Graphical Abstract

Energy transition implications for Bolivia. Long-term modelling with short-term assessment of future scenarios

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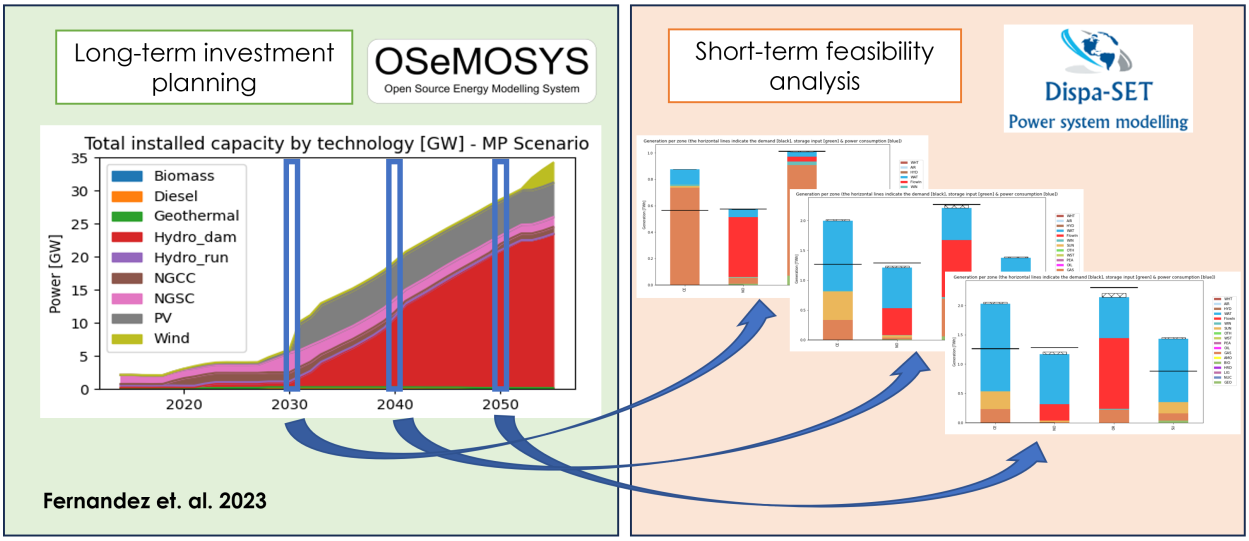
Energy transition scenarios for Bolivian energy sector until 2050. Long-term modelling with short-term assessment of power systems

Key results:

- A soft-linking process between two open-source energy models, OSeMOSYS (long-term model) and Dispa-SET (short-term model), is presented and applied for Bolivia's energy system.
- Explored scenarios show that development pathways that aim for the transition of the energy system are expected to be more cost-effective in the long run.
- To facilitate the transition process, significative investments in the power generation system must be considered and adequately planned for.



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Energy transition implications for Bolivia. Long-term modelling with short-term assessment of future scenarios

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Abstract

The global imperative of achieving carbon neutrality by 2050 to mitigate climate change has intensified the focus on the energy sector, given its significant contribution to GHG emissions. Like many other countries, Bolivia has set official goals for transitioning its energy sector. However, these still require robust planning and technical documentation to become a reality.

To better understand the effects of the transition process, a long-term optimization model (OSeMOSYS) was developed for the period 2020–2050. This model analyses the evolution of energy consumption, emissions, and required investments under alternative conditions. Additionally, a dispatch optimization model (Dispa-SET) was used to validate the technical feasibility of these scenarios periodically. Linking results from both models helps address limitations in the long-term model and determine a margin of error in its simulations.

This study explores three scenarios: Business as Usual (BAU), Mixed Policies (MP), incorporating policy-based measures, and Carbon Neutrality (CN), assuming a 95 % reduction of carbon emissions. Results suggest that adopting energy transition measures could reduce the system's overall cost in the long term. However, achieving this would require major investments, especially at the power generation level. Relative to BAU conditions, the MP scenario expects an 80 % reduction in emissions by 2050, but requiring discounted investments 3.5 times higher. The CN scenario would require even larger investments, with an average yearly undiscounted cost of 2700 million USD between 2020 and 2050, similar to 7 % of the current national GDP of Bolivia. These results highlight the significant challenge of transitioning Bolivia's energy sector.

Keywords: Energy modelling, Energy systems, Bolivia, Energy transition, GHG emissions, Energy policy, Carbon neutrality, OSeMOSYS, Dispa-SET

1. Introduction

Global warming, and the consequent alteration of climate patterns worldwide, is the most pressing issue humanity is facing in this generation [1]. In this context, most countries have acknowledged their responsibility and intentions to reduce their impact by limiting greenhouse gases (GHG) emissions [2]. To address this issue and prevent irreversible changes globally [3], various pathways and scenarios for reducing GHG emissions are being studied.

The consensus among nations is to achieve "carbon neutrality" by 2050 [4]. This would require all countries to phase out their GHG emissions by 2050 or to offset them with alternative technologies [5]. For the energy sector, this would involve transitioning from conventional energy sources (fossil fuels) to new ones (renewable technologies) for the production and supply of energy [6]. In this context, the concept of energy transition has gained traction and is being studied in developed countries [7] and developing countries alike [8].

Although there are many other ways to analyse a subject, the technical requirements [9], the economic implications [10] and the political factors [11] are the most frequently discussed. These three aspects are critical and will often focus on analysing: the optimal technol-

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ogy mix required to get to net-zero emissions; the local conditions and policies needed to facilitate the transition process [12]; the expected costs of implementation [13] in order to guarantee the feasibility of the transition process. For Bolivia, various models have been developed to study its energy sector and its evolution from different angles. For instance, short-term dispatch models such as Dispa-SET have been used to analyse the technical capabilities of the electrical system to handle increasing amounts of variable renewable energy [9] and study the operational requirements to increase renewable technologies penetration in the electric system [14]. However, while these models provide technical indicators and limits to be considered for a proper operation, the scenarios presented are explored mostly as sensitivity analysis of varying specific conditions in the system in a short- to mid-term scope.

Alternatively, long-term optimization models such as OSeMOSYS have been used to explore development scenarios, their investment costs and their environmental impacts over time, focusing on: export opportunities with neighbouring countries [15]; to simulate Bolivia's mid-term energy transition scenarios [16]; or to assess the impacts of policy implementation on reducing emissions from the electric sector [17]. In these cases, while the models are used to explore development scenarios within a large scope and to provide an array of potential alternatives for the system, some technical characteristics are disregarded or oversimplified reducing the reliability of their results.

For all these cases, the process of analysing the energy system, while complex in its details, usually assumes a simple and linear flow composed of processing input data, running a model under different conditions, and then assessing the results for each case [18]. However, the inclusion of additional steps and modelling tools allows the generation of complementary processes. These can take the form of loops between models to assess and improve the quality of the initial results [19].

This approach for coupling short- and long-term modelling tools to study energy systems has become increasingly relevant. Consequently, several case studies have started appearing in the literature, all with similar approaches but different modelling tools. Such are the cases of the coupling of TIMES and MEDUSA for studying the evolution of the Polish energy system [20]; the endogenization of short-term constraints into planning models (TIMES) to assess the reliability of the grid in alternative futures for the French power system [21]; or the coupling of Dispa-SET and TIMES for the analysis of the entire European energy system [22].

This work builds upon previous studies by expanding their scope and complementing the modelling efforts done for Bolivia [23]. The study does this by providing a soft-linking methodology for long-term (OSeMOSYS) and short-term (Dispa-SET) models that were previously explored only from stand-alone perspectives. Additionally, the selection of these tools provides another novelty layer to the study, by presenting a case study that uses only open-source tools with freely and easily accessible online documentation, simplifying their exploration, adoption, and usage by other potential researchers or institutions from the field. From an applicative point of view, this work also expands the scope of previous research by considering non-electrical demands and sectors in the long-term simulation. This is done to quantify the impact of transitioning the entirety of the system's demands to renewable sources. Finally, while the study is linked to the Bolivian case and the implications of its transition process, the general structure of the methodology and models can be extrapolated and applied to other study cases.

