A bi-directional soft-linking method for a Whole Energy System Model and a Power System Optimization Model. Application and analysis for the Bolivian case [†]

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Abstract. As the transition to low-carbon energy systems becomes increasingly urgent, countries and communities worldwide are searching for pathways to achieve this goal through long-term energy planning. As a result, several modelling tools have become available, each tackling issues using distinct approaches or addressing specific aspects of the system's behavior. Therefore, by considering a common objective and structure, redundancies among models can be used to check consistency and enrich them by including inputs or supplementary information from each other. This research explores the coupling of two energy system optimization models with different levels of detail regarding demand characterization, sector representation, spatial granularity, and temporal resolution to address energy planning challenges at the national level, using Bolivia as its case study. The work makes use of a whole-energy system model (EnergyScope Pathway-BO) to provide a comprehensive characterization of the entire energy system and future energy demands, and a power system optimization model (PyPSA-BO), which is used to analyze the expansion of the installed capacity in the future. To exploit the complementarities between both models, a bidirectional linking is proposed, where key outputs from each model are exchanged and iterative runs are made until results from both models converge within a 10% discrepancy margin. The method is applied to analyze two potential development scenarios for the Bolivian case study, and models converge in the total energy generation by technology after 5 iterations or fewer. Results for the Bolivian case show that strategic conditions are required to facilitate the transition of its energy system in the long term, such as large financial capabilities, electrification of energy demands, and integration of biomass as a key energy vector, all of which facilitate tackling its current systemic reliance on fossil fuels.

Acronyms and Nomenclature

1. Introduction

The transition towards sustainable energy systems is increasingly critical worldwide, prompting nations and communities to chart pathways for sustainable energy transitions. Central to this endeavor are long-term energy plans, which can be used to evaluate and define the resources and technologies necessary to meet future energy demands [1]. Energy System Optimization Models (ESOMs) serve as crucial tools in this

Acronyms	
CCGT	Combined Cycle Gas Turbine
EPI	Existing Policy Implementation
ESOMs	Energy System Optimization Models
GFST	Biomass Grate-fired Steam Turbine
GHG	Greenhouse Gas
HHI	Herfindahl-Hirschman Index
IAMs	Integrated Assessment Models
KPI	Key Performance Indicator
MES	Multi-Energy Systems Models
NDCs	Nationally Determined Contributions
NZE	Net Zero Emissions
OCGT	Open Cycle Gas Turbine
PSOMs	Power System Optimization Models
PV	Photovoltaic
ROR	Run-of-the-river
SIN	Sistema Interconectado Nacional
WESMs	Whole-Energy System Models
Sets	
$PHASE$	Set of transition phases
$TECH$	Set of technologies
EU	Set of end-use demand types
N	Set of buses (nodes)
S	Set of technologies
L	Set of branches (lines)
T	Set of snapshots (time periods)
Variables	
$\mathbf{C_{tot,trans}}$	Total transition cost
$\mathbf{C_{tot,capex}}$	Total capital expenditure
$\mathbf{C_{tot,opex}}$	Total operational expenditure
$\mathbf{C_{inv,phase}}$	Phase investment cost
$\mathbf{C_{inv,return}}$	Residual value of technologies
$\mathbf{C_{opex}}$	Operational expenditure
$\mathbf{ED_{eu,t}}$	Electrical demand
$\bar{\mathbf{G}}_{n,s}$	Generator nominal capacity
$\bar{\mathbf{H}}_{n,s}$	Storage nominal capacity
$\mathbf{F}_l$	Branch nominal capacity
$\mathbf{G}_{n,s,t}$	Generator dispatch at snapshot t
$\mathbf{H}_{n,s,t}$	Storage dispatch at snapshot t
Parameters	
t_{phase}	Phase duration
τ_{phase}	Annualization factor
y_{start}	Start year of phase
y_{stop}	End year of phase
$c_{n,s}$	Capital cost per generation unit
c_l	Capital cost per transmission unit
$o_{n,s}$	Operational cost per generation unit
w_t	Snapshot weight

context, enabling the analysis of alternative scenarios and supporting planning efforts [2]. Albeit ESOMs can have varying levels of technical, temporal, or spatial detail, these are usually defined by the complexity [3] and characteristics of the systems under study [4]. In this sense, a multitude of modeling tools have been developed and are currently available, each employing distinct methodologies to address specific aspects of a system's behavior [5], most of which are open-source [6].

However, unlike developed countries in Europe, which tend to be the ones creating and maintaining most of the open-source models [6], developing countries are still in the initial phases of adopting modeling tools as; historically, most of the plans they have are based on studies developed by external entities like consultancy companies, or, if plans are developed in house, these are based on proprietary or licensed restricted tools [7].

Nevertheless, this trend is shifting steadily as more open-source modeling tools have started to be used for country-level studies in South America, such as the cases of Ecuador [8], Colombia [9], Peru [10], or Bolivia [11, 12]. In these cases, whole energy systems models have become the most popular, followed by models focused on interdependence with other sectors, dispatch behavior, or power system characterization [13].

Among these ESOMs, while discrepancies exist in their structure or scope, overlaps can also be found as they usually consider similar objectives, structures, variables, or constraints [14]. Leveraging these redundancies among ESOMs could offer a means to validate results and consistency among them. Alternatively, models can also be complemented by the inclusion of inputs or supplementary information if a synergistic approach is considered for the tools. As a result, soft-linking methods between energy models have become increasingly popular [15].

Nevertheless, while in many cases the soft-linking method allows for improved analysis, as it can leverage the capacities of the models it uses, their development and application are limited to particular case studies. In South America only three cases can be noted: one from Bolivia which made use of OSeMOSYS, to evaluate long-term transition scenarios, and DispaSet, to assess/validate the energy mix operation of the system in particular years [16]; a case in Chile that used GCAM and H2RES to evaluate the impacts of renewable energy expansion in the long-term development of the country [17]; and a case study for Brazil which used MESSAGE and TIMES to evaluate future expansion scenarios of the energy system and REMIX to optimize the operation of the power generation mix [18].

Within this context, while the implementation of open-source energy models and modeling frameworks is increasing, there is still a gap regarding their adoption and development in terms of soft-linking experiences that can answer more complex questions and complete scenarios, particularly in the global south. The current paper tackles this gap by adapting two distinctive open-source energy models applied in Bolivia, as a reference developing country, and proposing a reproducible method that allows both models to interact and provide relevant feedback among them to improve the exploration of alternative development scenarios by exploiting synergies from the analysis of the energy system within the scope of each model.

This paper is organized in the additional following sections: Section 2 presents a literature review regarding energy models, their application and the contributions of this work; Section 3, which briefly presents the main characteristics of the models selected for the linking exercise (EnergyScope Pathway-BO and PyPSA-BO); Section 4 presents the methodology developed for the bidirectional linking of the models; Section 5 where the case study and scenarios considered are presented; Section 6 provides a compilation of the simulation results with the soft-linking method; and Section 7 compiles the conclusion and future work opportunities based on this research.

2. Literature review

ESOMs are computational tools developed to simulate, analyze, and optimize energy systems' operation, planning, and investment. Their primary goals include minimizing costs, reducing emissions, and enhancing energy security by leveraging mathematical optimization methods. These tools address the complex interdependencies within energy systems, providing actionable insights for sustainable energy transitions [19].

ESOMs encompass a variety of subtypes, each tailored to specific aspects of energy systems, of which two prominent categories are Whole-Energy System Models (WESMs) and Power System Optimization Models (PSOMs). WESMs capture the interactions and dependencies across diverse energy sectors, offering a holistic perspective that integrates electricity, heating, and transportation, among other sectors. This approach facilitates integrated energy planning, supports the development of long-term policy strategies by accounting for various energy carriers, and optimizes investment decisions to achieve cost-effective solutions [20].

Nonetheless, WESMs face certain challenges. Due to their inherently complex integration of multiple sectors, they often exhibit low resolutions in their dimensional analysis, limiting their ability to accurately represent sector-specific technologies, such as the dynamics of the electricity grid. Additionally, the computational complexity associated with modeling interdependent systems can be significant, requiring extensive data and processing power [21]. Therefore, many WESMs rely on simplified temporal representations, which can hinder their ability to effectively capture short-term operational dynamics [22].

On the other hand, PSOMs focus exclusively on the electricity sector, addressing key challenges such as grid stability, operational efficiency, and the integration of renewable energy sources. These models are particularly beneficial due to their high temporal resolution, often incorporating hourly or sub-hourly time steps, which enables detailed operational planning and precise representation of power system dynamics [21]. Moreover, PSOMs excel in grid-specific optimization by including technical constraints such as power flow, transmission capacity, and reserves, making them invaluable for addressing short-term challenges like dispatching generation units and managing ramping requirements [23].

Despite these advantages, PSOMs also have notable limitations. Their exclusive focus on the electricity sector often results in a narrow view of energy transition implications, as they lack insights into the interactions between neighboring sectors to the electric system and their changes, which most likely can affect the evolution of the system [24]. As a result, many PSOMs rely on exogenous demand profiles to represent changes in the future, which can fail to account for evolving trends influenced by cross-sectoral dynamics, potentially leading to distorted expectations of long-term plans and investment decisions [25].

Table 1 highlights commonly used ESOMs, particularly in developing countries, categorizing them by focus, purpose, and geographic application. Among WESMs,

Table 1. Compilation of existing ESOM's alternatives applied in developing countries

Model	**Focus**	**Purpose**	**Access**	**Time frame**	**Analysis**	**Demand characterization**	**Countries where applied**	**References**
EnergyScope Pathway	Whole-energy system	Optimization of investment & operation	Open source	Typical days - Hours	Pathway analysis	Endogenous (End-use service) characterization	Bolivia	[26]
PyPSA	Power system	Power flow and investment optimization analysis	Open-source	Hourly resolution	Snapshot analysis	Static (final demand) consideration	Bolivia, Brazil, Zambia, Botswana, Africa	[16, 27, 28, 29, 30]
DispaSET	Power System	Operational dispatch optimization	Open source	Sub-hourly resolution	Snapshot analysis	Static (final demand) consideration	Bolivia, Colombia, Africa	[31, 32, 33]
OSeMOSYS	Whole-energy system	Optimization of investment & operation	Open source	Time-slices	Perfect foresight (Pathway)	Static (final demand) consideration	Bolivia, Brazil, Costa Rica, Paraguay, Colombia, Ecuador, South America (sub-continent)	[34, 35, 7, 8, 36, 37]
LUT Energy System Transition Model	Whole-energy system	Optimization of investment & operation	Proprietary	Hourly resolution	Perfect foresight (Pathway)	Static (final demand) consideration	Bolivia, Chile, America (continent), Cameroon, Ghana, sub-Saharan Africa, Ethiopia	[38, 39, 40, 41, 42, 43, 44]
EnergyPlan	Whole-energy system	Simulation of energy system scenarios	Open source	Hourly resolution	Perfect foresight (Pathway)	Static (final demand) consideration	Chile, Colombia, Brazil, West African nations	[45, 9, 46, 47]
H2RES	Whole-energy system	Optimization of investment & operation	Open source	Typical days - Hours	Perfect foresight (Pathway analysis)	Static (final demand) consideration	Chile	[48]
TIMES	Whole-energy system	Optimization of investment & operation	Proprietary	Time-slices	Perfect foresight (Pathway)	Static (final demand) consideration	Argentina, Colombia, Peru, Brazil	[7, 49]
EMPIRE	Power system	Optimization of operation	Open source	Sub-hourly resolution	Stochastic modeling (Pathway)	Static (final demand) consideration	Bolivia	[50]
MATPOWER	Power system	Power flow and optimization analysis	Open source	Sub-hourly resolution	Snapshot analysis	Static (final demand) consideration	Zambia, Kenya, Brazil, Peru, Colombia, Ecuador, Paraguay, Uruguay	[51, 52, 53, 54, 55, 56, 57, 58]
Calliope	Whole-energy system	Optimization of investment & operation	Open source	Flexible time representation	Perfect foresight (Pathway)	Endogenous demand characterization	Nigeria, Egypt, South Africa, Kenya, Colombia, Brazil, Chile	[59, 60, 61, 62]

OSeMOSYS and Calliope stand out as the models more widely used, which is consistent with the time these models have been made available, with their first peer-reviewed papers available in 2011 for OSeMOSYS [63] and 2014 for Calliope [19], according to their repositories. OSeMOSYS in particular has been applied massively across developing nations, including Bolivia, Brazil, Colombia, and South America as a whole [35], owing its success to its early development, open-source nature, flexibility, accessibility to learning material, and community development. This being said, as time passed, each new WESM that appeared tried to cover specific gaps found to differentiate and to provide a complementary approach for the academic or commercial modeling needs. In this context, EnergyScope Pathway stands out by providing most of the same capabilities as other WESMs, but also offering the representation of the energy system based on end-use demand characterization (e.g., heating, mobility, lighting) instead of energy carrier demands (e.g., electricity, gas, diesel) as in other models, which enables technological shifts to be considered as part of the optimization process [26].

