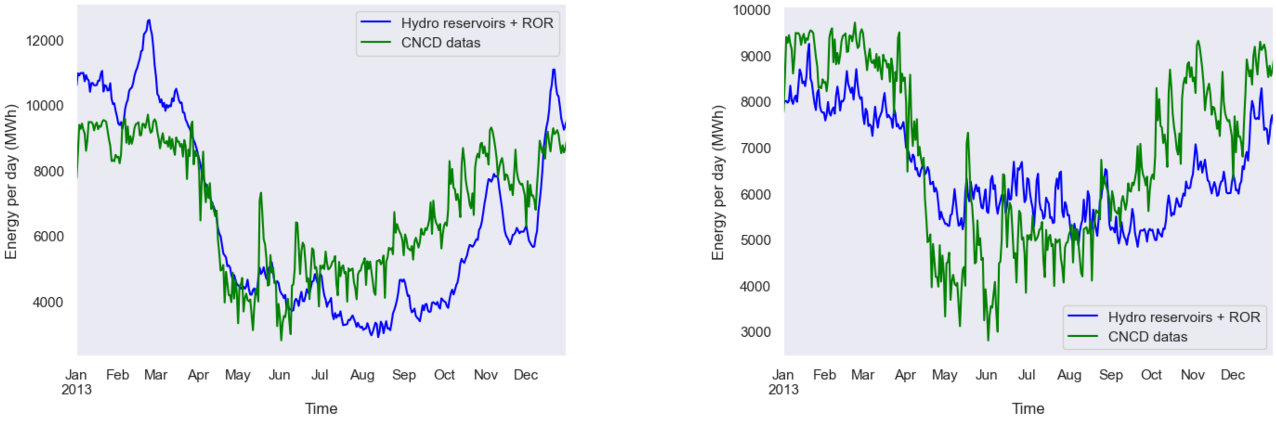
With a maximum capacity of 1352 hours, the reservoir-type plants play a more significant role in power production, particularly during the dry season. Indeed, it can be seen that as the run-of-river plants experience a decrease in production capacity, the stored energy is strategically released during this period, contributing to a smoother power production profile. This usage of storage helps mitigate the impact of low inflows and ensures a more consistent power output throughout the year.

As the storage capacity increases, the seasonal variations in power production become less extreme, and the shape of the results matches with the CNDC data. However, it is important to note that the overall production values are still higher in our model compared to the CNDC data. This suggests that other factors, such as efficiency considerations and the default multiplier, contribute to the observed differences.

To refine the model and improve its alignment with real-world data, further analysis and fine-tuning of the storage representation are necessary.

These observations highlight the influence of storage capacity on the power system's behaviour and emphasize the importance of accurately representing storage characteristics in the modelling framework.

Figure 5.10 illustrates the impact on hydropower production modelled by the system when a scaling factor is applied to the given inflow input. Notably, the modelled results closely matches with historical data from CNDC.



A - Max hour=6 h

B - Max hour= 1352

Figure 5.10: Impact of applying a scaling factor on hydropower production.

Chapter 6

Validation of the model

In this chapter, the model results will be compared to historical values to see if the changes that have been done to the model allow it to reflect properly the Bolivian model. For the scenarios and the computations results some parameters can be chosen. They are described in the following section.

6.1 Variable parameters

The parameters that can be changed to see their impact on the results are the following:

- Costs associated with different components of the energy system.
- CO_2 objectives.
- Activation of the extensible carriers function.
- Integration of new technologies.

6.1.1 Hypothesis

While some parameters are modified to analyse their impact on the model, the following parameters will be kept fixed:

- The clustering is considered as granted: 4 nodes.
- The power plants are the ones in the custom power file.
- Costs are just taken as EIA costs except the cost of the gas.

6.1.2 Gas price adjustment

As discussed in Section 2.2.1, a significant characteristic of the Bolivian energy system is the exceptionally low price of natural gas, primarily due to government subsidies implemented since 2012. This unique feature has a profound impact on energy dispatch and cost computation in PyPSA-Earth.

The initial gas price fixed in the default file is is 21.6 [EUR/MWh]. It is sourced from IEA 2011 [36], which represents international gas costs. In the cost computation module, the price of natural gas can be adjusted to accurately represent the energy mix in Bolivia. By modifying this parameter, the model can better capture the operational and economic aspects of the Bolivian energy system.

While the natural gas price is adjustable, it is important to note that other cost parameters, such as the lifetime, investment, and prices of alternative fuels, remain fixed to maintain consistency with the original data sources. These predefined values are based on reputable data sources like

EIA, DEA, DIW,... By keeping these parameters unchanged, the model maintains consistency with industry standards and validated information, facilitates result comparison, and ensures reliability when replicating the model for future studies.

Gas fuel cost In the POES 2012 [11], the price is referenced as

$$1.3\ [\$/Mbtu] = \frac{1.3}{1055.06}\ [\$/MJ] = 0.00123 * 3600\ [\$/MWh] = 4.435763138\ [\$/MWh]$$

As it has been explained in section 2.2.1, due to government policies, the gas prices in Bolivia have remained unchanged until now.

It is important to clarify that the gas price mentioned (1.3 [$\$/Mbtu$]) refers specifically to the cost of gas used for electricity production in Bolivia. This price represents the subsidized rate for gas used by power plants to generate electricity. The government subsidies have kept this price unchanged over time, ensuring a stable cost for electricity production. However, it's worth noting that this price may not necessarily apply to other sectors or individual consumers where gas is used for other purposes. [42] [5]

Since all the conversion from dollars to euros has been done by the data from 2013, following conversion ratio will be used: `USD2013_to_EUR2013` : 0.7532

$$3.3410[€/MWh]$$

6.1.3 Price of biomass and maximum generation limitation

In the default cost file of PyPSA-Earth, the biomass fuel price is initially set to 7 €/MWh based on data from the IEA in 2011 [36].

However, as explained in Section 2.3.1, it is challenging to predict the future biomass fuel price with certainty. While the current biomass fuel price in Bolivia stands at zero, reflecting the use of sugarcane residues provided by farmers free of charge, it is unclear whether this arrangement will persist in the future.

To account for potential variations in biomass fuel prices, it would be valuable to conduct sensitivity analyses or scenario simulations. However, in this study focusing on future simulations, we will retain the default value of 7 €/MWh for biomass fuel costs to maintain consistency with the PyPSA-Earth model. It is important to note that researchers conducting similar studies, such as the one conducted by Lopez et al. (2021) [43], have assigned specific prices to biomass fuels, such as 3.8 €/MWh.

Biomass generation limitation

In the PyPSA-Earth model, there is currently no maximum capacity potential set for biomass, unlike solar, wind, and hydropower technologies. The total biomass potential of the country, which is equal to 5.3 TWh with a maximum capacity factor of 72% (see section 2.3.1), results in a maximum installed capacity of 840MW for the whole country.

To establish a realistic value, historical data on capacity increases for biomass plants in other countries, as studied in Ritzkowsky X. thesis [44], suggest a conservative approach of considering a maximum expandable capacity of 50% of the biomass potential. This corresponds to 420 MW installed capacity in the whole country, representing a 637% increase over a 15-year period.

Furthermore, it is important to note that 85% of the installed capacity is concentrated in the Oriental Zone, specifically around Santa Cruz. Hence, the maximum expandable capacity can be allocated by zone, as presented in Table 6.1

Table 6.1: Biomass capacity restriction in PyPSA.

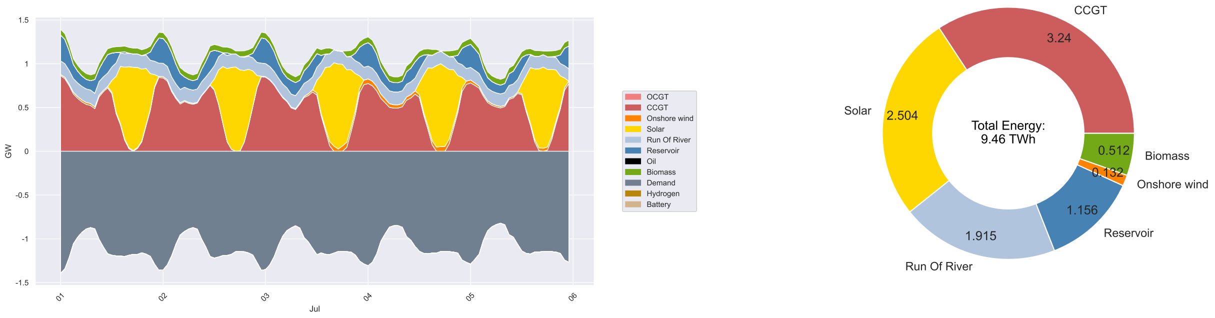
Zone	Share of potential	Theoretical potential
Northern	5 %	42.02 MW
Central	5 %	42.02 MW
Southern	5 %	42.02 MW
Oriental	85 %	714.26 MW

6.2 Validation of the model

6.2.1 Power dispatch

Influence of international gas prices on model adjustment

Figure 6.1 illustrates the energy dispatch outcomes derived from the modified model, where the impact of real gas prices on the Bolivian case has not been taken into account. In Figure 6.1-**A**, the representation showcases the hourly energy dispatch across the entire country from July 1st to 5th, 2020. Within this visualization, the demand curve is depicted in grey, representing negative values, while the production is shown in positive values, with distinct colors assigned to various energy carriers. Transitioning to Figure 6.1-**B**, the cumulative hourly production for the entire year 2020 is displayed in the form of a pie chart. Each energy carrier is uniquely represented by a different color segment within the chart, conveying the composition of the overall production landscape.



A - Hourly energy dispatch for July 2020 period **B** - Yearly total prediction for 2020

Figure 6.1: Energy Dispatch for 2020 prediction after adjusting the model (with international gas prices).

Figure 6.2 illustrates the optimized installed capacity for the year 2020. Initial and optimal capacities of different energy carriers are shown using two adjacent bars for each energy carrier :

- Initial Capacity (left bar): depicts the starting installed capacity for each energy carrier.
- Optimal Capacity (right bar): shows the optimized installed capacity for each carrier.

Each carrier is represented by a different color.

With European gas prices at approximately 21.6 €/MWh , there is a clear need for increased renewable energy production which is not compatible with the actual installed capacity of renewable in Bolivia. To meet this need for renewable, the model uses all the available hydro potential and emphasizes the expansion of solar power generation. Therefore it could be deduced that solar is a better option than other renewables.

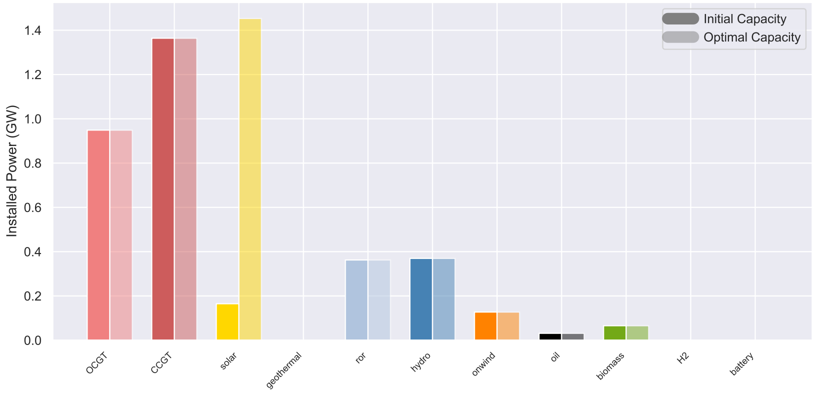


Figure 6.2: Installed capacity, projection for 2020, with international gas prices.

Through optimization, the model extends the installed capacity of solar power from 164 MW (as initially specified in the custom power plant file) to 1,773 MW. This increase in solar capacity is driven by the model's objective to minimize costs and reduce reliance on gas generation, given the high gas prices. As a consequence, solar power contributes significantly to the energy generation mix even if it does not completely displace gas generation, as the total yearly production of solar power is around 3 TWh compared to approximately 3.3 TWh of power production from gas.

Gas price adjustment to the Bolivian case

In Figure 6.3, the final results of yearly operation considering real Bolivian gas prices are shown:

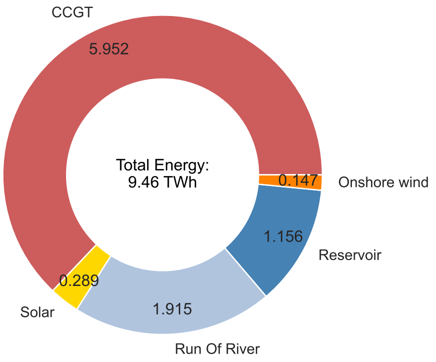


Figure 6.3: Yearly total 2020 dispatch, predicted by the adjusted model

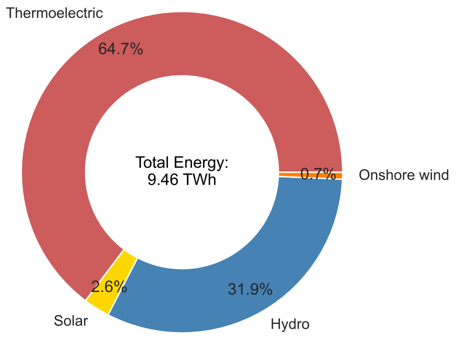


Figure 6.4: Yearly total 2020 dispatch, historical data

By replacing the international gas prices with the lower government-set gas prices unique to Bolivia and implementing policies that promote the economic attractiveness of gas-based power generation, the model's projections indicate a doubling of energy output from gas power plants. This change has minimal impact on the share of hydro energy, while the subsidies significantly curtail the contribution of other renewable sources, particularly solar PV generation. This phenomenon occurs because hydropower, benefiting from its low variable costs, operates at full capacity. However, solar production experiences a huge reduction. In contrast to the initial scenario where the optimization process prompted new investments in solar capacity (as evident in Figure 6.2), the model now prioritizes maintaining the existing installed solar capacity to avoid investment costs. This change reflects renewable's reduced competitiveness compared to gas under its opportunity cost.

Comparing the outcomes depicted in Figure 6.3 with the historical data presented in Figure 6.4 ([2],[3], [5]) reveals a strikingly close resemblance in the distribution of various energy resources. However, it's crucial to highlight that the historical data lacks specific details about thermoelectric power sources (such as CCGT, OCGT, or biomass) and the categorization of hydropower (run-of-river or reservoir-based), which limits precise identification.

Nevertheless, this comparison underscores the accuracy of the results and the successful applicability of the model to the Bolivian context. In terms of total energy production, renewable sources account for 37.1%, whereas historical data indicated a renewable proportion of 35.2% for the year 2020. The detailed breakdown of the distribution among different energy carriers can be found in Table 6.2.