2. Method

2.1. Modelling tools

The OSeMOSYS and Dispa-SET tools have been selected for this study considering that both models are open-source, and both have been previously developed for the Bolivian case. In this sense, to cover the basic understanding of both tools, their end-use goals and their specific objective functions are presented. The Open-Source Energy Modelling System (OSeMOSYS) [24] was selected to simulate long-term aspects of the energy transition. OSeMOSYS is an energy system optimization model expressed as a LP (linear programming) problem, with a governing objective function (OF) and auxiliary equations defining the constraints of the model [25].

$$\begin{aligned} OF_{\text{min cost}} = \sum_{r,t,y}^{YEAR,REG,TECH} \Bigg[& \left(\frac{\sum_{YY}^{YEAR} NC_{r,t,yy} + RC_{r,t,y}}{1 + DR_r^{y-\min(yy)+0.5}} \right) \\ & + \sum_{l,m}^{TS,MO} \left(\frac{RA_{r,l,t,m,y} \cdot YS_{l,y} \cdot VC_{r,t,m,y}}{1 + DR_r^{y-\min(yy)+0.5}} \right) \\ & + \frac{CC_{r,t,y} \cdot NC_{r,t,y}}{1 + DR_r^{y-\min(yy)+0.5}} + DEP_{r,t,y} - DSV_{r,t,y} \Bigg] \end{aligned} \tag{1}$$

Equation 1 provides the total accumulated costs required to satisfy exogenous energy demands in all time periods for several years. Costs in the objective function include fixed (FC) and variable (VC) operating costs, capital costs associated with new investments (CC) and costs related to emission penalties (DEP) or salvage values (DSV). These values are defined by region (r), technology (t), year (y) or time-slice (yy).

The unit-commitment and optimal power dispatch model (DispaSET) was selected to assess the power system's flexibility and adequacy. Dispa-SET does this by simulating short-term operations in power systems and considers the techno-economic constraints from a central planner perspective [26]. The model uses a MILP (mixed-integer linear program) based on Python and GAMS (General Algebraic Modelling System), and assumes constraints linked to generation units, nodal demands, and power system operational costs.

$$\begin{aligned}
OF_{\text{min cost}} = \sum_{u,n,i} \big[& (CostFixed_{u} * Commited_{u,i}) + \\
& (CostVariable_{u,i} * Power_{u,i}) + \\
& CostStartUpH_{u,i} + CostShutDown_{u,i} + \\
& CostRampUpH_{u,i} + CostRampDown_{u,i} + \\
& PriceTransmission_{i,l} * Flow_{i,l} + \\
& CostLoadShedding_{i,n} * ShedLoad_{i,n} + \\
& \sum_{chp} \Big(HeatSlack_{chp,i} * \Big(CostHeatSlack_{chp,i} + \\
& \quad CostVariable_{chp,i} * CHPLoss_{chp} \Big) \Big) + \\
& VoLL_{Power} * (LL_{MaxPower,i,n} + LL_{MinPower,i,n}) + \\
& VoLL_{Reserve} * (LL_{2U,i,n} + LL_{2D,i,n} + LL_{3U,i,n}) + \\
& \quad VoLL_{Ramp} * \Big(LL_{RampUp,u,i} + LL_{RampDown,u,i} \Big) \big]
\end{aligned} \tag{2}$$

Equation 2 shows the OF and its components, which include fixed costs, variable costs, start-up and shutdown costs, ramp-up and ramp-down costs, load shed, transmission, loss of load, spillage and water usage. Sets u, i, l, and n represent the power generation units, the simulated hours, lines and the zones, respectively [27].

The models OSeMOSYS and Dispa-SET have similar approaches to study energy systems. For instance, both have a bottom-up data structure, both use techno-economic variables and constraints, and both optimise the costs associated with their systems' operation. Nevertheless, the timeframes they use serve as their main differentiator. OSeMOSYS is a model that runs optimisations for investments over several decades. The basic time unit analysed is a year, which can be subdivided based on requirements or available data. In the case of Dispa-SET, the model focuses on minimising a system's operation costs, considering days as the basic time frame over cyclic periods (weeks, months or even a year). In this model, data granularity can get to the range of hours or minutes.

2.2. Soft-linking proposal

While OSeMOSYS can be useful to evaluate and propose future development scenarios for energy systems in the long term, its capability of adequately representing the system's behaviour in the short term is limited. In contrast, Dispa-SET can be used to accurately represent the system's behaviour and its components. However, its focus is set on analysing the system only under specific (given) conditions. Due to these characteristics, a complementarity between the tools has been identified, which can be exploited to better assess the development of energy systems.

In this sense, this study presents a soft-linking process between the long-term model (OSeMOSYS), which creates alternative development scenarios for energy systems, and the short-term model (Dispa-SET), which assesses the feasibility of the power system in such scenarios. Results from the short-term model can be later reintroduced into the long-term model to improve the proposal of future scenarios. A schematic of this feedback process and the interaction between models is presented in Figure 1.

Taking advantage of the characteristics of each model and the proposed soft-linking process, a six-step methodology was applied for this study. For each generalised step, details are provided regarding the particularities of the case study:

1. Energy system characterisation and alternative scenario definition: Overall characteristics of the energy system corresponding to the case study were defined. Based on them, both the long and short-term models were structured to represent the system's characteristics within their limitations. Three alternative development scenarios were set based on transition goals (BAU, MP and CN).
2. Initial run of scenarios with long-term model: Each scenario was run in OSeMOSYS for the period 2020–2050 to create a baseline of results and a benchmark of the system's behaviour in the future.
3. Long-term output data transformation to short-term input data: Python scripts were used to process modelling results from OSeMOSYS into inputs for Dispa-SET. Adapted data sets were the total electric demand, installed capacities by technology, carbon emission penalties and yearly fuel prices.

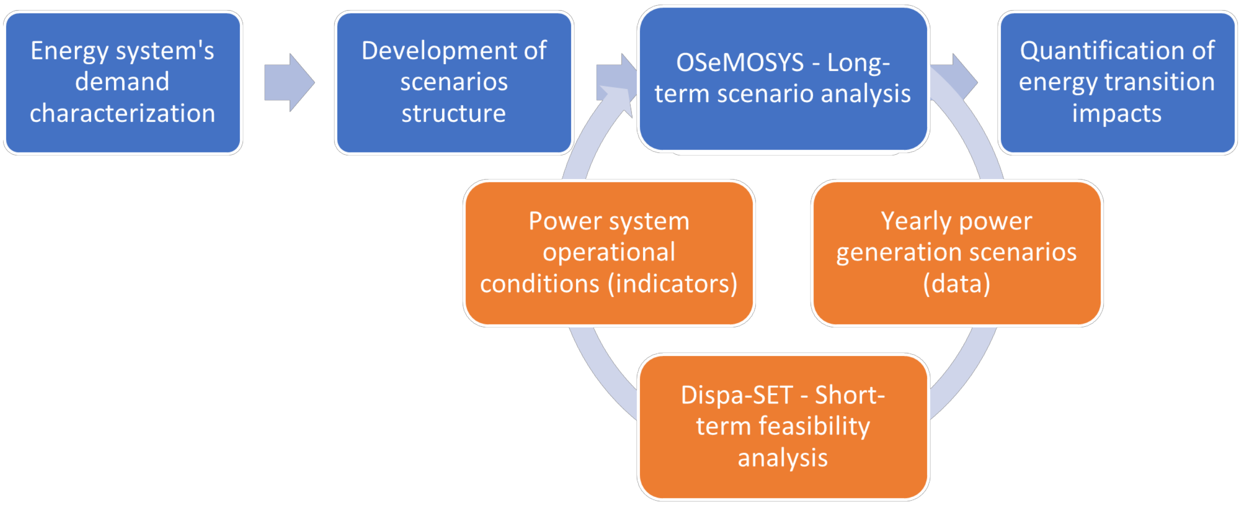

Figure 1: Proposed methodology for the long-term analysis of the Bolivian Energy System.

4. Periodic feasibility analysis of scenarios with short-term model: The model was run at different years for each development scenario. The year 2020 was run as a baseline, and years 2030, 2040 and 2050 were run to check the system's behaviour at different stages. Indicators used to assess the feasibility of the scenarios were the total load shedding and capacity margins.
5. Long-term model adaptation: Modifications were made to the long-term model structure to address technical shortcomings found in the feasibility analysis. To this end, constraints were adapted to consider and compensate differences between the proposed installed capacities by the long-term model and the capacity limitations found in the short-term model.
6. Scenario analysis: With the adapted model, the long-term model is rerun for each scenario. Results were later quantified and compared, focusing on the behaviour of costs and emissions to adequately assess the implications of each of the alternative transition scenarios and their conditions.

3. Case study

3.1. The Bolivian energy sector

Bolivia is a landlocked country in South America. It has a population of approximately 11 million and is a net energy exporter in the region, primarily due to its substantial natural gas reserves [28]. In 2014, Bolivia's natural gas (NG) exports reached a peak value of 150 kboe. However, these exports have been declining over time due to the depletion of natural gas reserves and the lack of new reservoirs being discovered [29].

Bolivia's domestic energy consumption added up to 43 kboe in 2020, with shares of 75.6 % of fossil fuels, with an even mix between natural gas, gasoline, and diesel. The resting 24.4 % of energy consumption comes from other sources, split between biomass and electricity [28]. Analysed by sectors, the transport sector is the main consumer, accounting for 49 % of the total. The next consumers are industry, residential and commerce/services, with 25.3 %, 17.3 % and 3.8 %, respectively [28].