On the PSOM side, MATHPOWER, PyPSA, and DispaSet are among the most utilized in the context of developing countries, with MATHPOWER being the most popular, as it has been one of the first models available for power flow analysis, already in 2009 [64]. Nevertheless, DispaSet, a relatively new model from 2014 [65], developed for more specific objectives linked to operational dispatch optimization, has still been used in several case-studies in developing countries such as Bolivia, Colombia, and Africa [31, 32]. Finally, despite being one of the newest models, presented in 2018 [66], PyPSA has gained a lot of traction given its high-resolution analysis capabilities for power systems, including power flow and investment optimization. Its open-source accessibility has enabled its application in several developing countries like Bolivia, Brazil, Zambia, Botswana, and Africa as a whole [16, 27, 28].

As a disclaimer, it is also important to recognize that other types of models can be considered to represent complementary aspects of the energy systems, such as Integrated Assessment Models (IAMs). This type of model aims at integrating and representing the interactions between neighboring systems (e.g. economy, environment, and energy) to provide an analysis at a higher (macro) level. Examples of these models include GCAM [67] or REMIND [68], both of which consider the representation and interactions between economic, land, climate, and energy systems. However, the additional complexity of integrating these relations in the analysis comes at the cost of providing results at regional levels (several countries aggregated), total yearly resolution (no dispatch representation), a fixed number of technologies or energy vectors, and low customization capabilities. Additionally, differences in structures and scales become relevant barriers when trying to link or compare IAMs and ESOMs, as additional pre- and post-processing stages are required to allow inter-model communication [69].

In this context, if the focus of a study is the technical aspects of the energy system, leveraging the similarities between ESOMs and PSOMs can offer several benefits for improving the reliability and depth of energy analysis. For example, by comparing their outputs, modelers can validate results and ensure consistency, as discrepancies between models might highlight assumptions or parameters that need refinement. This process helps improve confidence in the outcomes by cross-verifying the robustness of predictions and recommendations from different modelling approaches. In addition to validation, models can be complemented by integrating inputs or supplementary information to create a synergistic analytical framework. For example, data on sectoral interactions from WESMs can inform the electricity-specific decisions in PSOMs. In contrast, the high temporal resolution of PSOMs can refine the operational assumptions in WESMs.

To exploit these complementarities, various methodologies exist to combine, ranging from full integration (hard-linking) to more modular and flexible approaches (soft-linking). Hard-linking integrates multiple models into a single framework, allowing seamless data sharing and comprehensive optimization across systems. However, this approach is technically and computationally intensive, requiring significant effort to harmonize different models with varying structures and objectives, which can limit its application [70]. In contrast, soft-linking retains the independence of individual models while enabling the exchange of inputs and outputs between them and leveraging each model's strengths without needing full integration [71]. Therefore, the latter has gained popularity as it reduces computational complexity, has a simpler implementation, and proves to be more flexible regarding model adaptation [72].

The flexibility of soft-linking has been demonstrated in various applications, such as integrating high-resolution power system outputs into energy system models to improve their representation of flexible resources, wind curtailment, and base-load plant utilization. For instance, Deane et al. [71] introduced a soft-linking methodology between a PSOM (PLEXOS) and a WESM (TIMES), showing how technical details from the former can enhance the accuracy of the latter by addressing sectoral interdependencies and operational constraints more effectively. Similarly, Pavičević et al. [73] proposed a bi-directional soft-linking approach between EnergyScope and Dispa-SET, enabling the integration of short-term variability and assessing system flexibility needs with remarkable stability and reliability. Another example is provided by Younis et al. [74], who combined direct integration and soft-linking to analyze renewable integration in Colombia using TIMES and PowerPlan. Their study revealed how soft-linking methods could account for short-term operational constraints, leading to more reliable investment and planning outcomes for flexible generation capacity. Fernandez et al. [34] applied OSeMOSYS to evaluate Bolivian energy transition scenarios, incorporating prefixed values for non-electricity sector growth, while DispaSet validated and assessed the energy mix operation. Finally, Soria et al. [18] employed MESSAGE and TIMES to analyze future expansion scenarios of the Brazilian energy system and utilized REMIX to optimize the operation of the power generation mix.

These examples highlight the adaptability and effectiveness of soft-linking in bridging the strengths of different models to achieve robust and comprehensive energy system analyses. Nevertheless, despite these successful attempts at linking WESMs and PSOMs, all the PSOMs applied in these studies have primarily been unit commitment and dispatch models, dependent on exogenous inputs for representing power generation capacities. As a result, the interaction between WESMs and PSOMs often resembles a hierarchical relation with a "Leader" and a "Follower", where the PSOM (as a subordinate) validates the capacity expansion results generated by the WESM (as the controller).

Within this context, this article aims at contributing to the existing literature by: 1) presenting a review/compilation of ESOMs that have been applied in developing countries, with a focus on Latin America; 2) the identification of two complementary open-source ESOMs that have been adapted for a referential developing country (Bolivia), EnergyScope Pathway-BO (a multienergy model focused on the transition pathway of the entire energy system) and PyPSA-BO (a model focused on the representation of the power system with high temporal and spatial resolution); 3) the development of a bidirectional soft-liking method between these tools, with a parallel relation regarding the optimization of the generation fleet (in contrast to the common Leader-Follower relation in the literature); 4) presenting the first application of a bi-directional model linking analysis for the Bolivian power system.

3. Models' short descriptions

This section provides a summary of the tailored versions of the Whole Energy System Model (EnergyScope Pathway-BO) and the Power System Optimization Model (PyPSA-BO) utilized, as well as a comparison of both tools, which presents the complementarities and synergies that can be found in the models.

3.1. EnergyScope Pathway-BO

The EnergyScope model for Bolivia was developed using diverse data sources, including public reports, peer-reviewed studies, and other relevant national and international literature. The model presented in this article builds on previous implementations of the EnergyScope framework for Bolivia, including EnergyScope TD (a snapshot version)[75], and the EnergyScope Pathway model [26]. A subsequent study improved and expanded this approach, presenting a national pathway featuring three scenarios and a complete techno-economic database [12]. The resulting EnergyScope Pathway-BO model is a customized version of the original EnergyScope Pathway framework, adapted to the specific characteristics of Bolivia's energy system. It incorporates additional end-use demands and technologies, and extends the original code to include transition phases beyond the optimization window (2021–2050), as detailed in [12]. This improvement allows for a more detailed representation of investment timing, technology lifetime, and decommissioning, which are essential aspects for the present study.

In terms of formulation, the EnergyScope Pathway model considers the energy transition as a linear optimization problem that minimizes the total system transition cost over the defined planning horizon using a perfect foresight approach, as described in Equation 1. The transition is divided into five-year phases to capture changes in technology investments, societal inertia, and emissions [76]. Each representative year (2021, 2025, 2030, 2035, 2040, 2045 and 2050) corresponds to an optimization of the energy system, providing snapshot results for that specific year. The period between two consecutive representative years defines a phase (e.g., 2021–2025, 2025–2030, etc.), and these phases are connected through additional constraints to ensure temporal consistency across the transition pathway.

In this model, the energy system is optimized at an hourly resolution using a reduced set of representative days (to reduce the computational requirements of simulating every hour of every representative year). These days are selected using a mixed-integer linear programming formulation of the k-medoids clustering method. The clustering is based on six time series: electric power demand, low-temperature heat demand, cooling demand, solar generation, wind production, and hydro dam inflow [76].

$$\begin{aligned}
\text{minimize} \quad \mathbf{C_{tot,trans}} &= \mathbf{C_{tot,capex}} + \mathbf{C_{tot,opex}} \\
\text{subject to} \quad \mathbf{C_{tot,capex}} &= \sum_{p \in \mathit{PHASE} \cup \{\mathit{2015\_2021}\}} \mathbf{C_{inv,phase}}(p) - \sum_{i \in \mathit{TECH}} \mathbf{C_{inv,return}}(i) \\
\mathbf{C_{tot,opex}} &= \mathbf{C_{opex}}\mathit{(2021)} + t_{phase} \cdot \\
&\quad \tau_{phase(p)} \cdot \sum_{p \in \mathit{PHASE} \,|\, y_{start} \in P_{START(p)},\, y_{\mathrm{stop}} \in P_{STOP(p)}} \\
&\quad \left(\frac{\mathbf{C_{opex}}(y_{start}) + \mathbf{C_{opex}}(y_{stop})}{2} \right) \qquad (1)
\end{aligned}$$

Equation 1 showcases the main objective of the model which minimizes the total transition cost of the energy system ($\mathbf{C_{tot,trans}}$), in million €. This cost comprises the total capital expenditure ($\mathbf{C_{tot,capex}}$) and total operational expenditure ($\mathbf{C_{tot,opex}}$). The CAPEX includes all investments made during each phase $p \in \mathit{PHASE}$ ($\mathbf{C_{inv,phase}}(p)$) and subtracts the residual value of technologies still in operation after the end of horizon ($\mathbf{C_{inv,return}}(i)$). This salvage value is computed as the ratio of remaining lifetime to total lifetime. The OPEX term ($\mathbf{C_{tot,opex}}$) combines the operational cost of the base year (2021) with phase-specific costs, weighted by the annualization factor $\tau_{phase}(p)$, which considers both the duration of the phase t_{phase} (in years) and the discount rate. Within each phase, the average of OPEX from the start (y_{start}) and end year (y_{stop}) is used to account for the progressive evolution of operating costs. This approach enables the model to represent the transition as a sequence of interconnected snapshots. To maintain consistency, notation throughout the article is standardized as follows: sets are denoted by capital letters (e.g., *PHASE*, *TECH*), variables are in bold and with a capitalized first letter (e.g., $\mathbf{C_{inv,phase}}$, $\mathbf{C_{tot,capex}}$), and *parameters* are in italic (i.e., t_{phase}, y_{start}).

In addition to the cost optimization, the model is based on an energy balance structure that ensures all supplied, converted, and stored energy equals the end-use demand at each hour for every energy layer (e.g., electricity, low-temperature heat). This energy balance structure is also used to provide load profiles (particularly relevant for the electric sector) that account for changes in the technologies and/or energy vectors used to cover end-use services. A simplified representation of the Bolivian reference energy system and the model structure is provided in Figure 1.

