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Using PyPSA-Earth to address energy systems modelling gaps in developing countries. A case study for Bolivia

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Abstract:

Bolivia is a developing country in South America which is slowly starting its energy transition towards more renewable technologies. However, at this moment, Institutions in charge of regulating, operating, and planning the development of the sector are still working with "black box" (or licensed) models, which are costly and less transparent, and are highly dependent on external expertise to formulate national plans. A proper transition will arguably require endogenous know-how and resources to be sustainable, affordable, and sovereign for the country.
In this context, open-source energy models are increasingly used in Bolivia, mostly by academic and non-profit institutions. These are used to study alternative development scenarios, quantify environmental impacts and/or define potential techno-economic requirements.
Previous works have focused on the development of dispatch models that analyse the stability and operation over short-terms and on energy-balance models to study impacts over long-term scenarios. However, while operation and planning aspects are somewhat covered independently, the combination of both is still missing (i.e. high time and spatial resolution and long-term horizon perspectives).
To bridge this gap the PyPSA-Earth model was identified and used to derive a model specific for the Bolivian context using a dedicated workflow. The model is adapted to run and provide country-specific outputs regarding generation capacities, grid expansion and sector-specific demands, which are later compared with historical information to assess its accuracy and capabilities.
Modelling results provide inputs regarding the characteristics of the tool and quantify deviations of its outputs compared to the Bolivian system in 2020. Based on these, it is concluded that the flexibility of the model, combined with its transparent structure, show great potential for implementation.

Keywords:

Energy modelling; Open-source; Bolivia; Energy systems; PyPSA-Earth; Developing countries.

1. Introduction

1.1. General context

Energy modelling has been an extensively researched topic for several decades, particularly in the context of studying energy systems and their components, such as power generation systems, dispatch mechanisms, demand analysis, coverage, and operational capacities at the transmission and distribution levels. Because of this, a diverse range of models can be found in the literature and, depending on the study's focus, models can be classified based in several ways. The paradigm of data utilization, the solving approach, the spatial-scale, and the time-frame studied, among others, are examples of what this classification can be based on [1].

Nevertheless, even among different taxonomies, overarching objectives in energy modelling include enhancing the energy system's characteristics, supporting design and planning efforts, improving the understanding of system components and their interactions, and examining the relationships between various critical aspects. These aspects are mostly related to technology availability, cost reductions, environmental impacts, social factors, and policy implementation [2].

Over time, modelling tools have proliferated and evolved, primarily in industrialized/developed countries, where they were developed to address specific behavioural conditions and technical/operational characteristics. However, these models are subject to significant limitations when applied to developing countries, as they assume high standards of system operation, exhibit inflexibility in the parameters/factors considered, and may

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assume data availability, all of which often conflict with the reality of developing countries [3]. Furthermore, these tools were initially developed as closed and proprietary systems by large institutions, which had no obligation or incentive to make their tools publicly available. Consequently, there is a growing need for more open, flexible, transparent, and accessible modelling tools [4].

In the case of Latin America & the Caribbean, a region comprised mostly by developing countries, modelling requirements are driven by the region's characteristics [5]:

- a rapidly increasing energy demand;
- a strong correlation between energy consumption and economic growth;
- highly variable energy intensity consumption;
- increasing energy production costs;
- increasing penetration of non-flexible renewable powerplants;
- large heterogeneity in power systems across neighboring countries;
- the need to achieve universal access;
- improve networks stability at transmission/distribution level;
- dealing with outdated subsidization policies for fossil fuels.

1.2. Previous work and modelling experience in Bolivia

Although the energy sector has a distinct organizational structure in each country, with clearly defined actors and responsibilities, developing economies often lack the resources (technical, human or economic) to invest in their own capabilities. Bolivia is a prime example of this, as outsourced companies and tools have consistently been used for the formulation of planning efforts and strategic documentation [6], specifically for the electric sector [7]. However, due to the nature of the relation between institutions, most of the information provided is provided solely as results generated through black-box models and, reports that don't provide insights into the tools used.

Experience with energy modelling at the institutions in charge of the sector shows a big reliance on licensed tools, such as:

- SDDP (Stochastic Dual Dynamic Programming), a unit commitment hydrothermal dispatch model [8], developed by the company PSR [9];
- PowerFactory, a power system analysis model developed by DIgSILENT [10], used for studying the transmission network, among other uses [11];
- HOMER (Hybrid Optimization of Multiple Energy Resources), a modelling software owned by UL [12], that is used to design and study small hybrid power systems (isolated communities or microgrids) [13].

