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Implications of defining exogenous variables in Energy System Modeling with Integrated Assessment Models for transition planning

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ABSTRACT

The sustainable transition of energy systems heavily relies on models that provide diverse scopes and applications. This study explores how two modeling approaches can work in tandem and complement each other to provide a more robust framework for analyzing the development of energy systems at the country level. Specifically, we consider an Integrated Assessment Model (GCAM), to evaluate alternative transition scenarios in a country from a multi-sectoral level, and an Energy System Model (PyPSA-Earth), to optimize the expansion of the power system with high geographical and temporal resolution. In this study, we present tailored versions of these tools to analyze Bolivia as the case study, GCAM-Bolivia and PyPSA-BO. Our method employs a unidirectional soft-linking process, using carbon budgets and projected energy demands as the connecting parameters between models. In this sense, GCAM-Bolivia is used to derive six alternative development scenarios based on emission reduction targets until 2050, while PyPSA-BO is used to optimize the electric system expansion, including generation, storage, and transmission capacities. Results show that, regardless of the scenario, solar PV is the dominant technology for capacity expansion in the future and that the growth of the electric sector appears to have a non-linear relation with the emission reduction targets for the energy sector, where only reduction targets above 40% trigger an intensive electrification process. In these cases, a significant expansion of storage and transmission capacities distributed across the country is required to provide flexibility in the system.

1. Introduction

Since the Kyoto Protocol to the Paris Agreement, targets were established to limit the increase in global average temperature to below 2 °C compared to pre-industrial levels. To achieve this, literature has shown that Greenhouse Gases (GHG) emissions must peak before 2025 at the latest and decline by 43% by 2030 [1]. Because of this urgency, the study of different sub-sectors that contribute to climate change, mostly in the form of GHG emissions, has become more and more important around the world. Proper understanding of key sectors at the country level, particularly through modeling tools, is crucial for policy development, decision-making, investment planning, and resource allocation [2]. Such influence has given a great set of modeling tools in different disciplines that are particularly relevant to reach those goals, i.e. energy [3,4]; water [5]; agricultural/land-use [6]; economy [7]; food [8]; social, ecological [9] and climate [10]. However, the need to address complex global challenges related to climate change (extreme temperatures, drought, sea level changes, and mountain glaciers melting) [11,12], has pushed the rise of a particular type of models that focus on the association and interrelation of these sub-systems. In this sense, Integrated Assessment Model (IAM) tools have become prominent due to their capacity to characterize quantitatively such intricate interactions in the long-term, i.e. encompassing analyses that traverse disciplinary borders to capture the interactions between human and natural systems [13,14].

Currently, several IAM tools and frameworks have been established [3], like IMAGE, which employs a general equilibrium approach for system analysis [15], or MEDEAS-World, which uses system dynamics modeling to represent changes in its system [16]. Therefore, the usage of a specific model depends on the objective of the study. Among these models, the Global Change Analysis Model (GCAM) [17]

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Acronyms

ESM	Energy System Model
GCAM	Global Change Analysis Model
GHG	Greenhouse Gases
IAM	Integrated Assessment Model
LAC	Latin America and the Caribbean
NEB	National Energy Balance
PSOM	Power System Optimization Model
PyPSA	Python for Power System Analysis
PyPSA-BO	PyPSA - Bolivia

stands out as it can adequately explain the interplay between human activities and earth systems in a single platform, demands relatively low computational requirements thanks to its partial-equilibrium formulation [18], has a transparent and accessible structure thanks to its open-source nature, and can be used to explore alternative hypothetical scenarios prolonged to 2100 by five-year time-steps [19,20].

GCAM captures the behavior and interactions among five major systems — energy, water, land, climate, and the economy — across global and regional scales [21]. GCAM's employment is very extended in developed countries [22] over diverse fields, e.g. industry [23], transport [24], power generation [25], buildings [26], or agricultural and land-use [27]. However, its use in developing countries has been rather limited, with only a few studies focused on Latin America and the Caribbean (LAC). These studies have given the first notions for deep decarbonization needs, the technical and economic feasibility of carbon capture, a balanced mix of fuel sources in the transport sector, the critical demand increase for land due to food production [28], or the effects of Climate Change on the future supply and renewable energy sources' reliability [29]. At the continental level, studies have been conducted exploring the implications of the energy-water-land nexus concerning the Paris Agreement pledges [30] or focused on the economic implications of stranded assets in Latin America [31]. In addition, at a national level, specifically in Chile, researchers studied different pathways for achieving the Chilean NDC, along with the assessment of carbon sequestration [32,33]; moreover, the analysis of decarbonization scenarios carried out in Argentina and Chile (inside the Net Zero World Initiative) highlights the opportunities to increase the energy efficiency, scaling up renewable power generation and switching the source of fuel in transport and building heating sectors [34].

Because IAMs have a holistic approach, considering several sectors and systems transversally, they also have limitations when representing each of them, as the level of aggregation is rather large to allow computational tractability. This is particularly noticeable in the electricity sector since they typically do not capture technical features of a power system [35], such as the distribution of power plants, technology constraints, transmission lines, hourly dispatch, or storage. To tackle this, if the electric system is a relevant subject, more specialized modeling tools are often applied, normally defined as Energy System Model (ESM). These models can address operational aspects with higher spatial, temporal, and/or technological detail [36], with relevant examples being OSeMOSYS [37], EnergyPlan [38], or DispaSet [39]. Among these, Python for Power System Analysis (PyPSA) [40], stands out as a specific type of ESM, a Power System Optimization Model (PSOM), which was designed for power systems analysis purposes, focusing on the physics of power flows over multiple periods — typically a full year — and optimizing the total system costs given techno-economic characteristics and constraints of its components i.e. conventional generators, variable wind and solar generation, storage units, and mixed Alternating Current (AC) and Direct Current (DC) networks [41]. These characteristics, and its open-source nature, have positioned it as one of the main tools used for power system analysis in recent literature. However, while its application in the global north has been growing steadily, particularly after the development of the European model PyPSA-EUR [41], its application to South America or the LAC region is still new, with only a few examples, like the case for Brazil [42]. Initiatives such as PyPSA-Earth aim to extend the application of the model to a global scale [43], providing an automated workflow to collect large amounts of input data required for creating models in different countries around the world, of which recent applications are available for Kazakhstan [44] and Bolivia [45,46]. In both cases, the derived models are used to explore potential development scenarios of the country, considering only the expansion of the electrical system.

Similarly, other ESMs have been used for country-specific cases to explore development scenarios and expansion plans [47,48]. However, these scenarios are normally explored assuming objective-based conditions for the electric or energy systems, such as reaching net-zero emissions in the system [49,50], effects of the inclusion of new renewable power plants in the system [51,52], storage, and flexibility requirements [53,54], etc. Although these models can address specific questions with greater technical details, PSOMs are also limited as they do not endogenously account for the interrelations among several input parameters and mostly adopt assumptions to represent the trends, effects, or relations between them [55]. Clear examples of these are the energy demands, which tend to be estimated exogenously and influenced by other relevant factors like economic trends, technology costs, fuel prices, or population growth [56]. While efforts can be made to improve the characterization of these variables in ESMs, i.e by considering behavioral conditions [57] or geopolitical influences [58], generally IAMs tend to have advantages by providing a more integral perspective for scenario definition, as they consider the interactions across several sectors [59].

In this sense, the potential complementarity of IAMs and PSOMs for the analysis of national-scale energy systems is clear: IAMs like GCAM can provide a more detailed and robust characterization of the long-term development scenarios by considering several dimensions and sectors that interact with the energy system. In turn, PSOMs like PyPSA can be used to provide additional accuracy to the energy system characterization, compensating for the technical, temporal, and spatial oversimplifications usually made in the electric system representation. While literature that aims at leveraging the capabilities of two different tools currently exists, these studies mostly focus on improving technical representations in a particular dimension. The most common example is linked to increasing the temporal resolution in long-term ESMs by linking it with PSOMs (TIMES-PLEXOS) [60], a dispatch model (EnergyScope-Dispaset) [61], or a unit commitment model (TIMES-LUSYM) [62]. In contrast, when analyzing IAMs, most studies focus on the complementarity of socio-technical approaches or frameworks to improve the characterization and/or realism of transition processes [63].

A review of the existing methods for the coupling process between different models shows that in the case of ESMs, strategies like soft-linking or direct integration seem the most common for considering a secondary tool [35]. In the case of IAMs, linking techniques focus on bridging, iterating, or merging the model or its results with the secondary tool [64]. In both cases, it is noted that linking methods tend to focus on improving either ESMs or IAMs with the inputs from a secondary tool or model (macroeconomic models usually), but are rarely coupled between them, mainly due to the different approaches, scales, and scopes they have (e.g. more detailed and technical or more broad and transversal, respectively) [65]. Some relevant examples that have tackled the linking of IAMs to ESMs include the linking of a simulation-based ESM (EnergyPlan) and WILIAM (an IAM) [66], where the ESM model provides inputs regarding the dispatch behavior to the IAM; and the linking between a power system model (DIETER) and an investment development model (REMIND) [67], where market values are exchanged iteratively between the ESM and IAM.

Finally, it is also important to recognize that as linking IAMs and ESMs becomes a more common practice, as it provides a pragmatic solution to both models' limitations, additional relevance needs to be given to the standardization of the linking processes [68]. This would imply, for example, considering a proper harmonization process for all relevant parameters, adequately identifying all strategic overlaps between models, selecting the correct variables for information exchange, and acknowledging the limitations and discrepancies between the tools and their results. Within this context, this work aims to develop and provide a methodological framework for (1) analyzing a national-scale energy system with two types of models (IAM and PSOM) with different scopes and scales; (2) compare the differences between inputs used and outputs obtained from the IAM and PSOM; (3) identifying and exploiting synergies between them to provide a more robust long-term energy system analysis, and (4) represent the effects of using exogenously defined variables for a PSOM, derived from endogenously calculated results from an IAM, something underrepresented in the current literature.

Specifically, we propose a coupling method that enables the comparison and soft-linking of two models developed within well-established open-source frameworks — GCAM (as the IAM) and PyPSA (as the PSOM). This approach provides a more comprehensive representation of the energy system and its transition pathways by combining cross-sectoral interactions captured by the IAM with the high spatial and temporal resolution of the PSOM. To this end, the Bolivian energy system is considered as the case study, and its analysis is done utilizing PyPSA - Bolivia (PyPSA-BO), a model based on PyPSA-Earth and curated for Bolivia, and Global Change Analysis Model applied to Bolivia (GCAM-Bolivia), a new national version of GCAM (adapted from version 6.0) that represents Bolivia as an independent region. To achieve this, this study takes inspiration from previous work done regarding soft-linking between energy models and their methodologies, studies with the same object of study (Bolivia), and studies that used the aforementioned tools (GCAM or PyPSA). The most relevant sources include a study for Bolivia that analyzed how a long-term energy planning model and a short-term dispatch model can be used in tandem to improve their outputs [69]; the potentiality for usage of PyPSA-Earth as a modeling tool for analyzing the Bolivian power system [45], and the first implementation of PyPSA-BO as its own curated model for the country [46]; the integration of GCAM with a partial equilibrium model called the North American Natural Gas Model (NANGAM) [70]; the use of GCAM with the Highway to Renewable Energy Systems (H2RES) model, which evaluates the feasibility of the IAM-derived scenarios [71]; and the assessment of a bidirectional linking between the REgional Model of INvestments and Development (REMIND) and the Dispatch and Investment Evaluation Tool with Endogenous Renewables (DIETER) models [67].