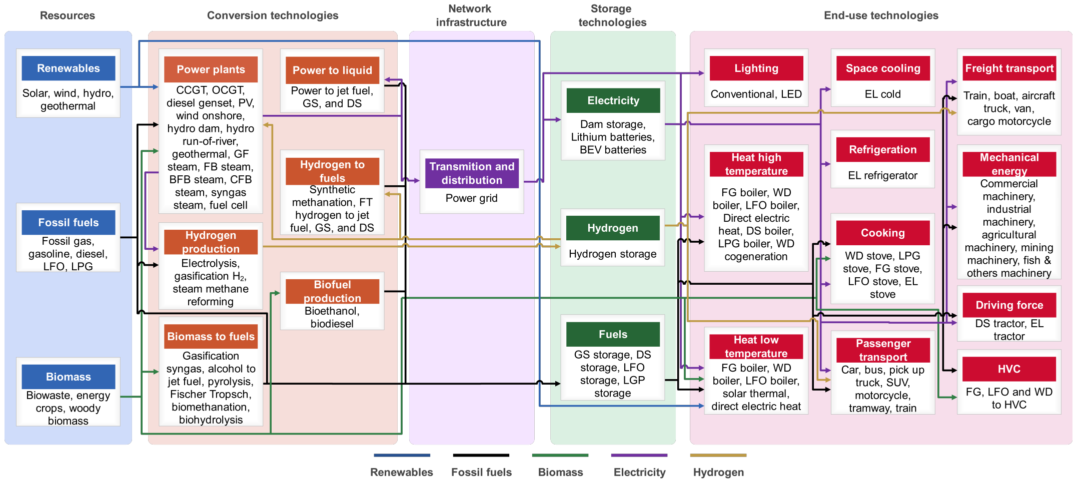

Figure 1. EnergyScope Pathway-BO reference energy system

The last version of EnergyScope Pathway for Bolivia, intermediate results, configurations, and datasets are publicly available in its open-source GitHub repository‡. The authors actively maintain this repository in collaboration with the University Research Center of Energies (CUIE) at UMSS-Bolivia.

3.2. PyPSA-BO

PyPSA-BO is a tailored version of PyPSA-Earth, an open-source global energy system model with data in high spatial and temporal resolution [30], adapted for the Bolivian case study. While the model is relatively new, previous versions and implementations of the PyPSA-BO model have already been presented at scientific conferences. In a first instance, the exploration of PyPSA-Earth and its application for Bolivia was presented [77]. In a second case, after tailoring PyPSA-Earth to the Bolivian case, the model is used to explore the impacts of water availability scenarios over the future development of the power system [78]. This work was eventually continued and finalized with the proper presentation of PyPSA-BO as a capacity expansion model used for the analysis of climate-induced extreme event scenarios [79]. In addition to providing country-specific literature, the PyPSA-BO model and its development have also been used to contribute to the main repository of PyPSA-Earth to improve the usage of the tool, particularly the implementation of complementary and customized information.

PyPSA-BO (and as such PyPSA-Earth) is driven by its main cost-optimization objective function, detailed in Equation 2, in its linear formulation version. In this equation, $\mathbf{c}$ and $\mathbf{o}$ represent the capital and operational costs for a specific bus ($n \in N$), technology ($s \in S$), branch ($l \in L$), or snapshot ($t \in T$). $\bar{\mathbf{G}}$, $\bar{\mathbf{H}}$, and $\mathbf{F}$ represent the nominal capacities of generators, storage, and branches, respectively. Dispatch values for specific snapshots, weighted by w, are represented as $\mathbf{G}$ for generators and $\mathbf{H}$ for

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‡ EnergyScope Pathway-BO — `https://github.com/CIE-UMSS/EnergyScope_Pathway_BO`

storage technologies.

$$
\begin{aligned}
MinimizeCosts = \sum_{N,S} c_{n,s}\bar{\mathbf{G}}_{n,s} + \sum_{N,S} c_{n,s}\bar{\mathbf{H}}_{n,s} + \sum_{L} c_l \mathbf{F}_l + \\
\sum_{T} w_t \left[\sum_{N,S} o_{n,s}\mathbf{G}_{n,s,t} + \sum_{N,S} o_{n,s}\mathbf{H}_{n,s,t} \right] \qquad (2)
\end{aligned}
$$

Currently, PyPSA-Earth covers close to 99% of the countries in the world, facilitating the creation and analysis of energy systems at a global scale [80]. However, PyPSA-BO makes use of PyPSA-Earth's base workflow and setup configuration and modifies certain scripts and data files to provide curated and country-specific information. Currently, the model is capable of representing the Bolivian National Interconnected System (SIN) and creating alternative configurations and yearly expansion analysis. The current version of the model is focused on showcasing the system dynamics from a supply point of view, focusing on resource availability representation and capacity expansion distribution.

Figure 2 shows the different stages in the predefined workflow, as well as the adaptations made, either by modifying code or introducing particular datasets instead, or in addition to the predefined sources. Particularly, within this workflow modified scripts are represented by a red outline, and new data sources are shown as blue boxes.

Most of these adaptations are made to improve data quality and availability regarding technical components, which include line distribution information [81], techno-economic characteristics of generators [82], aggregated final electric demand profile [83], inflow information for hydro units [84], or expansion limits per technology [85, 86]. The representation of more detailed aspects in the demand side (such as load management strategies or electric vehicles' interactions with the grid) is currently limited, making this a topic for further exploration and development in future work.

The PyPSA-BO model is updated periodically, and the different versions of the source code, intermediate results, and configurations are available online in its open-source repository on GitHub§, maintained by the authors and the University Research Center of Energies from UMSS-Bolivia (CUIE), along with all data sets used.

3.3. Models comparison

When considering the descriptions of each model (EnergyScope Pathway-BO and PyPSA-BO), it is possible to find relevant overlaps, like the focus on optimizing the expansion of their respective systems while minimizing total costs. However, from a structural point of view, several differences make them specifically suited to tackle different problems in energy systems. Particularly, EnergyScope Pathway-BO and PyPSA-BO differ in scope, resolution, and modeling objectives.

§ PyPSA-BO — `https://github.com/CIE-UMSS/PyPSA-BO`

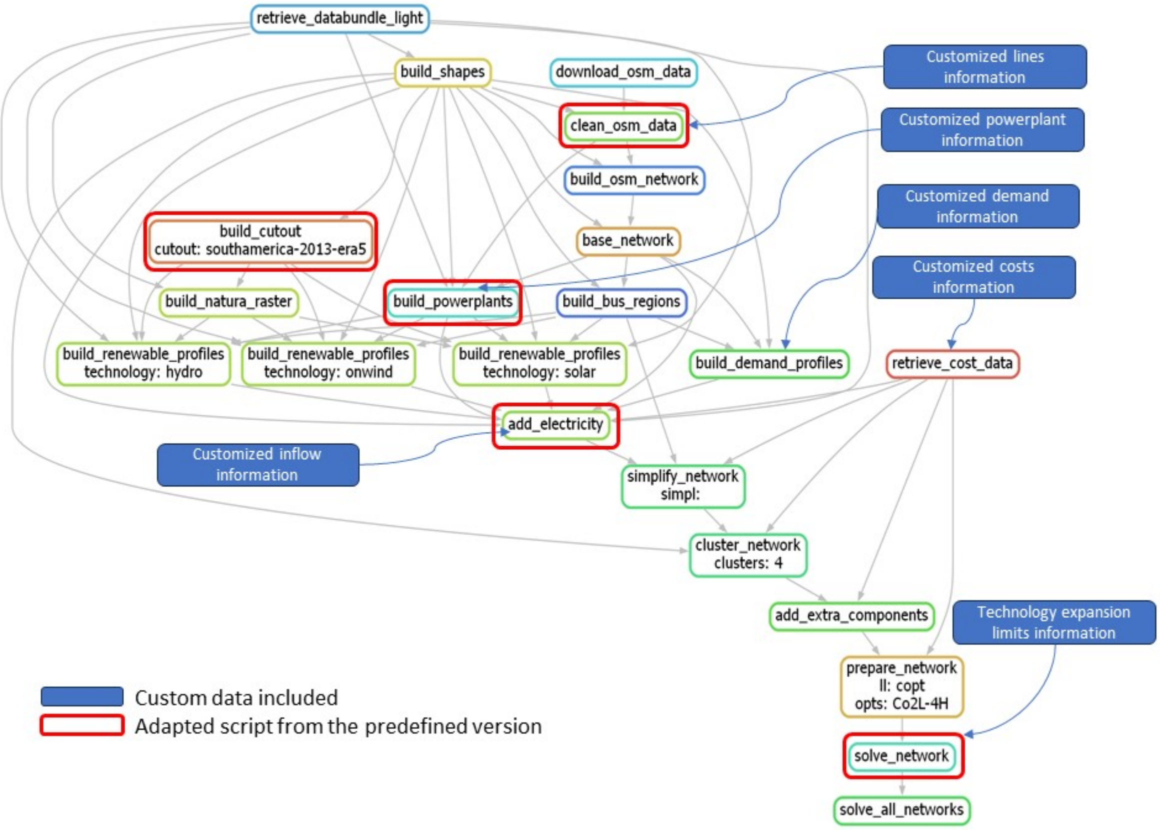

Figure 2. PyPSA-BO's modelling workflow and adaptations

EnergyScope Pathway-BO performs long-term, multi-year optimization of the whole energy system, integrating power, heat, transport, mechanical energy and fuels under a deterministic framework that minimizes total system costs using annualized CAPEX and OPEX values. It typically operates with hourly data condensed into representative (typical) days, which are repeated across the year, employing a single-node or aggregated spatial representation. Its main strength lies in its pathway analysis that connects the changes in the energy system across several periods (capturing investment and decommissioning dynamics), and its suitability for exploring alternative transition scenarios. However, its simplified spatial treatment and temporal aggregation can overlook short-term operational dynamics.

In contrast, PyPSA-BO focuses on power system expansion and dispatch optimization with a high degree of spatial and temporal granularity. It assumes perfect foresight and linearized power flow equations (although this can be changed in the base PyPSA framework), using hourly or clustered time snapshots for a single year within a multi-nodal network. Its strengths include detailed representation of grid interactions and spatial resource variability, while its limitations stem from substantial data requirements and limited coverage of non-electric sectors.

From this, two key synergies have been identified between them: EnergyScope Pathway-BO can be used to estimate the changes in final energy demand by sector (including the aggregated electricity consumption and changes in its profile due to potential new demands), as well as resources available for power generation (fossil fuels and biomass feedstocks, or carbon budgets allocated after the optimization process). PyPSA-BO can be used to provide a more detailed representation of the power system by including the impact of renewable resources availability and distribution, transmission restrictions in the system, and an hourly resolution for the electrical demand and generation profiles by technology.

4. Method

This section presents the methodological proposal for linking both tools, as presented in a simplified manner in Figure 3. First, the stages considered for the bidirectional linking are presented, followed by a compilation of method-specific features.

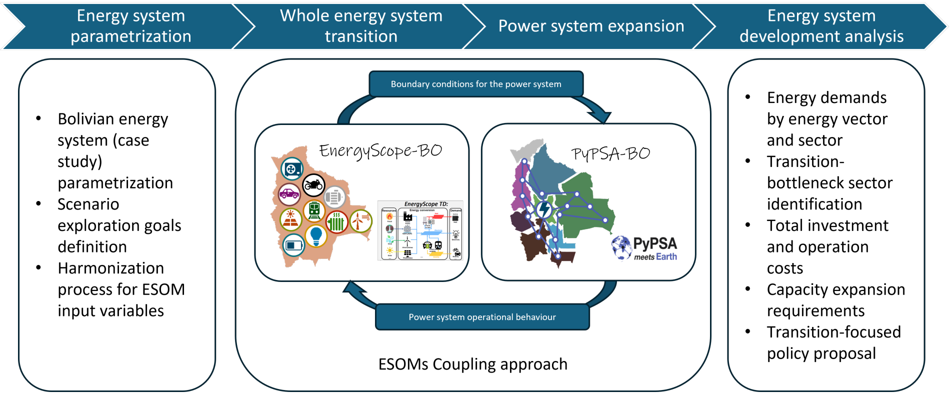

Figure 3. Study's general methodology

4.1. Bidirectional linking

As the characterization of ESOMs in the section 2 shows, models are developed based on the type of analysis required, resulting in models like EnergyScope Pathway-BO and PyPSA-BO to present relevant discrepancies, even if both models have been adapted to represent the Bolivian energy system. Specifically, one focuses mostly on the complex characterization of a system with multiple energy vectors, highlighting aspects like demand requirements and cross-sectoral interactions; the other one focuses on representing the dynamics and changes in a detailed power system where spatial and temporal granularity play a major role.