From a governmental and institutional perspective, outsourcing institutions for the analysis of the power system, with their own licensed modelling tools, can provide some advantages. For instance, that they can provide fast results and simplified information to decision makers, a highly trained technical team and proven experience. However, this practice has its downsides. First, it does not foster the development of local capacities in the institutions that require them, resulting in an overreliance on external know-how. Second, the costs of contracting external personnel, consulting companies, or acquiring licenses for private software are usually high. Third, planning efforts can only cover short to mid-term periods, as long-term scenarios are not flexible enough to be continuously and consistently adapted [14].

To tackle these problems, which aren't unique for the Bolivian case, an array of new open-source modelling tools have started to appear as efforts from various research institutions [4]. These models, which come on a wide array of alternatives, are currently being used to analyse energy systems across the world and seem to be able to answer some relevant questions linked to the design, operation and planning of the sector [15].

Particularly in Bolivia, open-source modelling tools have been started to be used by researchers to develop case studies for the electrical sector with a wide range of approaches: studying the dispatch capabilities of the interconnected electric system (Dispa-SET) [16]; analysing the electrification process based on grid expansion and microgrids for isolated communities (OnSSET - Open Source Spatial Electrification Tool) [17]; analysing energy demands consumption in rural communities (RAMP – Remote Areas Multi energy load Profiles generator) [18]; the optimization of design of microgrids (MicroGridsPy) [19]; or analysing evolution of investments based on policy implementation and sustainable development scenarios in the long-term (OSeMOSYS - Open Source energy MOdelling SYStem) [20].

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1.3. PyPSA-Earth

PyPSA-Earth, as many other models, has the general objective of exploring the development of energy systems by considering a set of techno-economic components and optimization functions. However, unlike the studies mentioned before, PyPSA-Earth provides a complementary look of the energy system from the power network perspective by analysing power flows in the system [21]. Additionally, the modelling tool can combine a high spatial resolution representation of the network (missing in OSeMOSYS), optimization functions for expansion of the system (missing in Dispa-SET) and focusing simultaneously on generation and grid components (missing from OnSSET) [22]. Additionally, the model's workflow structure is designed based on the PyPSA-Eur model, an open model dataset for the European region and used for operational and transmission expansion studies [23].

Both PyPSA-Eur and PyPSA-Earth are derived from PyPSA (Python for Power System Analysis), an open-source modelling framework tool designed for simulating and optimizing power systems focusing on the physics of the power flows over multiple periods (typically a full year) and optimizing the total system costs given techno-economic characteristics and constraints of its components [24].

PyPSA's structure considers a representation of power systems based on nodes, which correspond to buses or network elements (generators, loads, and transformers), and edges, which represent transmission lines or cables. The network is described using a linear and nonlinear equations, including Kirchhoff's laws, Ohm's law, and the power flow equations. These equations are used, using numerical optimization techniques such as Newton-Raphson or interior-point methods, to obtain the steady-state operating conditions of the system. PyPSA also includes a range of optimization algorithms for capacity expansion planning, unit commitment, and optimal power flow, which are used to optimize the system's economic and environmental performance under different scenarios and constraints [24].

The PyPSA-Earth model (previously PyPSA meets Africa) has been tested for Africa and a country-specific case, achieving close representations of the system compared to information available on international sources such as the World Bank (networks), Open Street Maps (substations and generation), IRENA (renewable resources) and Our World in Data (energy dispatched), among others [22]. In this sense, although the PyPSA-Earth tool has been proven valuable, its potential for implementation is still to be fully exploited due to its novelty and need for validation in other countries and regions. Because of this, and the fact that no open-source models haven't been used to analyse the Bolivian power network, the opportunity of testing a complementary tool for already existing models and efforts is worth being explored.

1.3. Aim of the paper

While the experiences presented are a good first step in addressing the national necessities for understanding and representing Bolivia's energy sector, the models used must be further developed and validated to ensure they can accurately represent national conditions. This, coupled with a continuous process of exploring new complementary tools, could eventually make the country self-sufficient in terms of know-how and analysis capabilities in the long-term.