The paper is organized as follows: Section 2 describes the methodology (GCAM-Bolivia, PyPSA-BO, and the proposed model coupling). Section 3 provides an overview of the Bolivian context as the case study and the scenarios evaluated. The results of our analysis are presented in Section 4, and relevant takeaways from the analysis are available in Section 5. Finally, Section 6 provides our research findings and includes considerations for future work, discussion, and comparative analysis.

2. Methodology

This section considers an initial introduction to the two modeling tools used, their adaptation process for the case study, and the proposed method to identify connection points, complementarities, and coupling of both tools.

2.1. Model linking approach

Model linking techniques combine the strengths of two or more energy models while acknowledging their limitations throughout three main steps: (a) Identify Specialized Models, (b) Data Exchange, and (c) Iterative Analysis [60]. While different studies can present variations on these steps, in general, a similar workflow is followed. A representative example is the Frigg framework, which considers an iterative process to find an optimal solution combining two separate models, one representing the energy system and the other representing consumer response to prices [72]. Depending on the case study, the problem analyzed, or the models used, certain stages might become more relevant than others, like the challenges and importance of identifying appropriate data exchange (connection) points, ensuring consistency between a national energy system model and a computable general equilibrium model [73]. In the same way, it is emphasized that to correctly couple two models (IAM/ESM), both should share certain common inputs, i.e. electricity demand and renewable generation to ensure comparable model results [35,62]. Additionally, an approach to linking top-down (normally IAMs) and bottom-up (normally ESMs) models for energy system analysis suggests the importance of the data exchange step, highlighting the Partial Information Strategy — where only key data points are shared between models — as a suitable method for large-scale implementation [74]. Based on these and previously mentioned literature, a 4-step methodology is proposed for this work, as shown in Fig. 1.

Step 1 (Calibration) and Step 2 (Stand-alone run) represent the definition of baselines for both tools, where scenarios are considered to exemplify the type of outputs that they can provide. During Step 1, a harmonization process is performed between the selected models (GCAM-Bolivia and PyPSA-BO) and official data, to uniformize the initial conditions for both tools. Results from Step 2 are used mainly for comparison purposes and to identify the limitations and/or considerations required to run them. Step 3 (Information exchange) is focused on the identification of linking variables for the exchange of information between models. Step 4 (Coupled run) is focused specifically on the analysis of results from the coupling process between tools, considering a unidirectional soft-linking approach, where results from a model are introduced manually to the other. Steps 1 to 3 are detailed in the rest of the Section 2 section, and step 4 is presented in the Section 4 section, where all outputs of the models (stand-alone and linked runs) are displayed.

2.2. GCAM-Bolivia

Developed at the Pacific Northwest National Laboratory, GCAM processes a set of assumptions — inputs — to create full scenarios of prices, energy, commodity transformations, and other flows across regions through five differentiated but interconnected systems: Macro-Economy, Energy, Land/Agriculture, Water, and Physical Earth [75].

GCAM-Bolivia is parametrized using the GCAM v6.0, where Latin America is segmented into distinct energy-economy sectors, including Colombia, Argentina, and Brazil, alongside two composite regions: South America Northern (French Guiana, Guyana, Suriname, Venezuela) and South America Southern (Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay). This research extracted Bolivia from the South America Southern region, resulting in 33 represented energy and macroeconomic regions. This process follows the methodology developed in [76,77], which has been utilized to develop other regional versions of GCAM, including GCAM-USA [78,79] and GCAM-LA [32,33]. GCAM-Bolivia evaluates multi-sectoral energy supply and demand, considering economy-wide carbon budgets. Additionally, it provides the energy demand of each consumer sector, such as buildings, industry, and the transport sector.

GCAM-Bolivia, focuses on the characterization and parametrization of the energy system, considering the standard regional characterization for the rest of the systems. The model considers 2015 as the base

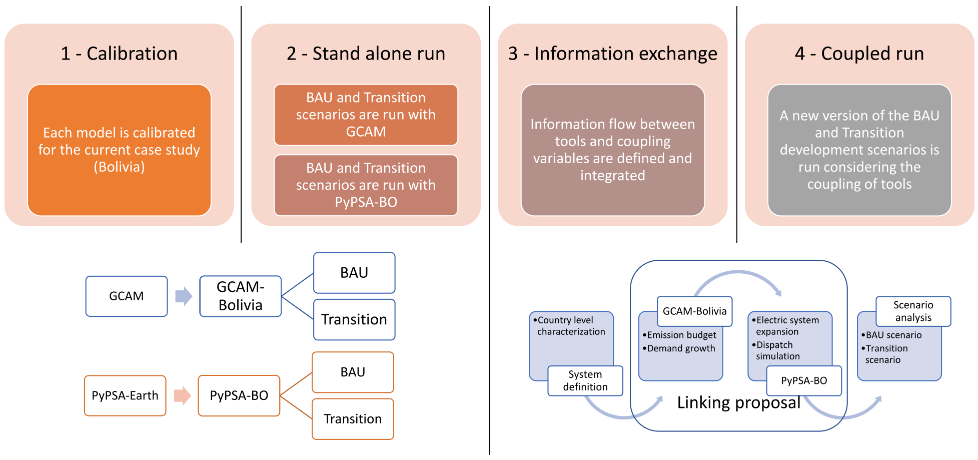


Fig. 1. Proposed methodology for analyzing the effects of coupling PyPSA-BO and GCAM-Bolivia

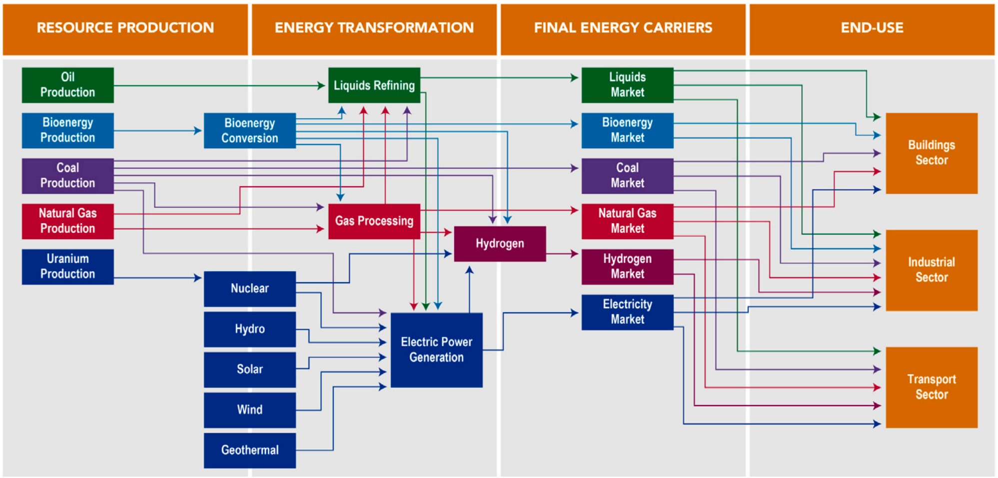


Fig. 2. Overview of energy production and transformation in GCAM.
Source: [82].

year and is calibrated using data from Energy Balances by IEA [80]. Specifically for the electricity sector, data from Bolivia's 2020 energy balance is used to calibrate the secondary sector (power sector) in that same year [81]. The reference energy system scheme is shown in Fig. 2, where energy vectors, transformation technologies, and consumers taken into account are displayed.

Finally, GCAM's usage of explicative variables and equations to represent trends or effects for the development of the system in the form of equations is another relevant differentiator. Some relevant examples are Equation (1), regarding the demand side of the energy system, and Eq. (2), regarding the supply side. Eq. (1) represents the relation between per-capita GDP (Y), population (N), prices (P), and energy demand (D), where demands are associated to industrial and transportation services in the region r and period t, and α and β are the income and price elasticities, respectively [83].

$$D_{r,t} = D_{r,t-1}(\frac{Y_{r,t}}{Y_{r,t-1}})^{\alpha}(\frac{P_{r,t}}{P_{r,t-1}})^{\beta}(\frac{N_{r,t}}{N_{r,t-1}}) \tag{1}$$

On the other hand, Eq. (2) is used to introduce a prioritization (logit) function that prevents the indiscriminate usage of one single technology (s_i) from N options, or to introduce trends for the development of the technology. In this equation α_i is the share-weight of technology i, c_i is the cost of technology i, and γ is the logit exponent (determined exogenously), which represents to what degree the share of each technology is affected by its cost or profit [21]:

$$s_i = \frac{\alpha_i \cdot c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j \cdot c_j^{\gamma}} \tag{2}$$

2.3. PyPSA-BO

Maintained by the Department of Digital Transformation in Energy Systems at the Technical University of Berlin, PyPSA is a modeling framework that models various power system components i.e., conventional generators, renewable energy sources like wind and solar, storage units, and mixed AC/DC networks. With these, it simulates power systems and optimizes dispatch and investment in new infrastructure [84]. To create a model in PyPSA, three types of inputs are required. First, Network data i.e. the physical layout of the power system, including: Buses or electrical nodes where power is injected or withdrawn from the system; Lines, which represent the electrical connections between buses; Transformers, which change the voltage level between different parts of the power system. Second, Component data that describe the characteristics of the elements connected to the network i.e. information about power generation capacity, efficiency, and operational costs of generators; Data like power output variability on wind and solar farms; Storage capacity, charging/discharging efficiency, and power limits of storage units. Third, Operational data that specify how the

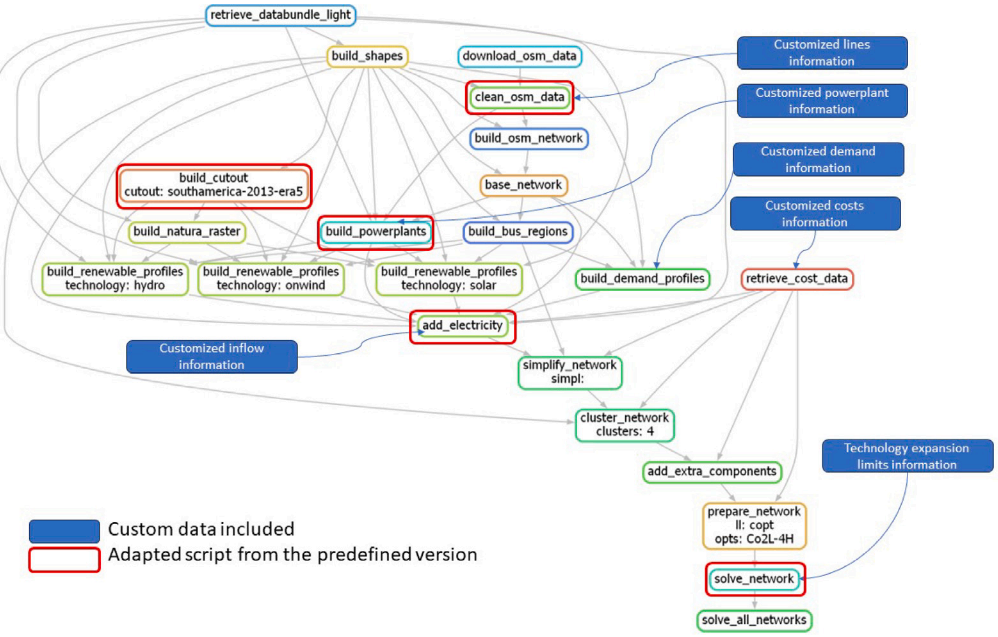


Fig. 3. PyPSA-BO adaptations based on the predefined workflow of PyPSA-Earth, where each box represents a dedicated script in charge of data collection or processing.

power system is intended to be driven i.e. Demand for the electricity needs at different points in the system over the simulation period [85].