Because of this, and the synergies identified between them in section 3, a linking methodology is developed that leverages their complementarities by providing information exchange and identifying the inputs that each model can receive from the other. Figure 4 summarizes the 7-step method, which can be described as follows:

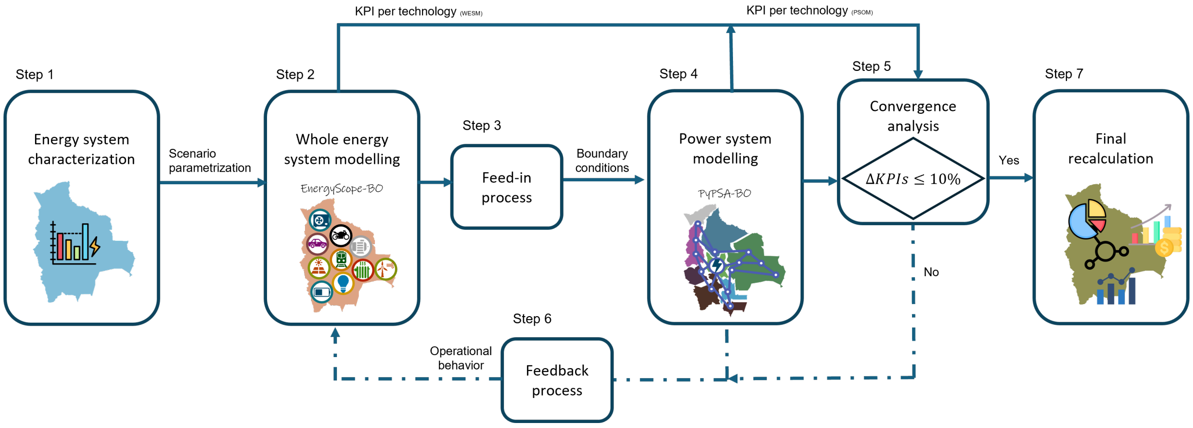

Figure 4. Proposed method for bi-directional soft-linking between EnergyScope Pathway-BO and PyPSA-BO

- Step 1 - System characterization: In this step, the objective is to clearly define all the relevant inputs required for the modelling process ahead, taking into account relevant operational and systemic constraints, techno-economic characteristics of its components, the resources definition, the system's generation and consumption initial compositions, growth trends and goals, etc. With this information, a scenario of interest should be formulated and parametrized, as well as providing a harmonized data set that can be used for both models in later steps. For this particular case, the Bolivian energy system is taken as a case study, and alternative future development scenarios are considered.
- Step 2 - Whole energy system modelling: This step constitutes the analysis of the energy system utilizing a WESM model (EnergyScope Pathway-BO in this case) in order to analyze its development under the scenario previously defined. Key outputs from this step include the final energy demands by consumer type or energy source, emission budgets by sector, and the technology mix used to cover the energy demands.
- Step 3 - Feed-in process: Based on the outputs of the WESM model, this step aims at formatting the information that will be included in the PSOM. The key outputs from this step (and inputs for step 4) are denominated as boundary conditions, as these cannot be defined endogenously by the PSOM. The boundary conditions include the total electricity demand expected in the system (as the model only considers one aggregated value for the country), feedstock resource availabilities for fuels (fossil and biomass), the carbon budget for the power system, and the total installed capacities for the year of analysis.
- Step 4 - Power system modelling: This step constitutes the analysis of the power system with the PSOM (PyPSA-BO in this case), taking into account the information from the system's characterization (step 1) and the boundary

conditions (step 3). This step aims at evaluating the operation of the power system as proposed by the WESM under more restrictive conditions derived from the model's higher granularity.

- Step 5 - Convergence analysis: This step is defined to compare Key Performance Indicators (KPIs) from both models and check if the discrepancies are within a reasonable margin of error. The convergence tolerance (differences lower than 10%) is defined based on the typical errors found in energy planning models, and to reduce the number of iterations required for the feedback process; however, it can be adapted based on the requirements and objectives of each modeler. In this case, total generation by technology is considered the main KPI for the analysis, although other relevant indicators are considered to evaluate results during (non-served energy) and after convergence (diversity index for capacity composition). After comparing differences between total generation by technology, if any of the differences are higher than the predefined convergence margin, a feedback process (step 6) is started to adjust the operation of the WESM. If differences in each technology are lower than the predefined margin, we conclude that the system characterization is adequate and the result compilation is started (step 7).
- Step 6 - Feedback process: This step aims at regulating the power system operation expectations in the WESM by including restrictions for the system expansion based on the operational behavior of technologies in the PSOM. Particularly, for the technology where the highest discrepancy is found, an expansion limit is defined considering the total generation expected according to the PSOM and the reference capacity factor expected in the WESM.
- Step 7 - Final recalculation: This step aims at, after convergence is reached, compiling the results from both models to characterize the development of the energy system for the analyzed scenario. Results for the power system are extracted from the PSOM, considering one final run after convergence, where only expansion limits for generation technologies are set to a minimum, to allow the model to adjust and cover any potential lost loads (fuel resource availability, expected demands and emissions are still considered as restrictions). With these new capacities, the WESM is run one final time with these values as the final capacity targets for the power system and the updated outputs from the non-electric sectors in the energy system are considered.

As one could expect, the way parameters are treated in each model reflects their respective scope and level of detail. In EnergyScope Pathway-BO, most system-wide parameters, such as technology deployment, fuel allocation, and carbon budgets are determined endogenously given the potential competition energy requirements among consumers. PyPSA-BO, by contrast, treats these variables as boundary conditions—derived from EnergyScope Pathway-BO outputs, and focuses on endogenously resolving the operation and dispatch of the power system. Hence, while EnergyScope Pathway-BO defines the macro-level energy system configuration, PyPSA-BO refines its operational feasibility by resolving resource availability and hourly dynamics. Table 2 presents a compilation of the more relevant variables considered in each model, highlighting how they are considered (endogenously or exogenously).

Table 2. Treatment of exchanged parameters and variables in EnergyScope Pathway-BO and PyPSA-BO

Parameter / Variable	EnergyScope Pathway-BO	PyPSA-BO
Final energy demand by sector	Endogenous – Optimized allocation of final energy among sectors and carriers.	Exogenous – Total electricity demand by year received from EnergyScope Pathway-BO.
Electricity generation by technology	Endogenous – Optimized based on simplified representation. Operational constraints added from PyPSA-BO during feedback.	Endogenous – Optimized dispatch and expansion subject to hourly operation and spatial constraints.
Installed capacities by technology	Endogenous – Investment and decommissioning optimized across multiple years. After convergence, installed capacities are fixed based on PyPSA-BO results.	Endogenous – During feed-in, initial capacities are fixed using EnergyScope Pathway-BO outputs. After convergence, base installed capacites are defined as a minimum.
Fuel availability allocation (fossil, biomass)	Endogenous – National values (total potential, reserves and imports) are distributed based on sectorial competition for energy demands.	Exogenous – Operational constraint received from EnergyScope Pathway-BO.
Sectorial carbon budgets	Endogenous – Allocated across sectors during system optimization.	Exogenous – Operational constraint derived from EnergyScope Pathway-BO.
Renewable resource potential (solar, wind)	Exogenous – Represented via average capacity factors. During feedback, values are adjusted based on PyPSA-BO outputs.	Endogenous – Modeled through hourly profiles and spatial distribution.

Finally, to provide a general idea of how key outputs from one model are adapted before being used as inputs in the other model, some basic transformations are required to obtain compatible formats for information exchange. Equation 3 showcases the treatment of outputs from EnergyScope Pathway-BO (sectoral final electric demands) to an aggregated final electric demand (exogenous parameter for PyPSA). Here $\mathbf{ED_{sec,t}}$ represents the electrical demand per *SECTOR* at each time period.

Equation 4 in turn showcases how the total dispatch per technology (total potential generation minus curtailments) estimated by PyPSA-BO is transformed to constraint operational capacity factors per technology (exogenous parameters for EnergyScope). To do this, the total dispatch of each technology in all nodes is divided by the total maximum potential availability per node in a year.

$$[Final\ electric\ demand_t]_{PyPSA} = \left[\sum_{SECTOR} \mathbf{ED}_{sec,t}\right]_{EnergyScope} \quad \forall t \epsilon T \tag{3}$$

$$[Capacity\ factor_s]_{EnergyScope} = \left[\sum_{N,T} (\mathbf{G}_{n,s,t}) / (\sum_{N} \bar{\mathbf{G}}_{n,s} * 8760)\right]_{PyPSA} \quad \forall s \epsilon S \tag{4}$$

4.2. Method-specific features

Unlike other linking exercises where one model is considered the "Main" or "Leader" tool (to estimate the expansion of the system) and another as the "Auxiliary" or "Follower" tool (to validate the operation) [74, 73, 34, 71], this method utilizes both tools with an iterative bidirectional feedback to analyze the expansion of electric system within different scopes and scales. This is done through the iterative correction of overestimations in both models regarding the capacity expansion and dispatch expectations derived from their simplified behaviors. In the first case (PSOM to WES), the WESM provides boundary conditions that the PSOM cannot simulate internally, like long-term electrical demand projections as direct inputs for the PSOM, and the electric generation emission budget and fossil resource availability as constraints. In the second case, the PSOM provides operational limits for each technology to the WESM, so that the simplified conditions (average availability for the entire country, no curtailment effects in generation, and typical days' behavior) do not overestimate the generation potential of the installed capacities.

Among the existing literature, the work of Pavičević et al. [73] shares the most in common, as it also employs EnergyScope and develops a bi-directional soft-linking method between a WESM and a PSOM. Nevertheless, this study introduces a key difference by employing PyPSA-BO as the PSOM, which explicitly represents the geographical distribution of renewable resources and electrical infrastructure. This enables a more accurate assessment of resource variability, operational limitations, and transmission bottlenecks, which in turn are employed to correct estimations made by the WESM during the feedback process.

Similarly, the study from Gong et al. [87] also makes use of a detailed PSOM (DIETER) and aims at integrating demand growth expectations from a complementary model (REMIND) with a bidirectional linking method. More recently, Odenweller et al. [88] extended this approach by coupling REMIND with PyPSA-Eur through a comprehensive bi-directional iterative soft coupling. In both cases, the model in charge of characterizing the demand is classified as an IAM, making it a much broader model that integrates additional economic and climatic characteristics in the system representation. Consequently, the linking method incorporates the exchange of economic parameters such as market values and sectoral electricity prices alongside operational parameters. However, in the present study, the adoption of economic parameters for the coupling is not feasible. Unlike IAMs, where shadow prices and market values are used as input data, EnergyScope handles these values internally within its cost-minimization framework, which allows for a more dynamic representation of prices. As a result, the feedback mechanism relies exclusively on operational parameters, which can be directly extracted from PyPSA-BO and interpreted within EnergyScope's structure.