One particular gap identified in the existing modelling toolkit developed for Bolivia is the lack of a model that focuses on network representation and expansion. Therefore, the present work aims to address this gap by deriving a country-specific model for Bolivia's power network from PyPSA-Earth, a new open-source modelling tool, and analyse its potential for application, explore requirements for guarantying future work, and identify possibilities for further contribution.

2. Methodology and calculations

Given the open-source characteristics of the model information required for running the model for particular cases is available online, in their github repository and their documentation webpage [25]. Using this information and the current version of the model, the following methodology was applied to derive a model for Bolivia based on PyPSA-Earth:

1. Workflow adaptation: The existing workflow framework for PyPSA-Earth was configured so that scripts and parameters are capable of running a "testing" version of the Bolivian case with its corresponding country-specific conditions.
2. Consistency analysis: In order to assess the accuracy of the model, an optimization scenario is run for the year 2020. This scenario considered variations of relevant parameters such as the number of buses/clusters considered or the time aggregation periods. Results from the optimization process and intermediate stages of the workflow, focused mostly in the representation of networks, generators and energy produced, are later compared with national historical data for the same year.

3. Identification of model's potential and development opportunities: Based on the results obtained in the previous step, a more in-depth analysis is conducted to explore future usage and implementation of the model for the Bolivian case, as well as opportunities for further development of the tool and contribution opportunities to enrich the code.

2.1. Case Study: The Bolivian energy system

Bolivia has undergone significant changes in the development of its energy/electricity system over the years. The Electricity Law of 1994 transferred state-owned companies to the private sector through a process called "capitalization." Prior to this, approximately 70% of electricity came from hydroelectric sources. The law aimed to promote intensive use of natural gas as the primary energy source for electricity generation, as large volumes of Natural Gas (NG) were unused at the time, by establishing a special price for NG used for electricity generation, below international prices [26]. Ever since, low natural gas prices have effectively blocked the development of new hydroelectric and renewable energy in the country, changing the situation so that by 2006, 70% of the generation was generated by NG thermal plants [27].

In 2006, with the arrival of a new left government, the energy policy changed. The electricity sector, along with the hydrocarbon sector, was nationalized, and the National Electricity Company (ENDE) was restructured into a vertically integrated corporation, a "national strategic and corporate public company" [28]. ENDE now has 12 subsidiary companies. ENDE, together with the CNDC (National Committee for Charge Dispatch), as the main coordinator for power dispatch, and AETN (Supervision Authority for Electricity and Nuclear Technology), as the main entity in charge of regulating the electric system, have been stablished as the key institutions that manage the large majority of the electric system in Bolivia [29].

In the last ten years, there have been three notable developments: the creation of the Vice Ministry of Electricity and Alternative Energies (VMEEA), the approval of a Policy on Alternative Energies for the Electricity Sector [30], and the installation of photovoltaic parks and wind farms for larger populations. These, together with newly published documents like the its national development plan (PDES 2021-2025) [31] or the updated NDC (Nationally Determined Contributions) [32], demonstrate the government's willingness to shift the previous paradigm regarding renewable technologies and incorporate them into the electricity sector. In both documents expressed goals are mentioned in which the country should achieve over 75% participation of renewable technologies in its electric system by 2030.

In 2020 Bolivia's National Interconnected System (SIN) recorded a capacity of 3,228.61 MW in its generation mixed and total production of 8,897.3 MWh [33], with conventional thermal plants (NG) being the main contributor with 63.3% of the share, followed by hydroelectric providing 32.3%, and a combination of solar, wind, and biomass power plants for the rest [34]. Currently, the installed capacity in the country is twice the amount required due to large efforts to expand and develop the power generation system to open a potential offer of electric energy to neighboring countries.

Finally, according to the 2020 yearly memoires of the sector's national institutions, Bolivia's power network was composed of high voltage transmission lines operating at 230, 115 and 69 kV, with an accumulated amount of 94 substations and 6340 km of powerlines across the SIN, in 8 of the 9 departments of the country [35]. In the generation aspect, 36 power plants, each with several generation units, are currently being operated [36].