Bolivia's national interconnected system (SIN) had a total installed capacity of 3318.8 MW in 2020, composed of 72.8 % of thermal power plants, primarily natural gas simple-cycle (NGSC) and natural gas combine-cycles plants, and 27.2 % of renewable power plants, mostly hydroelectric powerplants with minor wind and solar contributions [30]. A total of 8897.3 MWh was produced in the same year, with conventional NG plants providing 63.3 % of it, hydroelectric power plants providing 32.3 %, and a combination of solar, wind, and biomass power plants providing the remaining percentage [31]. As a result, the energy sector is the second biggest contributor to the total GHG emissions in Bolivia, according to statistics from the most recent national inventory of carbon emissions [32], and the third national communication [33], being only after the AFOLU sector (agriculture, forestry, and other land use).

To tackle this, the electrical subsector has been making significant efforts to reduce its dependency on conventional energy sources and reduce carbon emissions. These efforts are periodically defined and presented in national development plans, such as the "Plan Optimo de Expansion del SIN 2012–2022" [34] and the "Plan Electrico del Estado Plurinacional de Bolivia 2025" [35], as sectorial development goals. Moreover, these objectives have been ratified by international reports and agreements such as the Bolivian nationally determined contributions (NDC) [36] or the compliance of the Paris Agreement before the UNFCCC [37].

The latest documents, "Plan de Desarrollo Economico y Social 2021–2025" [38] and the newly updated NDC [39], consider a short to mid-term planning period and establish clear national-level goals. The most significant goals include increasing the proportion of renewable electricity production to 75 % and electrifying 10 % of the public transport sector by 2030.

While these development plans and national goals present sensible and ambitious objectives for Bolivia, they are still defined only as targets and do not consider development pathways for the long term. In this sense, complementary technical documents that study the evolution of the entire energy sector quantitatively are needed to properly plan the country's future [18]. To this end, the first step is to understand the connections between the long-term planning efforts, alternative development scenarios, their climate change mitigation potentials, their technical feasibility and the volumes of investments required to achieve them. This work represents a first attempt to answer these questions.

3.2. *OSeMOSYS - Bolivia*

The developed model is built upon previous work done for the Bolivian case with OSeMOSYS [17] and adapts its structure to accommodate additional sectors and energy demands. The model assumes Bolivia as one single region/node, isolated from other countries in terms of electrical connections, which is currently the case. The analysis period (up to 2055) is divided into three stages: A historical period corresponding to available observations, between 2014 and 2020; The projection analysis period of 30 years, between 2021 and 2050; A look-ahead period included in the model to avoid end-of-horizon effects, between 2051 and 2055. Across the modelling periods, a discount rate of 12 % is considered for future investments or costs incurred by the system, based on the referential values presented in the Bolivian electricity law [40].

The model has a yearly time step, with each year subdivided into six time-slices, corresponding to three seasons (rainy and dry seasons, three months each, and an intermediate season, six months); and day (6:00–17:59) and night (18:00– 5:59) cycles. This time resolution configuration is defined based on the results obtained in previous work [16] to capture the changes in the availability of resources, such as hydropower (seasonal) and PV or Wind (daily), while ensuring computational tractability.

The baseline model for Bolivia is built upon the characteristics of the national energy demands [28] and the current power generation system [41]. Figure 2 presents the relations between fuels (lines) and technologies (boxes) considered in the model, and details on the acronyms used can be found in the nomenclature section.

The "Resource supply" section consists of four technologies producing specific fuels and are connected to either the end-of-use sectors or energy conversion technologies. The second stage, "Transformation technologies", includes the conversion technologies (power plants) used to generate electricity, divided into conventional and renewable technologies. The electricity is then transmitted and distributed in the third stage,"T&D networks". Finally, the "End-use energy consumption" stage represents all the consumer sectors in the energy system and their final energy demands.

For each of these technologies, particularly for the power generation section, a set of parameters describes their operational characteristics and cost-competitiveness. Technical parameters include power plant efficiencies, operating lifetimes, capacity factors and availability factors. Economic variables consider the capital and operating costs of new investments (fixed or variable) for each technology. These values are estimated based on historical data of projects executed [42], under development [43] or in the feasibility study stage [44].

In the case of fossil fuel supply technologies, NG production is defined by the exploitation and production processes presented by Chavez et al. [29] and the values used in previous models [17]. In this sense, the model quantifies the costs associated with the availability/production of NG by considering investment costs for exploitation facilities and fixed costs for their operation.

For diesel and gasoline, as these are mostly imported fuels [28], costs are reflected directly by their prices at international markets with values of 9 million USD/PJ [45]. These are represented in the model as variable costs depending on the consumption at the end-use stage. For the case of biomass used in sectors other than power generation, mainly linked to cooking in ru-

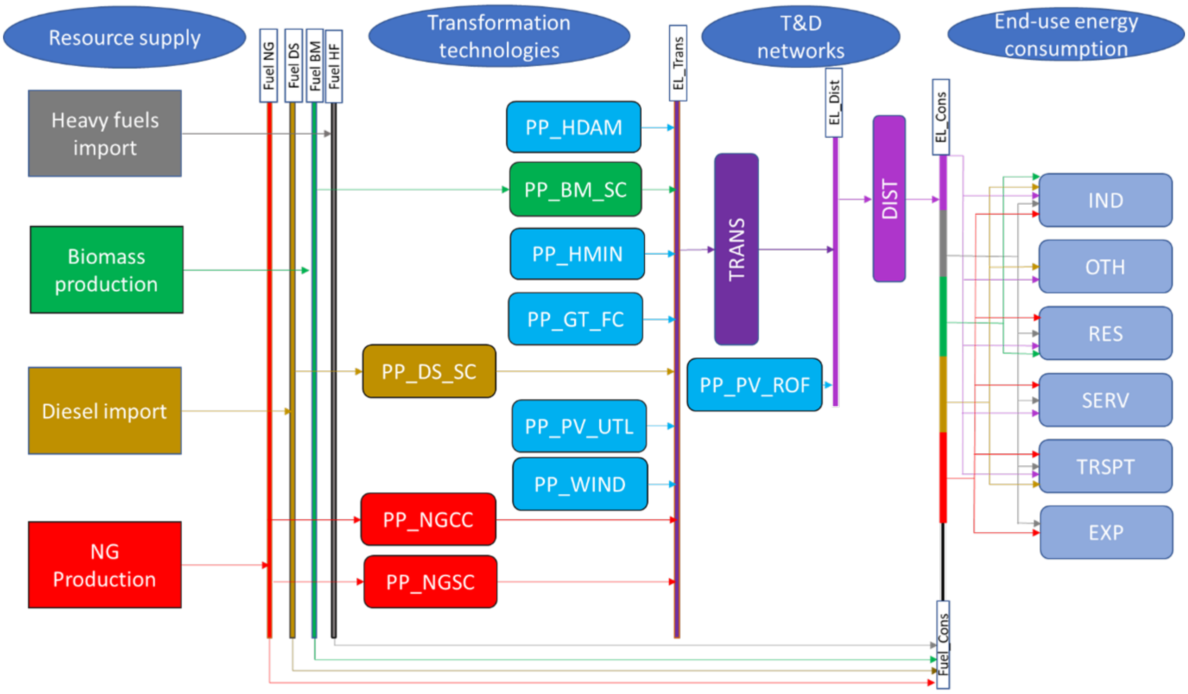

Figure 2: Referential energy system for Bolivia - Relations between fuels and technologies

ral areas [28], no market prices are defined since this is a resource the population will acquire independently and, therefore, no direct costs for the government can be considered.

The model also considers GHG emissions as carbon dioxide equivalent units (CO2e) using emission activity ratios for the technologies that indirectly produce a surplus of GHG emissions during operation. For fossil fuel-based technologies, these emission activity ratios are based on the carbon emissions factors from the IPCC guidelines [46] and are quantified in the “Resource supply stage”. For the hydroelectric plants and their impacts [47], a literature review was conducted to define values of GHG emissions linked to these technologies [48], especially in tropical reservoirs [49], where emissions are expected to be higher [50], with values that can vary between ranges of 0.5–3000 gCO2e/kWh [51]. In the case of geothermal power plants, there are some reports on emissions generated by their operation, with average values of 122 gCO2e/kWh [52]. However, GHG emissions are still very dependent on the specific sites. Studies have also estimated that, in some cases, power plants can reduce the expected amounts of CO2 emissions in the long term, compared to a geothermal system in natural conditions without interventions [53].

For this study, to be conservative, values in the lower range for hydropower plants from Brazil were used, given that in Bolivia, there is still a lack of local studies that can provide more precise information. For the rest of renewable technologies, emission factors are considered null. A summary of the emission factors used in the model is presented in Table 1.