This design choice finds support in both aforementioned studies [88, 87] as in both cases, the predominance of operational parameters in their convergence criteria suggests that technical constraints remain the primary mechanism for harmonizing energy system representations across different modeling scales, and that economic values are used only in cases where these can be directly introduced as an input. Notably, Odenweller et al. employ seven parameter categories for the feedback from PyPSA-Eur to REMIND, of which five are operational (capacity factors, peak residual load, hydrogen storage, battery storage, and grid losses) and only two are economic (market values and sectoral electricity prices).

Particularly, generation by technology is adopted as the key convergence criterion because it directly captures the alignment between the operational expectations of both models regarding how the power system meets energy demands. While installed capacity could be used, as it only reflects investment decisions, generation becomes a more complete indicator, integrating both capacity deployment and operational performance, making it a more relevant indicator for evaluating the consistency between models with different levels of temporal-spatial resolution and providing realistic solutions for future energy mixes. Other indicators, like non-served, are used to check the consistency of intermediate and final results (if the WESM is behaving in accordance with the PSOM), but not as a convergence criterion, as the focus of the linking is on long-term planning, and it cannot be independently calculated by the WESM.

Furthermore, compared to other studies that present a soft-linking process, the method presented here aligns the capacity and generation results in both models through an iterative process. For example, Deane et al. [71] and Soria et al. [18] linked models considering a unidirectional process from the WESM to the PSOM without a detailed feedback. On the other hand, while Pavičević et al. [73] and Fernandez et al. [34] included a feedback analysis between models, this one limits the interaction between models by adjusting the reserve margins as the regulatory variable. By integrating behavioral and operational constraints from the PSOM into the WESM, the presented method provides a consistent representation of capacity expansion, energy demand, resource availability, and system operation in both tools, instead of relying solely on the WESM for the expansion analysis.

Additionally, it is worth mentioning that the current method considers two separate open-source models with publicly accessible data sets, which facilitates the transferability and adaptation to other contexts or cases. This is considered a key factor for its replicability, as other studies have used historically licensed tools such as TIMES (as the WESM) or PLEXOS (as the PSOM) [71, 74, 18], which translates to financial barriers for entities or researchers that would like to follow their methods, something particularly relevant for entities with low financial capabilities, common in low- and middle-income countries. Similarly, the fact that both models are developed based on more flexible modeling frameworks (EnergyScope and PyPSA) allows potential users to expand, reduce, or adapt more specific aspects or features of the method and models, depending on their particular needs, which tend to significantly vary between developed and developing economies. An example of this can be linked to data availability, which tends to be openly available for large economies; however, given restrictions to data in developing countries, simplified or customized versions might be required to integrate case-specific information [77].

Regarding the information exchange mechanism, the type of data transferred is intentionally kept simple to facilitate communication between models, as the more variables are exchanged, the more complex the linking process can become [89]. As a result, the approach considered allows the information exchange to be done manually, without the need for dedicated intermediate scripts. This, in turn, reduces another entry barrier and allows potential users to focus on the usage of the main models. Additionally, by not relying on intermediate scripts (dependent on specific configurations or versions of the models), new versions or updates made in the tools can be easily integrated without the risk of compatibility issues.

However, it is acknowledged that manual data transfer may become a limitation when scaling the approach to larger systems or to cases involving more complex systems (with more technologies, energy vectors, subsystems, or regions). In such contexts, the use of a simple standardized data interface (e.g., a predefined CSV schema) or lightweight automation scripts would be advisable to ensure robustness, reproducibility, and scalability. To support this, a structured data exchange schema specifying transfer variables, data types, units, and direction of flow has been defined and provided as supplementary material, serving as a template for potential automated implementations.

The treatment of parameters outlined in Table 2 can also be compared with alternative decomposition strategies in the literature. Jacobson et al. [90] developed a Benders decomposition framework for energy systems planning that separates investment decisions from operational decisions through a mathematically master-subproblem structure. In the Benders decomposition scheme, investment decisions (analogous to installed capacities in Table 2) are determined in the master problem and passed as fixed parameters to operational subproblems, similar to how EnergyScope Pathway-BO provides capacities to PyPSA-BO during the feed-in phase. However, policy constraints such as carbon budgets are managed through budgeting variables that allocate annual limits across subperiods, whereas in the present study, sectoral carbon budgets are allocated endogenously within EnergyScope Pathway-BO and subsequently imposed as exogenous constraints in PyPSA-BO. Additionally, while Jacobson's decomposition returns dual information (shadow prices, Lagrangian multipliers) from subproblems to the master problem, enabling price-based coordination, it is important to recognize that its usage implies the development and reformulation of a model and the optimization problem formulation, which can be relatively complex for non-specialist users or when using pre-established modeling frameworks. The present soft-linking approach relies on operational parameters for feedback between two already established models and does not require adaptations to their problem formulations, thus limiting the number of modifications or adaptations required to run scenarios and simplifying its application.

When focusing on the coupling process, the adjustment to the WESM, done by limiting the maximum usable energy production (after curtailments) per technology, aimed at providing feedback linked to the temporal flexibility constraints and the curtailment rates considered in the model with higher resolution. In the first case, while hourly resource availability or generation profiles from PyPSA-BO (which considers strategic events, like consecutive days with low wind or solar availability) could be provided to EnergyScope Pathway-BO, because of the structure of EnergyScope Pathway-BO, impacts linked to very specific short-term temporal variation can get lost or minimized during the typical-days aggregation method. Increasing the number of typical days allows for this feedback to eventually get noticed by the model, but at a high computational cost for the optimization in EnergyScope. In the second case, while EnergyScope Pathway-BO is capable of estimating curtailment rates, because of the use of averaged values for the entire country, curtailment from renewables is underestimated. Therefore, to limit the overproduction of energy, a maximum value was provided based on the estimation of energy used per technology done by PyPSA-BO (the total energy production by technology minus their estimated curtailments).

The convergence tolerance, which defines the acceptable margin of difference between selected criteria (energy generation by technology in this case), should be set to ensure that a stable and reliable solution is reached within a reasonable computational time. In the literature, some studies do not specify a fixed tolerance value, but instead focus on the number of iterations required to achieve a sufficiently small difference in key variables or decide when to stop after analyzing the outcome of each iteration, as seen in Pavičević et al. [73], Haaskjold et al. [91], and Krook-Riekkola et al. [92]. In other cases, a tolerance value of 10% for energy consumption per energy carrier has been used for the bidirectional linkage between a computable general equilibrium model (GEMS) and an energy system model (TIMES), as in the analysis for Portugal [93], and 9% in similar studies [94], both resulting in consistent solutions without excessive computational effort. Although some studies have used stricter values (i.e. 1%) for soft-linking [95], the present study empirically adopts a 10% tolerance, following the approach of Fortes et al., as the models employed in this study also differ in their level of detail and time resolution.

To explicitly clarify the methodological novelty of the proposed coupling, this approach differs from existing WESM-PSOM and IAM-PSOM linkages in three key aspects. First, convergence is enforced simultaneously on both installed capacities and technology-level electricity generation, rather than being limited to dispatch feasibility, reserve margins, or price signals. This ensures consistency between long-term investment decisions and operational outcomes across models. Second, the PSOM used in the coupling is spatially resolved, with explicit representation of transmission constraints and geographically differentiated renewable resources. These features are actively used to constrain and correct potential overestimations of generation and capacity expansion in the WESM, which typically assumes nationally aggregated availability and simplified network representations. Third, the coupling is fully bidirectional and iterative in a strict sense: information flows repeatedly between models until convergence criteria are met, rather than being applied as a one-shot validation or post-processing step. Together, these features allow the proposed method to align capacity expansion, spatial feasibility, and operational performance within a single, consistent iterative framework.

5. Case study

This section presents the characteristics of Bolivia, as the case study in which the proposed method is applied. Additionally, details regarding the parametrization of the models and their validation are given, as well as the considerations for the scenarios modeled.

5.1. Bolivia's energy system

Bolivia relies heavily on fossil fuels to meet its energy demands, with its Total Primary Energy Supply reaching 202.9 TWh in 2021. Fossil gas dominates the supply, accounting for 80.7%, while oil derivatives contribute 11.9%. Notably, approximately 58% of the fossil gas is exported to Brazil and Argentina, underscoring Bolivia's strategic role as a regional energy supplier [96]. Domestically, energy consumption is concentrated in the transport sector, which consumed 44 TWh in 2021, followed by the industrial sector with 19 TWh, residential use with 12 TWh, and mining, agriculture, and fishing collectively utilizing 8 TWh. The commercial and services sector accounted for the smallest share, with a consumption of 3 TWh [97].

The power sector exhibits a similar dependence on fossil fuels, which remains the dominant energy source for over two decades. As of 2021, Bolivia's installed electricity generation capacity was 3.72 GW, with thermoelectric gas power plants contributing 71%, hydropower accounting for 20.4%, and renewable sources such as solar and wind comprising only 8.6% [98].

Bolivia holds considerable proven fossil gas reserves, estimated at 0.13 trillion cubic meters as of 2023 [99] (approximately 1290 TWh of energy, enough to cover domestic demand for the coming years, but not to maintain exports). However, declining production has negatively impacted the nation's economy in recent years, given its significant contribution to fiscal revenues and tax income through exports. In contrast, proven oil reserves are limited, estimated at 2 million cubic meters in 2023 [100] (approximately 20 TWh of energy, not enough to cover yearly domestic demands). Consequently, Bolivia faces a significant challenge in its reliance on imports of diesel, gasoline, and other oil-based products, as well as the issue of how to manage the dwindling gas reserves (either to save them for domestic consumption or continue designating them for exports).

At the same time, Bolivia possesses vast renewable energy resources, offering substantial opportunities for achieving greater energy security, diversifying its economy, and contributing to global efforts to combat climate change. PV power potential is estimated at an impressive 40 TW [101], while onshore wind resources could contribute up to 260 GW [101]. Hydropower also holds significant promise, with 6.09 GW identified for large hydro dams and an additional 0.91 GW for run-of-river systems

[102]. Geothermal energy potential stands at 0.98 GW [85], complemented by abundant biowaste resources—woody biomass residues capable of producing 150 TWh annually and wet biomass residues providing an additional 28.02 TWh per year [103].

5.2. Models' parametrization and validation

Both models were previously validated for the base year in the studies that presented the extended Bolivian versions. EnergyScope Pathway-BO was validated by comparing its outputs against primary energy consumption values from the National Energy Balance and total GHG emissions from the Climate Watch data repository and the sieLAC database. The model accurately represents the Bolivian energy system, estimating a total primary energy consumption of 93.57 TWh for 2021, with slight underestimations only for wood and LFO. For GHG emissions, the model estimates total emissions from fuel combustion at 18.99 $MtCO_2$, which falls within the reported range of 18.20–18.96 $MtCO_2$ (excluding refinery consumption), demonstrating good agreement with national inventory data [104].

PyPSA-BO was validated by comparing model outputs against historical generation patterns and renewable resource availability. Wind and solar power generation were validated using average capacity factors from real utility-scale plants at San Julián (wind) and Uyuni (solar), showing good consistency with reported performance. For hydroelectric resources, hourly inflow data was directly integrated into the model workflow to accurately represent water availability. Simulation results confirm that the modeled installed capacities align with historical values. However, due to the model's optimization framework and system simplifications, the operational dispatch of thermal units (combined cycle gas turbines, open cycle gas turbines and diesel gensets) differs slightly from observed patterns. This discrepancy reflects the model's cost-optimization objective, which does not fully capture mandatory dispatch regulations, scheduled maintenance, and socio-technical factors that influence real plant operations [79].