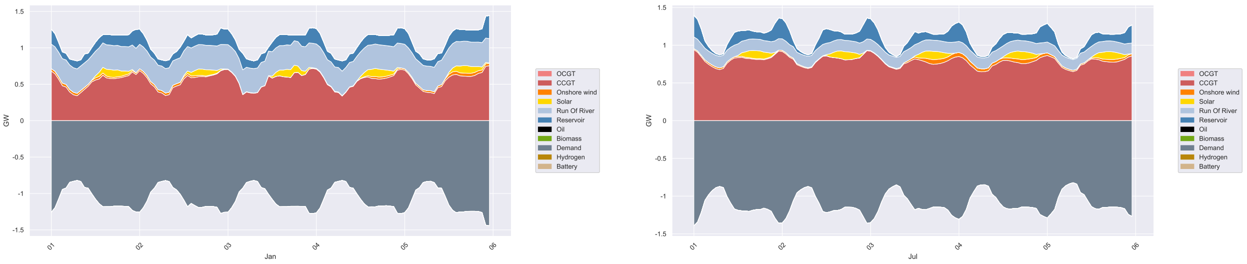
Table 6.2: Comparison of shares of carrier predicted by the model with historical data for the year 2020.

Carrier	Historical	Model's predictions
Thermoelectric (gas+biomass)	64.7 %	62.9 %
Wind	0.7 %	1.6 %
Solar	2.6 %	3.1 %
Hydro	31.9 %	32.4 %

While the model dispatch is matching quite fairly the historical one, some discrepancies in the model's predictions can be observed. Particularly, there's an absence of contribution from biomass sources, which might be attributed to the model not factoring in adjustments to biomass prices discussed in section 6.1.3. Furthermore, the model's prediction of gas production relies solely on CCGT, which differs from the real life situation where there is a mix of OCGT and CCGT. This divergence arises because Bolivia's installed CCGT capacity adequately meets the gas-powered energy demand, leading the model's optimization to favor these more efficient power plant types over OCGT. This logical situation raises questions about the real-world mix of power generation technologies and the role that OCGT plants play in Bolivia's energy generation.

6.2.2 Behavior of the hydro model

In this section, we validate the behavior of the model when predicting hydropower generation using the final model configuration explained in the previous section. This model depicts very well the 2020 historical data. This validation is facilitated by Figure 6.5, which provides insights into the hourly energy dispatch for different periods.



A - January 2020 period

B - July 2020 period

Figure 6.5: Hourly energy dispatch for 2020 prediction, after adjusting the model (with Bolivian gas prices).

The analysis of these two distinct periods of the year confirms the model's accuracy at depicting hydroelectric power genera6on

During the rainy season, depicted in Figure 6.5.**A**, the model showcases a prominent reliance on hydropower production, contributing significantly to daily energy output. This model's matching is especially apparent in the dominance of run-of-river (ROR) hydropower plants, showcasing their effectiveness during this season.

Conversely, the dry season, represented by Figure 6.5.**B**, demonstrates a strategic shift towards gas-based production, while still maintaining a level of hydro contribution. In this scenario, the model highlights the role of reservoir-type hydropower plants in complementing the energy supply. These reservoirs, charged during the rainy season, are effectively used during dry season, particularly during hours of peak demand.

The model's successful representation of these dynamic shifts validates its ability to capture the intricate behavior of hydropower generation and its ability to take seasonal variations into account. The incorporation of hydro storage capacities showcases how reservoir-type hydropower plants can serve as valuable energy sources during dry season, contributing to a resilient and adaptable energy supply system.

6.2.3 Demand coverage

In section 4.1.2, the need for model adaptation was discussed to address the issue of energy generation exceeding the demand, a result from the load-shedding technology in isolated zones that are not included in the national interconnected system (SIN).

To solve this issue, the model was changed by focusing solely on the network within the SIN. Through the adjustment of the clustering process, the model achieved a good balance between energy production and demand, ensuring that the energy generated closely matches the demand within the network.

Table 6.3: Demand and production data from the simulation for 2020 (final configuration).

Characteristics	**Values**
Demand	9.46 TWh
Production	9.56 TWh
Load shedding	0 TWh
Yearly enegy stored	0TWh

Table 6.3 presents an overview of the demand and production data obtained from the simulation for the year 2020, reflecting the completed model configuration. The model's outputs exhibit a close match to the real-world data for Bolivia. This matching between simulated and actual values emphasizes the efficacy of the model's refinements in establishing a harmonized energy system that maintains equilibrium between demand and production.

6.2.4 Costs and prices

The subsidies provided for gas in Bolivia have a substantial impact on the price of electricity production and the Levelized Cost of Electricity (LCOE). With these subsidies, gas power generation becomes more cost-effective, leading to a reduction in the price of electricity for consumers. Additionally, the subsidies contribute to lowering the LCOE for gas-based electricity production by reducing operational and investment costs. As a result, gas power plants become more economically competitive on the energy market. These effects on pricing dynamics and cost competitiveness highlight the significant influence of subsidies on the affordability and feasibility of gas power generation in Bolivia. This evolution of the prices can be observed in the figure 6.4.

Table 6.4: Prices and costs comparison.

	With international gas prices	With current Bolivian gas prices	Historical data
Total yearly cost [€]	$264.54e6$	$76.9e6$	/
Marginal price [€/MWh] (yearly mean)	41.73	11.3	13.84 [45]

The average annual marginal cost for the year 2020 was 13.84 (€/MWh) (without tax), with a minimum monthly average of 11.38 (€/MWh) and a maximum monthly average of 16.27(€/MWh). [16]

Chapter 7

Evaluating Energy Scenarios in a Changing Climate

This chapter uses the customized PyPSA-Earth model to create predictive scenarios for the future, using the model's potential for strategic decision-making. By analyzing the results, the advantageous features of PyPSA-Earth that offer valuable insights for policymakers can be highlighted. The potential impact of global warming on hydropower production in Bolivia will be of special interest

7.1 Scenarios

2020 Baseline

This scenario represents the energy mix in Bolivia in the year 2020, incorporating multiple inputs that have been adjusted based on historical data. These inputs include factors such as the cost of subsidized gas, the existing legacy capacity[1], and the hydropower inflow data. Detailed explanations regarding the adjustments made to the model to accurately represent Bolivia's energy mix are provided in Section 5. Moreover, the demand in this scenario has been adjusted to match the documented total annual demand of 9.46 TWh in 2020, as elaborated in Section 2.4.

2050 BAU

The 2050 BAU scenario provides a Business As Usual projection for Bolivia's energy development in the year 2050. It assumes that current trends and practices will continue without significant deviations, considering the actual conditions without additional changes or policies [41].

The demand projection for this scenario, as calculated in Fernandez Vazquez's 2023 paper, based on the results of OSeMOSYS [41], indicates that the total energy demand in 2050 would be nearly three times higher, amounting to 669.3 PJ, with an electricity share of 10.9%. This results in an estimated electricity demand of 20.26 TWh.

Considering a BAU evolution, no $C0_2$ emission limit has been fixed.

In this BAU projection, the impact of the following parameters needs to be analysed:

- **Decommissioning of old power plants:** The BAU scenario assumes that all gas power plants in Bolivia will be decommissioned by 2050. However, it is important to consider the possibility of retrofitting these power plants, which may offer an alternative option. To gain a comprehensive understanding, two scenarios will be analysed: one scenario with the decommissioning of old

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[1] In this context, "legacy capacity" refers to the existing installed capacity of power plants that were operational prior to the scenario's focal year

power plants and the other one considering retrofitting them. This comparative analysis will provide insight into the impact of the retrofitting option on the energy landscape.

- **Using international gas price:** Currently, the model assumes the current Bolivian gas price for future projections that are influenced by government policies. To gain a comprehensive understanding, it is necessary to assess how the model's outcomes for the future would change when using international gas prices. This analysis will help evaluate the change in the future energy mix related to different gas pricing policies.

By understanding the consequences of a change of these parameters, policymakers and stakeholders can make informed decisions about Bolivia's energy future in the BAU scenario.

2050 Carbon Neutrality (CN)

The CN scenario assumes that Bolivia has reached the zero CO_2 emission goal by 2050. Indeed, the CO_2 limit parameter of the model then needs to be set to 0.

To have a precise projection of the demand with this goal, some demand-side parameters should be taken into account such as the Energy Efficiency Measures (EEM) and the Electrification of Energy Demands (EED), for a consideration of the 0 emission limit applied to the total energy system, inducting a necessity to replace all the fossil fuel demand by electricity. [41]

However, due to the uncertainties and approximations associated with these demand-side parameters, applying them may lead to unrealistic or extreme increases in the country's energy demand. As a result, for the purpose of this study, we will ignore these complexities and keep the demand at 20.26 TWh, which aligns with the projections for a BAU demand. This decision is also consistent with this study focusing solely on the electricity sector, excluding complexities related to the total energy demand. For the CN scenario, several different parameter changes are considered as well:

- **Biomass resources limit:** As explained in section 6.1.3, the PyPSA-Earth model currently does not consider a limit on the biomass extension, and thus, it doesn't account for the limited biomass resources in the country. To analyse the impact of this parameter, a constraint can be set to observe the effect on the final energy production.

- **Inflows changes:** One of the primary objectives of this study is to assess the impact of global warming on the changes in inflows and the effect it has on hydropower production. This parameter change will help understand the consequences of altered inflow patterns on the overall energy generation landscape.

7.2 Results

The outcomes of the various scenarios, each incorporating distinct options and conditions, have been simulated. In the following section, we will analyse these results and draw key conclusions about Bolivia's future energy projections using the PyPSA-Earth model. All the projections are made for the year 2050, compared with the baseline year 2020.

7.2.1 Business As Usual

The first results analysed are the outcomes of the scenarios considering the Business As Usual framework, where no specific constraints on CO_2 emissions are set.

Scenario 1: 2050 BAU, no decommissioning

In this first BAU 2050 scenario, the new power plant projects for renewable energy sources are added to the model, these include hydroelectricity, biomass, wind, and geothermal power plants. However, the decommissioning of old gas power plants is not considered, supposing that they are retrofitted. Additionally, the gas price is considered subsidized, an approach similar to the one used for the 2020 baseline scenario explained in Section 6.1.2.

The distribution of total yearly energy dispatch for the 2020 baseline and the 2050 BAU scenario is depicted in Figures 7.1 and 7.2, respectively. Notably, the energy mix of the 2050 BAU scenario appears to rely even more heavily on gas than the one of the 2020 baseline. This outcome is partially attributed to the substantial installed gas power capacity, influenced by both retrofitting and favourable subsidized gas prices. The increase in geothermal and hydropower production is due to the consideration of future power plant projects for 2050. The model does not invest in renewables. Additionally, the available biomass and oil installed capacities are left underutilized. This outcome is closely tied to the cost-effectiveness of gas as a fuel option, with both biomass and oil being relatively more expensive alternatives.

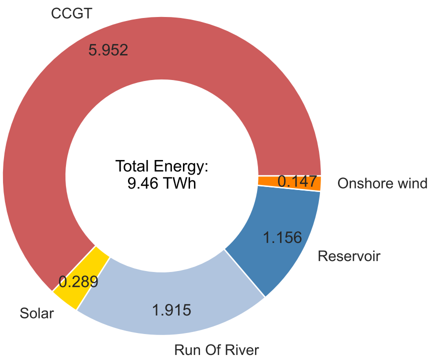


Figure 7.1: Yearly energy production dispatch for the 2020 baseline.

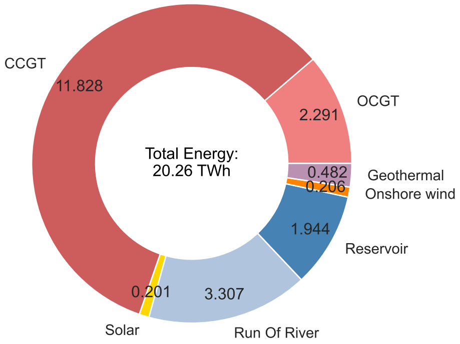


Figure 7.2: Yearly energy production dispatch for the 2050 BAU scenario, no power plant decomissioned

Figure 7.3 illustrates the optimized installed capacity for the year 2050. It visually contrasts the initial and optimal capacities of different energy carriers. Each energy carrier is represented by two adjacent bars representing the initial and the optimal capacity and one colour represents one carrier.

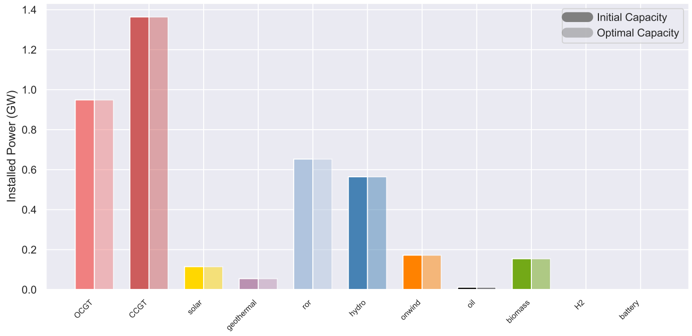


Figure 7.3: Installed capacity for the 2050 BAU scenario, no power plant decommissioned.

In this graph, one interesting outcome of not considering the decommissioning of gas power plants can be seen: no new gas power plants are installed in this scenario. This finding is in step with previous predictions mentioned in Section 2.4. It appears that the existing gas power plant capacity from 2020, after being retrofitted, is still sufficient to meet the increased electricity demand in 2050 although it is more than double the demand of 2020.

Scenario 2: 2050 BAU, considering decommissioning

In this variation of the BAU scenario, the power plants are considered inactive after reaching their designated operational limits (and are removed from the model), resulting in very little legacy capacity from old gas power plants. Indeed, total remaining capacity is about 0.1 GW and consists only of CCGT types. This decommissioning also induces a decrease in the solar and wind installed capacity. This adjustment in the model's configuration enables us to observe how the system responds when there isn't sufficient existing capacity to meet demand. It allows the analysis of the system's expansion capability, strategically employed to invest in the establishment of new power plants.

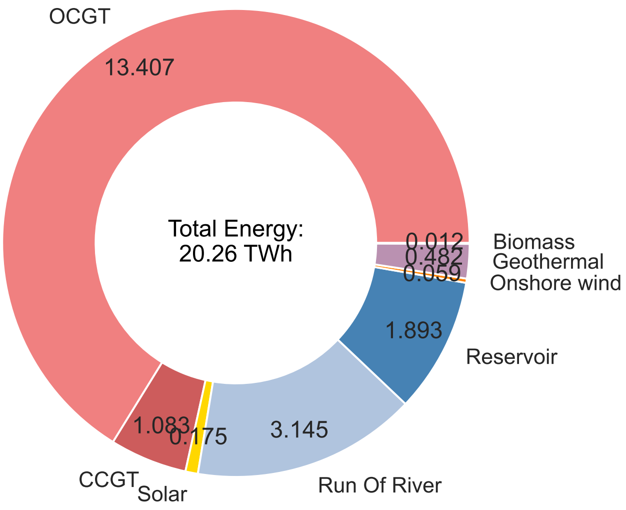


Figure 7.4: Yearly energy dispatch for the 2050 BAU scenario, considering decommissioning.