3.3. Dispa-SET - Bolivia

In this model, Bolivia is split into four regions, namely central, north, oriental, and south regions, as defined by the TSO [35]. The total annual capacity for power plants is split amongst each region based on historical data on the Bolivian power system [41]. The time resolution is 1 h, and the time horizon is an entire year, with a rolling optimization horizon of four days and a look-ahead period of one day to reduce the simulation time.

To simulate the curve of power demand in the country, an average of hourly available data from 2016 to 2020 was used [41]. This average demand curve was later normalised and used to represent the hourly variations over time for different annual electric demands. A snapshot of the variations considered in the load curves for the first week of January and July 2020 is presented in Figure 3 to illustrate the daily and seasonal variations in the data.

Technology/Fuel	GHG Emissions by activity ratio
Large hydroelectric (Dam)	0.0212 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Small hydroelectric (Run-off)	0.0007 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
PV	0.0000 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Wind	0.0000 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Geothermal	0.0000 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Diesel	0.0743 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Other liquid fuels	0.0693 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]
Natural gas	0.0562 [$\mathrm{MtCO}_2e/PJ_{electricoutput}$]

Table 1: Emission factors considered for each technology and fuel used in OSeMOSYS

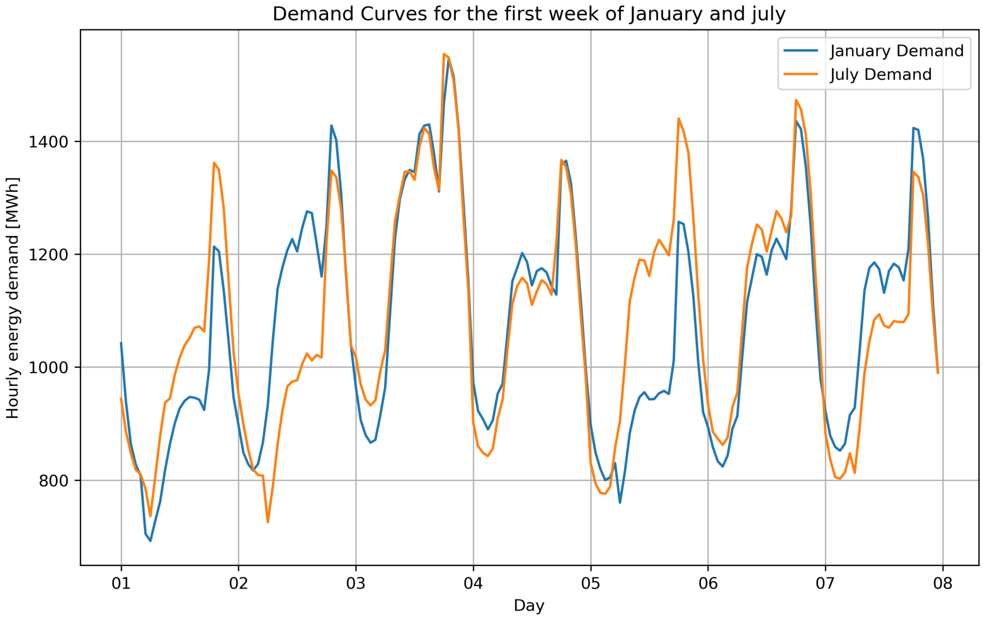

Figure 3: Referential electrical energy demand curves [MWh] in Bolivia for the first week in January and July 2020.

Transmission line capacities, known in Dispa-SET as net transfer capacities or NTC, are also generated based on historical data from 2016 to 2020 and work from Navia et al. [14] and Rojas et al. [9]. These are later upscaled according to the analysed peak load of each year.

The same technologies and fuels presented in Figure 2 are considered for the power system, with the same distinction between renewable and non-renewable but with an additional distinction related to their ability to store energy (mainly in the case of hydropower). The characterisation of power plants in the model is defined by combining one technology and one fuel (i.e., the fuel NG with technology NGCC) and by introducing plant-specific parameters such as power capacity, emissions intensity, ramp-up and ramp-down conditions, start-up and shut-down costs, reserve capabilities, etc.

3.4. Alternative scenarios

To study the evolution of the energy system in the long term, projections of energy consumption in Bolivia are required. To this end, 20 years of historical information from the annual Energy Balance Reports from 2000 [54] until 2020 [28] are processed with a simple moving average calculation on the yearly increments. Energy demands from 2021 to 2055 were calculated with this method for each fuel in each sector.

To ensure consistency, the projections are compared to international databases [55], prospective energy demands for Latin America until 2040 [56], the short-term Bolivian projections [57] and projections in previous work [16]. Results show slight deviations in the comparable periods. An incremental trend can be expected in all the energy demands; however, slightly different growth rates are observable for each sector and fuel. These energy demands are the primary exogenous input for the models and are used to characterise the development of the energy system.

The first scenario assumes Business-as-Usual (BAU) conditions and is constructed based on the system's characteristics in 2020 [30] and historical trends from the last two decades. It is assumed that no additional environmental policies are imposed [16], and the current development plans are all implemented [38].

The Mixed Policy scenario (MP) is a policy-driven scenario focused on promoting energy transition measures and built upon a set of four policies implemented from 2025 onwards and include: reductions in NG subsidies (NSR) for the electric sector, which currently have fuel prices well below international prices [58]; the implementation of carbon taxes (CTI) based on international experience [59]; the implementation of energy efficiency measures (EEM) across all sectors [60]; and the electrification of energy demands (EED) in Bolivia [16].

EEM measures are inspired by work done in different countries and regions, like the case of Ecuador [61], Europe [62], and Asia [63]. Expected results are to achieve a 20 % reduction in energy consumption across all consumer types for the country by 2050. This value is based upon a study conducted for Bolivia that assumes a total reduction of 8.5 % by 2035 and states that the total energy efficiency potential remains to be matched [60]. EED measures aim for total electrification by 2050 in all sectors to identify the magnitude of the challenge ahead. For each sector, the main consumer type is considered and used to represent its energy intensity and equivalent electric energy demands. Referential consumers identified are: for transport, private vehicles [64]; for industry, boilers and ovens [65]; for commerce and services, heating demands [66]. NSR assumes a linear increment of the current subsidised price of 1.3 USD/Mbtu [34] until it reaches international prices [67] to allow fair competition among technologies, which is currently led by renewables [68]. CTI introduces a carbon tax of 30 USD/tCO2e from 2025 onwards, based on a benchmark of values used in other countries [69].

To represent these policies and their effects on the system, different processes are used to include them in the model. Increments in NG prices and implementing carbon taxes are done by modifying variables and parameters available in the model. Measures affecting the total expected energy demands in the system, electrification and efficiency, are calculated externally and introduced as exogenous variables for each scenario.

The Carbon Neutrality scenario (CN) is a goal-based scenario focused on limiting sectorial carbon emissions. It builds upon the MP scenario by making use of an additional constraint in the model. This constraint introduces a progressive carbon emission cap [70] to achieve emission reductions until 2050, replacing the carbon tax in the previous scenario [71]. This carbon cap can be used to infer the carbon price (shadow price) needed in the MP scenarios to induce the prescribed emissions reductions [72]. The carbon price is calculated as the dual value of the carbon cap constraint.

In this scenario, the emissions are limited to 95 % because the current technology mix considered is not suitable to reach net zero goals without providing extreme results. The "last 10 %" of system decarbonisation is known to be significantly more complex than the first 90 % [73] and usually requires negative emission technologies such as direct air capture or bioenergy with carbon capture and storage, which are not considered in this work. Table 2 provides a summary of the key considerations taken into account in each scenario.

For the sake of transparency and reproducibility, the models and the input data are released under open licenses and are available in a Zenodo repository (https://doi.org/10.5281/zenodo.7633742).

4. Results and discussion

4.1. Simulation of the long-term planning model in isolation

This section presents the results of running the OSeMOSYS model outside of the soft-linking framework to provide the baseline for the following steps of the study. Among the diversity of model outputs, three are selected to represent how the system evolves: the evolution of the total energy consumption by fuel; the electrical energy generation mix; the total annual emissions in the energy sector. Results for the BAU scenario are displayed in the following figures.

Figure 4 indicates a stable growth in demand, which doubles in 20 years to reach a value of 669 PJ in 2050. Of the accumulated energy demand, electricity accounts for 12 % in 2020 and 14 % in 2050. Contrary to most decarbonisation scenarios, the BAU case does not promote a strong electrification rate, which explains why the latter percentage remains stable. This is a result of current national plans that focus on incrementing the renewable generation share in the electric sector but do not explicitly present electrification goals for other energy-consuming subsectors [39].