2.2. PyPSA-Earth's Workflow for the Bolivian case

The general structure of PyPSA-Earth is comprised by a workflow with the following main stages: Automated data retrieval from open-source data bases (downloading data for the pre-defined case); data pre-processing and inputs generation (specific data filtering processes used for representative variables); base network generation (inputs are used to create a network model with PyPSA); network optimization for given conditions (solving the desired problem). Following these steps, a post-processing stage is required, in which results have to be explored [37]. While these stages of the workflow can be straightforward, several internal/intermediate processes are considered in each step, amassing to over 20 specific python scripts that deal with each of the tasks required to run the model. The automated handling of these tasks is done with the use of Snakemake, a workflow management tool [38].

Depending on the configuration of the model, what commands are run and their interdependency, rules can be considered or ignored by snakemake. This configuration of the model/simulation is made on an specific file (config.yaml) that works as the main framework definition section, which enables which rules are to be taken into account as well as global parameters considered in the model: number of clusters/buses used to simplify the model, optimizing the network based costs and/or line's volume, emission limits, time resolution and others.

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While the PyPSA-Earth model can run easily with a predefined configuration, it is a relatively general model, which needs to be enriched when "zooming" on a particular country. To optimize processing times between runs, a testing-version is set-up considering most of the default configurations, half a year period analysis, 10 clusters to aggregate information of the system and time steps of 8 hours.

After an adaptation process, a running version of the model was achieved for which the case-specific workflow for Bolivia is represented in **Figure. 1.** Additionally, the following changes represent the biggest modifications required to create an operative case for similar countries in the region:

- Specific weather data for South America was considered during the extraction process of online repositories (Copernicus Climate Data Store) [39].
- Landcover data retrieved from the predefined data bundle has been manually replaced by landcover maps for the South America (ProtectedPlanet) [40].
- Offshore wind turbines have not been taken into account in the model to facilitate the execution of the workflow during the creation of renewable availability profiles for offshore wind resources, because of Bolivia's condition as a landlocked country.