PyPSA-Earth is a model developed and based on PyPSA, capable of creating and analyzing country and region-size energy systems with a global range [43]. The model is differentiated from others by its high spatial and temporal resolution, and an automated and customizable workflow that facilitates data extraction from online repositories, pre-processing tasks for adapting the information, creating a network model compatible with PyPSA, and solving the optimization problem linked to the expansion of the system. The version v0.3.0 of the model is capable of producing functioning models for nearly every country in the world, requiring minimal modifications to the configuration file (based on the desired outcomes) [86].

Regarding the mathematical formulation of the model, PyPSA-Earth is driven by its cost-optimization objective function, as presented in Eq. (3). Here c and o represent the capital and operation costs associated with a specific bus (n), generation or storage technology (s), branch (l) and snapshot (t); G, H, and F represent the nominal capacities of generators, storage (storage units and energy stores), and branches (links and lines) respectively; dispatch values at specific snapshot, weighted by w, are g for generator and h for storage technologies. Eq. (3) represents the components considered in a linearized version of the objective function used in the model, which can be extended to include startup or shutdown costs (converting the problem into a mix-integer linear program) or considering quadratic marginal cost (converting the problem into a quadratic program).

$$Minimize(TotalCosts) = \sum_{n,s} c_{n,s} G_{n,s} + \sum_{n,s} c_{n,s} H_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t \left[\sum_{n,s} o_{n,s} g_{n,s,t} + \sum_{n,s} o_{n,s} h_{n,s,t} \right] \tag{3}$$

Additional equations (constraints) linked to the model include the system's Energy balance, which enforces a balance of energy in each bus (following Kirchhoff's current law), Dispatch limits, which guarantee a consistent generation behavior (not surpassing their nominal capacities, dependent on resource availabilities or security margins), Power flow, which enforces that power flows in lines and transformers behave following the linearized formulation of KVL (Kirchhoff's voltage law), and other Global constraints (Operational limits for generators and stores, CO2 Emission limits for the system, Cost limits for transmission expansion, or even custom constraints). All of these constraints (and their corresponding mathematical formulations) are properly detailed in the PyPSA documentation webpage [87].

Results from the direct application of the model to the Bolivian case showed that the tool's use is quite simple, given the transparency of the model and documentation available, and provides a good characterization of renewable resources such as solar and wind availabilities extracted from Copernicus Climate Change Service [88]. However, due to the limited quality of data available for the country in the default repositories used by the model (OpenStreetMaps [89]), additional changes had to be considered to enrich the model and improve its quality [45]. Fig. 3 shows the most relevant modifications to the base workflow of PyPSA-Earth to adapt it for the Bolivian case, including the provision of additional datasets curated based on other studies and national reports to provide locations and characteristics of components such as: transmission lines distribution [90], techno-economic characteristics of generators [81], or demand profiles [91], among others further detailed in [46]. Keeping up with the open-source philosophy [92], the current version of PyPSA-BO has been released and is available in a dedicated GitHub repository (PyPSA-BO), along with links for all data sets used.

2.4. Model comparison and complementarity

Based on the general structure of the modeling frameworks and the characteristics of each customized model, a comparison of their end goals and how a (non-exhaustive) list of parameters is considered in each of them is shown in Table 1. This compilation serves as the base for defining the flow of information between models based on their variables/parameters, which can either be provided exogenously or defined endogenously. In this sense, depending on how each of these variables is tackled in both tools, they can be used to define the inputs for each model and, therefore, the basis for the linking process:

- If a parameter is considered endogenously or exogenously in only one of the tools (N/A on the other), it represents a boundary where only one model is suited to integrate information or provide relevant results. Some examples of these types of parameters

Table 1
GCAM-Bolivia and PyPSA-BO comparison for input and output definition and usage.[a]

	GCAM-Bolivia	PyPSA-BO
Model Definition		
Model Scope	Cross-sector scenario development and analysis	Electric system expansion analysis
Modeling Approach	Partial equilibrium model	Cost-optimization model
Constraints focus	Resource availability	Techno-economic operation
Time resolution	Yearly	Hourly
Time horizon	Pathway analysis 2015-2100 (every 5 years)	Myopic optimization (yearly)
Number of nodes	1 node per region	Customizable number of nodes per region
Model Input/Output Parameters		
Water resources availability	Exogenous variable	N/A
GDP changes	Exogenous variable	N/A
Population growth trend	Exogenous variable	N/A
Land usage restrictions	Exogenous variable	N/A
AFOLU CC capacities	Exogenous variable	N/A
Climate restrictions	Exogenous variable	N/A
Renewable resources availability	Exogenous variable	Defined endogenously
Technology characterization	Exogenous variable	Exogenous variable
Fuel costs	Exogenous variable	Exogenous variable
Energy demand	Defined endogenously	Exogenous variable
Carbon budgets	Defined endogenously	Exogenous variable
Energy production	Defined endogenously	Defined endogenously
Electric capacity expansion	N/A	Defined endogenously
Dispatch characterization	N/A	Defined endogenously
Spatial representation	N/A	Defined endogenously

[a] Parameters are considered endogenous if at least some calculations are made inside the model before their usage.

can be the population growth trends, land usage restrictions, or climate restrictions, all of which are exclusively considered in GCAM and provide relevant inputs for the energy system analysis, as they can indirectly affect the development of the power system. Similarly, outputs like dispatch characterization, spatial distribution, or capacity expansion values are obtained exclusively by PyPSA, providing more realistic outputs that are oversimplified or directly disregarded in the other model.

- If a parameter is defined by one of them (endogenously) and introduced in the other (exogenously), it represents a path for the flow of information between tools. Particularly for the case of information exchange from GCAM to PyPSA, these would represent the energy demand and carbon budgets (for the electric system). Potentially, if feedback from PyPSA to GCAM were considered, Renewable resource availabilities could also be exchanged.
- If a parameter is considered exogenously (input) in both tools, it represents a point where harmonization is required in the data. For this case, this would be mostly linked to the techno-economic parameters used for characterizing generation technologies (power plants) and energy vectors (fuels), values which are matched in both models to allow for an adequate comparison.
- If a parameter is calculated endogenously (output) in both tools, it represents a point where convergence between models can be studied. For the case of GCAM and PyPSA, this point would be designated to Energy production values for the electrical system, as this represents one of the few outputs that both models provide and are directly comparable.

As a result of this analysis, a linking process between GCAM-Bolivia and PyPSA-BO is proposed, aiming at exploiting the more robust setup for scenario development done by GCAM, and integrating this into PyPSA to conduct a detailed representation of the expansion expectations for the electric system. With this objective in mind, the linking proposal considers an unidirectional flow of data — from GCAM-Bolivia to PyPSA-BO — that allows for a simple and direct scenario exploration framework. Additional stages, such as integrating feedback from PyPSA-BO to GCAM-Bolivia, or reaching a convergence between outputs in both models, are considered out of the scope of this work but are recognized as relevant areas for future work. A graphical representation of the flow of information into and between the models is presented in Fig. 4, where the structural definitions and parameters are exemplified, as well as the potential feedback PyPSA could provide to GCAM.

Finally, it is also worth mentioning that the proposed method differs from other previously mentioned implementations that dealt with IAMs and ESMs. For example, it uses the more holistic scope of the IAM to inform the optimization of a more specific sector with the ESM, which is the opposite case of the EnergyPlan-WILIAM linking [66], where a simulation-based ESM is used to provide corrective inputs for the energy system representation in the IAM. On the other hand, our method focuses on coupling specifically an IAM with a PSOM (a particular type of ESM) to tackle more intricate conditions and operational constraints of the dispatch behavior, something that can be oversimplified when less granular ESM are considered [93]. Regarding the linking variables, the proposed method identifies and uses technical variables/parameters as potential information exchange paths (energy demand, carbon budgets, resource availabilities, or energy production) to link the models, unlike in the case of DIETER-REMIND [67], where economic parameters (market values for the energy production) are exchanged.

3. Case study

This section presents the referential conditions for the case study used in this work, the Bolivian energy system, and the calibration results of the models for the year 2020. Additionally, the context and considerations assumed for the development of future scenarios are presented.

3.1. The Bolivian context

Bolivia is a developing economy located in the center of South America. The country has a surface over a million square kilometers, is landlocked, and its energy system is mostly isolated from other countries in the region, with gas pipelines being its only interconnection to other countries. In the last 10 years, the country has been a net energy exporter, derived from its large natural gas reserves and contracts with Argentina and Brazil. By 2020, the total energy production in the country was estimated to be 125 kboe, from which exportations took the biggest share, with 73 kboe of natural gas and 1 kboe of oil exports, and only 46 kboe were designated as domestic consumption

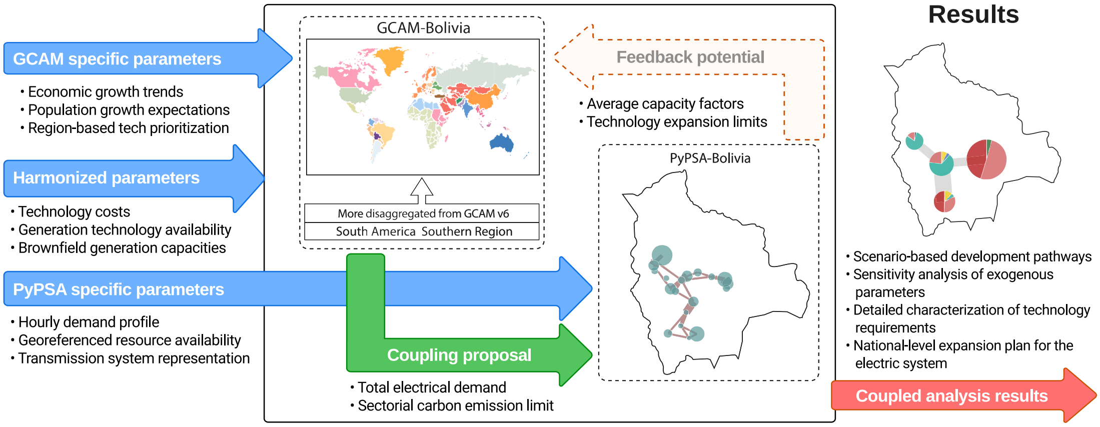


Fig. 4. GCAM-Bolivia and PyPSA-BO integration general framework.