In Figure 7.4 and 7.5 an interesting result can be showed. When the model starts with no gas plants (in the initial configuration), it deduces that the optimal choice is to exclusively install OCGT gas power plants. This conclusion emerges due to the continued availability of gas at subsidized prices, causing the fuel cost difference between OCGT and CCGT (due to the difference in efficiency) to be negligible compared to investment cost, CCGT costing twice as much as OCGT. Moreover, given the absence of CO_2 emission constraints, the model favors fossil-fuel-based power plants over renewable sources, the gas price advantage being a major factor in investment decisions.

Note: It's important to underline that the model's setup restricts the possibility of expanding hydroelectricity in this specific case. It's worth mentioning that even when attempting the model with the option for expandable hydroelectricity, no discernible alterations in outcomes were observed. This outcome is attributed to the substantial investment costs associated with establishing hydropower plants, coupled with the lack of competitiveness in renewable investments. This lack of competitiveness

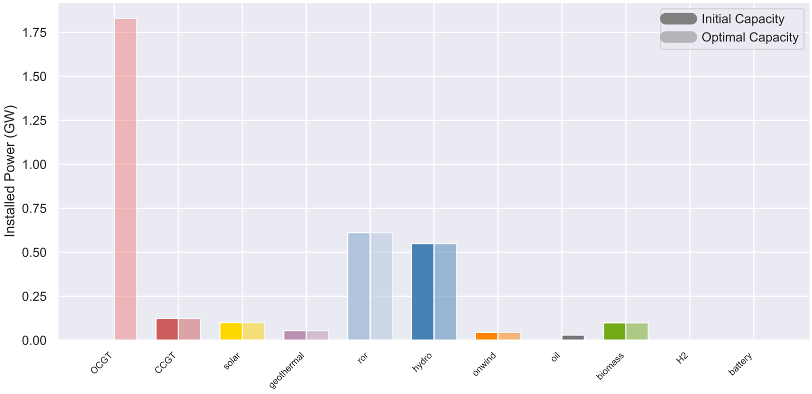


Figure 7.5: Installed capacity for the 2050 BAU scenario, decommissioning considered.

is primarily a result of policy decisions aimed at maintaining cost-effectiveness in gas-fueled energy production.

The installed capacity distribution in the map can be seen in Appendix E

Scenario 3: 2050 BAU, considering decommissioning, without subsidized gas prices

In order to analyse the gas price influence, this last variation of the BAU scenario considers an international gas price. As a reminder, the international gas price is set at 21.6 €/MWh [36], a sharp contrast with the previously subsidized rate of 3.341 €/MWh.

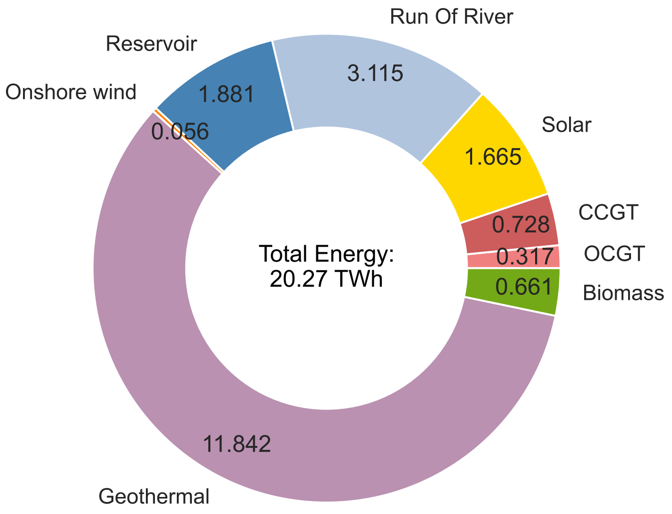


Figure 7.6: Yearly energy dispatch for the 2050 BAU scenario, considering decommissioning, using international gas prices.

This figure shows that, with international prices of gas taken into account, other energy sources gain a competitive advantage over fossil fuel-powered plants. Notably, geothermal energy in Bolivia emerges as a particularly favourable choice, showing its expansion potential, but also solar power. This

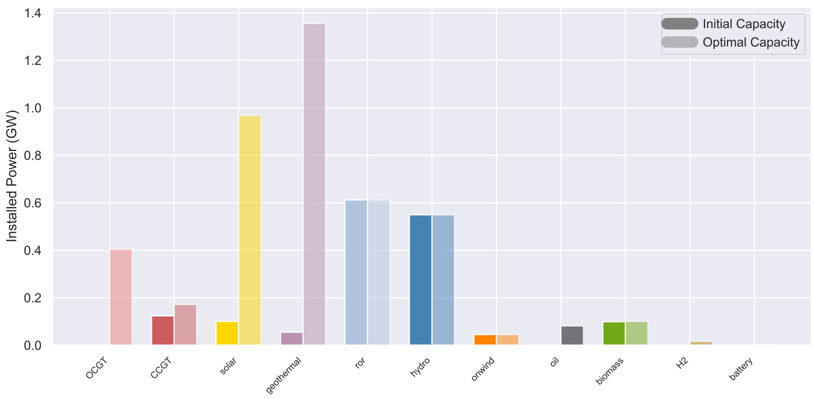


Figure 7.7: Installed capacity for the 2050 BAU scenario, decommissioning considered, international gas prices.

observation leads to the conclusion that the huge gas consumption in Bolivia is primarily a consequence of government policies. This can be seen in Figure 7.6 and 7.7.

Furthermore, it is valuable to examine how the installed power is distributed among the different zones, benefiting from the spatial representation capabilities of the PyPSA-Earth model. Despite having only four zones in this study, analyzing the power plant investments in each zone allows us to have a deeper comprehension of how the model reacts to the characteristics of each zone. In Figure 7.8 the installed capacity is divided into 4 graphs representing the 4 zones. On each graph, for each carrier, the initial capacity (in solid bars) and the optimal capacity (with reduced opacity) are shown.

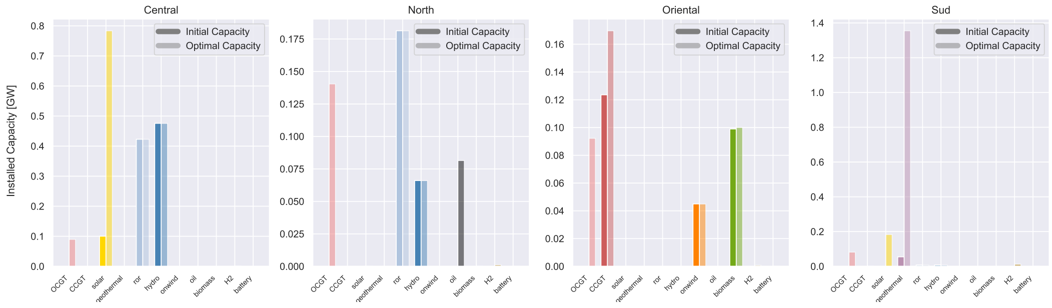
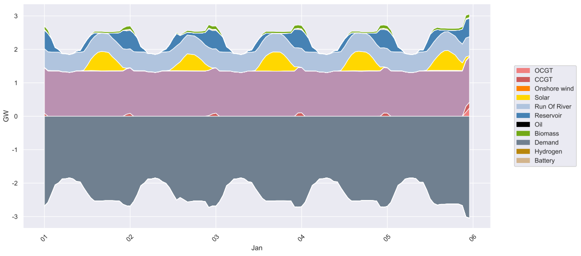


Figure 7.8: Installed capacity per zone for the 2050 BAU scenario, power plants decommissioning considered, with international gas prices.

The insights from Figure 7.8 reveal notable developments in power distribution. Specifically, a substantial increase is observed in geothermal power installation within the southern region. This decision seems to be a consequence of the existing initial installed capacity in this region and it aligns with the region's geothermal potential, as elaborated upon in Section 2.3.1. Solar capacity experiences increases exclusively in the central and southern regions, those being the zones characterized by higher solar capacity factors, as introduced in Section 2.3.1. This emergence of intermittent energy sources results in the installation of storage devices, although at a very low scale.

Looking at the gas power plant installations, a clear pattern emerges within their small shares of the total installed power: a continuation of OCGT power plants is being built, but there's also a noticeable increase in CCGT type units. This shift seems to be a response to strategically allocate CCGT units to meet higher-capacity gas demands, where the investment makes more sense. Conversely, for power plants intended to fill intermittent gaps from renewable sources, a measured adoption of

OCGT units is preferred. This decision is likely based on the understanding that while OCGT units consume more gas, the investment required is lower, making them suitable for occasional use. This pattern can be analysed in the hourly dispatch represented by Figure 7.9



A - January

B - July

Figure 7.9: Hourly energy dispatch for the 2050 BAU scenario, considering decommissioning, with international gas prices.

NB: It is important to consider that biomass and geothermal sources are not subject to limitations imposed by the AtLite library, unlike solar and wind. Therefore, relying solely on geothermal may not be a practical solution.

7.2.2 Carbon Neutrality objective

The following scenarios take an emissions limitation of zero $C0_2$ into account.

Biomass limitation

The total yearly dispatch for the 2050 CN scenario can be seen in Figure 7.10

A - Without biomass limitation

B - With biomass limitation

Figure 7.10: Yearly energy dispatch for the 2050 CN scenario.

As explained in Section 6.1.3, the biomass potential is not limited by the PyPSA-Earth model. As a consequence, biomass is an attractive option motivated by the cheap price of fuel and stable production, especially when compared to the variable output of solar and wind sources that require costly battery investments for stabilization. It's important to note that the model only focuses on the electricity sector, overlooking other potential uses of biomass in heating or industry. While heating demand may not be significant in Bolivia, biomass could still find valuable applications in a broader energy context. As can be seen in Figure 7.10.**A**, the optimized solution for the scenario with zero CO_2 emissions favours the establishment of new biomass power plants, underlining its favourable role within the considered framework.

In Figure 7.10, the impact of constraining biomass energy generation becomes evident. This limitation prompts an escalation in solar production, driven by the zero-emission mandate and the ample solar resources available within the country. In Figure 7.10-**B**, a noteworthy phenomenon emerges: the total energy production experiences an almost 2 TWh increase. This outcome is linked to the fact that when the optimized energy mix comprises intermittent sources like solar, it's predictable that the model integrates storage into the system. The exploration of this storage integration is undertaken in the subsequent paragraph. Nonetheless, even at this stage, it's observable that, owing to inherent losses in storage, the total yearly production must be augmented to sufficiently meet demand.

Renewable extension in PyPSA-Earth

Figure 7.11, shows the optimal installed capacity (compared to the initial capacity) for the last scenario of CN, with biomass limitation.

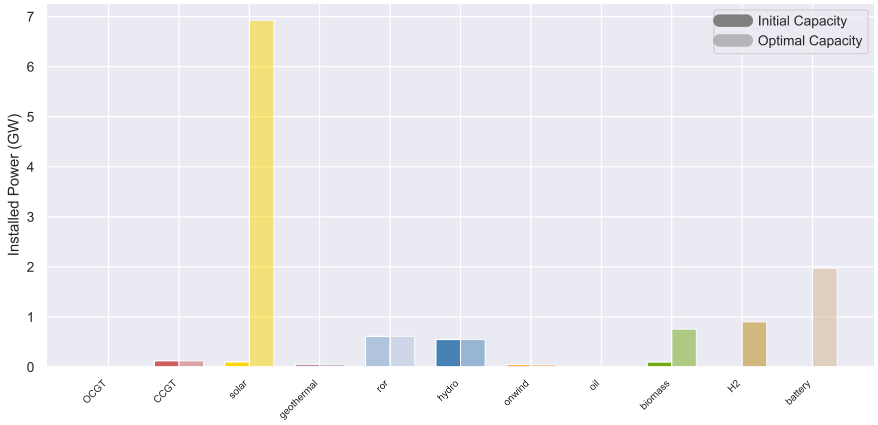


Figure 7.11: Installed capacity for the 2050 CN scenario, considering biomass limitation.

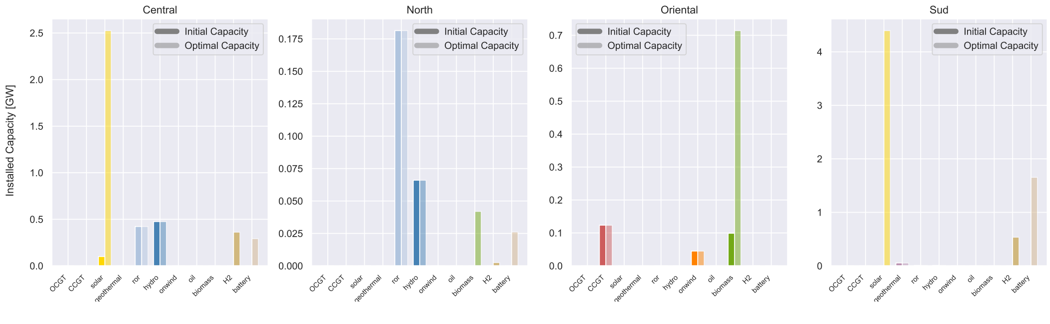


Figure 7.12: Installed capacity per zone for the 2050 CN scenario, with biomass limitation.

Figure 7.12 highlights very well how the expansion function of PyPSA-Earth is working. The solar installed capacity is extended in the regions where the resources are the more abundant (central and south region) (as it can be seen in Figure E.2) and batteries are used in these regions to balance the variability of the solar production. This can also be seen in Figure 7.13 which represents the resulting yearly demand of each carrier, divided by zone. Finally, the installed capacity necessary for this last scenario is represented in the map by Figure 7.14.