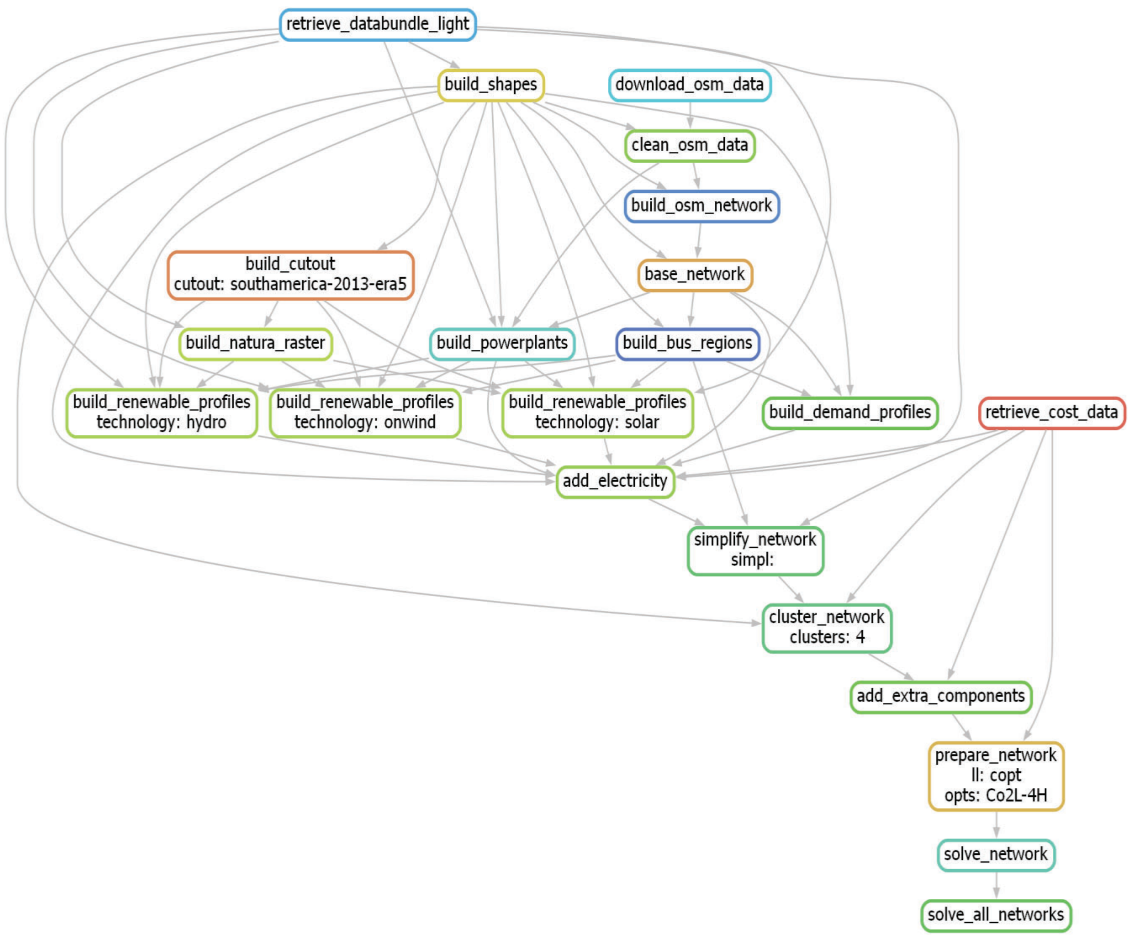

Figure. 1. Case-Specific workflow considered for Bolivia based on PyPSA-Earth.

For the sake of transparency and following the good practice of open-source modelling, a version control of the model can be found on a github repository: https://github.com/carlosfv92/pypsa-earth-BO, where relevant files, details of changes made on scripts and steps taken to run the Bolivian case are available.

2.3. Validation scenarios

Given the characteristics of the model, simulations use a predefined set of data sources to extract bundles of georeferenced information for a given country/region. Information extracted from these sources, combined with some precalculated datasets, allows the workflow to generate the databases required for creating the base network and optimizing its expansion. A list of the most relevant sources and the information they provide is available in **Table.1.**

Table. 1. Relevant data sources for the PyPSA-Earth workflow.

Source	Information extracted
Open Street Maps [41]	Network topology and components
Copernicus Climate Change Service [42]	Climate and weather data
HydroSHEDS [43]	Environmental variables
DRYAD [44]	Economic parameters
Shared Socioeconomic Pathways [45]	Global energy demand projections

After the model is setup for the Bolivian case a validation scenario is considered to study the outputs that can be obtained with the model, taken into account the following characteristics:

- Optimization of the system based on operational costs
- Operation of an entire trial year (2020)
- Time aggregation of 6 hours
- Non existing practical upper limit for emissions
- No restriction regarding the usage of emitting or renewable technologies
- Weather data based on historical information (year 2013)
- Default data sources from online repositories

To have a general grasp of the model’s capabilities the analysis on results was focused on three aspects: network representation, powerplants installed capacity and energy demand coverage. For the first case, a major focus is given to how the model recognizes and processes available information regarding substations and transmission lines by modifying clustering values in the configuration and running different cases to compare them to with the existing Bolivian grid. For the second and third case, using a 4-node clustered version of the network, the optimized installed capacities and energy production are revised and compared to the existing operational conditions of the power system.

3. Results and discussion

3.1. Bolivia’s transmission network simulation

To compare the capacities of the model to properly represent the Bolivian network in 2020, the model was run with different clustering objectives. Utilizing the plotting functions of networks generated with the PyPSA package and the intermediate results from the workflow, it’s possible to explore different states and conditions of the system.

Some examples of what can be analysed are: The base network that the model creates after downloading and filtering default data, which assumes the totality of “usable” data, meaning properly georeferenced, defined and tagged elements (lines, substations and generators); Clustered networks created based on the defined number of buses that are given to simplify the network and the rest of characteristics of the model structure; The optimized network, which results from the final stage of solving the objective function of the system and can include additional or complementary elements in the buses, depending on the technical capacities of the system and their costs.