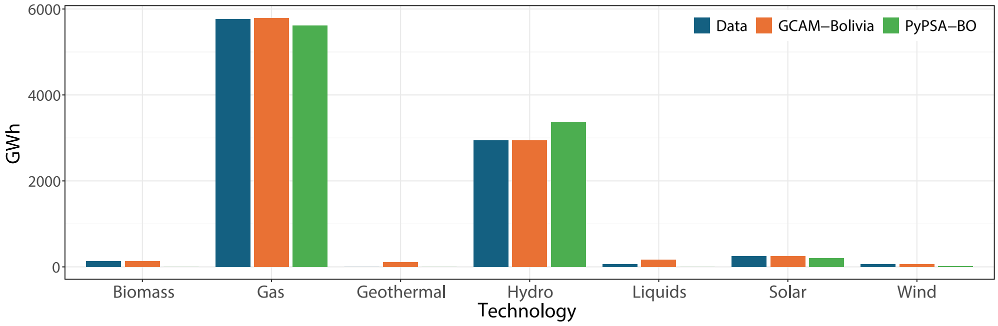


Fig. 5. Comparison between historical power generation and the results of GCAM-Bolivia and PyPSA-BO after calibration for the year 2020.

(including refineries' self-consumption and fuels transport losses) based on its National Energy Balance (NEB) [94]. This domestic consumption is highly dependent on fossil fuels, as in 2020, more than 84% of the total energy consumed was evenly distributed among gasoline, diesel, and natural gas, which are directly used in the transport, industry, and residential sectors. The remaining shares of energy consumption come from biomass (4%), used mostly in the residential sector, and electricity (12% of the total energy demand).

Regarding the national electric system in particular, it can be said that its share in the national consumption is still relatively minor, as the country has a small economy and is not industrialized. In 2020, the electric system was also strongly dominated by fossil technologies, as gas-based thermal units comprise over two-thirds of the total installed capacity (63.3%), with the rest of it being renewable technology, mainly hydropower (32.3%). In 2020, the official installed capacity was reported to be 3.2 GW, and the total electricity generation was estimated to be 9212.3 GWh [81].

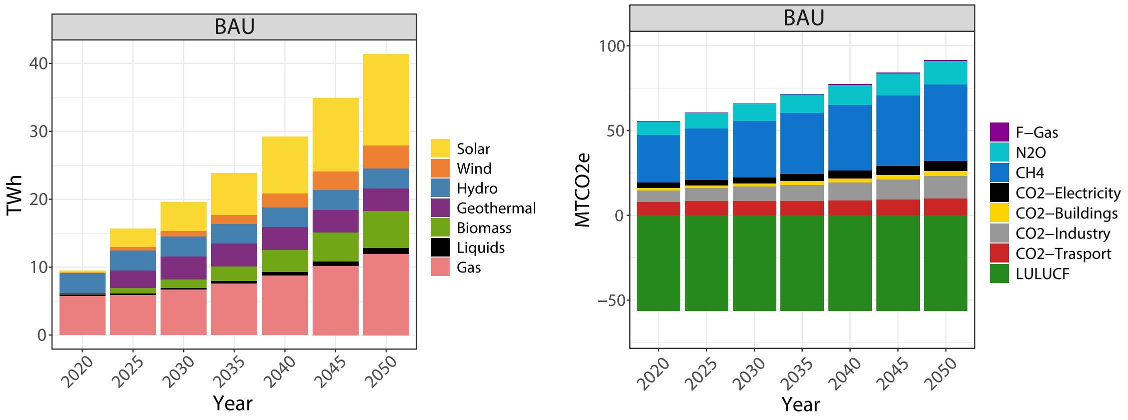
Nevertheless, the current situation of the system has been changing in the last years as, for the electric sector, the government has been making steady efforts to introduce transition goals and include new renewable-based power plants in the generation system, which are consistent with the updated NDC presented in 2022 [95]. 2030's goals aim to increase the total installed capacities of the generation system up to 5 GW, the share of energy produced by renewable technologies to be 79%, and to promote the implementation of new technologies like electric vehicles, hydrogen production, and large-scale storage. Finally, a complementary situation that pushes the transition of the entire system is linked to the depletion of natural gas reserves, accompanied by the drop in the production of fuels registered in its NEB. Therefore, to reduce the need for importation and the country's dependency on fossil fuels, transition scenarios and long-term development plans have also become increasingly relevant due to their strategic value for the economy.

Within this context, an initial calibration of both GCAM-Bolivia and PyPSA-BO is made to simulate the behavior of the system, taking as a reference the year 2020. Investment and operational costs for both models were extracted from [69]. To calibrate the socioeconomic sector in GCAM, data from the National Statistics Institute [96] was used to adjust the population projections from 2020 to 2050, and Bolivia's GDP was adapted based on the percentage increases from the Inter American Development Bank [97].

Fig. 5 shows the calibration outputs from GCAM-Bolivia and PyPSA-BO for the electric sector, compared with the official data for 2020 obtained from [81]. For GCAM-Bolivia, the share weight linked to each electricity sector was modified to match the historical outputs and managed to achieve an aggregated representation with a 2.6% difference for 2020. For the case of PyPSA-BO, calibration was made considering the installed capacities of all generators available in the country [98], the current hourly shape of the energy demand [81], and the distribution of transmission lines [90]. Due to the optimization approach considered in PyPSA-Earth, results tend to diverge slightly more compared to historical data; however, the error threshold for the total generation is still below 5%, and the behavior of different technologies generally matches the registered values.

3.2. Development expectations

Because the majority of Bolivia's national development plans and strategic documents only assume short to mid-term projections, until 2030 [99], a longer-term governmental transition plan is still to be fully determined and made publicly available. As a result, there is a necessity to analyze the development of the Bolivian energy system under alternative conditions, within a bigger time frame, and with more ambitious goals. This is particularly relevant, as projections that consider over 20 years in the future can be used to confirm if measures



(a) (b)

Fig. 6. GCAM-Bolivia stand-alone modeling results for the BAU scenario: (a) Electricity generation by technology from 2020 to 2050 and (b) GHG by Sector from 2020 to 2050.

or advancements made in the short to mid-term would have a relevant impact in the long-term [100]. In this sense, two traditional pathways are envisioned to define the limits within which the future of the system could be located: A Business As Usual (BAU) and a Transition scenario.

For the BAU scenario, the system behaves according to the historical trends and capacity expansion limits for certain generation plants. For hydro power plants, a constant generation and installed capacity equivalent to that in 2020 was assumed for the future. This is due to the big uncertainty regarding water resource availability across the country, social acceptance of new hydro projects in Bolivia, and lack of advancements in the previous development plans of the country regarding large-scale hydro projects in the Amazon River [101]. Similarly, geothermal expansion is limited based on the only study that estimates the available potential registered for Bolivia [102], where the value is expected to be between 600 and 1200 MW. Finally, biomass potential is also limited to 1700 MW for this study, based on the expected growth of agricultural wastes estimated in 2020 that can be used for power generation [103].

The Transition scenario implements a CO2-zero target by 2050 aiming to decarbonize the end-use sectors, namely transport, industry, and buildings, as CH4 and N2O emissions linked to food and agriculture cannot be easily abated. This scenario is built upon the assumption that Bolivia will abide by its current transition goals for 2030 and continue its transition pathway until 2050, consistent with the current climate agreement the country has signed and presented [95]. Aside from the carbon-neutral target for the energy sector, the same restrictions for the expansion of the power system in the BAU are considered. Finally, no additional goals or implementation plans are considered for the period 2020–2050, allowing the model freedom to optimize the system without any particular requirement on capacity or generation shares to be covered by generation technologies.

4. Results

This section presents the modeling results for the BAU and Transition scenarios when these are run in GCAM-Bolivia or PyPSA-BO in isolation, as well as the analysis considering the coupled approach.

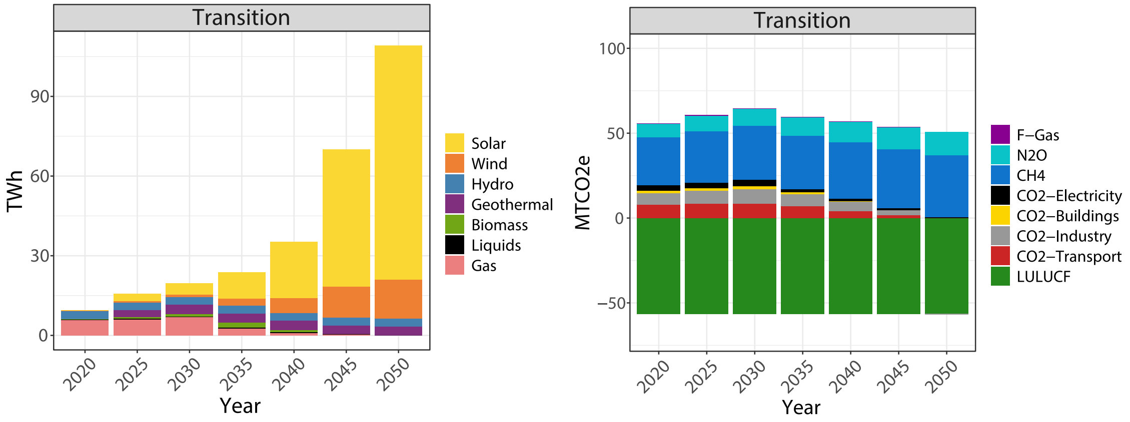
4.1. IAM modeling results

Results of the analysis with GCAM-Bolivia, Fig. 6(a), show a significant increase in electricity demand, nearly quadrupling the referential value from 2020. According to these results, by 2050, the proportional dependency on fossil fuels in the power system should be reversed, as gas shares become close to a third of the generation and renewable generation is deployed massively to cover the expected demand growth. This growth is explained by the endogenous projection of energy demands done by GCAM, based on the socio-economic parameters considered during the calibration process.

Another relevant output of the model is shown in Fig. 6(b), which presents the composition of Bolivia's GHG emissions in CO2 equivalent units in the BAU scenario. In this case, the majority of emissions correspond to N2O and CH4 emissions, linked to land use change and production sectors such as beef, corn, and dairy, among others, which increase proportionally with population growth. This is of particular interest as current estimates of emissions from other non-energetic sectors are scarce, often disregarded, or not up to date [104]. Regarding CO2 emissions, most of these come from the energy sector, which includes electricity production and direct consumers such as industry, buildings, and transport. In 2020, 34% of the total emissions were estimated to come from the energy sector, increasing to a share of 36% by 2050. Finally, because an official and updated characterization of the Land Use, Land Use Change, and Forestry (LULUCF) sector in Bolivia is not available, the regional estimates from GCAM in 2015 are considered. The value for carbon sequestration capabilities of the country (negative emissions) is also kept constant under the assumption that national goals stated in the latest NDC will prevent and limit deforestation, fires, and land use change [95].

In contrast, the transition scenario assumes a peak CO2 emissions of 22.37 MtCO2e until 2030, following the BAU trend, and a linear reduction to achieve zero CO2 emissions by 2050 across all end-use sectors (transport, industry, buildings). The CO2 emissions targets for all years can be visualized in Fig. 7(b), which impacts electricity generation (see Fig. 7(a)), where renewable energy becomes predominant compared to the BAU scenario, eventually reaching 96% of total generation based on Wind, Solar, Biomass, and Hydro technologies. A comparison of results between the BAU and Transition scenarios in 2050 exemplifies the increase required in the annual generation, where solar generation becomes the most relevant technology for energy production, reaching 88.25 TWh, followed by wind generation, reaching 14.54 TWh.

Finally, Fig. 8 shows how the buildings, industry, and transport sectors change their end-use energy consumption. Here, a generalized electrification process can be seen in the transition scenario, where most of the energy demands are replaced by electricity in comparison with the BAU. Nevertheless, the building sector continues to use biomass for heating at around 29%, and the transport sector starts using hydrogen at a share close to 21%. The industry sector maintains the generalized trend of working with more electricity, keeping a small share of liquids (5.81%) in the mix, which is abated externally (from the energy use sector) with other relations linked to agriculture and production (i.e. production of fertilizers for the agricultural sector), as well as the increase of biomass use in the buildings sector.