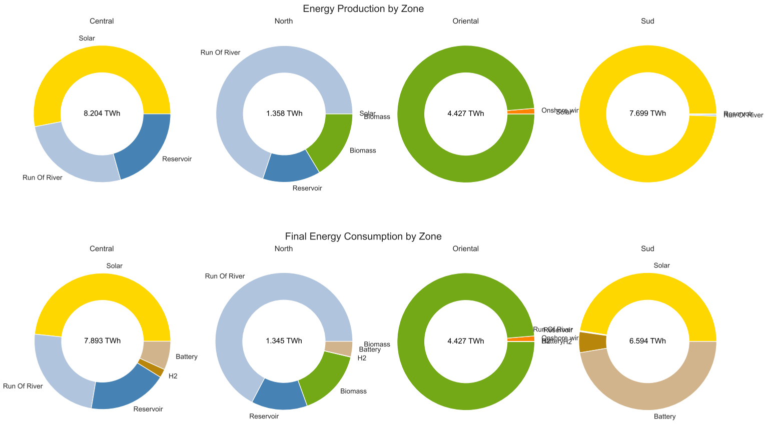
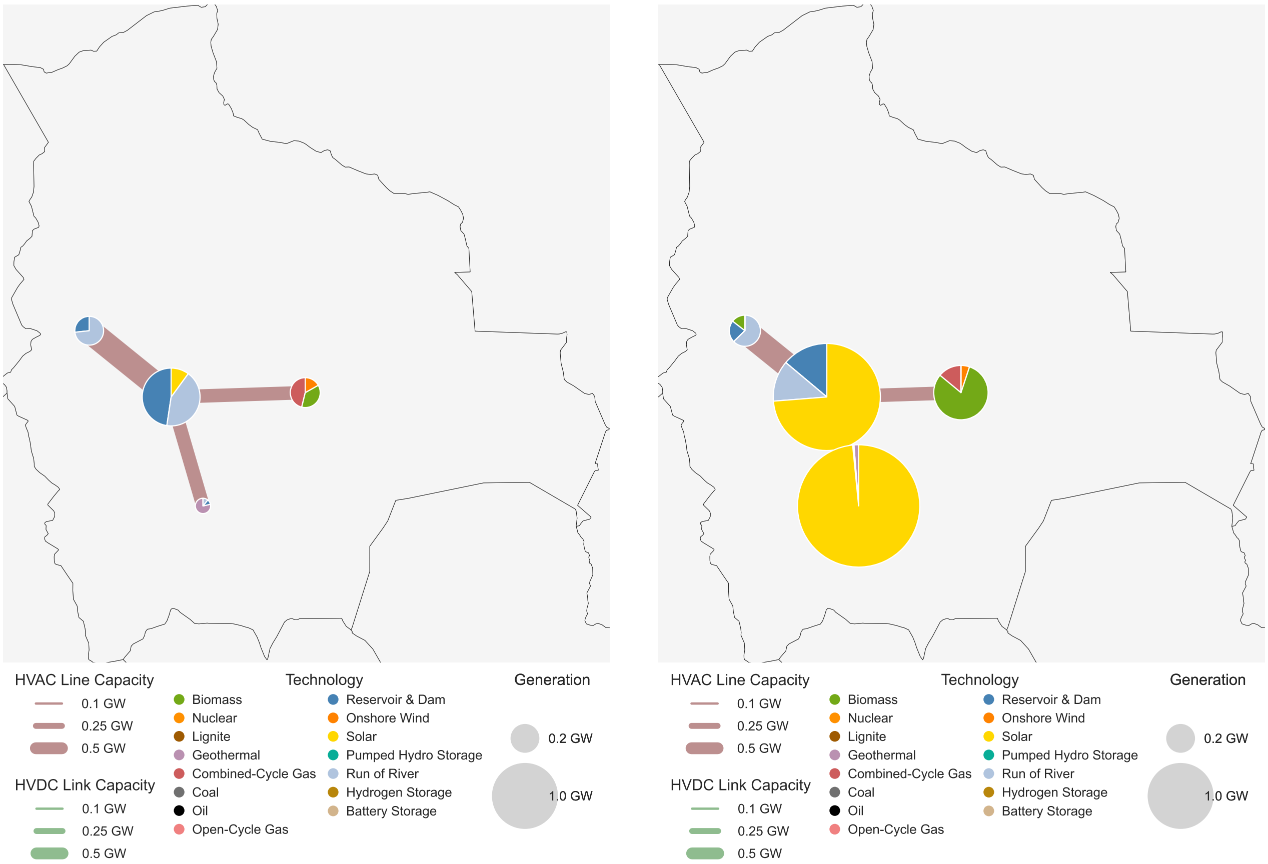


Figure 7.13: Primary yearly energy production [**Top**] and final energy consumption [**Bottom**] by zone. For the 2050 CN scenario, with biomass limitation.



A - Initial

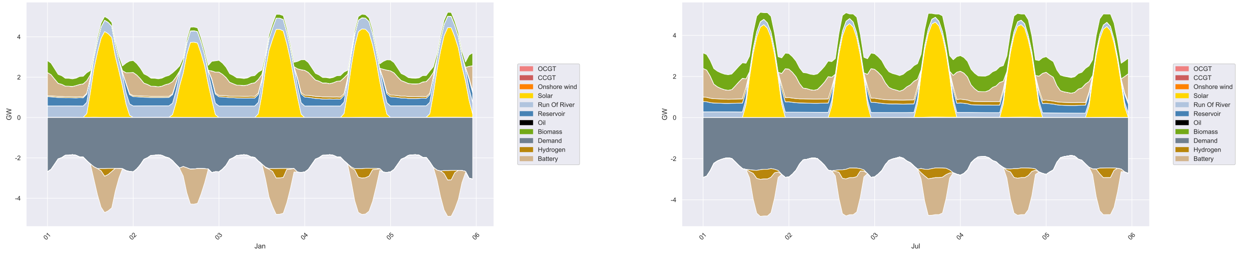
B - After optimisation (extension)

Figure 7.14: Representation of the 4-zone clustered network. Installed capacity by zone for the 2050 CN scenario, with biomass limitation.

Energy storage

The energy dispatch, represented in Figure 7.15 allows a better understanding of the behaviour of the storage in the model since it has an hourly representation of the total power dispatch in the country.

During January's rainy season, hydropower is abundant, reducing the need for biomass. Even though solar energy is reduced, the substantial hydropower output leads to higher global renewable energy in January compared to July.



A - January

B - July

Figure 7.15: Hourly energy dispatch for the 2050 CN scenario, with biomass limitation

Global storage use is lower during the rainy season due to increased hydropower production. Nevertheless, hydrogen technology, playing a strategic role, is used mainly for charging, addressing seasonal energy fluctuations. Hydrogen usage shifts toward discharging in the dry season to meet heightened demand.

It is noteworthy that batteries are uniquely managing short term variations responsible for balance daily fluctuations of production while hydrogen can be also used for long-term storage.

7.2.3 Study of the impact of inflows change

As elaborated and examined in Section 2.3.3, there's a noticeable global trend in Bolivia where precipitation levels have been decreasing over the years. Among these years, 2016 stands out as the driest. To simulate this trend, and with the modifications made to the PyPSA-Earth inflow models, inflows data from 2013 is replaced by historical SDDP data from the year 2016. The results of this approach are depicted in Figure 7.16, representing the total energy production for a year, and Figure 7.17, illustrating the hourly dispatch. In Figure 7.16, it can logically be observed that using inflow data from a dry year leads to less energy produced by hydropower sources. Consequently, more biomass is used and additional solar capacity is installed.

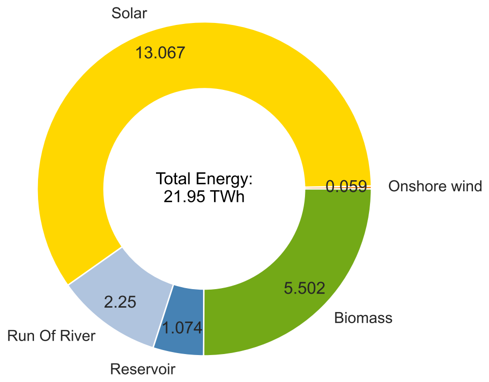
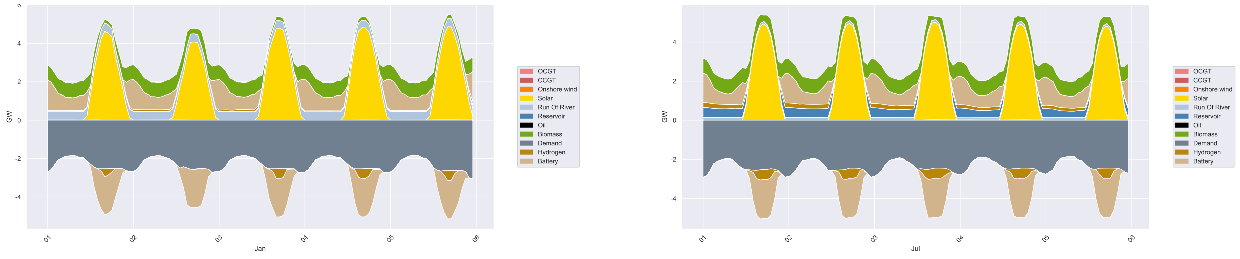


Figure 7.16: Yearly energy dispatch for the 2050 CN scenario, considering 2016 inflows (dry year).



A - January

B - July

Figure 7.17: Hourly energy dispatch for 2050 CN scenario, considering 2016 inflows (dry year).

In Figure 7.17 an interesting observation can be made : during the wet season in January, the contribution of hydropower sources to energy production is relatively low. Energy generation stems solely from RoR sources rather than Reservoir sources. In contrast, during the dry season, while RoR production logically decreases, some production from reservoir sources can be seen. This can be attributed to the substantial water storage capacity of reservoir-type hydropower plants. During the rainy season, water is accumulated for subsequent release during the dry season, thus maintaining a constant energy output.

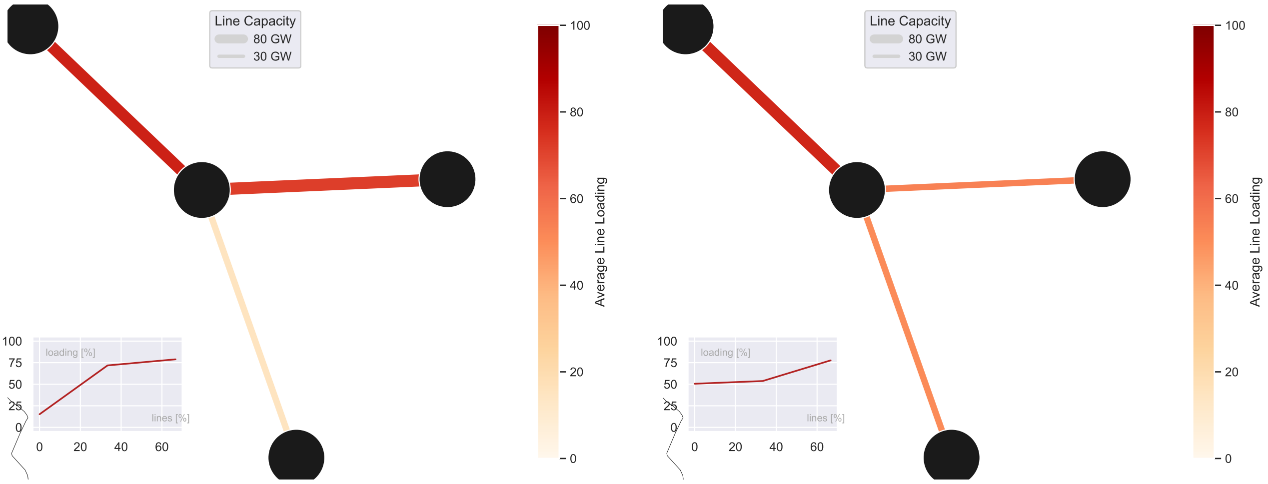
7.2.4 Line loading

Similar to the capacity extension capability we previously explored for generator expansion, PyPSA-Earth also introduces a capability for managing line capacity expenditure. As mentioned before, PyPSA-Earth is a model that considers technical constraints such as overloading. By continually verifying compliance with these limits, the models ensure the stability of the network. If the line loading is out of the limits, the line's capacity will be expended by the model. For 2050 demand, results showed that none of the scenarios analysed previously would necessitate the installation of new line capacity.

To meet the N-1 security criterion, PyPSA-Earth incorporates a global safety margin specifically designed for High Voltage Alternating Current (HVAC) lines. This safety margin enforces that line loading remains at or below 70% of their nominal capacities. As depicted in Figure 7.18, it's clear that there is no overloading in both the BAU and CN scenarios. These figures illustrate the average line loading on the map, as well as the proportion of lines that fall within specific loading ranges. Clearly, no line exceeds an average loading of 75%. As depicted in Figure 7.18, the line configuration remains unchanged between the initial and optimized states. This indicates that the installed line capacities are sufficient to support interconnections among the four zones for the 2050 demand projections. Further insights from the figures highlight that during the CN scenario, the connection between the southern and central zones is nearly overloaded. This is due to the increased solar production mainly originating from the southern region. Conversely, the link between the eastern and central zones experiences reduced usage.

However, it's worth noting that the line loadings are approaching the accepted limits, and with increasing demand, line capacity expansion may become necessary at a given point of time. This prospective need is vividly illustrated in Figure 7.19 for a demand projection of 100 TWh. The outcome reveals a significant loading increase in two out of the three lines. Additionally, in this scenario, remaining around the 75% loading range is more complicated.

NB: These are simplified results since we are in the case of 4 cluster configurations with only 3 lines that sum the capacity of every line. In real life case, where the lines are considered individually, some of them should have to be extended. These conditions should be further explored in future works.



A - 2050 BAU scenario **B** - 2050 CN scenario

Figure 7.18: Average transmission line loading in the map: BAU VS CN scenario.

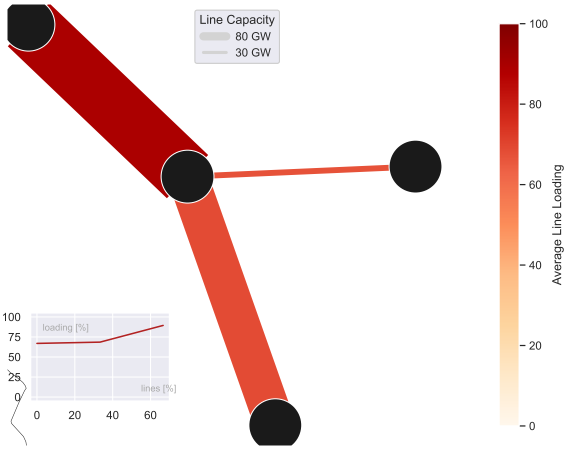


Figure 7.19: Average transmission line loading for a 100 TWh demand scenario.

7.3 Comparison of the scenarios

In Table 7.1, the results for every scenario can be compared.

Installed capacity and resulting costs

For the 2020 projections, the total yearly demand is 9.46 TWh, which increases to 20.26 TWh for projections in 2050. As stated previously, the total installed capacity in 2020 was oversized for covering the peak demand and therefore in the 2050 scenario **BAU1**, which doesn't consider decommissioning, this installed power is still sufficient to cover the increased peak demand. Consequently, in the **BAU1** scenario, no new power plant need to be installed, and the marginal price is close to the baseline one of 2020. Once the old power plants are decommissioned, new installed capacity needs to be added. In the **BAU 2** scenario that keeps the gas price of opportunity of the Bolivian case, these new power plants are only OCGT gas plants, which results in low costs, at the expense of increased CO_2 emissions. For the last BAU scenario, **BAU3** considers a switch to international gas prices and the newly installed power plants are primarily geothermal power plants but also some solar capacity. A global increase

Table 7.1: Results comparison of the different scenarios.