Figure 5, displays the participation of the different generation technologies used to supply the electricity demand. According to the results, most of the demand

	BAU	MP	CN
Energy consumption trend	Historical evolution of fuels consumed by sectors	Total electrification of energy demands until 2050	Total electrification of energy demands until 2050
Energy efficiency	Not considered	20% overall reduction for electric consumption	20% overall reduction for electric consumption
Carbon taxation	Not considered	Fixed tax (30 USD/tCO_2e)	Not considered
NG costs for electricity	Subsidised price (1.3 USD/Mbtu)	Levelized to international prices by 2050	Levelized to international prices by 2050
Annual emission limits	Not considered	Not considered	95% reduction compared to BAU in 2050

Table 2: Summary of policies considered for the BAU, MP and CN scenarios

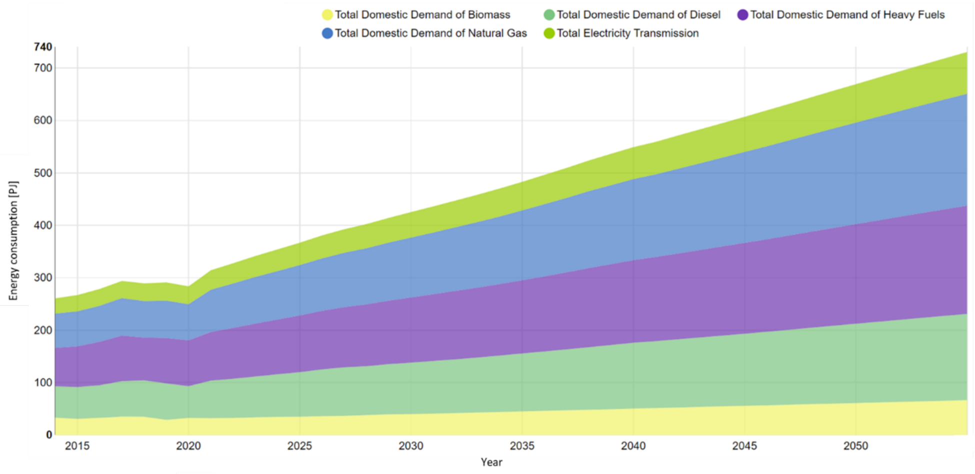

Figure 4: Total energy consumption in Bolivia by fuel [PJ] in the period 2014–2055.

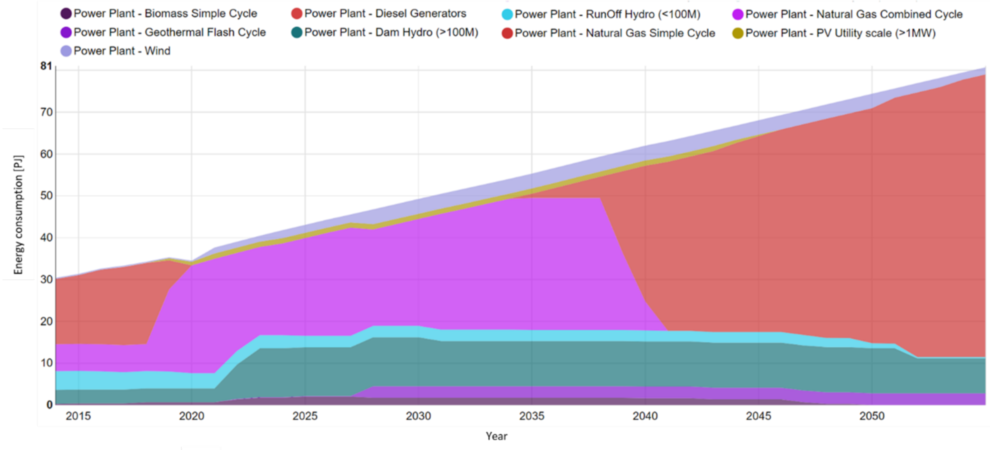

Figure 5: Total energy consumption in Bolivia by fuel [PJ] in the period 2014–2055.

is covered by open-cycle and combined-cycle natural gas turbines, with a smaller share of hydroelectric units and marginal participation from the remaining generation technologies. This behaviour reflects the system's current situation when considering the subsidised prices of local fuels used in electricity generation.

Finally, the carbon emissions associated with the internal demand of the energy system show a clear trend of sustained growth throughout the analysed period, with a total of 15 MtCO2e in 2020 and almost 39 MtCO2e by 2050, consistent with the trend of sustained use of fossil fuels. A compiled version of these results, and those from the MP and CN scenarios, is presented in Table 3, where values are expressed for each decade analysed.

From Table 3, some key outputs are linked to the shift trends in the Total energy demand and the Electricity share in energy demand rows for the MP and CN scenarios, compared to the BAU. In both cases, the overall reduction of the total energy demands and the increase of electricity shares in the system are results of the implementation of efficiency and electrification measures. In addition to these, the Renewable electricity share and the Main generation technology rows provide an idea of how technologies evolve to cover the electrical demands in each scenario and replace fossil fuel-based technologies.

The evolution of the MP scenario shows a straightforward behaviour in which the model perceives new electrical demands and covers them with the inclusion of new hydro powerplants. This is possible given that these power plants represent the most cost-efficient mechanism to provide energy in the system. For the CN scenario, the hydropower share is displaced by other renewable technologies such as PV (2030) and Wind (2050). This results from the limitation on emissions for each year and the consideration that hydropower plants have small GHG emission factors. Additionally, another interesting output is that while PV is relevant initially, given its low cost, it reaches a limit due to its unavailability at night-time and its necessity to partner with other regulable technologies (such as hydro). This results in Wind becoming a more relevant technology over the years to cover the incremental trend of energy consumption.

4.2. *Short-term assessment of long-term scenarios*

The power systems proposed as outputs of the OSeMOSYS model run in isolation are tested for adequacy and flexibility using the Dispa-SET model. For 2020, with the historical power generation capacities, there is no indication of a lack of flexibility or adequacy: energy not served (ENS) is always zero, and the capacity margin (CM) remains positive. However, this is not the case anymore for 2030 or the subsequent simulations.

In the BAU for 2030, Table 4 shows that load shedding is required, with a value of 0.96 % ENS, indicating that the system is facing a lack of capacity or power transmission to cover the demand in a zone. For the 2040 simulation, ENS is 5.6 %, and a negative CM of 657.72 MW is registered. The year 2050 has similar results, confirming a significant lack of installed capacity. Similar results are obtained for the MP and CN cases.

While the results show a general lack of capacity for the power system after 2030, some particularities are worth noting. For instance, while the BAU scenario can provide energy demands for 2030 with the expected installed capacities of the system, the MP and CN cannot match the power requirements due to a sharper increase in energy demand, resulting from the electrification of sectors that were previously using fossil fuels.

By comparing the CM with the total installed capacities expected for each simulation, it is possible to confirm that additional capacities are required across scenarios. These additional capacities range between 1 and 10 % in all the scenarios and years simulated with Dispa-SET. While this clearly signifies a shortcoming in the capability of OSeMOSYS to properly consider the system's flexibility requirements in the power generation system, this would also mean that the current version can provide a tentative power system for the Bolivian case within a margin of error of 10 %.

4.3. *Adaptation of the long-term model*

Results from the short-term analysis shed light on the limitations of the long-term model, mainly by demonstrating insufficient power generation capacities to provide the expected energy demands in all the scenarios. This lack of adequacy in the long-term model can be addressed and improved in several manners, each with its own advantages and drawbacks:

- By adapting technology variables such as capacity and availability factors to limit the dispatch of power plants and reduce their general operational capacities to force more realistic values. However, this method can be somewhat arbitrary given that it will rely on the dispatch characteristics reported by the short-term analysis, which differ depending on the year/scenario considered.

- By adapting the energy demand distribution over the existing timeslices to simulate more extreme requirements of the system that should be covered. The drawback of this method is the artificial alteration of the original energy demand curve, which might result in biased simulations.

- By including additional time slices to better capture the variables mentioned earlier. However, this

	Baseline	BAU			MP			CN		
	2020	2030	2040	2050	2030	2040	2050	2030	2040	2050
Total energy demand [PJ/year]	283.7	425.3	549.3	669.3	383.5	416.9	450.1	383.5	416.9	450.1
Electricity share in energy demand [%]	12.0	11.4	11.1	10.9	29.2	60.3	86.8	29.2	60.3	86.8
Main generation technology [%]	NGCC 75.8	NGCC 52.8	NGSC 53.3	NGSC 77.0	NGCC 59.5	HDAM 67.4	HDAM 86.3	PV 27.7	HDAM 41.6	WIND 50.7
Renewable electricity share [%]	24.1	48.8	37.0	25.1	21.1	86.7	95.9	71.8	97.7	98.5
Installed capacity [GW]	3.09	4.24	3.26	3.33	5.63	19.18	28.67	10.16	24.7	37,97
Emissions [$MtCO_2e/year$]	15.0	24.0	31.4	38.7	20.7	13.2	7.9	17.9	10.2	1.8

Table 3: Long-term simulation results per decade for the BAU, MP and CN scenarios.