(a) (b)

Fig. 7. GCAM-Bolivia stand-alone modeling results for the Transition scenario: (a) Electricity generation by technology from 2020 to 2050 and (b) GHG by Sector from 2020 to 2050.

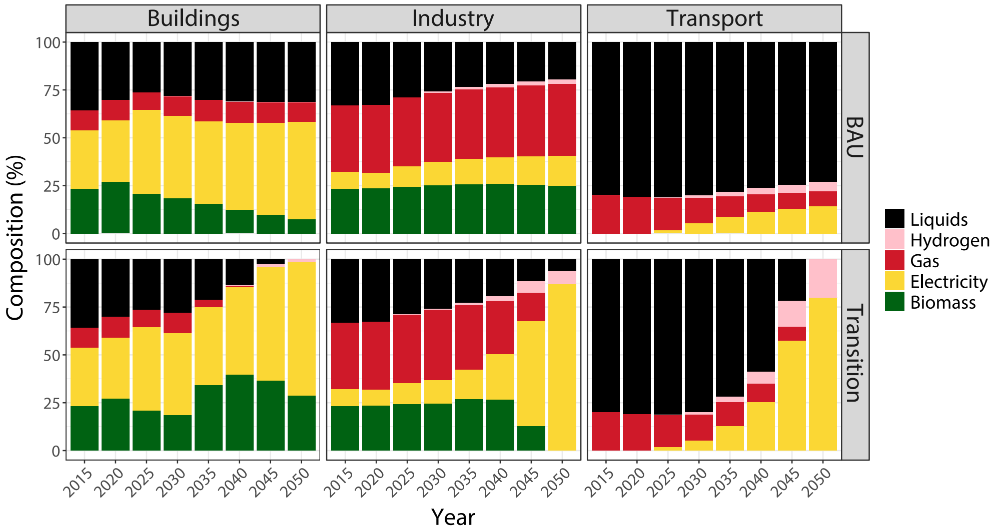


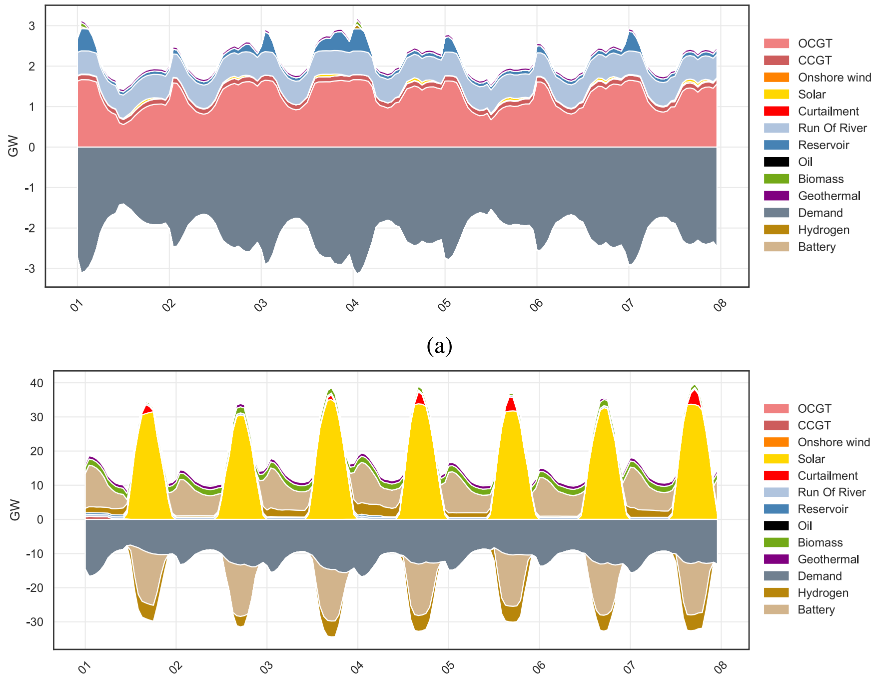
Fig. 8. Technology composition in the building, industry, and transportation sectors for BAU and Transition scenario from 2015 to 2050 according to GCAM-Bolivia stand-alone run.

4.2. PSOM modeling results

PyPSA-BO provides additional technical details on the power system by considering more components (generators, lines, and substations) and their geospatial distribution, with brownfield expansions. While these characteristics are considered in more detail compared to GCAM-Bolivia, the expansion analysis will be completely dependent on the scenario definition and the values considered for it. To provide a baseline for the type of results that the stand-alone model can produce, the main exogenous variables for scenario development in the model (expected demand and carbon budget for the electric sector) are extracted from [69]. From this study, the demand growth from the Business-as-Usual (BAU) and Carbon Neutrality scenarios is extracted, considering 20.26 TWh and 108.52 TWh, respectively, and only a carbon emission limit of 1.8 MtCO2e in the Carbon Neutrality scenario, as the BAU does not consider an emission limit (not formally defined in national policies [95]). These values are then used alongside the characteristics presented in the case study section to create the BAU and Transition scenarios.

Results from Fig. 9 show the effects that the aforementioned variables would have on the expansion of the electrical system in Bolivia according to PyPSA-BO. In a BAU scenario (Fig. 9(a)), the system is kept in a similar condition as it currently is, where thermal units compose over 2/3 of the energy generation and hydro units cover the rest of the demand. The main reason for this is related to the mild increase in demand growth (compared to results from GCAM), based only on the population growth trend. Additionally, even though several plants are expected to be decommissioned by 2050, due to the low (subsidized) price of natural gas in Bolivia and the lack of any emission reduction targets [105], gas-based power plants are still used to cover most of the demand [81].

In contrast, in a Transition scenario (Fig. 9(b)), demand growth is expected to increase significantly as emission budgets are fixed to a specific value. In this case, the system expands almost entirely based on the most cost-effective technology (solar PV), uses as much capacity as possible from other flexible sources (biomass, hydro, and geothermal), and provides the missing flexibility with complementary storage technologies. Aside from the difference in scale in both cases, the appearance of curtailment effects in the system is also noticeable. This is a consequence of the growth of non-flexible renewables in the system and the lack/limitation of cheap alternatives for regulating the system.



(a)

(b)

Fig. 9. PyPSA-BO stand-alone results for the dispatch during the first week of January 2050: (a) BAU scenario (historic demand growth trend and no carbon budget) and (b) Transition scenario (adapted demand growth trend and carbon budget.

4.3. Soft-linking modeling results

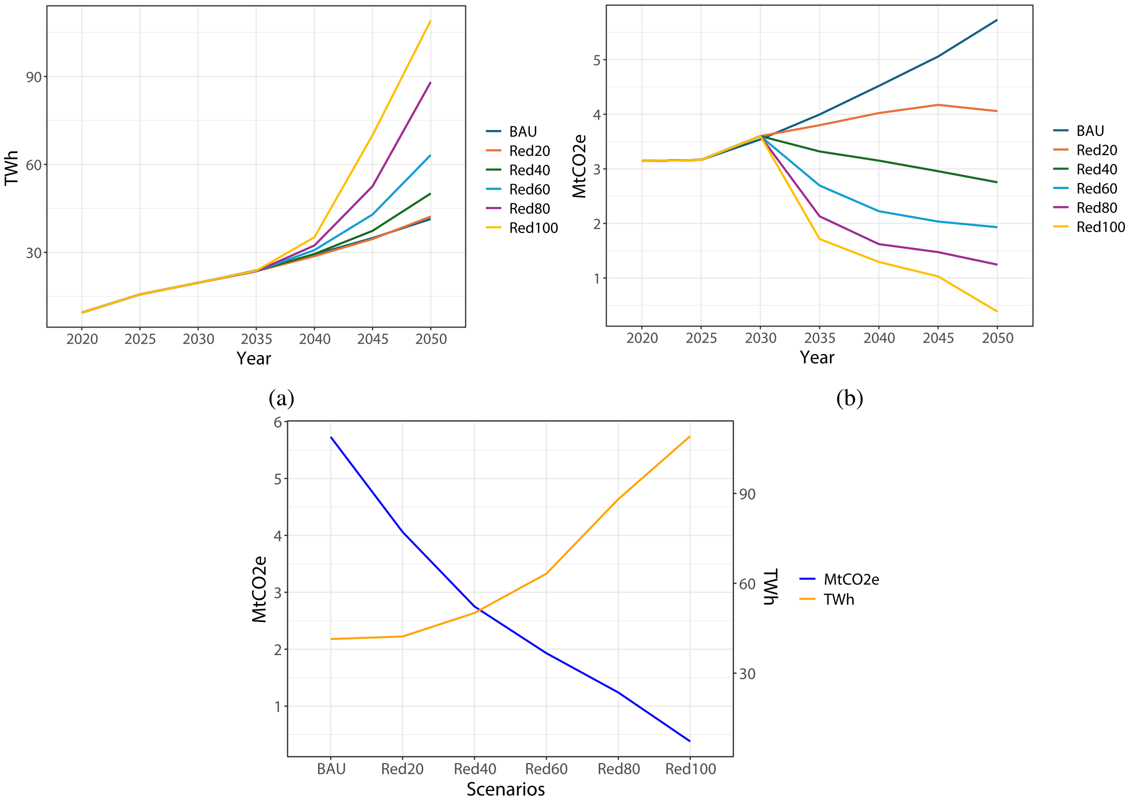
To better exploit the characteristics of the coupled analysis, GCAM-Bolivia is used to run a set of 6 scenarios for the transition analysis: a BAU, where no CO2 emission reductions are expected, and 5 scenarios where incremental reduction targets of 20% compared to the BAU are considered until reaching the zero-emission target (Red20, Red40, Red60, Red80, and Red100) by 2050. In each scenario, emissions targets for each period are set based on a linear reduction from the 2020 historical values until the 2050 emission goal is reached. The scenarios are proposed to reflect different levels of implementation seen in climate action plans, as shown in Fig. 10, where alternative emission targets are explored, making the scenarios practical and relevant for real-world policy, and representing a progressive, manageable energy transition [106]. In these scenarios, emission reduction targets are defined for the entire energy sector, but only data related to the electric sector is considered and extracted for its inclusion in PyPSA-BO. Particularly, the emission budget designated for the electrical sector (Fig. 10(b)) and the expected total electrical demand (Fig. 10(a)).

Results for the year 2050 of each scenario are then introduced into PyPSA-BO to evaluate the cost-optimal expansion of the power system (final electrical demands and carbon budgets for the electric sector, shown in Fig. 10(c)). The total electrical demand estimated by GCAM is used to scale up the country's current load curve, based on historical data [91], and this value is then distributed in the nodes considered in the PyPSA-BO's model using the country's population density and GDP distribution maps, and the surface area considered for each node. The electric system carbon budget is directly introduced into the model as an additional global constraint for the optimization process. After running the entire workflow and the power system's expansion optimization is complete, results are ready for exploration (additional details on each of the steps considered in the workflow can be found at PyPSA-Earth's documentation webpage [107]). Some of these results are represented in Fig. 11, where the generation and demand profiles for the first week of 2050 are displayed for each scenario.