	2020	2050 Projections					
	Baseline	BAU 1	BAU 2	BAU 3	CN 1	CN 2	CN 3
Demand [TWh]	9.46	20.26					
Installed capacity [GW]	**3.43**	**4.04**	**3.44**	**4.28**	**4.34**	**9.06**	**9.68**
Energy production [TWh]	9.46	20.26	20.26	20.27	20.41	21.69	21.95
Renewable production [TWh]	3.50	6.14	5.76	19.22	20.40	21.69	21.95
Installed storage [GW]	**0.00**	**0.00**	**0.00**	**0.02**	**0.69**	**2.87**	**3.32**
Yearly energy stored [TWh]	0.00	0.00	0.00	0.02	0.39	4.94	5.77
Lost in storage [TWh]	0.00	0.00	0.00	0.01	0.15	1.43	1.69
Curtailement [TWh]	0.00	0.00	0.00	0.06	0.00	0.15	0.18
CO_2 emissions [MtCO_2]	2.23	5.57	6.88	1.71	0	0	0
Average cost [€/MWh]	4.90	7.17	11.83	28.00	35.38	43.89	47.95
Marginal price [€/MWh] (yearly mean)	11.3	13.83	16.39	39.22	45.78	68.79	68.46

BAU1: Business-As-Usual projection without considering decommissioning.
BAU2: Considering decommissioning.
BAU3: Considering decommissioning and international gas prices.
CN1: Carbon-Neutral projection without biomass limitation.
CN2: Limitation on biomass potential.
CN3: 2016 (dry year) inflows.

in total installed capacity can be observed. This results in a substantial costs increase since the installation of geothermal and solar plants is very expensive. Moreover, the remaining gas plants are fuelled by more expensive gas, leading to higher costs. The installation of new power plants involves not only OCGT types but also CCGT, which requires more significant investments.

Regarding the Carbon neutrality projections, in the first scenario **CN1**, a notable portion of the increased capacity is assigned to the biomass carrier. Biomass energy sources have a distinct advantage compared to other renewable sources like solar or wind due to their lower variability of resources. This reduced variability means that biomass power generation can maintain a more consistent output, which translates to a more stable supply of energy. Consequently, while biomass may not require as large an installation capacity as solar or wind, it still contributes significantly to the overall energy generation and the marginal price remains within the same range as the one in the **BAU3** scenario. On the other hand, a significant change in the price, caused by the doubling of the installed capacity, occurs in the **CN2** scenario, where biomass installed capacity is limited, leading to the need for installing a considerable amount of solar capacity.

Renewable proportion of generation and impact on CO_2 emissions

Due to their low investment costs, OCGT plant installations represent a large share of gas powerplants. As a logical consequence, the renewable part of the total energy produced decreases significantly from **BAU1** (where 30% of production is renewable) to **BAU2** (only 26% renewable). As a result from this renewable decrease and from the fact that $OCGT$ power plants emit more CO_2 than $CCGT$ due to their lower efficiency, CO_2 emissions increase from 5.57 $MtCO_2$ to 6.88 $MtCO_2$. However, when considering international gas prices , a remarkable change in the renewable proportion can be observed. Indeed, in the **BAU3** scenario, the renewable production now constitutes 86% of the total, leading to very low CO_2 emissions of 1.71 $MtCO_2$. This demonstrates that the Bolivian energy system, heavily reliant on gas, is highly influenced by governmental policies, and a shift to higher prices such as international prices would result in a substantial decrease in CO2 emissions. Nevertheless, as seen in the previous paragraph, this reduction in CO_2 emissions is accompanied by a significant increase in electricity prices, posing a challenge for the population of a developing country. This calls for additional policies that provide financial support for renewable deployment to mitigate the potential cost increase. A common logical consequence of the three **CN** scenarios is that the shares of renewable is 100%, accompanied by a notable absence of CO_2 emissions totaling 0.

Storage, load shedding, and losses in storage

Comparing **BAU1** and **BAU2**, taking into account decommissioning and enabling the installation of power plants with almost 0 legacy capacity ensures the absence of load shedding issues. In the **BAU3** scenario, as the energy mix shifts due to increased gas costs, load shedding problems become more severe, possibly due to the higher proportion of renewable production without sufficient storage infrastructure. This load shedding challenge is further exacerbated in the initial **CN1** scenario, where electricity generation relies primarily on biomass. However, this issue is largely resolved in the **CN2** scenario, where a substantial amount of storage infrastructure is implemented, adding to 2.87 GW of batteries and hydrogen technologies. This significant investment results in a relevant increase of the marginal price. While there are still some storage losses, the demand is at least adequately covered by the overall production.

Remarks about $\mathrm{CO_2}$ emissions computation

$\mathrm{CO_2}$ emissions have been computed considering only the emissions of Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT) gas power plants, as well as geothermal power plants.

For each scenario, emissions have been computed using the following formula:

$$\mathrm{CO_2} = \mathrm{CCGT} \times \frac{1}{\eta_{\mathrm{CCGT}}} \times \mathrm{CO}_{2,\mathrm{gas}} + \mathrm{OCGT} \times \frac{1}{\eta_{\mathrm{OCGT}}} \times \mathrm{CO}_{2,\mathrm{gas}} + \mathrm{geothermal} \times \frac{1}{\eta_{\mathrm{geo}}} \times \mathrm{CO}_{2,\mathrm{geo}}$$

where:

- $\mathrm{CO_2}$ is the total $\mathrm{CO_2}$ emissions for the scenario $[MtCO_2]$.
- CCGT is the total electrical energy production from CCGT in each scenario $[TWh_{el}]$.
- OCGT is the total electrical energy production from OCGT in each scenario $[TWh_{el}]$.
- geothermal is the total electrical energy production from geothermal power plants in each scenario $[TWh_{el}]$.
- $\eta_{\mathrm{CCGT}} = 0.5 \left[\frac{\mathrm{TWh_{el}}}{\mathrm{TWh_{th}}}\right]$ (Source: DIW datadoc [46])
- $\eta_{\mathrm{OCGT}} = 0.39 \left[\frac{\mathrm{TWh_{el}}}{\mathrm{TWh_{th}}}\right]$ (Source: DIW datadoc [46])
- $\eta_{\mathrm{geo}} = 0.239 \left[\frac{\mathrm{TWh_{el}}}{\mathrm{TWh_{th}}}\right]$ (Source: DIW datadoc [46])
- $\mathrm{CO}_{2,\mathrm{gas}} = 0.187 \left[\frac{\mathrm{MtCO_2}}{\mathrm{TWh_{th}}}\right]$ (Source: EIA [37])
- $\mathrm{CO}_{2,\mathrm{geo}} = 0.026 \left[\frac{\mathrm{MtCO_2}}{\mathrm{TWh_{th}}}\right]$ (Source: EIA [37])

The emission factors provided here account for emissions resulting from fuel combustion and electricity production but do not consider emissions related to construction, maintenance, decommissioning, and transportation of technologies.

Chapter 8

Conclusion

The primary goal of this work was to contribute to the definition of long-term energy transition scenarios in Bolivia, using the PyPSA-Earth model. In that regard, the PyPSA-Earth model has first been adjusted to the Bolivian case. The main contributions have been the modification of the clustering process, the modification of the generator configuration, and replacing the inflows input data. The importance of having robust data concerning hydropower for Bolivia justified a dedicated focus on this phase, given the substantial role of hydropower production in the total energy mix and its growth potential for the future.

Subsequently, the adjusted model's outcomes have been compared with historical data to validate that they match, while a specific focus was put on the hydropower behaviour for an accurate representation of the Bolivian energy landscape.

Having successfully adjusted the model, it was used to simulate various scenarios for future projections of the system. Initial scenarios followed a Business As Usual (BAU) pattern, exploring three distinct cases characterized by varying considerations on power plants, decommissioning and gas prices.

Subsequently, Carbon Neutrality (CN) scenarios were generated, with and without biomass maximum potential constraints. These configurations of the CN scenario are distinguished by its significant integration of renewable sources, particularly geothermal and solar energy. As a result, this scenario places a strong emphasis on hydropower production as a central component as well as storage technologies .

One of the emphasis of the scenarios was to assess the influence of climate change on hydropower production and its implications for the future energy mix. Specifically, the study addressed the trend of reduced precipitation in tropical regions, including Bolivia's location. This was investigated by using inflow data from the historical driest year, specifically 2016, to simulate an extreme scenario and evaluate its consequences.

8.1 Findings summary

The findings of this study, resulting from the scenarios, highlight that the existing installed capacity (as for 2020) has the potential to accommodate a projected increase in annual demand reaching 20TWh by the year 2050. However, it is important to note that a significant portion of this capacity, primarily consisting of gas installations along with some hydropower plants, will be decommissioned before the target year.

In the context of a Business as Usual (BAU) projection, our results underscore the substantial impact of gas prices on the outcomes. By substituting actual Bolivian gas prices, supported by government policies to keep it cheap, with international prices, the energy landscape experiences a notable shift. In particular, geothermal energy emerges as a prominent contender, presenting a promising opportunity for Bolivia's energy future.

Incorporating CO_2 emission constraints into our analysis introduces further dynamics. Geothermal energy, which initially stood out, gets replaced by alternative sources like biomass and solar power that are considered as 0 emissions technologies. Both biomass and solar possess considerable potential within Bolivia's context. However, this transition results in increased costs, primarily attributed to the necessity of battery installations to manage the variability of solar production.

To make this transition viable and ensure the integration of renewables into the energy mix, the introduction of subsidies becomes imperative. These financial incentives would play a pivotal role in supporting the adoption of renewable energy sources and offsetting the elevated costs associated with their implementation.

To summarize, this study emphasizes the need for strategic planning and policy interventions to harness Bolivia's energy potential. The results of the simulations highlight the big renewable potential of the country allowing for a transition to a 100% renewable energy mix in accordance with the accords signed for a 0 emission goal. Nevertheless, this won't be possible without the intervention of the government to finance the transition since a transition to a neutral carbon energy mix results in a severe increment of costs, which are even more relevant in a developing country such as Bolivia.

8.2 Contribution to the fields of energy planning and modelling

This master thesis significantly contributes to the realms of energy planning and modelling, specifically within the context of Bolivia. The approach adopted in this study encompasses the following key aspects:

Firstly, this study addresses the unique challenges that arise in the energy landscape of a developing country like Bolivia. By deeply understanding the country's context, this work provides insights into the challenges and opportunities that play a crucial role in shaping Bolivia's energy transition strategies.

Secondly, a key contribution is the adjustment and application of the PyPSA-Earth model within the Bolivian context. This model, tailored and validated using historical data, holds promise for future studies. The robustness of the model's outcomes, stemming from the model validation with historical data, establishes a strong basis for policy discussions and strategic planning. In particular, the PyPSA-Earth model offers advantages such as being open-source, offering spatial granularity for technical constraint assessment, employing hourly time steps based on real-world hourly data (weather, demand, etc.), and enabling long-term studies.

Furthermore, a notable aspect of this study involves the detailed representation of hydropower in the model, considering its significant importance in Bolivia's current and prospective electricity mix. This specialized model captures the distinct dynamics of Bolivia's energy landscape, leading to a more precise depiction of potential hydropower in future transition scenarios.

Lastly, the development of scenarios encompassing policy interventions and economic conditions gives policymakers, energy planners, and stakeholders valuable insights. These insights can help them in making well-informed decisions that can guide Bolivia toward achieving sustainable energy objectives. The exploration of this study's scenarios outlines a feasible path toward carbon neutrality, underscoring the importance of evaluating multiple trajectories to ensure long-term sustainability.

8.3 Limitations and future research directions

Outside of the scope of this study, many future works can be done in order to improve what have been done here. Notably the following points could be the subject of future research:

- **Enhanced inflows computation:** The computation of inflows in the PyPSA model could be improved. As discussed in Section 4.3, current inflow computation methods exhibit limitations. Addressing factors like the normalization process, which currently assumes a single hydropower plant per zone, and accounting for unique cases of hydropower installations, such as upstream reservoirs, could yield more accurate inflow estimations.

- **Cost supply curve for renewable sources:** When evaluating the costs associated with various energy sources, especially renewable options, the prevailing cost assumption can be calculated using a cost supply curve. This curve reflects an escalating cost trend as the deployment of new energy generation capacities increases. In essence, as the number of installations grows, the associated costs also rise, capturing the incremental effort required for establishing new power plants. By incorporating this approach, the model's outcomes would better mirror real-world scenarios. For instance, in the context of the CN scenario, sources of renewable energy other than solar could be implemented, such as wind potential.

- **Expanded network node representation:** Future studies should explore scenarios with more node representations. By incorporating additional nodes, the interconnections between zones could be more effectively investigated, making analysing the technical constraints such as line loading more effective.

- **Line expansion capability analysis:** A deeper investigation into the expansion capabilities of transmission lines could offer valuable insights into enhancing the efficiency and resilience of the energy network. By assessing the optimal expansion of transmission infrastructure, future research could guide strategic decisions in building a more robust energy grid.

- **Climate change mitigation strategies:** Exploring efforts to mitigate the impact of climate change through sustainable energy solutions such as the integration of advanced technologies or innovative policies that promote the adoption of renewable energy sources and reduce carbon emissions.