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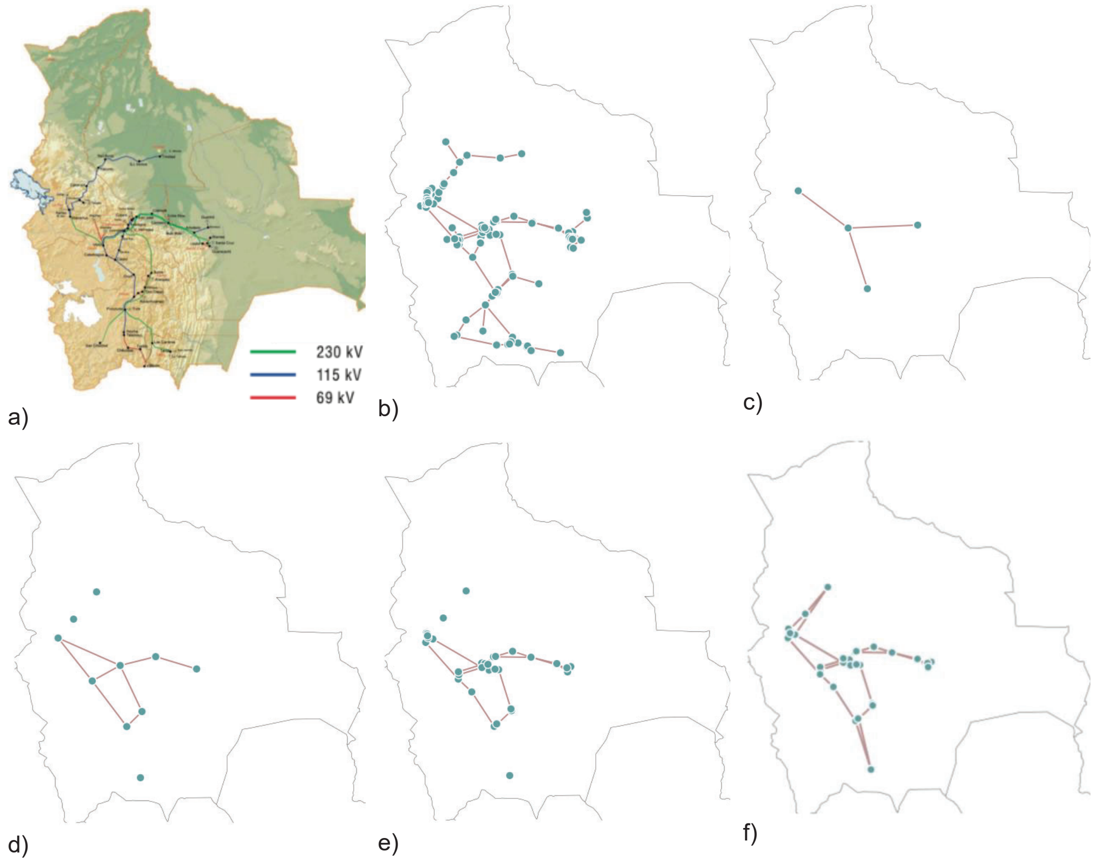

Figure. 2. Network recognition and clustering for Bolivia based on PyPSA-Earth: a) Bolivian transmission network in 2015 according to sectorial development plan *[6]*; b) Representation of the base network and lines pre-simplification and optimization; c) 4-node optimized version of the Bolivian network; d) 10-node optimized version of the Bolivian network; e) 37-node optimized version of the Bolivian network; f) 37-node optimized version of the Bolivian network with forced augmentation of powerlines.

A mix of these different cases, and the way they graphically represent the network, is available in **Figure. 2.** When comparing the real network in 2015 (a) with what is available from online repositories (b), it can be seen that most of the network's elements are considered and most of the relevant characteristics can be found in both cases like the connection rings in the south and central parts of the STI (Backbone Network System), as well as most of its 69, 115 and 230 kV lines. When the model is later clustered and optimized to a four node simplification (c), results are consistent with the 4-zone aggregation that the Bolivian network uses in their planning efforts: the southern area, central area, oriental area and northern area [29]. This representation, even though simplified, provides an overall good understanding of how the energy is used in the country and has already being used in previous studies focused on dispatch to simulate the Bolivian system [16].

After this minimal clustering, increasing numbers of nodes in the system are run (d), however, a limit was found at 37 nodes (e). This limit of nodes representation is derived by the simplification process of the available data into the base network used by PyPSA-Earth before the optimization, which aggregates the system considering only high-voltage components of the system (recognizing only 37 usable points to represent buses).

Because of this same reason, only lines above 30 kV are considered in the analysis, dropping several of the lower voltage lines, which leads to the assumption of several nodes as isolated from the rest of the grid. While this condition might seem problematic, it is important to take into account the scale for which PyPSA-Earth was created (regional and international analysis), therefore high voltage lines were given priority [22]. In this sense, this would represent a great opportunity for future work, given that if the scope/array of lines considered is modified, this could help study and represent potential integration strategies for isolated communities, which is a major focus according to national policies [32].