In the BAU scenario defined with inputs from GCAM-Bolivia (Fig. 11(a)), the electrical demand growth for the country has a significantly bigger increase as compared with the BAU from the PyPSA stand-alone run (Fig. 9a). This is a result of the indirect integration of GCAM assumptions for expansion analysis, which considers the influence of both the population growth and the expected GDP of the country for the definition of energy demands, as previously shown in Eq. (1). Additionally, while the usage of fossil fuel plants is not limited for the energy sector in this case (Fig. 11(a)), emissions are defined by the historical growth trend and constant participation shares of all emitting subsectors considered in GCAM (industry, transport, electricity generation, etc.). Because of this, the expected emission growth rate in the electrical sector (2.7 times higher in 2050 than in 2020) is lower than the electrical energy demand growth rate (5.1 times higher in 2050 than in 2020). As a result, the electrical system is also constrained in PyPSA by the "electrical carbon budget" (which grows at a different rate than the carbon budget for the entire energy sector) that promotes the introduction of renewable technologies such as Solar and Biomass.

When smaller reduction targets are included in the model (20% and 40% reductions, corresponding to scenarios Red20 and Red40 in Fig. 11), budgets still allow the use of thermal units. However, their usage is mostly relegated to provide flexibility in the system as other technologies start to cover most of the base-load. Nevertheless, while this effect is noticeable, demand growth rates for electricity consumption are still minor compared to the coupled BAU scenario. In both cases, the system starts to provide more attention to Solar as the main generation technology, and as a result of its lower flexibility, the inclusion of storage capacities becomes necessary. As emission reduction targets for the entire energy system become even more ambitious, the effects on the electrical system are more severe, as both the electric-specific emission budgets reduce and demand growth increases.

Scenario Red60 marks the inflection point where the system becomes predominantly solar-based, and storage becomes pivotal for the expansion of the electrical system, as thermal units are no longer available due to the constraint on emissions, hydro power capacity



(a)

(b)

(c)

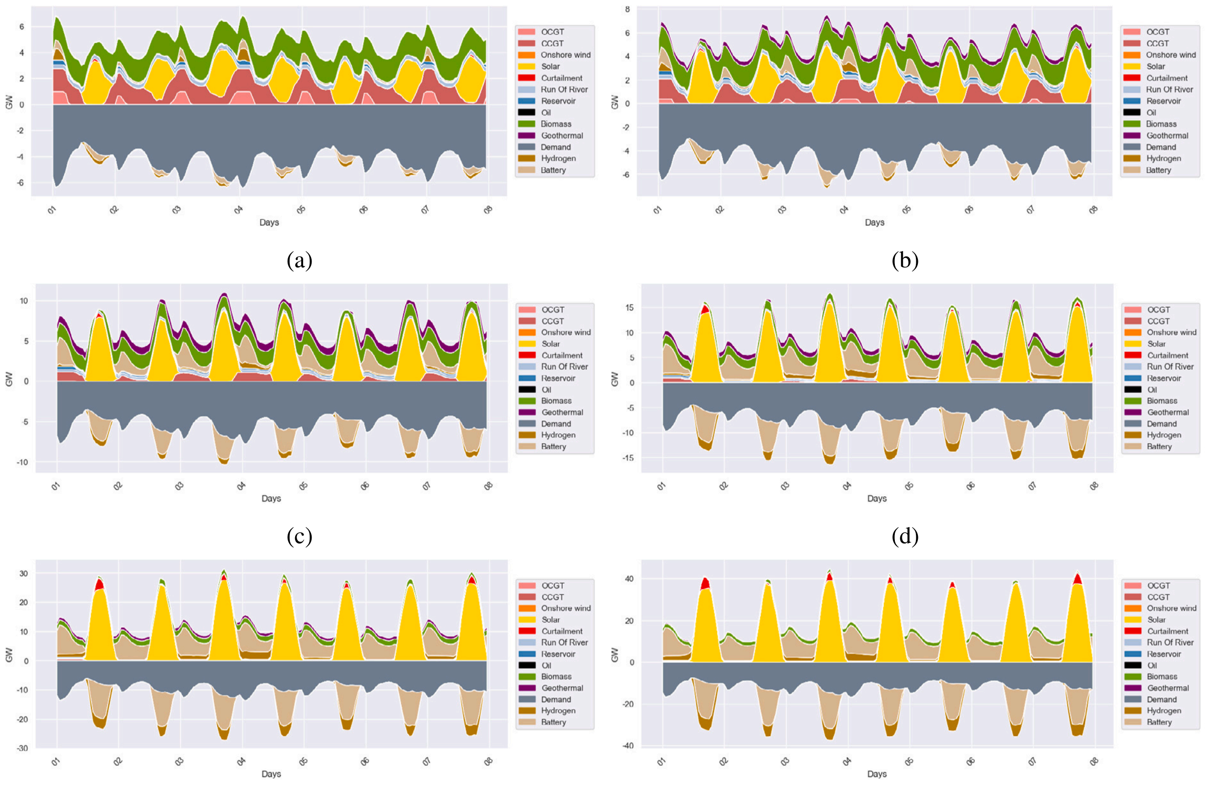
Fig. 10. Scenario comparison of the evolution of the electric sector according to GCAM-Bolivia: (a) Electrical demand growth from 2020 to 2050, (b) Power generation emission budget from 2020 to 2050, and (c) Changes in electricity demand and electric emission budget in 2050 under different emission reduction targets scenarios.

becomes negligible compared to the overall size of the system, and biomass and geothermal expansion potentials are saturated. Finally, scenario Red100 represents the most extreme case, where the emission budget for the electrical sector would become marginal, and the demand would increase the most due to the electrification needs of transport, buildings, and industry.

Fig. 12 presents the spatial distribution of installed capacities (both for generation and storage requirements) expected in 2050, considering 22 nodes for Bolivia for the Red40 scenario, the threshold point before electrification is kick-started. The analysis of this spatial configuration for the power system serves to obtain 3 takeaways: First, the electric system is sensitive to the distribution of solar resources in the country, focusing on the expansion of PV systems in the south-western part of the country, where higher irradiation is observed [108]. Similarly, due to the lower availability of wind resources in the country, the expansion of this technology is limited and relegated to the oriental part of the country; Second, the massive expansion of solar PV will only be possible if a parallel deployment is done for storage technologies to provide flexibility. This expansion of storage considers utility-scale batteries for the short-term regulation of the power system, with 6 h storage capacity [109] and hydrogen-based storage systems for the mid-term, composed of electrolyzers for hydrogen production, fuel cells for electricity generation, and underground reservoirs with storage capacities up to 168 h (assuming that depleted gas fields could be used for storage and technical implementation is possible) [110]; Third, the expansion of the transmission system will be focused on lines in the northern part of the country, which will require additional capacities, to allow an adequate flow of power among nodes that cannot regulate their generation locally (with the usage of storage technologies).

Regarding the current transmission capacity in the system, the average capacity according to the lines inventory is 134 MW per line, estimated based on voltages for each transmission line [111], and their corresponding nominal currents according to PyPSA's predefined line types [112]. Considering 22 nodes, the model assumes an average nominal capacity in the lines of 534 MW and a total added capacity of 14.82 GW across 28 lines considered in the system (after aggregation due to clusterization). Independent of the scenario, results show that major changes would be required for the electrical system as the demand is expected to increase significantly. For the Red40 scenario, the transmission system is expected to require an expansion close to 50% of the current capacity, with 4 major lines being expanded in the northern region (with transmission capacities required between 900 and 1200 MW). While this expansion is significant, it is relatively small in comparison to the generation capacities, thanks to the expansion of storage systems in each node. Results would follow a similar trend for the BAU and Red20 scenarios, as the growth of demand and carbon emission budgets would not drastically affect the expansion of the system. However, the Red60, Red80, and Red100 scenarios, due to the exponential growth in solar PV, would require a proportional expansion in the transmission system, tripling the current transmission capacities in the most extreme case.

Regarding installed capacities, the Red40 expects a total installed generation capacity of 17.7 GW (for a peak load of 8GW) and a total of 45 GWh energy storage capacity for regulation. These values also present an intermediate scenario as installed capacities fall between 10 GW and 64 GW expected for the BAU and Red100 scenarios, to cover peak loads between 6 GW and 18 GW, respectively. Similarly, the storage capacities in the system are expected to be between 17GWh and 352GWh in the BAU and Red100 scenarios, respectively, which are comparable to 15% and 118% of the average daily energy consumption.

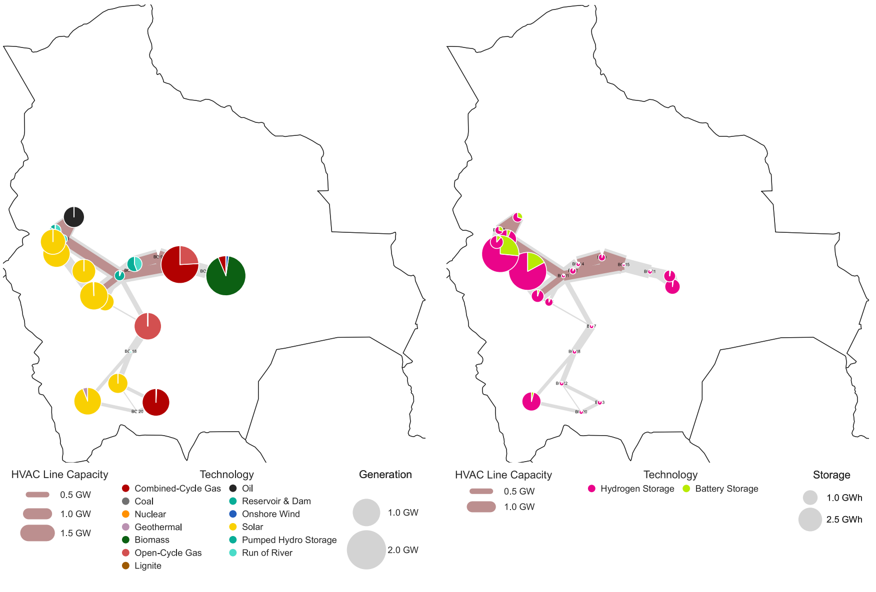


(a) (b)

(c) (d)

(e) (f)

Fig. 11. Hourly electricity dispatch by technology for the first week of 2050 according to PyPSA-BO based on GCAM-Bolivia scenarios: (a) BAU (no carbon budget), (b) Red20 (20% emissions reduction), (c) Red40 (40% emissions reduction), (d) Red60 (60% emissions reduction), (e) Red80 (80% emissions reduction) and (f) Red100 (100% emissions reduction).



(a) (b)

Fig. 12. Installed capacity and transmission expansion distribution by technology in 2050 for the Red40 scenario according to PyPSA-BO: (a) Generation capacity and (b) Storage capacity.