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Appendix A

Hydroelectricity in Bolivia: current status and potential

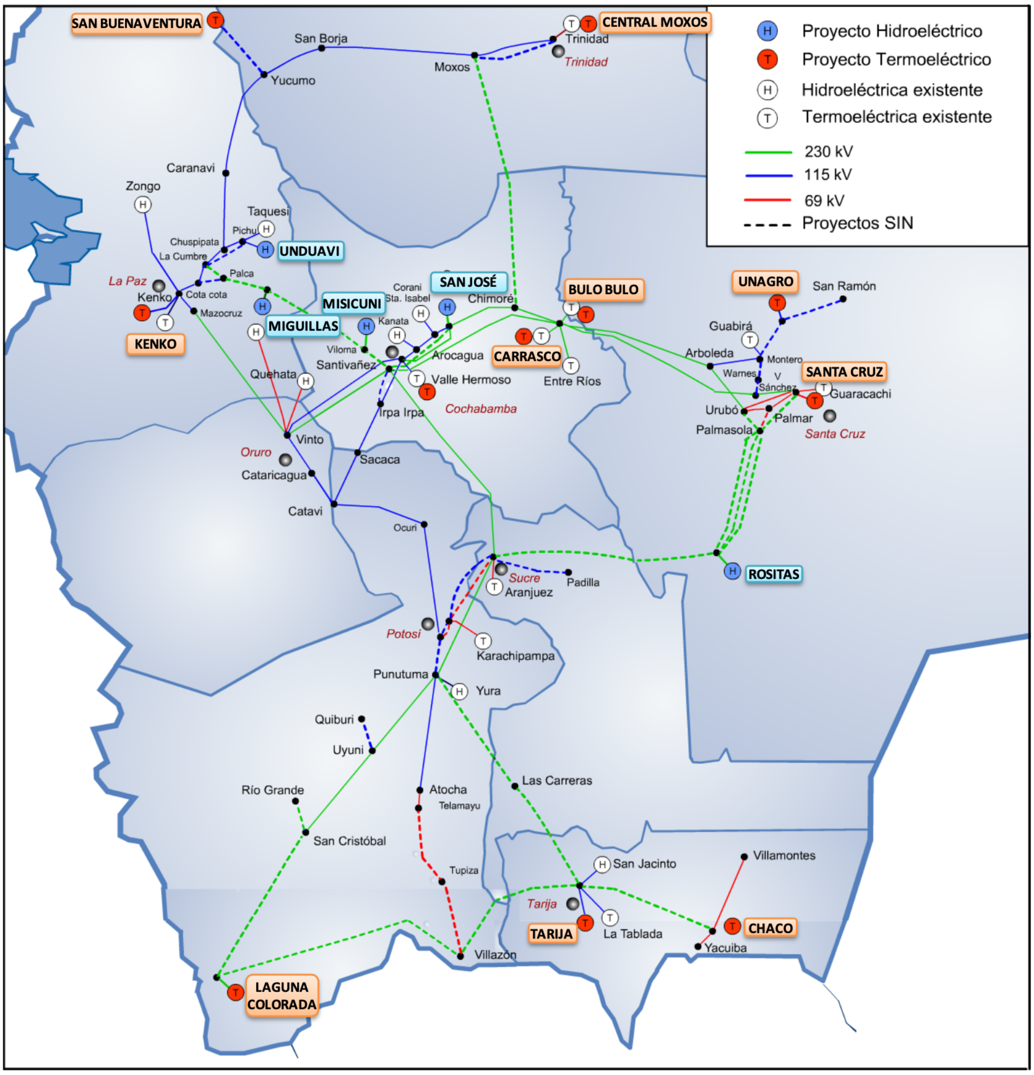


Figure A.1: Map of POES projects for 2022.

Existing hydropower plants in Bolivia

Actually in Bolivia the hydropower plants are the following:[16]

Major powerplants

1. **Sistema Corani** One of the oldest and most important hydroelectricity systems in Bolivia, located in Cochabamba department, consisting of several power plants:
    - Corani (entered into operation in 1967) with a generation capacity of 64 MW (since 2018)
    - Santa Isabel (began operating in 1973) with a generation capacity of 91 MW (since 1983)
    - Sant José 1 (began operations in 2018) injecting 55 MW
    - Sant José 2 (began operations in 2019) injecting 69 MW

    Total (9 units):

    - 147 MW in 2011 [11]
    - 276 MW in 2023
2. **Sistema Zongo** A major hydroelectricity system located in the Andes mountains (in the La Paz department), consisting of several power plants. Total (21 units):
    - 187 MW in 2011
    - 187 MW in 2023
3. **Sistema Misicuni** A relatively new hydroelectricity, located in the Cochabamba department, system that began operations in 2014
    - Fase 1: 80 MW in 2014
    - Fase 2: 120 MW in 2023
4. **Sistema Taquesi** Located in the Sud Yungas province in the La Paz department Total (4 units):
    - 89 MW in 2011
    - 89 MW in 2023
5. **Sistema Miguillas** A hydroelectricity system consisting of multiple power plants that provide power to both Bolivia and neighboring countries. Total (9 units):
    - 21 MW in 2011 (same for 2023)
    - 221 MW expected in the future

    Minor powerplants
6. **Sistema Sant Jacinto** 2 generating units on the rivers Tolomosa and Molino, located in the Potosi department
7. **Sistema Yura**
8. **Sistema Kanata**
9. **Sistema Quehata**

NB: This powerplant configuration is added and adapted in the model in section 5.2.

Future projects and opportunities for hydroelectricity development

Projects under construction

- Ivirizu project: Sehuencas y Juntas (290 MW) (1160 GWh) located in rive Ivirizu (Cochabamba, national parc Carasco)
- Increase of Miguillas complex: Umapalga and Pallilada projects (203 MW)

Controversial projects [47] In the PEEP 2015-2025 (*Plan Electrico del Estado Plurinacional de Bolivia*) [12], 3 strategic large hydropower plants to be constructed are identified :

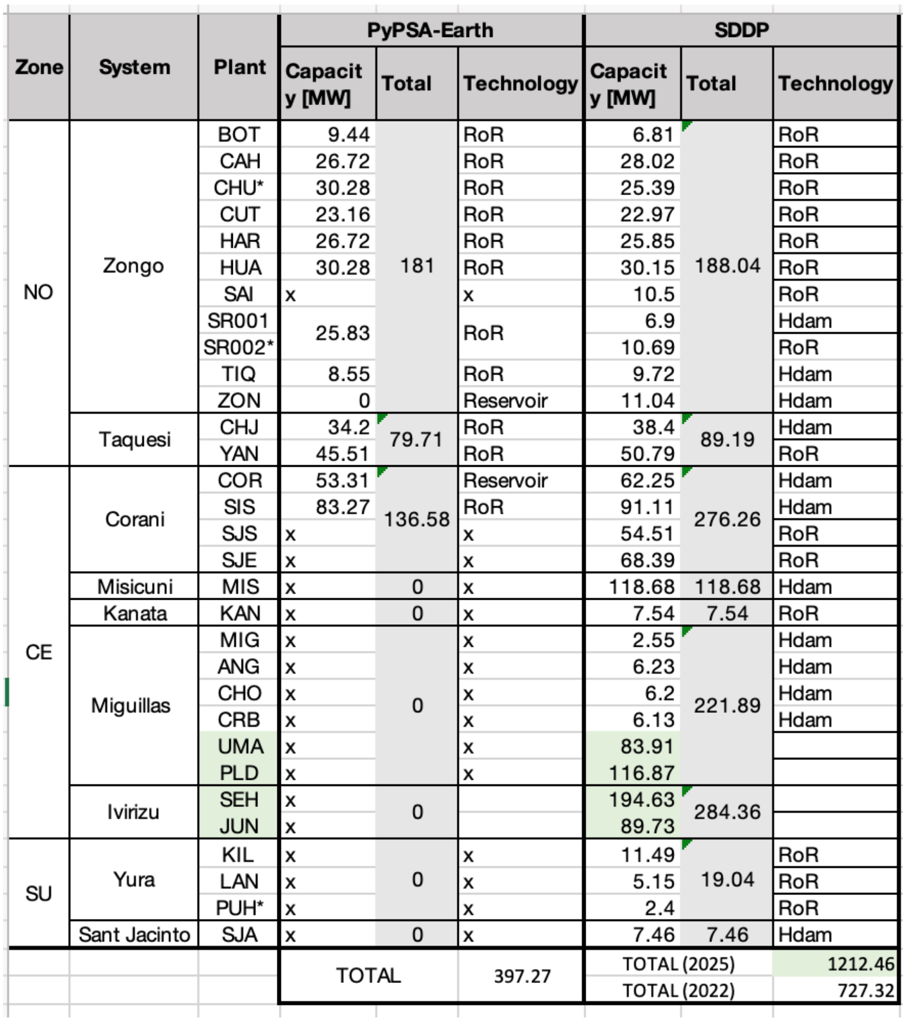
- Cachuela Esperanza located on Beni river/basin (with 990 MW installed capacity, 5,465 GWh), expected to get commissioned in 2025
- El Bala also located on Beni River, specifically in El Bala Gorge (with 1.680 MW)
- Río Grande hydropower complex in Grande River basin (with 2.882 MW capacity)

NB: The El bala dam construction project is controversial due to its location in the Madidi national park where many indigenous communities are living. With this project, more than 4,000 Indigenous people would be displaced and this would also impact fish and farm as well as tourism activities. That represent a big risk for the indigenous people that are not all agree with this project. [48]

NB: 5first in the central zone, last one in the south

Opportunities for Hydroelectricity Development Discuss the potential for developing new hydroelectric projects in Bolivia, despite the challenges Highlight the advantages of hydropower, including its renewable and low-carbon nature

Comparison of the PyPSA hydropower plants with literature



Zone	System	Plant	PyPSA-Earth Capacity [MW]	PyPSA-Earth Total	PyPSA-Earth Technology	SDDP Capacity [MW]	SDDP Total	SDDP Technology
NO	Zongo	BOT	9.44	181	RoR	6.81	188.04	RoR
		CAH	26.72		RoR	28.02		RoR
		CHU*	30.28		RoR	25.39		RoR
		CUT	23.16		RoR	22.97		RoR
		HAR	26.72		RoR	25.85		RoR
		HUA	30.28		RoR	30.15		RoR
		SAI	x		x	10.5		RoR
		SR001	25.83		RoR	6.9		Hdam
		SR002*				10.69		RoR
		TIQ	8.55		RoR	9.72		Hdam
		ZON	0		Reservoir	11.04		Hdam
	Taquesi	CHJ	34.2	79.71	RoR	38.4	89.19	Hdam
		YAN	45.51		RoR	50.79		RoR
CE	Corani	COR	53.31	136.58	Reservoir	62.25	276.26	Hdam
		SIS	83.27		RoR	91.11		Hdam
		SJS	x		x	54.51		RoR
		SJE	x		x	68.39		RoR
	Misicuni	MIS	x	0	x	118.68	118.68	Hdam
	Kanata	KAN	x	0	x	7.54	7.54	RoR
	Miguillas	MIG	x	0	x	2.55	221.89	Hdam
		ANG	x		x	6.23		Hdam
		CHO	x		x	6.2		Hdam
		CRB	x		x	6.13		Hdam
		UMA	x		x	83.91		
		PLD	x		x	116.87		
	Ivirizu	SEH	x	0		194.63	284.36	
		JUN	x			89.73		
SU	Yura	KIL	x	0	x	11.49	19.04	RoR
		LAN	x		x	5.15		RoR
		PUH*	x		x	2.4		RoR
	Sant Jacinto	SJA	x	0	x	7.46	7.46	Hdam
			TOTAL		397.27	TOTAL (2025)		1212.46
						TOTAL (2022)		727.32

Figure A.2: Comparison of the default PyPSA hydropower plants (OSM) with literature.

Appendix B

Computation of inflows in PyPSA-Earth

Inflows per zone

In the `add_hydro` rule of the `build renewable` function, the inflows for each region are, using a correction factor, based on the water availability:

```python
inflow = correction_factor * func(capacity_factor=True, **resource)
func = getattr(cutout, "hydro")
```

- By default, the correction factor is fixed to 1.
- The `"hydro"` method refers to the hydropower generation simulation capability provided by the Atlite library. Atlite is a Python package used for analyzing and modeling renewable energy systems, particularly focusing on solar and wind resources.
- The `cutout` object is used to prepare the hydro resource data by calling the `prepare()` method with the hydrobasins feature selected.The hydro method in `atlite.cutout()` estimates the water availability for hydroelectricity generation using the runoff data from Copernicus, as well as the hydrobasins shapefile and the flow speed of the rivers provided in the configuration file. When using the atlite.cutout() function with the `hydro` method, it allows you to extract hydrological data for a specific geographical region or coordinate. This data typically includes information about water inflow, river discharge, and other relevant parameters required for hydropower generation modeling.
- The `capacity_factor` parameter is set to `True` to compute the capacity factor for each grid cell. The capacity factor is proportional to the sum of installed capacities of hydropower plants in the zone. This is a way to allow additional expansions in the future (based on records of energy produced)

Inflows per power plant

Since the `hydro profile` file contains data for 81 zones instead of individual power plants, the `add_electricity` function creates a new variable called `"inflow_t"` to store the inflow time series specifically for zones that contain hydropower plants. This selection process is achieved by creating an index variable called `"inflow_idx"`, which combines the indices of run-of-river and reservoir-based hydropower plants from the powerplant file.

```python
  inflow_t = (inflow.sel(plant=inflow_stations).assign_coords(name=inflow_idx))
```

NB: the inflow data for each power plant within a given zone may not be explicitly available in the hydro profile file. To address this, the code uses the bus ID DataFrame to map the indices of the `"inflow_t"` DataFrame to the corresponding bus IDs of the hydropower plants and selects only those power plants that are present in the `"inflow_idx"` variable. This ensures that the inflow data is correctly assigned to the corresponding power plants within the subset of hydropower plants considered in the model.

Adding hydropower plants to the network

As it can be seen in figure B.1, the 27 powerplants introduced in the powerplant CSV file are distributed around the zones determined previously. The inflow have to be considered for each of these powerplants according to the region they are in.

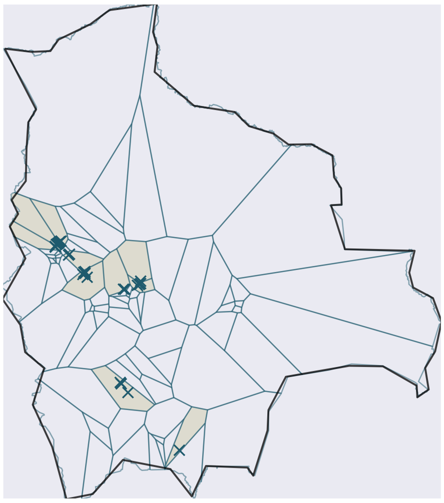


Figure B.1: Hydropower plants localisation and zones.

When adding hydropower plants to the network, the `add_electricity` function handles the inflows differently based on the type of power plant.

The run-of-river (RoR) For run-of-river power plants, the function computes the `p_max_pu` variable, representing the maximum power output, by using the inflow data and the nominal capacity of the plants. This computation ensures that the power output is limited by the plant's rated capacity and the available water inflows. The process is depicted in Figure 4.13.

In the `attach_hydro` rule of the `add electricity` function, the RoR plants are added to the network using the following code :

```
n.madd( "Generator", p_max_pu=(inflow_t[ror.index].divide(ror["p_nom"], axis=1).where(lambda df: df
    <=1.0, other=1.0)) )
```

For each run-of-river power plant, the corresponding inflow time series is selected using the plant's bus ID and divided by the nominal power of the generator. This division yields the maximum available power output as a function of time. The `p_max_pu` attribute of the generator is set to this corrected maximum power output. If the ratio of the maximum power output to the rated capacity exceeds 1, the code limits it to 1 since the generator cannot produce more power than its rated capacity.

The Reservoir-Based Hydropower Plants Unlike run-of-river power plants, reservoir-based hydropower plants have the ability to store energy for later use, allowing for more flexible and optimized use of hydro resources. However, in the context of the `add_electricity` function, determining the `p_max_pu` variable for reservoir-based power plants is not possible since it depends on the optimization process of the model, which determines the optimal energy storage.