Finally, an alternative way to impose the model to consider power flows between nodes can be achieved by forcing the optimization to include a minimum number of interconnections to allow a better representation (f). However, the forced creation of new networks would already represent predefined discrepancies that could affect the rest of the analysis, especially when comparing historical years.

To avoid the creation of isolated nodes and avoid forcing the model to create already existing lines, the 4-nodes representation is used for the rest of the analysis, and, even though this configuration provides a simplified version of the network, it can still be comparable to “existing” conditions.

3.2. Energy demand aggregation and simulated installed capacities

Results from the optimization of the system with the 4-node clustering configuration of the system, show an expected energy demand of 7,558.73 GWh for the entire year, distributing it as shown in **Figure. 3.** These results are in agreement with the total historical energy demand in Bolivia in 2020, according to the Bolivian authorities [29], presenting a discrepancy of 13.5%. Regarding the distribution of energy demands, the representation of the areas in the model is properly encapsulated, showing the same pattern of aggregation of energy consumption in the buses as the one provided in official documentation of the country, with the biggest outlier being the oriental area, having a deviation of 25.2% between the modelled data and the historical values.

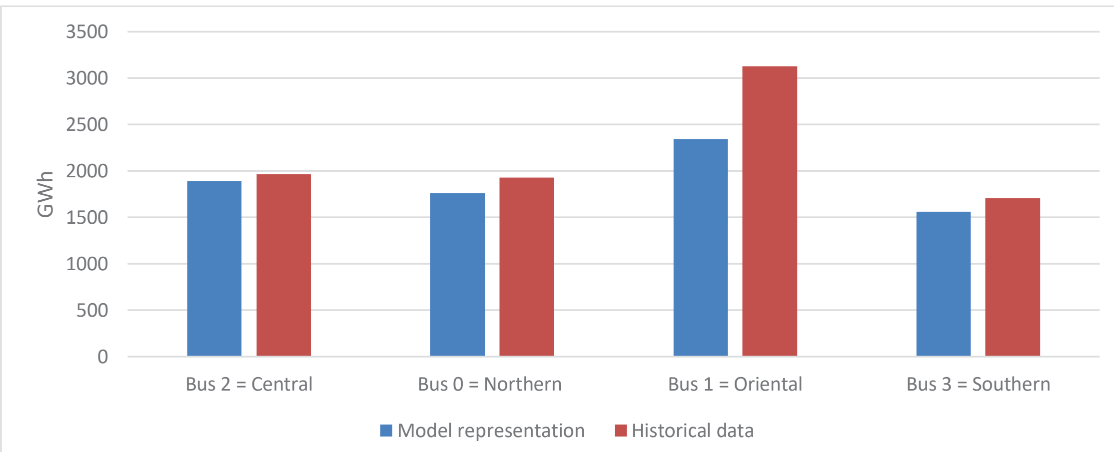

Figure. 3. Comparison of estimated energy demand by node in the model and registered energy demand in Bolivia for the year 2020.

These differences can be explained by the use of aggregated data at a global scale, which assume average growth trends in different scenarios but not at regional or country specific cases [45]. Bolivia in particular, seems a very atypical country due to a large period of sustained economic growth since 2010, where its GDP has had an average yearly value of over 3.5% [46]. This value is significantly larger than what was registered in the rest of the Latin-American region, with and average growth of lower than 2% in the last 10 years [47]. However, making data closer to historical values can be somewhat addressed in the model by adapting some sections in the configuration file. These changes should allow to increase the scaling factor of the referential time series data, by modifying data files used by the model or by including an additional section on the workflow for using country specific trends.

On the other hand, the analysis of installed capacity and its optimization shows structural discrepancies regarding the information used. **Table. 2.** Presents the details of the composition of the available powerplants according to the model and online data sources (Available capacity), the optimized values to cover the 2020 demands (Optimized capacity), as well as the actual data registered for 2020 in Bolivia (Real capacity):

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Table. 2. Modelling results for the installed capacities in the Bolivian power system for 2020.