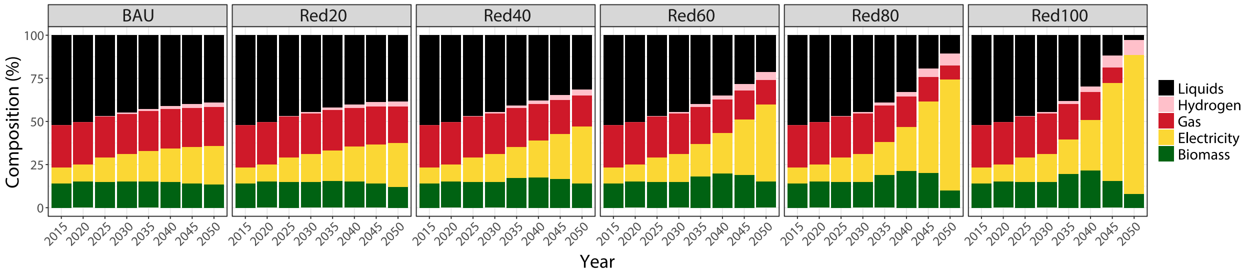


Fig. 13. Evolution of the fuel usage composition in the energy system (electric supply, building, industry, and transport) for each scenario from 2015 to 2050.

5. Discussion

Based on the outputs from the modeling exercise, this section provides a summary of the main findings and takeaways from their comparison and interpretation, as well as stating key divergences between models, limitations, and future work.

5.1. *The role of exogenous assumptions in coupled IAM–PSOM outcomes*

Results from the stand-alone runs of GCAM-Bolivia and PyPSA-BO highlight both the strengths and structural limitations of each modeling framework. GCAM-Bolivia represents the energy transition as a system-wide reallocation of energy vectors, in which fossil fuels are progressively displaced by electricity, hydrogen, and biofuels in response to economy-wide emission constraints. This structure enables the model to capture cross-sectoral interactions and long-term demand evolution, but it necessarily relies on stylized technology representations that may overestimate or underestimate the feasibility of specific options.

By contrast, PyPSA-BO provides a detailed, spatially and temporally resolved representation of the power system, explicitly accounting for hourly dispatch constraints, renewable variability, and storage requirements. When run in isolation, however, the model depends entirely on exogenously specified demand trajectories and emission limits, which are not endogenously linked to broader socio-economic dynamics or non-electric sectors. As a result, expansion pathways can become highly sensitive to subjective scenario assumptions, particularly under deep decarbonization.

The coupled framework illustrates how these limitations can be mitigated by aligning macro-level drivers with system-level feasibility. Demand growth and emission budgets derived from GCAM incorporate the combined effects of population growth, economic development, and sectoral substitution, leading to substantially different expansion outcomes compared to stand-alone PyPSA runs. In particular, higher mitigation ambition translates into both tighter carbon constraints and accelerated electrification, reshaping the relative competitiveness of generation and flexibility technologies even when techno-economic parameters remain unchanged.

These findings underscore that high-resolution power system models are not neutral with respect to scenario framing. When demand growth and emission limits are defined independently of cross-sectoral dynamics, infrastructure needs under ambitious climate targets may be systematically underestimated. The proposed soft-linking approach between IAMs and PSOMs, therefore, provides a more internally consistent framework for the representation of transition pathways by ensuring that operationally detailed models respond to socio-economic and policy drivers that are determined endogenously at the system level.

5.2. *Insights and implications from the system-level transition dynamics*

One of the main insights from the coupled GCAM–PyPSA analysis is linked to the changes in electrical demand. Results from alternative scenarios reveal a non-linear relationship between economy-wide emission reduction targets and electricity demand growth, indicating that electrification emerges as a dominant mitigation pathway only beyond a certain level of climate ambition. As shown in Fig. 10(c), electricity demand increases moderately under low mitigation scenarios (BAU and Red20), but accelerates sharply once emission reduction targets exceed 40%. This behavior suggests the presence of a threshold effect rather than a proportional response between mitigation ambition and electrification.

This non-linearity arises from the interaction of two structural mechanisms. First, increasingly stringent emission budgets progressively constrain the direct use of fossil fuels in end-use sectors such as transport, buildings, and industry. Beyond moderate reduction levels, incremental efficiency improvements and intra-sectoral fuel switching become insufficient to meet emission limits, making electrification the primary mitigation option. Second, as the electricity supply itself becomes increasingly decarbonized, electricity becomes both an environmentally and economically attractive substitute for fossil-based energy vectors, reinforcing demand growth through positive feedback. Although a formal statistical validation of this relationship is beyond the scope of this study, the observed pattern indicates that linear assumptions regarding electricity demand growth can underestimate infrastructure needs under deep decarbonization pathways.

To complement this observation, impacts from the implementation of different reduction targets for the energy system are further exemplified in Fig. 13, where the mixes of energy sources used for the entire energy sector are displayed by comparing all 6 scenarios. Here, it can be seen that under the low mitigation ambition scenarios (BAU and Red20), the fuel usage composition shares are relatively stable. However, as the reduction targets become more ambitious (60% or higher), renewable-based electricity (and hydrogen to a smaller degree) starts to displace the use of other energy vectors.

It is also important to note that even in the most extreme scenario, where net emissions for the entire system are set to zero (Red100), trace amounts of emissions in the energy sector are still noticeable, mostly coming from hard-to-abate processes that use fossil fuels, like the industry sector. This outcome highlights that full decarbonization of the energy system is constrained not only by power sector transformation but also by technological and structural limitations in specific end-use applications, and the emission capture capabilities of the land sector.

5.3. *Model divergences, method limitations and future work*

The current linking exercise serves as a first step for presenting the benefits of using two complementary models (GCAM-Bolivia and PyPSA-BO), which provide an additional layer of robustness to the study of expansion scenarios. However, it also showcases the discrepancies between results from each model. In this sense, by exploring where their perspectives converge and diverge (something essential for

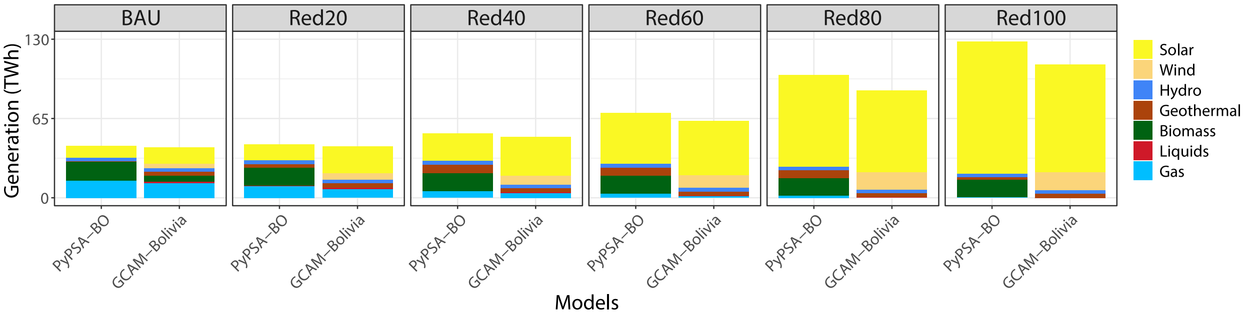


Fig. 14. Energy dispatch by technology for 2050 scenarios according to PyPSA-BO and GCAM-Bolivia.

designing meaningful information exchange between models) potential feedback loops (as indicated in Fig. 4) are defined, which can allow the refinement of both models in the future.

Despite this, it is important to acknowledge that the main limitation of this study is linked to the focus on the energy system, as data availability and quality remain a constraint for non-energy sectors. Particularly, inputs in GCAM for the economy, climate, water, and land sectors assume the predefined conditions of the larger regions that include the country, instead of considering country-specific data. While adequate, the use of these more generic values can have a relevant influence on the results obtained, as the growth trends for energy demands and the availability of resources and emission budgets for the country would be based on regional averages. Future work should focus on expanding the level of detail and country-specific information included for each of the relevant sectors in the GCAM-Bolivia model.

Regarding model discrepancies, a comparison of the total electrical energy produced in the system in 2050 (Fig. 14) shows that the behavior of the energy system is mostly consistent, as total energy production covers the expected electrical demands in the system, and hydro, gas, and oil power plants behave similarly in all scenarios. This is also consistent with the general logic for the optimization and equilibrium models, as both would aim to make the most out of the limited amount of hydro due to its higher availability while limiting the usage of polluting technologies such as gas and oil. Nevertheless, despite this alignment, yearly energy outputs present differences (up to 18% in 2050), as higher amounts are registered in PyPSA-BO results. This difference is attributed to the model considering efficiency losses for storing and dispatching energy from storage technologies to provide energy during hours with no solar radiation and where other technologies cannot provide the total power demanded. Because of the structure and resolution of GCAM-Bolivia, this effect cannot be tackled directly as storage is not an expandable technology. For GCAM-Bolivia to consider this effect, some changes can be made to the characterization of non-flexible technologies, e.g., increasing their costs to include the storage component internally or reducing their dispatchability based on the expected curtailment.

Another relevant difference is the use of wind resources, which are expected to grow significantly according to GCAM, in contrast to PyPSA, which estimates only a marginal growth for the technology. This effect results from GCAM considering a prioritization parameter, the logit function presented in Eq. (2), which affects the share of technologies considered in the generation mix based on regional trends, in addition to cost differences, and prevents the cheapest or the most profitable technology from capturing total market share. PyPSA-BO, by contrast, selects technologies strictly based on system-wide cost minimization subject to operational constraints and resource availability. Rather than representing an inconsistency, this difference highlights how alternative modeling assumptions encode distinct interpretations of technology diffusion and policy influence.

In this sense, while the definition of shares of technologies considered could be extracted and introduced from one model into the other with minor adjustments, defining which should be the one providing inputs should be guided by the analytical objective of each study. A cost-focused analysis should consider PyPSA-BO as the one defining the shares, as its optimization approach would provide the most cost-effective generation mix. On the other hand, a case aiming to adopt international or political trends could consider GCAM-Bolivia as the one defining the shares, as these objectives and their impacts can be directly included in the model. In either case, a careful calibration is required to avoid unrealistic outcomes, such as the deployment of technologies that are economically, institutionally, or politically infeasible in the national context (e.g., nuclear power in Bolivia).

Finally, future work should explore the process of defining additional relevant variables, and the path for information exchange between tools (bidirectional linking of the models), allowing operational constraints identified at the power system level to inform long-term demand and technology trajectories. In these cases, the feedback process would require additional calibration based on iterative runs, which can be highly sensitive to the definition and convergence of the variables/parameters exchanged. A good example of this effect is represented by the behavior of biomass generation, where PyPSA-BO makes use of the entire biomass potential, and GCAM-Bolivia tends to reduce its usage as reduction targets are more ambitious.

This is explained because PyPSA considers that the potential usage of biomass, defined based on biomass waste from the sugar-cane industry, will be available only for the electric system. In addition, costs linked to this technology are defined exogenously and assume a null fixed price for its fuel (as power plants are located in the same place as agricultural wastes are produced). In the case of GCAM, these two conditions are inherently different as biomass usage is affected by additional relations nested within its cross-sectoral framework. Regarding prices, the model estimates the quantity and price of waste-biomass endogenously (based on the characterization of the Land/Agriculture module of the model). This effect, and considering non-electric energy demands from other sectors, creates competition for the biomass wastes, which tends to favor other non-electric uses, therefore, providing different amounts for PyPSA and GCAM. Future work is expected to consider these types of structural differences to reduce the discrepancies of overlapping results.

5.4. Transferability beyond the Bolivian case

Looking beyond the Bolivian case, the transition dynamics identified for Bolivia are consistent with findings from system-level energy transition studies conducted in other developing regions. Integrated assessment and power system analyses for countries in Latin America (such as Chile [32], Argentina [34], or Colombia [113]), Africa (like Botswana [114] or Cameroon [115]), and Asia (such as India [116] or Vietnam [117]), show that increasingly ambitious climate targets (e.g. net zero emissions) lead to accelerated electrification of end-use sectors, a growing reliance on renewable electricity, fuel switching to clean energy carriers, and (with varying levels of requirements) the need for carbon capture or carbon sinks to compensate hard-to-abate emissions from the energy sector.