The core harmonization of parameters between both models comprises the lifetime, investment, and fixed O&M costs of power generation and electric storage technologies, as well as fuel prices and emission factors. Table 3 details the values of these parameters.

Table 3. Harmonized parameters for power generation technologies and resources. The abbreviations are: CCGT: Combined cycle gas turbine, GFST: Biomass grate-fired steam turbine, OCGT: Open cycle gas turbine, PV: Photovoltaic, ROR: Run-of-the-river

Technology	**Investment Cost [M€/GW]**	**Fixed O&M Cost [M€/GW]**	**Lifetime [years]**	**Reference**
CCGT	1139.16	17.09	30	[105, 106]
OCGT	856.27	21.41	30	[107, 105, 106]
Diesel Generator	384.60	5.77	30	[107, 106]
PV	544.35	17.03	30	[108, 106]
Wind Onshore	1231.90	20.42	30	[109, 106]
Geothermal	3003.09	75.08	50	[107, 106]
GFST	1560.87	36.21	30	[110, 106]
Hydro Dam	2206.30	22.06	100	[111]
Hydro ROR	2000.26	20.00	100	[107, 111]
Fuel Cell	339.00	10.17	20	[76, 112]
Lithium Battery	156.66	0.24	15	[76]
Dam Storage	0.00	0.00	100	[76]

Resource	**Price [€/MWh]**	**Emission Factor [ktonCO$_2$/GWh]**	**Reference**
Fossil Gas	4.40	0.202	[113, 114]
Diesel	124.52	0.267	
Geothermal	0.00	0.03	[112]
Biowaste	10.32	0.00	[86]

5.3. Scenarios considered

To test the implementation of the proposed method, two development scenarios, Existing Policy Implementation (EPI) and Net Zero Emissions (NZE), are employed. The EPI scenario incorporates policies from the National Interconnected System (SIN) expansion plan [115] and the latest update of Bolivia's Nationally Determined Contributions (NDCs) [116]. This planning framework extends only to 2030 (and it is kept constant until 2050 for this case) and does not define explicit GHG reduction targets. It emphasizes infrastructure deployment, such as new power plants, expanded electric public transport, biofuel production, industrial heat electrification, and broader LED adoption. However, beyond these specific initiatives, the decarbonization of other sectors remains entirely unaddressed. In contrast, the NZE scenario incorporates a linear reduction in emissions to achieve a decarbonized energy system by 2050. It features a more diversified set of options, including sector-specific electric technologies, synthetic fuel production, and different energy storage solutions. A summary of key characteristics for both scenarios is provided in the Supplementary Information section.

The decision to employ two scenarios in this study is based on the aim to explore different future energy system architectures. The EPI scenario reflects a policy-driven change of the energy system, while the NZE scenario introduces decarbonization constraints that limit the available options to meet the diverse sectoral demands. This contrast leads to a more complete understanding of how policy frameworks can shape and affect energy transition. Moreover, from a methodological perspective, the use of two distinct scenarios allows for an assessment of how the linking process behaves under varying conditions. As pointed out in other studies, both the number of iterations and runtime are sensitive to the complexity and structure of the scenario being modeled

[95, 117, 118]. Therefore, including both cases not only supports the analysis of transition conditions for the case study but also the validation of the applicability and efficiency of computational resources related to the soft-linking approach under different assumptions.

6. Results and discussion

This section provides the results obtained by the application of the linking method presented in two alternative development scenarios for Bolivia (EPI and NZE); the validation of the linking method based on the comparison of three model configurations: (i) EnergyScope Pathway-BO executed in isolation (WESM-only), (ii) PyPSA-BO executed in isolation (PSOM-only), and (iii) the bidirectional linking (coupled) solution; the main advantages and limitations of the proposed method compared to other cases available in the literature; and a compilation of policy implications and transition bottlenecks identified with the scenario analysis.

6.1. Validation of the bidirectional coupling method

Results from the method implementation, independently of the scenario, show that the bidirectional linking is capable of providing an intermediate point for the expansion of the power system, which takes into account the implications of the transition in neighboring sectors inside the energy system and the caveats of a more detailed power system representation. Consequently, the composition of the resulting power systems deviates from those obtained through isolated model runs, as the feedback between tools allows for a more balanced assessment of technological potentials and system limitations.

To support this, a detailed evaluation of the performance and advantages of the application of the bidirectional linking is presented by explicitly comparing isolated model runs (PSOM-only and WSEM-only) with the coupled method based on their generation and capacity expansion results. The validation analysis focuses on four aspects: capacity adequacy and operational feasibility, correction of spatial and temporal aggregation biases, cross-sectoral resource consistency, and convergence behavior.

Figures 5 to 8 present the resulting capacity expansions and electricity generation for the EPI and NZE scenarios in 2050, comparing EnergyScope Pathway-BO and PyPSA-BO runs in isolation, and the resulting mix with the bidirectional linking method. It should be noted that small differences can be seen between the total generation outputs in the models run in isolation and the coupled method. These differences are a consequence of the recalculation process of demands in EnergyScope Pathway-BO, as each feedback loop updates the optimal allocation of resources and technologies across sectors.

6.1.1. Capacity adequacy and operational feasibility To verify the capacity expansion adequacy in the models, a comparison is done of the installed capacities obtained

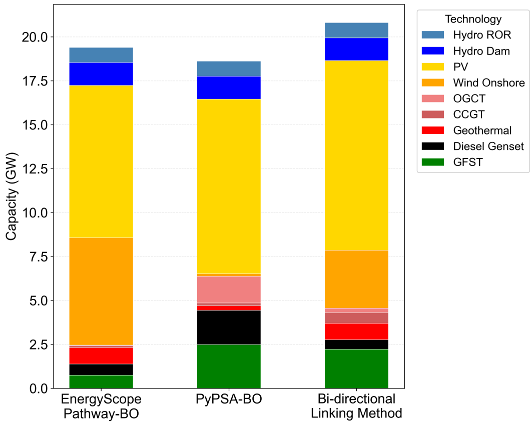

Figure 5. Installed capacity in the year 2050 under the EPI scenario

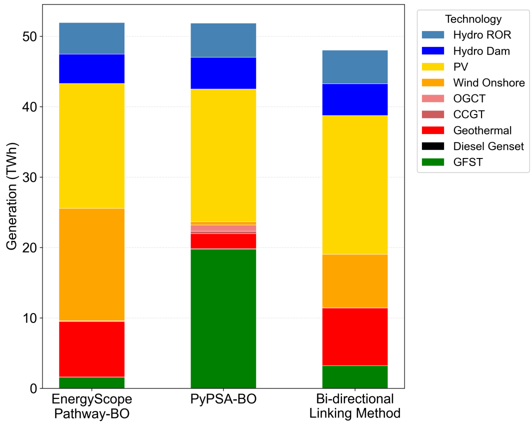

Figure 6. Electricity generation in the year 2050 under the EPI scenario

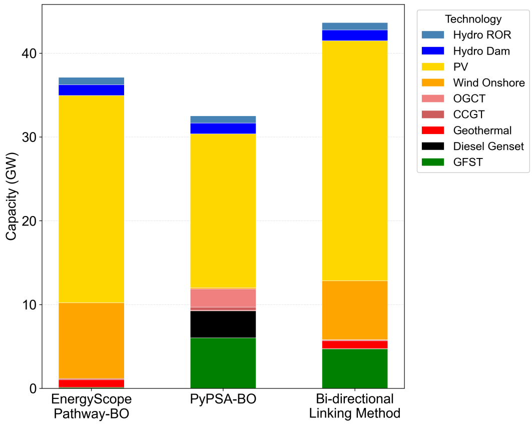

Figure 7. Installed capacity in the year 2050 under the NZE scenario

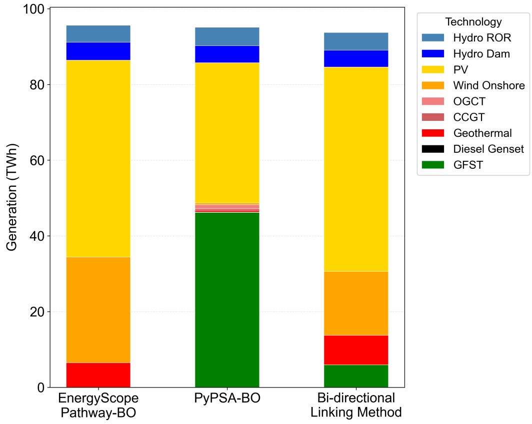

Figure 8. Electricity generation in the year 2050 under the NZE scenario

from running EnergyScope Pathway-BO (WESM-only) and PyPSA-BO (PSOM-only) in isolation, and the bidirectional linking method. From Figures 5 and 7, it can be seen that the isolated model runs obtain lower total installed capacities in both scenarios as a result of their corresponding simplifications, overestimating the availability of variable renewable resources (WESM) or feedstock fuels (PSOM), as seen in Figures 8 and 6.

When capacity expansion results from EnergyScope Pathway-BO are directly introduced into PyPSA-BO, and only dispatch feasibility is assessed, significant levels of non-served energy can also be appreciated. Specifically, load shedding reaches 4.5% and 6.9% of total electricity demand in 2050 for the EPI and NZE scenarios, respectively, indicating that the WESM-only solutions underestimate installed capacities when evaluated under hourly operational constraints.

This under-sizing effect arises from the simplified structure of WESM, which relies on nationally averaged capacity factors, limited temporal variability, and neglects spatial resource heterogeneity. As a consequence, lower installed capacities are sufficient to satisfy annual energy balances but insufficient to ensure system adequacy at the operational level, something commonly reported and discussed in similar studies [34, 73, 71, 74]. The coupling process solves this issue by using PyPSA-BO to define and constrain the operational behavior of the system, which limits (eliminates) non-served energy in the optimization process.

6.1.2. Correction of spatial and temporal aggregation biases Another key contribution of the coupling is the correction of spatial and temporal aggregation biases inherent to the WESM representation. This adjustment is particularly evident for wind power plants, whose expansion is significantly higher in the isolated EnergyScope Pathway-BO runs (with an average capacity factor of 0.34), leading to optimistic generation estimates as shown in Figures 6 and 8 and reduced capacity requirements, as shown in Figures 5 and 7.

In contrast, PyPSA-BO explicitly represents geographically differentiated wind resources, transmission constraints, and regional capacity factors, resulting in more conservative expansion expectations. The linked configuration produces a more conservative outcome (with an average capacity factor of 0.29) by limiting the expansion to regions with the highest wind potentials and feasible transmission capacities, as illustrated in Figure 9 and Figure 10. In this configuration, the system favors a more spatially distributed generation mix, with regions producing energy locally based on their resource availability, instead of assuming high-availability across the country and no investment requirements in the transmission system to facilitate its distribution in the country.

6.1.3. Cross-sectoral resource consistency Regarding the generation expectations, the coupled analysis also mitigates the overestimation of fuel-based generation capacities. In isolated PyPSA-BO runs (PSOM-only configurations), feedstock-based resources such as biomass (GFST), gas (OCGT or CCGT), or diesel are used without taking into account sectoral competition (i.e., gas or biomass that could be used in the transport sector or for producing heat as an energy service), resulting in unrealistically high availabilities, as shown in Figures 6 and 8.

By integrating feedstock limitations from EnergyScope Pathway-BO, where resource allocation competition across sectors is explicitly represented, the linked model constrains the power sector's access to these fuels. This limitation reduces the role of flexible but scarce technologies like biomass and drives the system to rely more on other technologies, such as solar and wind.