	BAU			MP			CN		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
CM [MW]	759.64	657.72	939.46	708.17	8192.33	1519.30	1518.48	3777.91	3647.57
ENS [%]	0.96	5.60	6.22	2.27	8.80	9.47	5.49	5.84	4.25

Table 4: Short-term simulation results per decade in scenarios compared to the baseline values.

would result in an exponential increase in the computational requirements for solving the optimization problem.

- By increasing the value of the CM requirements of the system used in the energy balance constraint, thus ensuring an overcapacity capable of covering some of the differences between the expected high loads and low VRES availability. However, this method focuses on providing additional capacity to cover energy consumption and, therefore, might prioritise technologies with higher energy yields instead of increasing uniformly installed capacities.

For this work, the last approach is selected, and to implement it, the total reserve margin required every year is increased by 10 % from 2020 onward. This increase in the original reserve margin (22 %) translates to the power system dimensioning by forcing the model to add additional installed capacity. The main constraint used in the model to enforce the reserve margin is specified in Equation 3.

$$RP_{r,yy,y} * RM_{r,y} <= \sum_{tech}^{TECH} \left[\left(NC_{r,t,yy,y} + RC_{r,t,yy,y}\right) * RMT_{r,t,y}\right] \tag{3}$$

This constraint enforces that, for every region (r), time-slice(yy) and year (y), the capability of producing energy by the system (RP), increased by the reserve margin (RM), is always at least equal to the total installed capacity of technologies, new (NC) and residual (RC) capacities, that are tagged to be capable of providing reserve margin (RMT).

By increasing the reserve margin, inputs from the short-term analysis of the power generation capacities are taken into account in the long-term model, and each scenario is run to improve the generation mix and reduce the discrepancies between the stand-alone model and the revised model, which can be found in Table 5.

For the BAU scenario, the system has to increase its total capacity by up to 7.5 % by 2050 compared to the stand-alone model, however, changes in the energy mix are not noticeable. This effect is derived from the overreliance of the system on one technology type to produce its energy, which, for this case, means that NG thermal plants given their artificial competitiveness. For the CN and MP scenarios, while total capacities on the

	Baseline	BAU			MP			CN		
	2020	2030	2040	2050	2030	2040	2050	2030	2040	2050
Main generation technology [%] NGCC	75.8	NGCC 52.8	NGSC 53.3	NGSC 77.0	NGCC 46.4	HDAM 68.8	HDAM 86.3	HDAM 31.5	HDAM 41.2	WIND 41.6
Installed capacity [GW]	3.09	4.25	3.47	3.58	5.99	19.29	28.63	10.42	26.45	38.78
Emissions [MtCO$_2e/year$]	15.0	24.0	31.4	38.7	18.5	13.3	8.1	17.9	10.2	1.8

Table 5: Long-term simulation results after short-term assessment and adaptation of the reserve margin (BAU, MP and CN scenarios).

system also increase over time up to 2.5 % compared to the stand-alone model, the composition of the power generation mix is also modified. In these cases, technologies such as PV and wind are partially replaced by other renewable technologies with higher energy yields, such as hydro and geothermal.

Finally, a more detailed representation of how emissions would behave over time is shown in Figure 6. As expected, an uninterrupted increase in emissions is present in the BAU scenario, due to the historical fossil fuel consumption trends that are continued over time. The MP scenario allows a continued reduction until 2050, thanks to the electrification process and the transformation of the power generation system. After this year, emissions are stabilised thanks to the mix of policies that disincentivise emission-intensive technologies. Finally, the CN scenario complies with the imposed annual emission limits, reaching zero emissions by 2050.

4.4. *Costs associated with the energy transition*

From a national perspective and according to its regulations, Bolivia has the competence and mandate to provide availability of resources to its population in the different forms that it demands [74]. In this sense, the government must guarantee the Bolivian population access to all energetics (electricity, NG, diesel, etc.) to cover their needs.

According to the characteristics of the model, the costs taken into account for the system associated with the provision of end-use energy are investment and fixed costs, linked to the development and operation of the power generation sector and production of NG; and variable costs, linked to the operation of power plants and the importation of fossil fuels for each demanding sector. In this sense, costs associated with the availability of energetics can be estimated and used to represent the total economic efforts that the government must plan for.

Figure 7 compares the total costs incurred by the system for each scenario (lines), which represent yearly expenditures to meet the total energetic demand. Additionally, the annual investment portions (dashed lines) corresponding to each case are also shown. The differences between total costs and investments correspond to the operational costs of the system (fixed and variable).

BAU presents an incremental trend, with an average value of 5400 million USD/year in the period 2020–2050, mainly corresponding to the variable costs from the importation of fossil fuels. Alternatively, the MP and CN show higher upfront costs in the early years of the transition, followed by a reduction in operational costs linked to the zero marginal cost of renewable power plants. This is exemplified by the convergence trend between total costs and investments in these scenarios.

If total costs are discounted for 2020–2050 and actualised to 2020, the net present value (NPV) expected would be 36,300 million USD for the BAU, 35,520 million USD for the MP and 37,540 million USD for the CN. These values show that a transition process should be convenient in the long term for Bolivia, by having a lower accumulated cost in the MP scenario compared to the BAU. For the CN scenario, while achieving the goals set seems to be more expensive, if the change of yearly costs trend continues compared to the BAU, CN conditions would also become more convenient in the longer term.

These results are consistent with literature that analyses the costs of energy transition or decarbonisation at regional scales [75], national or sub-national levels [76] and even by technologies available [77]. In all cases, electrification measures and high renewable penetration in the power system are the main drivers for decarbonisation. This demonstrates the technical and economic feasibility of the energy transition for the first 95 %. However, the last percentages of decarbonisation, known to be the hardest [78], would require policies and technology shifts such as carbon capture and removal to offset the incremental costs of reducing this final share of emissions [79]. Finally, to compare implementation

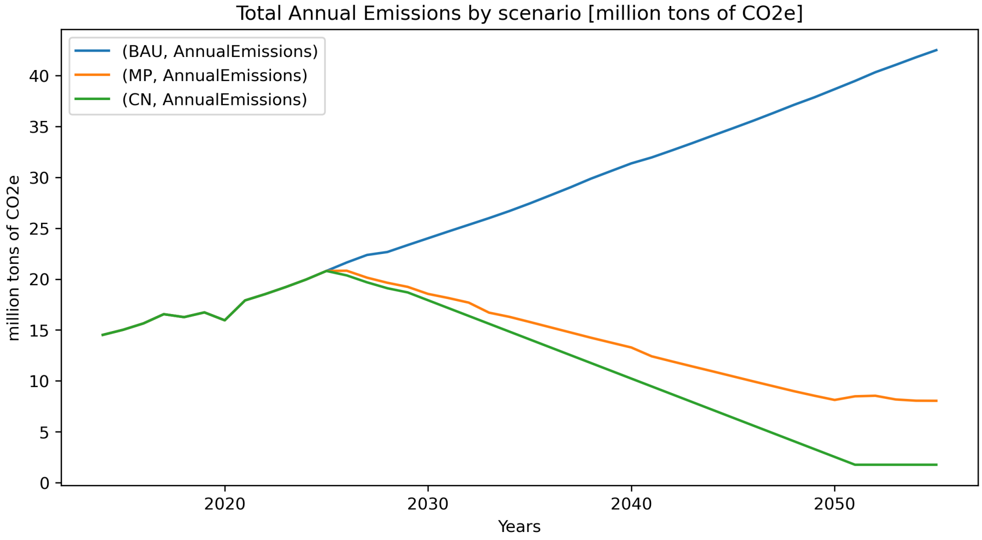

Figure 6: Total annual CO2e emissions from the energy sector [MtCO2e] for the BAU, MP and CN scenarios.