To account for the influence of inflows on reservoir-based hydropower plants, the `add_electricity` function introduces an `inflow` parameter. This parameter represents the inflow data, which indicates the water inflows into the reservoirs over time. However, it does not directly determine the power output. Instead, it serves as an input to the optimization model, allowing it to determine the most efficient way to store and use the available energy within the hydro reservoirs.

The method used for assigning power plants of the reservoir type is illustrated in Figure B.2.

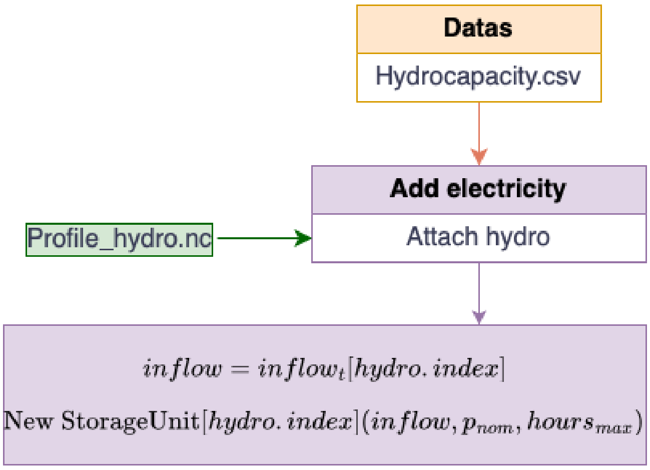


Figure B.2: Assigning power plants of the Reservoir Type.

This code adds storage units to the network and assigns their nominal power based on the `p_nom` values from the hydropower plant information. The `max_hours` parameter determines the number of hours the reservoir can sustain power generation at its maximum capacity. It represents the energy-to-nominal power ratio and is typically determined based on the volumes indicated in the power plant CSV file for each power plant, scaled to match historical data at the national level. However, in this implementation, the default value of 6 hours is used for all reservoir-based power plants. That issue is discussed in section 4.3

Furthermore, the corresponding inflow data for the hydropower plants is selected using the `inflow_t` variable. This inflow data will be used in later stages to compute the maximum power output, taking into account the efficient use of storage functionality.

Hydropower plants for Bolivia representation By incorporating both run-of-river and reservoir-based hydropower plants, the `add_electricity` function enables a comprehensive representation of hydroelectricity in the PyPSA-Earth model. It considers the specific characteristics of each type of power plant and their interaction with inflow data, allowing for accurate modeling and optimization of hydropower generation based on the available water resources.

Repartition per clustered zone

In the `solve_network` function, the hydropower plants are considered by clustering them into three zones: BO0, BO2, and BO3 as it can be seen in figure B.3. The clustering is based on the geographical location of the power plants and aims to group them together for the purpose of analysis and computation.

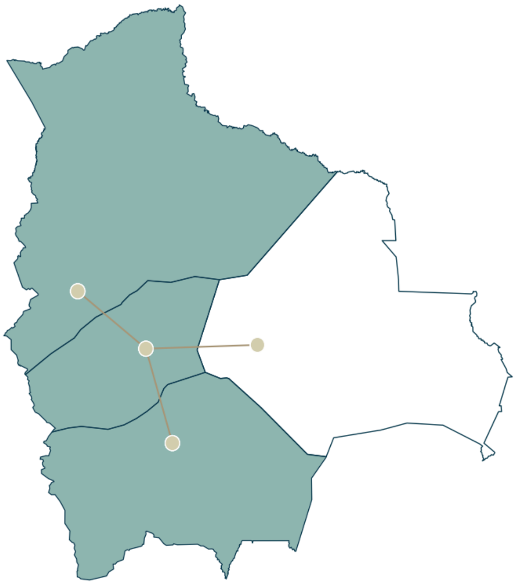


Figure B.3: Clustered zones containing hydropower plants.

After the `solve network` rule is executed, the results include new timeseries values for each zone. These values provide important information about the hydropower plants, such as:

- **p :** The power output of the hydropower plants in each zone for every timestep
- **p dispatch :** The dispatched power from the hydropower plants, taking into account the network constraints and optimization objectives (refers to the optimal power flow)
- **state of charge:** The state of charge of the storage units associated with the hydropower plants.

Customizing inflow data: results in PyPSA-Earth

The graph on the left-hand side displays the hourly power production results, while the graph on the right-hand side provides a daily sampling of the storage power results for more visibility. It is evident from the graphs that the power production from storage-type hydropower plants exhibits significant fluctuations, which will be explored in detail in the subsequent storage section.

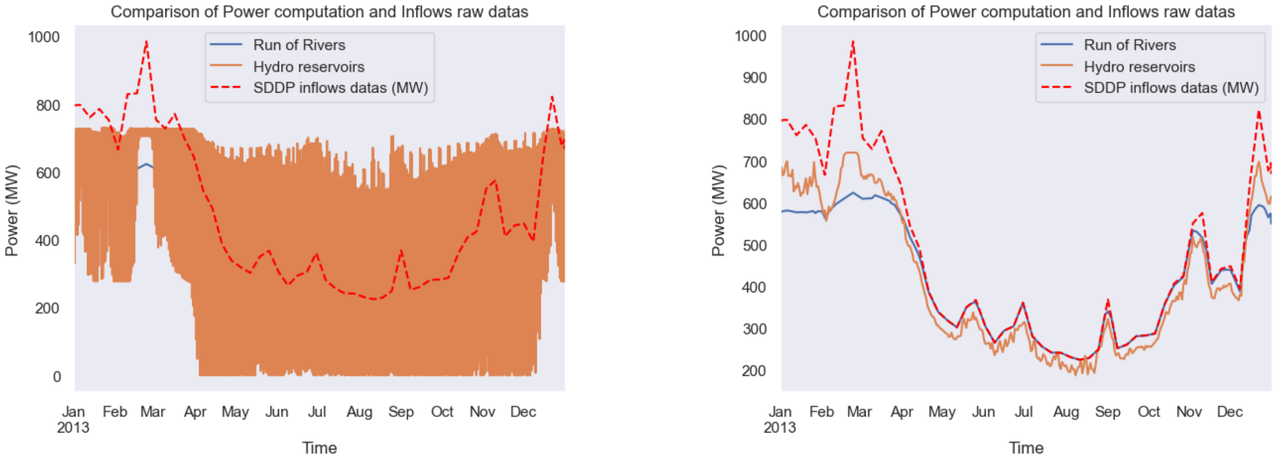


Figure B.4: Comparison of computation of power produced by Run-Of-River and Hydro.

Appendix C

Details on the adaptation of the clustering process

In the process of simplifying the Bolivian power grid network for the purpose of modeling, the network was clustered based on the number of buses that were defined beforehand. For a 4 zone clustering, the resulting network was aligned with the four-zone aggregation plan of the Bolivian network: southern area, central area, oriental area, and northern area. However, problems arose when the number of clustered buses was increased beyond four. Some buses were incorrectly identified as isolated due to the model's limitations in only considering high-voltage components and dismissing lower voltage lines.

Figure C.1: Comparing hourly reservoir hydropower production with daily sampling.

To address this issue, the `augmented_line_connection` parameter can be set to `True` in the Python file. This will allow for the creation of additional connections between nodes in the network by forcing the optimization to include a minimum number of lines required for each node. Nevertheless, this method could increase the incompatibilities with the solved network created by the model and the feasible network, resulting in inacurate results compared to historical and feasible data.

Later, the code has been adapted with a modification of the `simplify network` and `cluster network` in order to take better into account the isolated buses. Also, the `group_tolerance_buses` parameter, which specifies the maximum distance in meters between nearby buses that will be merged into a single cluster, was increased. This could potentially solve the issue of buses being incorrectly identified as isolated, as they may now be clustered with neighboring buses that were previously considered too far away. However, increasing the tolerance too much may also cause neighboring clusters to be merged together, leading to inaccuracies in the clustering representation. Therefore, the optimal value for the group tolerance parameter should be carefully considered and tested in the context of the specific study. While this improved the clustering, one bus still remained isolated. Further modifications may be necessary to accurately represent the Bolivian power grid in the model.

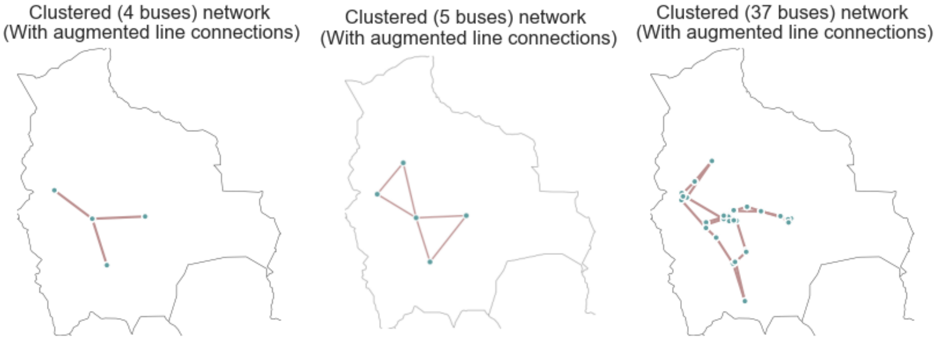


Figure C.2: Comparison between the clustered networks with augmented line connection.

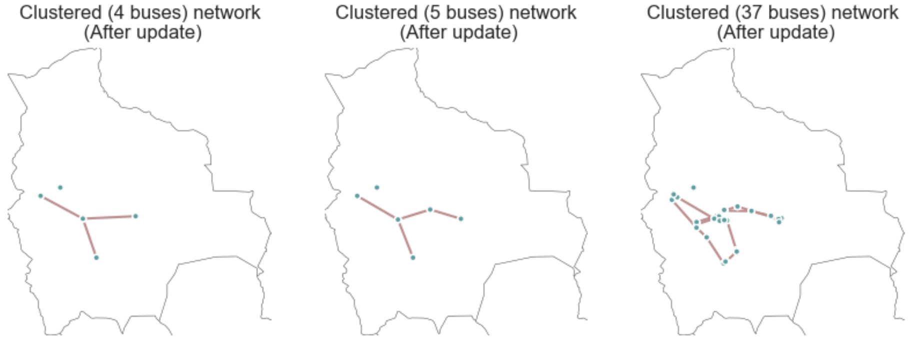


Figure C.3: Comparison with the increased bus group tolerance.

It is important to note that this versiion of the model cannot accept clustering beyond 32 buses, considering only 32 usable points to represent buses and contains 1 isolated bus for any clustering (even with the 4 buses clustering). It is essential to note this limitation, and this could be potentialy solved by decreasing the voltage level requirement or any other solution. Therefore, this version updated is not gonna be taken into account for the first model.

Conclusion The adaptation of the clustering process of PyPSA-Earth to the Bolivian case has shown promising results. The representation of the country with a 4-node representation, corresponding to the four main zones of Bolivia, aligns well with the division of the country and previous research conducted in Bolivia (Figure 5.1). As discussed in Section 2.1, this approach is coherent and provides a meaningful representation for the clustering process. [14]

By using the 4-node representation, the clustering process can capture the heterogeneity and distinct characteristics of each zone in Bolivia. This approach allows for a more accurate analysis and modeling of the energy system, taking into account the specific needs, resources, and constraints of each zone. Furthermore, it facilitates the identification of region-specific challenges and opportunities for sustainable energy planning and development.

Appendix D

Details on the adaptation of the inflows data

Refining Inflow Normalization

As explained in section 4.2.3, the inflows are normalised in order to meet the annual production reported by EIA data. However, the normalization method used for other regions may not be appropriate for Bolivia, as it results in extremely high inflow values. Therefore, a new normalization method is needed.

In the first run of the model, since pypsa-earth consider a total potential of 1.004766e+14 MWh per year, with EIA data reporting around 3e6 MWh/year, it became evident that the previously employed normalization method needed revision.

The `add_electricity` function uses these inflow data as input to compute the hydropower production. However, since the inflow datas are not properly normalized it results that `add_electricity` function is unable to properly constrain the hydropower plant's production capacity. As a result, there was no data generated for this section and hydroelectricity potential wasn't taken into account in the model. To rectify this issue, it is crucial to ensure that the inflow data undergoes appropriate normalization before being used as input for the `add_electricity` function.

To address this, the following changes were implemented:

- Normalization Method: The previous normalization method, `'hydrocapacity'`, was replaced with `'eia'`. This alteration was necessary as there is no hydrocapacity information available for Bolivia.
- Repository Updates: The `'build_renewable'` and `'add_electricity'` functions were modified to incorporate the changes. Additionally, updates were made to the config file (hydro part).
- AtLite Library Adjustments: The conda environment was updated to accommodate the revised functionality.

Figures D.1 and D.2 provide a comparison of the inflows computation for the all country before and after these updates.

As a result of these updates, the obtained results now align more closely with the EIA data and the documented information. The updated version indicates a total potential of approximately $17e6MWh$ for the entire country, reflecting a significant improvement in the accuracy and reliability of the analysis.

Furthermore, the refinement of the raw inflow data in PyPSA-Earth enables accurate consideration of hydropower in the model. With the more precise inflow data, the available inflows for both Run-Of-River (ROR) and reservoir-type hydropower plants can be computed, this one is represented in the

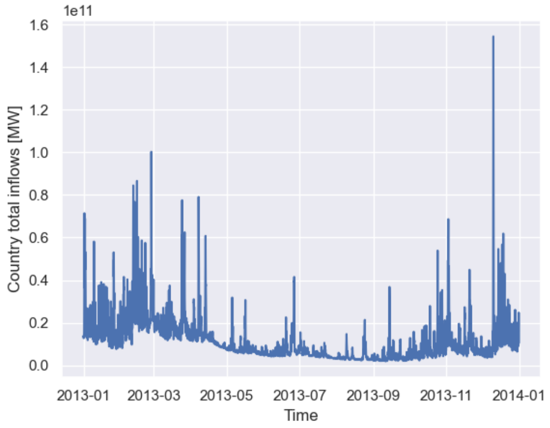


Figure D.1: Inflows at the first run of Bolivia case.

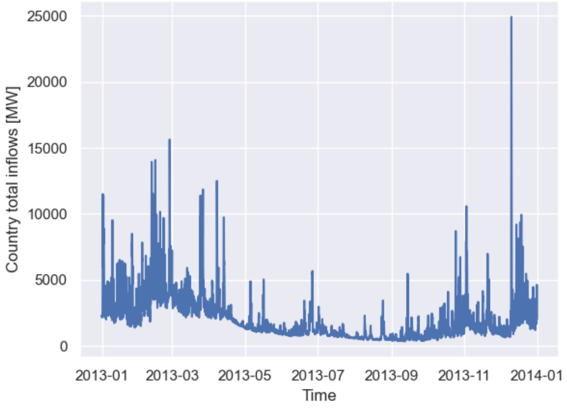


Figure D.2: PypPSA inflows datas after adapatations.

figure D.3. This one is computed by taking the inflows per powerplants as described in section 4.2.4 and sum the resulting inflows for all the power plants in the country. For a total of 8.317e6 MWh for one year. This inflow computation allow for the determination of the resulting power produced by these hydropower plants over time.