It is important to note that the assumed limits on biomass and gas availability for the country are fixed based on currently available data. This is a key factor for the results obtained, as no new exploitation fields have been identified (for gas) and

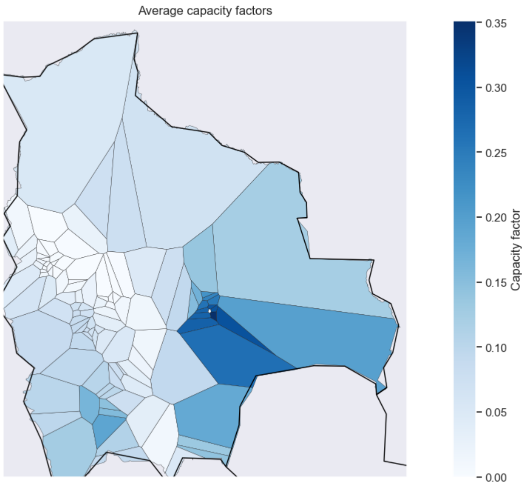

Figure 9. Wind capacity factor distribution in Bolivia

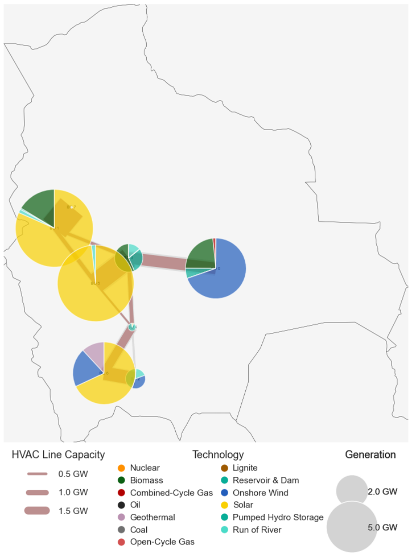

Figure 10. System capacity expansion distribution for 2050 in the EPI scenario

no alternative sources of biomass are considered (aside from agroindustry residues) [86]. While alternative scenarios and conditions could be explored, as they represent strategic changes and limitations for the development of a carbon-neutral system, their analysis deserves a more in-depth review, as the one made for the impact of potential development of e-fuels for the transition of Brazil [119], which currently fall outside of the scope of this paper, but could potentially be addressed with the method and models currently proposed.

6.1.4. Convergence behavior and robustness Regarding convergence behavior, while comparisons among configurations are not possible (as PSOM-only or WESM-only runs do not require convergence), differences are observed between scenarios, particularly considering the number of iterations required to reach a specific level of convergence. As a reference, for a 10% convergence criterion, the EPI scenario requires five coupling iterations (350 minutes) to reduce the discrepancy between the estimated energy produced in the WESM compared to the PSOM, whereas the NZE scenario converges after only two iterations (180 minutes). Similarly, using a more relaxed threshold (15% tolerance as the convergence criterion) results in the EPI scenario converging after three iterations (equivalent to 210 minutes), and the NZE scenario after two (120 minutes).

Table 4 compiles these metrics for the EPI and NZE scenarios, considering additional convergence thresholds, showcasing that as the convergence tolerance becomes stricter, the number of iterations increases and the computational time rises.

These differences also reflect the more restrictive nature of the NZE scenario, where stringent emission targets dominate system optimization and limit the deployment of emitting technologies, in contrast to the EPI scenario, where the electric system is primarily constrained by fuel availability and renewable resource potentials. As a result, both the number of iterations to reach similar convergence criteria and the average runtime per iteration tend to be lower in the NZE compared to the EPI.

Table 4. Convergence performance metrics for EPI and NZE scenarios

	EPI					**NZE**				
Convergence threshold	20.0%	17.5%	15.0%	12.5%	10.0%	20.0%	17.5%	15.0%	12.5%	10.0%
Number of iterations	1	2	3	4	5	1	1	2	2	3
Approximate runtime (minutes)	70	140	210	280	350	60	60	120	120	180
Maximum remaining discrepancy (energy)	18.5%	15.5%	14.4%	10.4%	6.6%	17.2%	17.2%	10.6%	10.6%	7.2%
Energy non-served (based on WESM)	4.5%	3.2%	2.4%	1.6%	0.9%	6.4%	6.4%	4.7%	4.7%	0.3%

Additionally, Table 4 also showcases the behavior of other relevant parameters, like the remaining discrepancy in energy production for the technology with the highest energy generation difference between the WESM and the PSOM (before the final run with the PSOM), and the non-served energy that could be expected (if WESM capacities were considered). In both cases, results show that, through the iterative process, the exchange of information between models improves the capacity adequacy expectations, as differences between generation outputs in both models and the non-served energy expected in the WESM consistently reduce with the number of iterations.

6.2. Advantages, limitations and future work

The current version of the model presents a straightforward linking process that facilitates the exchange of information between two complementary ESOMs, which makes use of overlapping outputs of the power system (energy and capacity) to regulate their expectations for its expansion. While other relevant and potentially complementary feedback strategies exist, focusing on different technical or economic aspects, the current structure and objectives of the models can restrict their direct implementation. For example, cost-based feedback tends to require that one of the models directly integrates the final output of the other as an exogenous parameter without feedback [120], or as a cost function based on marginal and shadow prices which are not necessarily recalculated in both models, as in the case of the MESSAGE-MACRO models (energy and macroeconomic models) [121]. This simplified linking approach aligns with recent discussions in the literature [89], which emphasizes that the more variables are considered for information exchange, the more complex the linking mechanism and convergence process become.

Similarly, interpretative challenges that can emerge when distinct modeling paradigms are combined, as coupling can alter not only the quantitative outputs but also the qualitative understanding of system behavior. This is a result of assumptions and boundary conditions being often propagated across models without an explicit analysis, comparison, or harmonization. Therefore, the clear specification of linking pathways, exchanged variables, and assumptions is crucial for interpretation and reproducibility, something which is tackled in the proposed method. For example, in the case of PyPSA-BO and EnergyScope Pathway-BO, because both models run independent optimizations and estimate costs endogenously, extracting the specific costs of certain variables (external or not considered in the structure of the other model) becomes problematic. For instance, shadow prices of emissions obtained by PyPSA would represent the marginal costs of emissions only for the electric system, and would include additional costs like transmission lines expansion (which are not considered in the current version of EnergyScope). However, because EnergyScope Pathway-BO optimizes the costs for the entire energy sector, values are bound to be different and not converge (even in cases where high electrification rates are expected). Future work in the linking method can focus on improving additional components (like the transmission system) by exploring complementary or alternative tools, like using the myopic multicell version of EnergyScope [122] instead of the current one (pathway version).

Regarding the convergence criterion analysis, the current implementation of the method proposes a 10% threshold from a practical point of view (to limit the number of iterations and runtime of the coupling). Nevertheless, as the behavior observed from the implementation of considering alternative convergence thresholds, future work could focus on finding cost-optimum values for the coupled analysis, focusing on resolution time and the evolution of the requirements as tolerances become more restrictive. Additionally, identifying which parameters or variables have the highest impact on the convergence of results, and/or quantifying the impacts of considering additional variables for the feed-in and feed-back processes, can represent relevant research lines for the future, as it can be seen that specific constraints (like electric carbon budgets) have relevant effects on the resolution runtime in the models.

Another (conceptual) challenge of model linking lies in the interpretation of results [89] as the integration of two independently optimized systems implies that underlying assumptions are transferred between models. This transfer can introduce hidden dependencies that may bias outcomes or reduce transparency if they are not considered properly or taken into consideration for the interpretation of results. The differences observed in expansion and generation estimations between PyPSA-BO and EnergyScope Pathway-BO exemplify this issue (Figures 5 to 8), as they reflect distinct model perspectives rather than inconsistencies in implementation. Recognizing this interpretative challenge is essential to correctly assess the scope and credibility of linked-model results, as shown and discussed in the comparison of models run in isolation and the coupled analysis.

6.3. Policy implications and transition bottlenecks

From a political point of view, results from the scenario analysis also provide relevant insights regarding the political implications of transition scenarios for the case study of Bolivia. Particularly, by comparing the outputs from the two scenarios, one driven solely by existing political goals (EPI) and another where hard decarbonization targets are expected (NZE), specific transition bottlenecks can be found.

Regarding the diversification of the power generation mix, the Herfindahl-Hirschman Index (HHI) can be used to provide relevant insights. This metric is calculated as the sum of squared generation shares of all sources, where values range from near zero (perfect diversification) to one (complete concentration), with lower values indicating greater diversification and energy security [123]. Following classification ranges adapted from market concentration analysis [124] and applied to energy system diversification assessment [125], HHI values below 0.15 indicate highly diversified systems, values between 0.25 and 0.50 show low diversification, and values above 0.50 indicate severe concentration risks.

For the particular case of Bolivia, the analysis reveals varying levels of diversification between 2021 and 2050. The 2021 base year presents an HHI of 0.3070, classified in the low diversification range, resulting from a significant dependence on fossil gas, which represents 49.04% of total generation through combined cycle gas turbines. Looking ahead to 2050, the EPI scenario achieves the best diversification with an HHI of 0.2459, reaching the moderately diversified category through a distribution among PV (41.08%), geothermal (17.02%), and onshore wind (15.81%). In contrast, the NZE scenario presents the highest HHI of 0.3797, remaining in the low diversification range as a result of severe concentration in PV reaching 57.59% of total generation. This comparison demonstrates that while both future scenarios substantially increase renewable energy share, a trade-off between aggressive decarbonization and generation diversity exists in cost-driven systems, as the NZE scenario achieves a higher decarbonization target through the massive deployment of a single technology, whereas EPI considers a more balanced mix, as a result of not considering an absolute emission reduction goal.

An analysis on the consumption of energy based on the service it provides, depicted in Figures 11 and 12, highlights significant shifts in final energy consumption patterns under each of the scenarios, even though the overall structure is kept, where mobility remains the largest energy consumer in both scenarios (48.3% in EPI, 47.4% in NZE), followed by heating and cooking. The EPI scenario is characterized by fossil fuel dominance across several sectors: LPG accounts for 85.9% of cooking energy, fossil gas and biomass dominate heating, and gasoline leads in mobility. In contrast, the NZE scenario exhibits widespread electrification and renewable energy adoption. Electricity exceeds 80% in heating and mechanical energy applications, reaching 93.5% in cooking. In the mobility sector, passenger transport is primarily electrified, while freight transport relies predominantly on biofuels and e-fuels. A detailed description of the results, focused on the transition effects of each scenario, is available in the Supplementary Information section.

In terms of GHG emissions, the EPI scenario emits 9.3 $\mathrm{MtCO_2}$ in 2050, representing less than half (49%) of the operational emissions in 2021 but remaining short of carbon neutrality. Nevertheless, it can be seen that the measures considered in the EPI scenario,

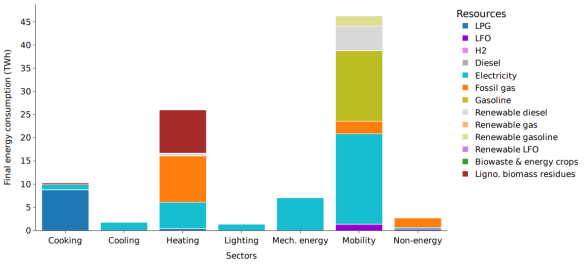

Figure 11. Final energy consumption (96 TWh) differentiated by end-use service and carrier in the year 2050 under the EPI scenario

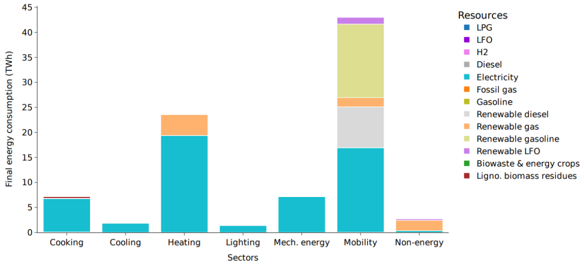

Figure 12. Final energy consumption (87 TWh) differentiated by end-use service and carrier in the year 2050 under the NZE scenario

alongside the cost minimization objective, are capable of affecting the expected shares of technology deployment, reducing the participation of fossil fuels in the energy matrix, and promoting electrification. The NZE scenario effectively eliminates fossil fuel-related emissions by introducing the emission constraint; however, it still accounts for 0.9 $MtCO_2$, primarily due to geothermal power plant operations. Given that these emissions originate from naturally occurring non-condensable gases released during geothermal energy extraction, their accounting is subject to discussion. To achieve full carbon neutrality, additional mitigation measures or compensation strategies should be explored to address these residual emissions from non-fossil sources.