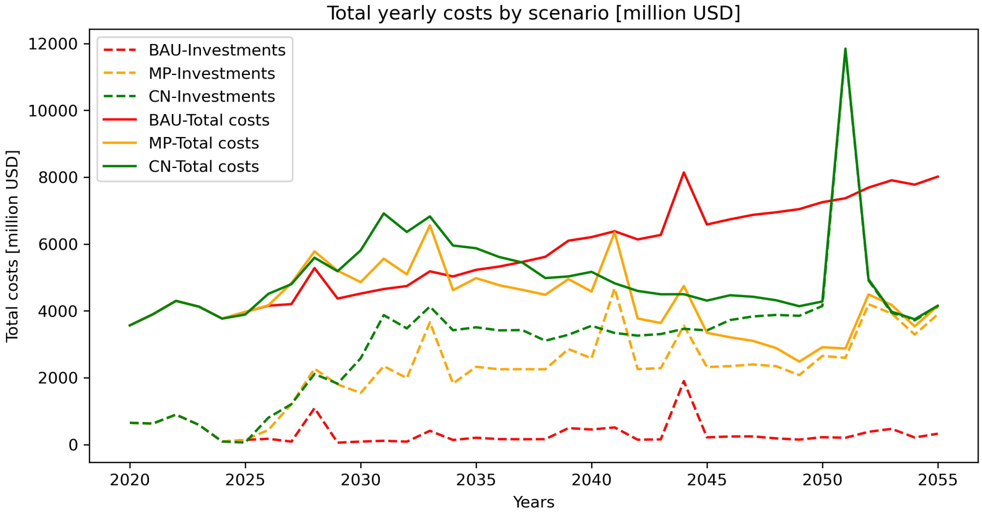

Figure 7: Total yearly costs (Variable, Fixed and Investment) by scenario [million USD] for the BAU, MP and CN scenarios.

requirements between the CN and MP scenarios, the carbon price to reach the emissions targets is estimated as the marginal price of the CO2e emissions constraint [80]. This calculation is paired with a sensitivity analysis carried out by setting the 2050 emission limit to 85 %, 90 % and 95 % reductions, compared to the BAU emissions.

Figure 8 shows that the maximum required carbon price for the three cases reaches 41, 64 and 76 USD/tCO2e for the period 2025–2050. These values are obtained for 2030 and 2032, meaning that enforcing a carbon price is required relatively early in the energy transition. After these years, prices are reduced gradually, which can be explained by the previous investment in renewable energy infrastructure and the predominance of other policies such as the reduction of fossil fuels subsidies. It can also be seen that an exponential increase in prices and a reduction of time available for their implementation is to be expected if larger shares of emissions have to be cut. An additional reduction of 5 % from the MP scenario (a total reduction of emissions of 85 %) would account for a 36 % increase

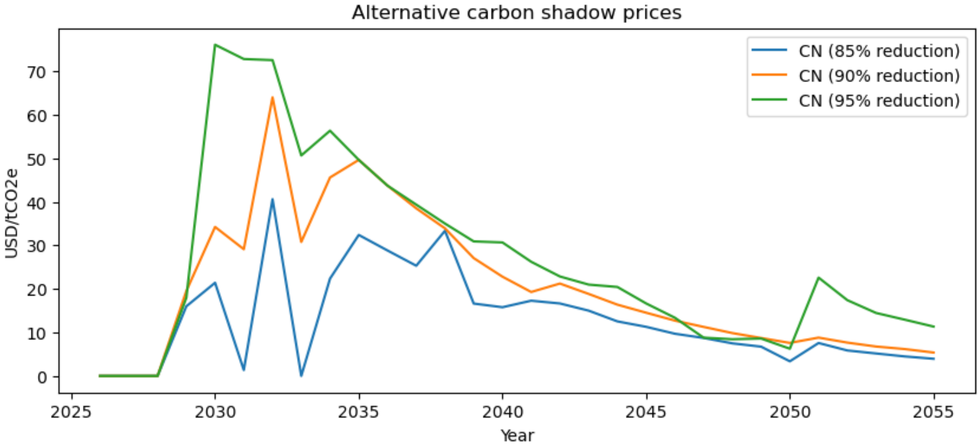

Figure 8: Carbon shadow price evolution for alternative carbon caps in CN scenario.

in carbon prices; an additional 10 % reduction from the MP scenario would result in a carbon price increase of 114 %; and 15 % additional reductions (total reductions in emissions of 95 %) would represent a 153 % increase on the carbon price, accompanied with an earlier implementation required.

4.5. Power transition requirements for Bolivia

Due to the high relevance of the electric sector in the scenarios, and the focus of the model in the power generation system, a more specific analysis is done. As shown in Table 4 and Fig. 9, results from the MP scenario embody the conditions that would allow Bolivia to start its energy system to transition from conventional to renewable technologies, reducing its GHG emission output. However, due to the significant increase in electrical energy demanded, this transition process requires major changes in the power generation mix. Figure 9 shows the changes that the electrical system should go through regarding installed capacities and capital investments for the BAU and MP scenarios.

As a reference, in BAU, the available installed capacity decreases over time due to the decommissioning of power plants that have reached the end of their life and the current over-capacity installed in the country. In this case, limited investments in power plants, compared to the 2014–2020 historical values, would be necessary, adding to a NPV of 2800 million USD for investments in new capacity between 2020 and 2050.

Due to the implementation of transition policies, the MP scenario shows an entirely different evolution, where installed capacity increases to a total of 28.6 GW by 2050 (nearly 7 times the values expected in the BAU scenario) and investments between 2020 and 2050 add up to a NPV of 9800 million USD (3.5 times higher than in BAU conditions). In other words, shifting the current energy system, which is heavily reliant on fossil fuels, would demand significant investments and adaptations in the electrical system.

Alernatively, Figure 10 compares results obtained for the MP and CN scenarios. In this case, smaller variations between the CN and MP scenarios regarding the total installed capacity can be appreciated. However, while these values have a lower variation, the mix of technologies is affected by the GHG emission restriction and the replacement of technologies like thermal powerplants or large hydropower. The trace participation of NGSC plants is replaced by NGCC, and a large share of hydro is replaced by a mix of wind turbines and geothermal plants for their reduced emissions. However, given the sensitivity of the model towards emissions, results have to be carefully reviewed in the future once country-specific emission intensities for both hydropower and geothermal power plants are available.

This change in technologies comes with a significant increase in investments, given the higher costs of technologies selected. In this sense, the CN scenario requires a NPV for investment of 12,700 million USD between the years 2020 and 2050, becoming 1.3 times the amount expected in the MP scenario and 4.6 times the amount of the BAU scenario. If the average of yearly undiscounted investments is considered, this scenario would require every year over 7 % of the national GDP in 2020, without considering operational costs [81]. This value compares to the entire public investments for the year 2018, used for the development of infrastructure, social services and the productive sector (energy production, industry and agricultural processes), high-

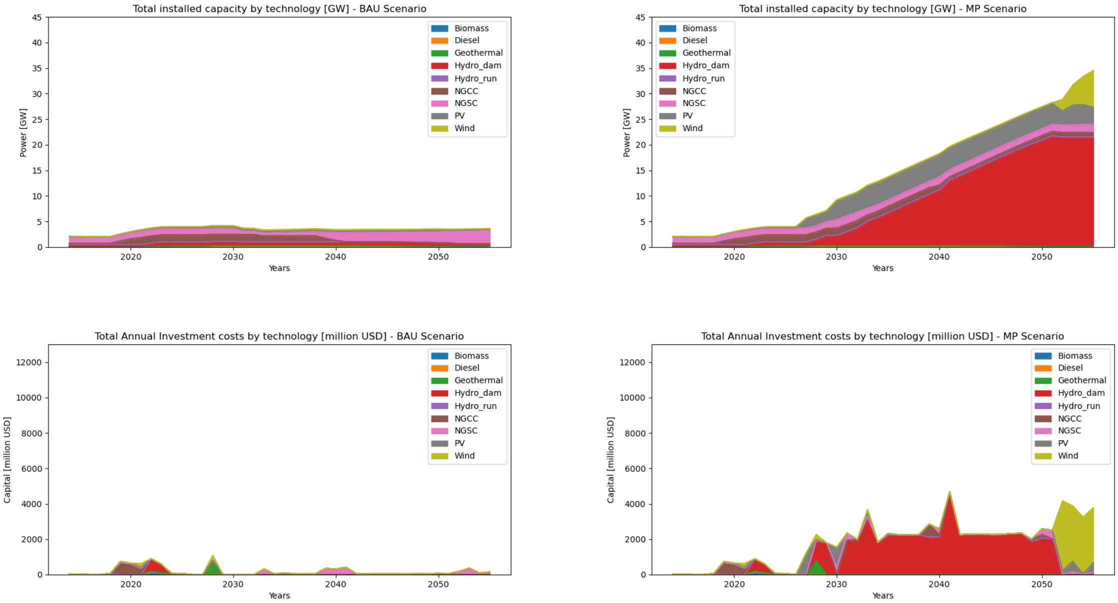

Figure 9: Modelling results of the MP scenario (right) compared to the BAU results (left) for the 2014–2055 period. Total installed capacity in Bolivia by technology [GW] (Top); Total annual capital investment in Bolivia by technology [million USD] (Bottom).