These dynamics reflect the structural role of electrification as a system's response, and a dominant mitigation pathway, once economy-wide emission constraints become sufficiently stringent. As a result, to represent the impact of these constraints in the electric system evolution, a more holistic view of the energy system is required, as non-electric sectors would become electrified, increasing the history-based demand growth expectation significantly. In this sense, the coupled modeling framework is particularly valuable for capturing cross-sectoral interactions that may be overlooked when electricity demand trajectories are defined independently of economy-wide climate constraints or based on historic trends.

At the same time, empirical evidence highlights that the relationship between electricity consumption and emissions is highly context-dependent, with electrification contributing to emissions reductions only when supported by a sufficiently clean power mix [118]. This is particularly relevant in emerging economies such as India, where historical increases in electricity consumption have been associated with higher emissions, compared to other BRICS countries, which can be continued in the absence of deep power-sector decarbonization measures [119]. Nevertheless, it is important to also highlight that the Bolivian case exhibits distinctive features that shape its transition pathway. The presence of significant hydropower capacity provides a degree of inherent system flexibility not available in other contexts, while subsidized natural gas prices delay the economic displacement of thermal generation under low mitigation ambition. Moreover, Bolivia's isolated power system limits opportunities for regional balancing through cross-border trade, amplifying the importance of domestic storage and transmission expansion, as shown in Fig. 12.

These findings suggest that while the non-linear relationship between mitigation ambition and electrification observed in the Bolivian case is likely relevant for other developing and emerging economies with similar conditions, quantitative outcomes remain highly sensitive to national resource availabilities, power-system structure, and institutional conditions, limiting direct transferability without country-specific calibration. As such, Bolivia should be viewed as a representative but not universal case for energy transitions in the Global South and developing economies. Future work should focus on statistically validating the non-linear relation between electrification and mitigation targets, their sensitivity to strategic technical conditions, and analyzing how the identified mitigation threshold (emission reduction targets over 40%) and the relation emissions-electrification would behave in other countries.

Regarding the application of the proposed soft-linking method, while capable of providing more robust scenarios and capacity expansion results, it is also somewhat limited to the availability of both an IAM and a PSOM already calibrated for the particular case study. While the proposed models (GCAM and PyPSA) represent potential applicable alternatives for the development of these models for each potential country (due to their open-source nature), it is important to acknowledge that the adaptation of the models for the country-specific conditions, the parametrization of inputs, and calibration of outputs are stages that require a representative amount of time and effort from technical personnel. On the other hand, independently of the models selected, it is also important to acknowledge that the application of similar frameworks and model adaptations can encounter some technical barriers. Specifically, it has been identified that the structures of both Integrated Assessment Models and Energy System Models tend to vary significantly and that, to facilitate information exchange, additional pre- and post-processing stages are required so that the selected models can interact properly [65].

As a result, only a few examples exist in recent literature that have tried to couple IAM and PSOM models. Coincidentally, two of the most recent examples consider Germany as their case study and make use of already available region or country-specific versions of the models. In the first case, DIETER (PSOM) is used to capture the dispatch in the electric system [67], and in the second case, PyPSA-Eur (PSOM) is used to represent the country's power system behavior [120]. In both cases, REMIND (IAM) is used to capture macroscale energy-economy-climate interactions, and the linking is conducted by the exchange of information focused on demand growth trends and costs of the electric system. As one could expect, most of the rest of linking applications have been done in developed countries, as these countries have a higher amount of curated models and experienced modelers, which can cover the requirements for cross-model linking exercises.

Nevertheless, similar examples of soft-linking exercises can also be seen in developing countries, albeit where the coupling is made between different types of models. Some examples include the case of Vietnam, which uses custom dispatch and capacity expansion models (ESMs) [121]; Chile, where GCAM (IAM) and H2RES (ESM) are used [93]; Colombia, which uses two ESMs (TIMES for capacity expansion and Powerplan for dispatch simulation) [122]; Brazil, which coupled MESSAGE (IAM) with TIMES and REMIX (ESMs) [123]; or Bolivia, which coupled two ESMs (OSeMOSYS for capacity expansion and DispaSet for dispatch analysis) [69]. These experiences make the case for the feasibility of replicability and transferability of the methodology to other countries, and show that its application is mostly dependent on the development and adaptation of the specific type of models (IAMs and PSOMs) for the country under analysis.

6. Conclusions

This study introduces GCAM-Bolivia, a version of the Global Change Analysis Model tailored specifically for the country's energy sector, which analyzes Bolivia's energy landscape considering carbon limitations. The model underwent a calibration process for the energy system representation using data from local sources, aligning its predictions closely with real-world data from 2020. GCAM-Bolivia opens avenues for further research, offering insights into different transition scenarios for Bolivia that consider the interrelations between neighboring systems (socioeconomic, land, climate, and water) and their effects among them. The study also makes use of PyPSA-BO, a power system model based on PyPSA-Earth, tailored for the Bolivian case to represent its electric system with a higher spatial and temporal resolution, allowing for a more detailed assessment of infrastructure expansion and operational feasibility.

A review of the general structure and outputs of both models facilitates the identification of specific strengths, limitations, and synergies between them. In this context, it can be stated that GCAM-Bolivia can provide a rough understanding of the development of the energy system from a holistic point of view, while PyPSA-BO can represent the Bolivian power system, its components, and its development in the future with substantially higher technical detail. While each of these approaches provides relevant insights into the transition of energy systems, differences in model scope, resolution, and parameter representation imply that results from each tool must be interpreted within their respective domains. Based on this characterization, a methodological proposal for exploiting synergies between tools is made to provide a robust analysis framework for exploring different development pathways towards mid-century carbon neutrality scenarios, tested for the Bolivian case.

More generally, this approach illustrates how soft-linking integrated assessment models and power system optimization models can help bridge long-term climate objectives with short-term infrastructure feasibility at the national scale. For the proposed linking framework, the flow of information between the two models is defined based on the type of inputs and outputs they can provide, where overlapping parameters create opportunities for data flow, while non-overlapping parameters explicitly delimit boundaries for the coupling approach (where one tool can be used to provide detailed contextual information to the other).

For this study, the method considers a unidirectional soft-linking used to analyze 6 development scenarios (BAU, Red20, Red40, Red60, Red80, and Red100) defined by different emission reduction targets for the energy sector, followed by a detailed characterization of the electric system expansion, identified as the central driver for the transition of the energy systems. GCAM-Bolivia is used to estimate the energy demand growth considering economic and social trends for the country (GDP and population), to quantify the electrification rates under alternative emission reduction targets, and to allocate a specific carbon budget for each subsector in the energy system. This information is then integrated into PyPSA-BO to explore the optimized expansion of the electrical system for 2050, including hourly dispatch behavior, spatial distribution of installed capacities, and transmission and storage reinforcement requirements. As a result, this approach allows for a consistent unidirectional translation of long-term climate targets into operational electric system configurations.

Regarding policy implications from the scenario analysis, scenarios BAU, Red20, and Red40 represent cases where the development will require significant but feasible changes compared to the current size of the system, mainly driven by its growth trends. For the electric system, this entails expanding and transitioning the generation mix towards a more renewable composition (mainly solar and biomass), increasing the transmission system, and introducing storage technologies for regulating the dispatch. More ambitious scenarios (Red60, Red80, and Red100) are expected to have much more disruptive effects as the system kick-starts a massive electrification process to comply with emission reduction goals. In these cases, previously non-electric energy demands shift to emission-free sources, mainly covered by renewable electricity, leading to systems with a strong dependence on solar generation to meet the increasing energy demands and comply with low-emission targets. Results from intermediate scenarios further reveal a non-linear relationship between emission reduction targets and electrification levels, highlighting the importance of considering cross-sectoral interactions when assessing long-term energy system transitions.

Depending on the scenario, changes for the electric system can vary widely: power generation growth ranges between 10 to 65 GW, transmission expansion from 40% to 300%, and storage capacities from 22 to 417 GWh (BAU and Red100 scenarios). Taken together, and comparing the electric system growth to emission reduction targets of each scenario, results suggest that the relationship between mitigation ambition and electrification follows a non-linear pattern, indicating that planning approaches based on incremental or proportional demand growth assumptions may substantially underestimate future infrastructure and flexibility requirements once emission reduction targets exceed certain thresholds. While this behavior could be expected in other developing countries with similar conditions, the quantitative value of the mitigation threshold should be estimated for each country in particular (a 40% emission reduction target for the Bolivian case).

From a Bolivian perspective, the linking exercise also provides policy-relevant insights into the transition process of the country. These include the imperative to electrify end-use sectors to reduce fossil fuel dependency while increasing demand for low-carbon electricity to achieve ambitious mitigation targets; the relevance of the LULUCF to cover/compensate trace emissions expected in the hard-to-electrify sectors, highlighting the need for integrated policies that take into account emission policies at a country level and transversally across different sectors; and the grid expansion requirements to facilitate the power flow across the country, which can be mitigated by incorporating storage technologies. Together, these insights illustrate how the linking proposal translates long-term climate objectives into concrete infrastructure and planning challenges at the national level.

Finally, while the coupled analysis presented in this work is based on an unidirectional linking between GCAM-Bolivia and PyPSA-BO, it is important to highlight the need for further methodological development. In the current framework, the impact of IAM exclusive parameters over the PSOM is limited to only explicitly overlapping parameters (electrical Demand growths and Carbon budgets). Further work is needed in three main areas: (1) To explore how additional and not directly linked IAM-based parameters could be included or represented within the ESM framework (i.e. water resources availability, land usage restrictions, or forestry carbon capture capacities). (2) To explore the feedback process from PyPSA-BO to GCAM-Bolivia to close the linking process and improve the capabilities of both tools in parallel with a bidirectional flow of information and possible convergence criteria. (3) To validate the application of the soft-linking framework and the insights taken for the particular case of Bolivia with other relevant cases, particularly developing countries in the Global South.

CRediT authorship contribution statement

Carlos A.A. Fernandez Vazquez: Conceptualization, Methodology, Software, Visualization, Data curation, Formal analysis, Investigation, Writing – original draft. **Francisco Flores:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft. **Ray A. Rojas Candia:** Validation, Writing – original draft. **Julio Pascual:** Validation, Writing – original draft. **Felipe Feijoo:** Methodology, Software, Supervision, Funding acquisition, Writing – original draft. **Sylvain Quoilin:** Methodology, Software, Supervision, Funding acquisition, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sylvain Quoilin reports financial support was provided by Academy of Research and Higher Education (ARES). Felipe Feijoo reports financial support was provided by National Agency for Research and Development (ANID). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data and code used for the power system modeling of this paper are openly available at the PyPSA-BO GitHub repository (https://github.com/CIE-UMSS/PyPSA-BO), currently maintained by the Centro Universitario de Investigaciones en Energia (CUIE). The specific version used can be found under the release tag “GCAM_PyPSA_2025”.

Data and code used for creating and running GCAM-BO can be found at the Zenodo repository (https://zenodo.org/records/15750728). GCAM version 6.0 is required for creating the country-specific version of the model.

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