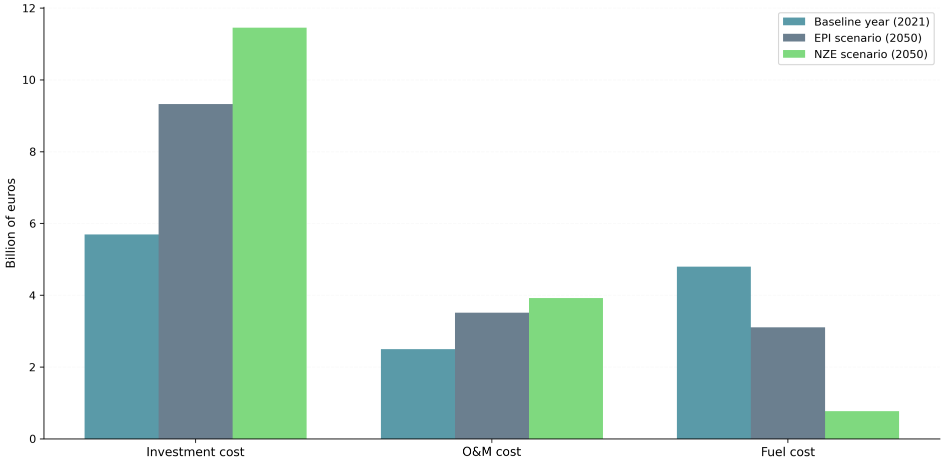

Figure 13. Total investments, and final yearly O&M and fuel costs for Bolivia's energy system: 2021 baseline and 2050 scenarios (EPI and NZE)

Future costs in 2050 show substantial increases compared to the 2021 baseline across most categories in both scenarios (Figure 13). Investment costs rise by 164% under EPI (from 5.7 billion € in 2021) and by 201% under NZE, reflecting the capital needs of a decarbonized energy system. Operation and maintenance (O&M) costs follow a similar trajectory, increasing by 141% under EPI (from 2.5 billion € in 2021) and 157% under NZE, driven by more advanced and extensive infrastructure requirements. In contrast, fuel costs decline significantly by 2050, decreasing by 35% under EPI (from 4.8 billion € in 2021) and by 84% under NZE, indicating substantially reduced dependence on imported fossil fuels in the net-zero pathway. If opportunity costs are considered for the fuels used in the system (i.e. selling fuels at international prices instead of consuming them at the subsidized price), a case can be made where the NZE scenario becomes much more profitable than the EPI in the long term.

Additionally, this analysis of Bolivia's energy transition reveals three key bottlenecks that could complicate progress toward a sustainable and decarbonized future:

- First, the EPI scenario highlights the system's inertia related to the continued reliance on fossil fuels, although to a lesser extent (accounting for 40.9 TWh in 2050). This ”systemic inertia”, or the resistance of the system to change its consumption and generation mix, is the result of considering constant (subsidized) prices for fuels like natural gas, which can lead to a lower competitiveness of other technologies, and no new exportation contracts are expected in the future, which guarantees the resource availability for domestic consumption until 2050. Both of which disincentivize the change of the system to different technologies, unless more restrictive conditions appear (like reaching zero emissions by 2050 in the NZE scenario). This intertia (not to be confused with the inertia linked to reserves in power systems) can also be seen in other studies that analyze scenarios that maintain conservative assumptions or trends linked to BAU conditions. For the Bolivian case, this inertia has been documented to limit the change of the system's energy mix in the long-term [34], and limit the effectiveness of short- and mid-term policies or plans [11], thus showcasing the importance of considering appropriate and representative conditions for the system's fossil resources in the future. In the case of studies that consider other types of models, such as IAMs or System Dynamics Models, the inertia can become less noticeable through the endogenous inclusion of social or economic behaviors [126] or by integrating macro conditions or targets linked to predefined scenarios [87, 88].
- Second, while the scenario analysis demonstrates that transition scenarios, with ambitious electrification and renewable energy adoption goals, could provide potential benefits in the long-term, these are bound to encounter substantial financial barriers as higher investments would be required. Particularly, the more ambitious the scenario, the higher would be the investment (i.e. the NZE scenario would require an additional 123% increase in investments compared to the EPI scenario in 2050), most of which need to be available in the early years of the transition period. This is a common trend in several studies that analyzed the decarbonization or full transition to renewables in South America, where countries like Chile, which recognizes the high upfront cost of transition and frames it as

theoretically possible [39], or Brazil, where the high investment costs of transition are justified by the potential savings from reducing the usage of fossil fuels [46]. As a result, if transition scenarios are to be expected in the future, it is of vital importance for Bolivia to secure sufficient financing and financing mechanisms to facilitate them.

- Third, while clear and cost-effective targets can be set based on the analysis made, the logistical complexity of diversifying energy resources across sectors poses big challenges. As such, reaching these targets will imply several efforts regarding technology development, adoption, and deployment. For example, in terms of the expected growth, the power system should consider a yearly growth of about 40% of its capacity until 2050 (something without precedents in the country); regarding technology adoption, sectors like cooking or heating should start introducing alternative technologies to the widespreed use of conventional gas; and in terms of deployment, sectors like transport would require specific strategies to fully replace the current transport fleet, and developing the infrastructure to produce and procure the selection of e-fuels corresponding to each scenario. Overcoming each of these obstacles will require targeted policies, dissemination campaigns, and coordinated strategies to balance technical, political, and social aspects required for promoting the transition. As a result, more detailed studies are required to analyze each of the relevant aspects of the transition, focusing on every end-use demand and key energy vectors. A good example of this type of effort can be seen in Brazil, where e-kerosene is considered as a potential energy vector to replace conventional fuels in the country and for the aviation sector, and therefore a specific analysis on its development, deployment, and impact is done [27].

Regarding other general results from scenarios aiming at carbon neutrality, takeaways are consistent across the literature, as even in early studies [127], large deployments of renewables (mainly solar and wind) are expected to cover the energy requirements of the system. Particularly in studies that tackle this issue using two models, REMIND and DIETER for Germany [87] or GCAM and H2RES in Chile [17], the change in the energy systems' matrix is a result of the need for reducing the use of fossil plants and covering new demands as a result of electrification processes (both as a consequence of needing to reduce emissions).

Nevertheless, while the results obtained from these studies provide a general framework of consistency as they are aligned with the results obtained for Bolivia, it is also worth mentioning that the specific use of IAMs as the reference model to represent the transition process also differentiates their outcomes. For instance, while GCAM also handles end-use demands in some sectors to represent the growth of energy demands, sectors like industry or buildings tend to be grouped up and dependent on regional statistics for their representation. Similarly, while REMIND (and GCAM) provides a pathway analysis with 5-year steps, the characterization of technologies is fixed to a given number and assumes yearly aggregated values to represent their characteristics. While it is true that descaling techniques have appeared, such as DSCALE [128], which allows for regional studies made with IAMs to provide country-specific insights. However, given the additional data processing stage required to get country-specific outputs, a case can be made regarding its usage, especially if model linking is expected in secondary stages. As a result, given the focus on the technical aspects of the energy system, the use of a WESM as EnergyScope becomes more relevant.

7. Conclusion

The present study demonstrates the effectiveness and benefits of bi-directional soft-linking in improving energy system characterization and analysis by integrating a whole-energy system model (WESM) with a power-system optimization model (PSOM), and presents its application considering the Bolivian energy system as its case study.

By linking a WESM and PSOM through an iterative approach, the method captures both the integrated evolution of the energy system and the detailed expansion of its power sector, while ensuring that long-term planning remains consistent with short-term operational feasibility. This provides a more realistic representation of the system and its behavior, compared to their stand-alone application, offering a robust tool to assess sectoral interactions, resource constraints, and investment needs under alternative national-level transition scenarios. For this study, country-tailored versions of the WESM and PSOM models are used (EnergyScope Pathway-BO and PyPSA-BO, respectively); however, the overall method can be easily extrapolated to other models or case studies.

While other studies emphasize rapid convergence methodologies, system adequacy conditions, or the integration of modelling tools, the present approach focuses on an accessible, replicable, and flexible linking method that facilitates the exploration of alternative development scenarios. This is achieved by using two open-source models, based on transparent modelling frameworks that can be easily adapted and have no inherent licensing or acquisition costs. Additionally, the current structure of the information exchange process is kept simple, allowing for a manual transfer of data for models of the current size. Automation or the development of intermediate pre-processing scripts is recommended if the complexity of the models is expanded, such as considering additional technologies, number of buses, or new constraints.

Results from the coupled analysis highlight the advantages of adequately representing key variables such as fuel-usage competition in cross-sectoral contexts (done with the WESM) and detailed resource availability and dispatch restrictions representation (done with the PSOM). The insights from the application of the method for the Bolivian case also emphasize the necessity of integrating both perspectives to avoid the underestimation of capacity expansion needs of variable and heterogenously distributed renewables like wind (if no spatial or temporal details are considered) or the overestimation of feedstock availabilities of biomass or fossil fuels for generation purposes (if no cross-sectoral interactions are considered) across scenarios.

Regarding transition takeaways for Bolivia, the analysis of development scenarios (EPI and NZE) made with model linking framework allows for the identification of three relevant bottlenecks for the transition of the energy sector: 1) the availability of natural gas for domestic consumption and subsidized prices of fossil fuels generate a systemic inertia that hinders and slows the diversification of the energy system. Unless these conditions are revised, or much more global and restrictive objectives are considered, like achieving carbon neutrality, transitioning the Bolivian system will be difficult; 2) transition scenarios, while potentially beneficial in the long term, are expected to require substantial and early-stage financial investment flows to facilitate the expected growth and change of the energy generation and consumption mix. This is a particularly relevant barrier for Bolivia, considering the size of its economy and its baseline condition as a country heavily reliant on fossil fuels; and 3) although clear and cost-effective targets can be identified, the complexity of transforming a national energy system will require coordinated efforts across sectors to manage unprecedented growth rates in the electric sector, massive deployment of new technologies, or the adoption of new appliances or types of energy services. To support this process, additional and complementary studies are needed focusing on the technical, logistical, and social dimensions of the transition for each relevant sector and energy vector, providing the evidence base required to design effective and actionable policy measures.

Future research should focus on extending the adaptability of bi-directional soft-linking by exploring additional regulatory variables/parameters that can be exchanged between the models, integrating socio-economic and environmental factors, and expanding the analysis to consider regional energy trades. Moreover, a better representation and incorporation of non-energy sectors and variables (such as land usage or water availability) or the representation of more complex system dynamics (like demand-side management strategies or electric vehicle batteries representation) would allow for an improved modeling framework and provide a better understanding of the energy transition from a national perspective. These advances will support a better and more complete representation of the energy systems modeled, more effective policy-making, and energy transition scenarios that are more realistic and potentially feasible.

Acknowledgments

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Data Availability

Data and code used for the results of this paper are openly available at the PyPSA-BO (https://github.com/CIE-UMSS/PyPSA-BO) and EnergyScope Pathway-

BO (https://github.com/CIE-UMSS/EnergyScope_Pathway_BO) repositories.

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