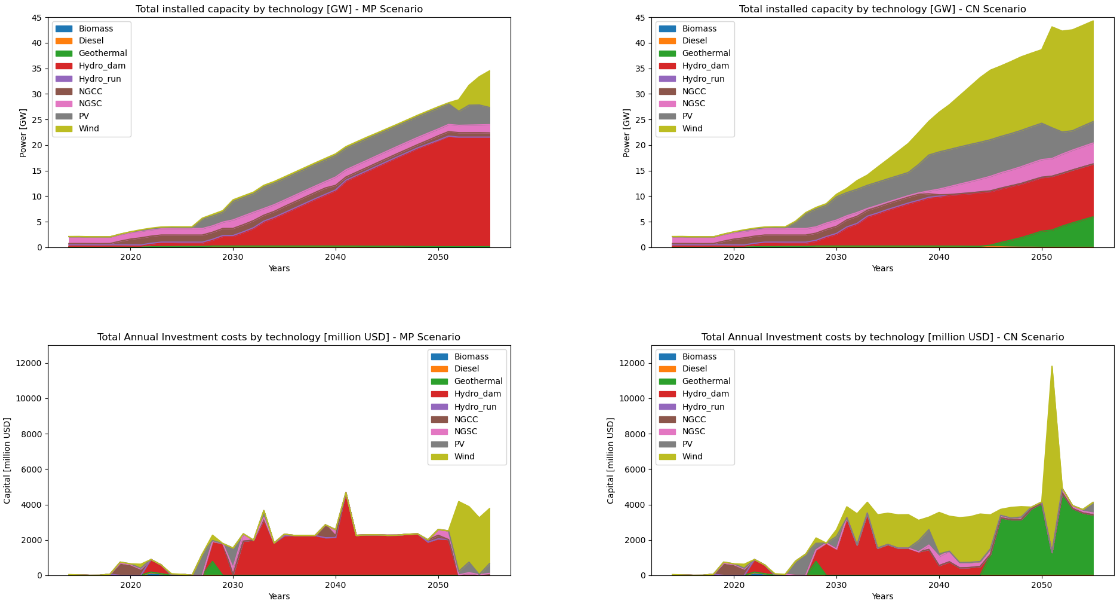

Figure 10: Modelling results of the CN scenario (right) compared to the MP results (left) for the 2014–2055 period. Total installed capacity in Bolivia by technology [GW] (Top); Total annual capital investment in Bolivia by technology [million USD] (Bottom).

lighting the magnitude of the challenge ahead [82].

4.6. Limitations and future work

This work presents the transition process of the energy system from a new perspective by considering the entire energy system and the effects of shifting fossil fuel demands to electrical consumption. For computational tractability reasons, the energy system model uses a lower time resolution than similar long-term models to expand the representation of different energy demands [17]. However, to address this limitation, the feasibility of the power generation scenarios produced by the long-term model is reviewed with a complementary short-term modelling tool, as is the case in studies for other countries or regions [22].

While feasibility and margin of errors can now be quantified in the modelling results, there is still room for improvement and future work that should focus on tackling complementary aspects. For instance, while simple regressions on historical data were used to simulate the growth of energy demands [83], more complex econometric models could be used [84], and seasonal variations or explicative variables like the GDP should be integrated into energy demand projections [85].

Additionally, it is worth noting that the long-term model considers the system as a single node and therefore disregards additional constraints linked to the internal flow of energy in the system or the geospatial dimension. To address this issue, future studies should consider disaggregated versions of the system to consider expansion of the transmission network, to better represent the availability of resources, and to explore how the system will evolve at a subnational level.

At the structural level, the long-term model simulates scenarios with aggregated fuel consumptions for the more relevant sectors in Bolivia. While this configuration can provide a rough estimate on the implications of transitioning of the system, the MP and CN scenarios assume very idealistic conditions for the future, as mentioned in the characterisation of the measures assumed (EED, EEM, CTI and NSR). Improving disaggregation would allow a more detailed representation of activities, services, and technologies, which in turn would translate into more detailed end-use requirements and the ability to explore more sector- and technology-specific policies [86]. This approach is further backed up given that it has been explored in studies from countries like Chile [87] or Ecuador [88], that analysed similar transition scenarios with alternative modelling tools like LEAP or the LUT Energy System Transition model, respectively.

Additional conversion routes for alternative fuels, such as hydrogen, biofuels or carbon capture, should also be explored to account for additional possibilities in terms of energy provision and sector coupling. In addition to this, considering potential carbon sinks could also help to provide the last percentages of decarbonisation in a much more cost-effective way than oversizing very specific renewable technologies.

Both options are particularly relevant when the composition of energy demands is more refined and would allow to simulate transition scenarios for hard-to-abate sectors such as aviation or the cement industry [89]. Similarly, alternative technologies that escape the scope of a centralised system, such as PV distributed generation for residential or industrial consumption, could be explored.

5. Conclusions

This research studies the Bolivian energy system and its long-term transition towards a more renewable and sustainable energy mix. Three scenarios are explored explicitly, based on a mix of management and goal-based measures. A BAU scenario is defined as the baseline in which energy demands double in each sector over a 20-year period. This trend is accompanied by an increase in GHG emissions, starting at a value of 16 [MtCO2e] in 2020 and reaching a value of 38.7 [MtCO2e] in 2050. Additionally, this scenario presents no significant development of the electrical sector other than historical tendencies and current projects stated in the national development plans. In this scenario, NG-based technologies are preferred in the power generation system to provide electrical demands due to artificially low (subsidised) prices for fossil fuels.

In contrast, a scenario with proactive national policies (energy efficiency improvement goals, electrification of energy demands, carbon taxing, and reduction of national subsidies to NG) results in a shift towards renewable technologies for the power system. Expected emissions drop to 8.1 [MtCO2e] in 2050, representing a reduction of 48 % in relation to the year 2020 or a reduction of 80 % compared to the emissions expected in 2050 for the BAU scenario. Nevertheless, the active policies scenario (MP) does not reach carbon neutrality by 2050, global target required to limit climate change impacts. To simulate this goal within the limitations of the models, a near net-zero scenario is simulated where carbon emission limits are fixed every year, reaching 95 % carbon reductions in 2050 (CN).

The simulations demonstrate that proactive energy policies can result in a system whose overall cost is lower than the BAU. In other words, an energy transition based on renewable energy is currently more cost-effective than traditional fossil fuel-based energy system. However, this would require significant upfront initial investments, which raises the question of financing that complementary research needs to address.

While the policies simulated in this work do not allow to reach full decarbonisation, it is demonstrated that further emissions reductions can be achieved by increasing carbon pricing: a carbon tax assumed in the MP scenario of 30 USD/tCO2e can achieve approximately 80 % of reductions in the system, whereas a price of 76 USD/tCO2e would be required to reduce emissions by 95 %. However, it can also be expected that the increment in carbon prices would become exponential the closer the scenario gets to carbon neutrality and, therefore, additional decarbonisation technologies and mechanisms with higher cost-effectiveness should be explored.

From an economic point of view, the NPVs of the investments for power capacity expansion for the MP scenario would represent an increase of 3.5 times compared to investments in the BAU. The CN would require investments 4.6 times higher compared to the BAU, or an average of yearly undiscounted investments of over 2700 million USD or 7 % of the current GDP in Bolivia. While subject to caution, these estimations are relevant enough to reflect the order of magnitude of investments required to achieve the transition of the Bolivian energy system by 2050.

From a methodological point of view, long-term energy planning models such as the one explored in this research, when run in isolation, can require trade-offs between a low time resolution and additional details to be included. If not appropriately considered, the model's capabilities to adequately represent the power system can be overestimated. While these results provide a broad understanding of the energy transition in terms of costs or impacts, complementary models are still required to further refine the analysis. A first attempt at this complementary analysis has been carried out in this study with the inclusion of a short-term modelling tool to assess the adequacy and flexibility of the proposed scenarios from a power generation operational aspect.

Results from the Dispa-SET model indicate that the power generation capacities identified with OSeMOSYS were not sufficient after the year 2030 in any of the considered scenarios, with a total ENS varying between 1 % and 10 %. These discrepancies have been addressed by increasing the reserve margin constraint in the OSeMOSYS model based on the feedback from Dispa-SET. This soft-linking iterative process can be used as often as required to assess the feasibility of new scenarios or different configurations of the long-term model.

Future research for the Bolivian case should focus on improving the energy demand projections with econometric models; expanding the model structure to include alternative transition pathways with carbon-neutral fuels and complementary technologies; including carbon budgets and compensation with other sectors besides energy; and disaggregating the energy demands structure to better represent the impacts of policy implementation. Alternatively, the proposed methodology and tools explored in this study represent a good framework that can used and extrapolated to other study cases, particularly other developing countries that still need to explore their transition pathways and the implications these would have from a technical point of view.

Credit author statement

Carlos A. A. Fernandez Vazquez: Conceptualization, Methodology, Software, Visualization, Writing original draft, Writing review and edit, **Thomas Vansighen**: Software, Validation, Visualization, **Miguel H. Fernandez Fuentes**: Resources, Data curation, **Sylvain Quoilin**: Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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