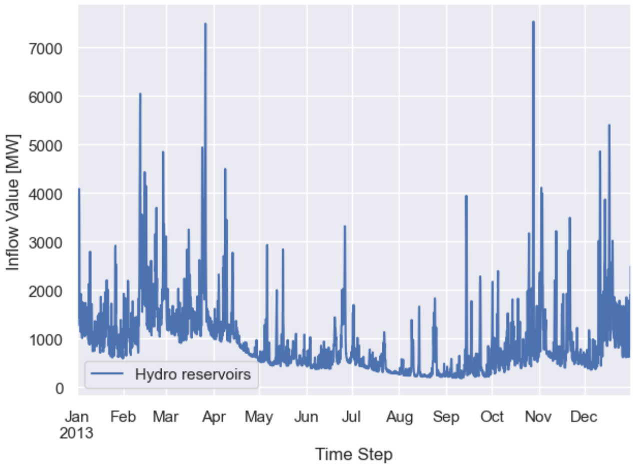


Figure D.3: Results of inflows for PyPSA computation.

The computed time series of total inflows and resulting power for hydropower plants offer valuable insights into the availability and use of hydropower resources throughout the modeled time period. These time series capture the variations in inflow levels, providing a detailed analysis of the hydropower generation potential within the Bolivian context. Furthermore, incorporating these refined inflow data enables a more accurate dispatch of the optimal energy mix, considering the specific characteristics and behavior of hydropower generation.

Inflows results with all the hydropower plants as reservoirs

To simplify the model and streamline the process, all hydropower plants have been encoded as reservoir-type power plants. The result can be analyse in the figure D.4 for both dry and wet season. It can be seen that during the wet season, the optimised system consider aproximatively half of the production by hydropower. Conversely, this one is smaller during the dry season.

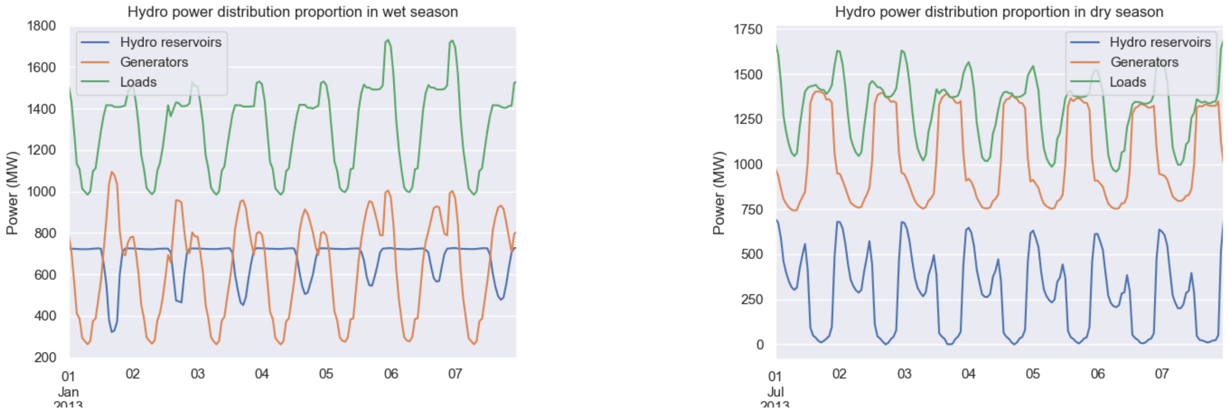


Figure D.4: Comparison of the hydropower proportion in the energy mix during dry and wet season.

Appendix E

Installed capacity map representation

BAU without decomissioning

Figure E.1

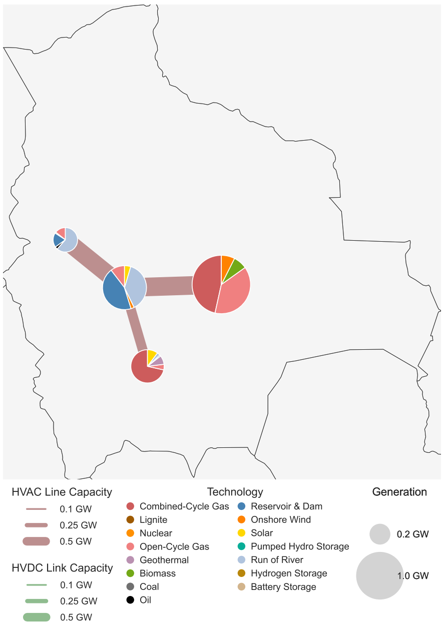
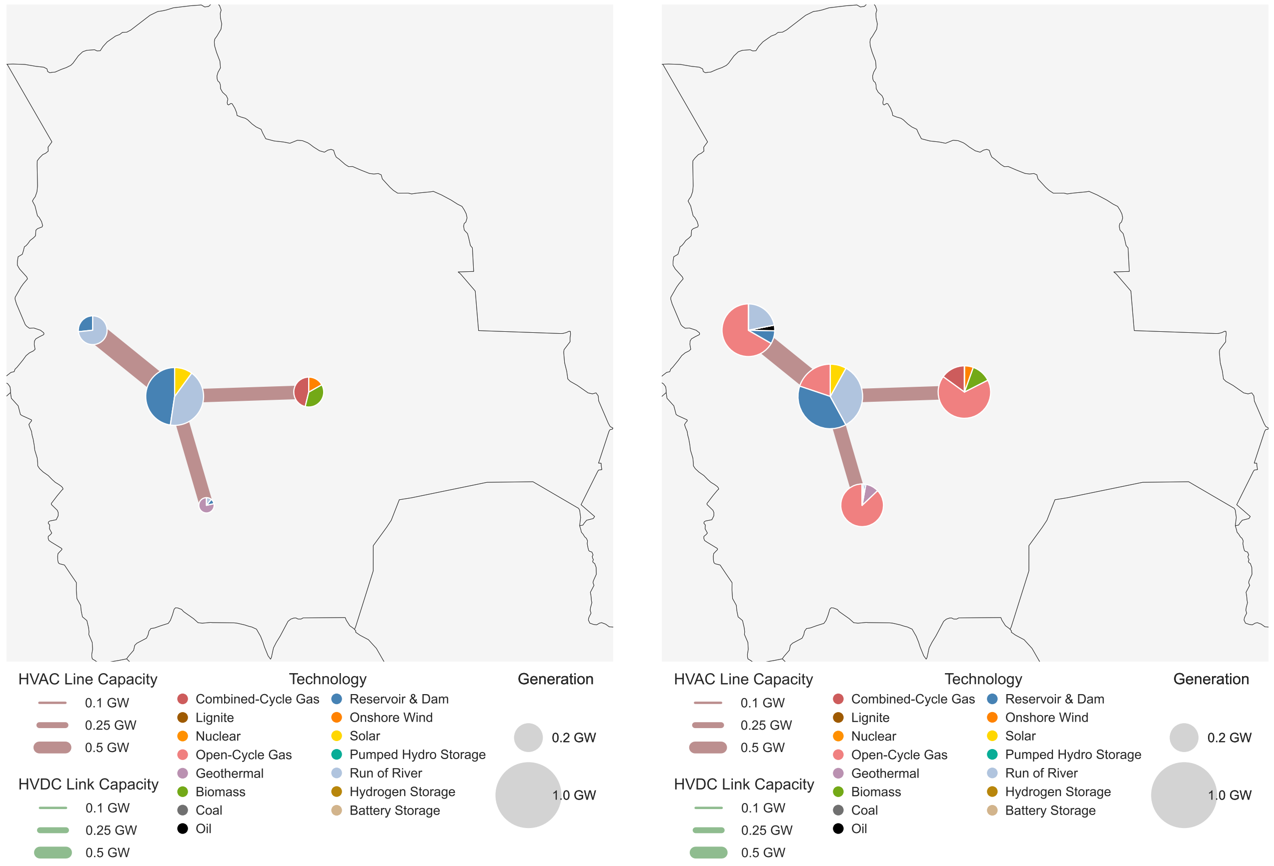


Figure E.1: Map of initial installed capacity 2050 BAU, no power plant decommissioned.

BAU with decomissioning

Figure E.2



A - Initial

B - After optimisation (extansion)

Figure E.2: Map of initial and optimal installed capacity 2050 BAU, power plants decommissioned.

Appendix F

Demand projection

Future Demand Projections from CNDC

The annual report of the CNDC provides a demand projection until 2032. Their expectation for 2030 is approximately 19% higher (13.535 TWh) compared to the projection done by PyPSA (11.338 TWh). Figure F.1 illustrates this difference.

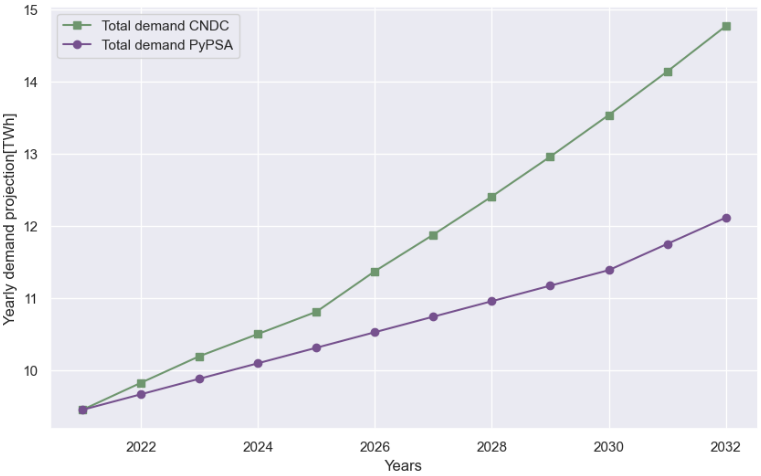


Figure F.1: Comparison of demand projections between CNDC and PyPSA for the year 2030.

The disparity between the two sources of demand projection is anticipated to persist and potentially increase over time. In light of this, our approach for demand projection involves consistently using the year 2030 as the base year and scaling it using a scaling factor to align with the data predicted by CNCD. By employing this methodology, we aim to ensure that our projections are in line with the expectations of CNCD.

Looking ahead to 2050, we need to determine the demand data predicted by CNCD to proceed with the scaling factor calculation. Since specific data for CNCD's demand projection in 2050 is currently unavailable, we will use the information from 2032 as a reference point. By analyzing the trends and patterns in the demand growth from 2032 to 2050, we can project the future demand and determine the scaling factor required to align our projections with the expected demand for 2050.

Appendix G

Cost computation PyPSA-Earth

In the context of Pypsa Earth, the cost computation for electricity generation is a crucial aspect that needs to be understood and adapted to specific cases, such as the Bolivian scenario. Bolivia's unique characteristics, such as its substantial gas subsidies, make it an exceptional case that requires special consideration when modeling the cost of power plants.

When determining the cost of electricity generation, two fundamental components are taken into account: capital costs and marginal costs. The capital cost refers to the initial investment required to build a power plant, while the marginal cost represents the ongoing expenses associated with operating and maintaining the plant.

Data Acquisition To accurately model and adapt the Pypsa Earth framework to Bolivia, it becomes essential to consider the equation employed for cost computation. This equation incorporates both the capital and marginal costs for each power plant involved in electricity production.

In PyPSA-Earth, the costs for power plants can be obtained in two ways. Firstly, they can be downloaded from the default cost file provided in the PyPSA-Earth repository. Alternatively, external data providers can be used as a source for obtaining cost data. The configuration flag `retrieve_cost_data` in the PyPSA-Earth configuration file determines whether the cost data for power plant technologies should be retrieved from external sources or used from the existing cost data file located in the `data/costs.csv` directory.

The default cost file used in PyPSA-Earth incorporates data from reputable organizations, including the U.S. Energy Information Administration (EIA), the German Energy Agency (DEA), and the German Institute for Economic Research (DIW). These organizations provide valuable information regarding the costs associated with electricity generation.

The default cost file contains various parameters and values that are essential for cost computation. These parameters include:

- Lifetime: The expected operational lifespan of the power plant, indicating the number of years it is expected to be in service.
- Investment: The initial capital investment required to build the power plant, encompassing construction costs and equipment expenses.
- Operating and Maintenance (O&M) Costs: The ongoing expenses associated with operating and maintaining the power plant throughout its operational lifetime.
- Efficiency: The efficiency of the power plant, representing the ability to convert input fuel or energy into useful electricity output.
- Fuel Price: The price of the fuel or energy source used by the power plant to generate electricity.

By incorporating these parameters and values from the default cost file, PyPSA-Earth ensures that the cost computation process accounts for key factors that influence the overall cost of electricity generation.

Data processing Once the data is downloaded, it is processed within the `load_cost` rule of the `add_electricity` function. This processing ensures that the data is in a standardized form, typically expressed uniformly in terms of either megawatts (MW) or megawatt-hours (MWh). Additionally, within this function, the capital and marginal costs are calculated for each technology.

The capital cost is computed using the following formula:

$$\text{Capital\_cost} = \left(\left(\text{Calculate\_annuity(lifetime,discount rate)} + \frac{\text{FOM}}{100.0}\right) \times \text{investment} \times \text{Nyears}\right)$$

On the other hand, the marginal cost is determined by the following formula:

$$\text{Marginal\_cost} = \text{VOM} + \frac{\text{fuel}}{\text{efficiency}}$$

Assignment to Components After the cost data is processed and calculated using the equations, the obtained capital and marginal costs are assigned to the generators and storage units in the PyPSA-Earth model. This assignment occurs within the `add_electricity` function, specifically in the `attach_wind_and_solar`, `attach_conventional_generators`, and `attach_hydro` rules.

In these rules, the generators (and storage units for hydro reservoir cases) are added to the network using the `n.madd()` function, which adds units with multiple attributes to the network.

By assigning these cost-related attributes during the network construction process, PyPSA-Earth incorporates the computed cost values into the model as well as the efficiency found in the input cost file. This ensures that the generators and storage units are associated with their respective capital and marginal costs, allowing for accurate economic analysis and simulation of the electricity generation system.

Particular case of gas

In the Bolivian energy model, the price of gas plays a crucial role and requires special consideration. As mentioned earlier, the government has established policies resulting in differentiated prices exceptionally low (specifically for electricity production) by enjoying opportunity of gas resources in the country

To accurately represent the Bolivian energy system, adjustments are necessary to reflect these subsidized gas prices. Section 6.1.2 provides detailed information on the process of adapting the gas price and considerations for selecting the appropriate fuel price.