Carrier	Available capacity [MW]	Optimized capacity [MW]	Real capacity (2020) [MW]
OCGT	914.34	1099.40	1029.05
CCGT	-	-	1239.83
Oil	33.99	33.99	31.58
Onwind	25.52	25.52	27.00
Ror	344.00	344.00	-
Res	-	-	734.83
Solar	119.22	119.22	115.07
Biomass	-	-	51.25
Total	1437.07	1622.13	3228.61

Results regarding power generation show that the automated workflow using online data sources underestimates the existing capacities in the model in the year 2020. This is clear when comparing the total Available capacity with the total Real capacity, which is almost twice the value that online data sources take into account. Additionally, other relevant characteristics regarding how technologies are defined in the model can be found, compared to historical information from the national entities:

1) All the NG turbines are considered only as Open Cycle Gas Turbines (OCGT), which is not currently the case, given that several units and centrals are currently operating in the system with Combined Cycles (CCGT);
2) Hydropower in the Bolivian case is mostly composed by small reservoir units (Res), however, all available hydro units are recognized as run-off river powerplants (Ror) in PyPSA-Earth;
3) While not critically significant in terms of capacity, biomass powerplants (Biomass) are not being taken into account in the model, when in reality there is a small installed capacity available.

These discrepancies can be explained by two reasons. The first one being that, for older powerplants, information might not be fully or properly updated in the online data sources like Open Street Maps or PowePlantMatching. This is consistent with the fact that newer plants such as solar or onshore wind (Onwind) are accounted for, while large capacities in the other cases (thermal and hydro) are absent. The second reason would be the lack of proper tagging in the newer centrals, which have been created as expansions from other plants or where several units have been adapted or have grown over time.

Clear examples of these two cases are powerplants with two phases but the same name, like the hydro centrals San Jose 1 & San Jose 2, or the OCGT in Warnes, which were converted into CCGT with additional installed capacities [29]. Both of these issues can be sorted out by considering a country-specific set of data to replace the one generated by the model, however, while this functionality is currently available, there are some mismatching problems that have to be tuned to properly be used.

Finally, when analyzing the optimized capacities proposed by the model to cover power demands in the system, values are quite similar to the historical peak capacity covered in Bolivia, with a value of 1,565,80 MW [34]. This would mean that, while the mix of powerplants used by the model can vary between optimized and historical values, its capacity to optimize the system in order to cover future demands operates properly. The main reason for this variation is that the model does not have the same initial generation (legacy) capacities available in order to operate them, and the current over capacity installed in Bolivia [35], which was enforced mostly due to political reasons rather than technical requirements.

4. Conclusions and future work

Open-source tools are a valuable asset for countries and institutions immersed in energy system modelling. While this topic has been historically worked and developed by private entities and their own private tools, with their current growth, it can be expected that open-source models will eventually be able to replace licensed/black-box software used in energy system modelling.

A key example of this type of tools is PyPSA-Earth, a modelling tool that was developed within an open and transparent framework that allow its developers (and users) to generate simplified representation of the power system network of regions or countries in the world. Some of the novelties of this modelling tool are the integration of georeferenced information into the power flow analysis, the use of predefined online data sources, an optimization approach linked to the operation of the power system and the use of a detailed time resolution.

In this sense, the model was adapted to run the country-specific case of Bolivia for the year 2020 and it outputs were later compared to historical data to assess the capabilities of the model. Results show a high potential for its implementation in the future given that its scope and results are complementary to already developed tools. This would help filling gaps in the modelling requirements and capabilities for a better comprehension of the country's power system.

However, it is also important to address that the work done here is an introductory process to study the capabilities and conditions of the tool in order to assess its applicability in developing countries, with Bolivia being only a case study. Aside of the previous results obtained, several additional, configurations and outputs should also be explored in future work. These aspects are mostly linked to fine tuning of the model in order to allow the change of certain default data files to local-based information in order to improve the capabilities of the tool to represent country-specific cases in a manner closer to reality.

In parallel, particularities of the model's capabilities found in this work should be followed through and developed. For instance, adapting the model to include and focus on additional high voltage lines (voltage levels of 69 and 115 kV for example), would represent a relevant change in the tool and a potential big contribution to the PyPSA-Earth model. Doing this would allow the model to better represent smaller scale systems, as it is not possible to make the assumption that the grids behave or have the same topology as the ones in developed countries

Another example would be to update or further develop the process and adaptations required in the model to use customized data sets of information regarding generators and alternative energy demand projections. Both of these would allow the model to increase the flexibility of PyPSA-Earth by improving its capacities to work in countries with less reliable data in the online sources.

Finally, another potential aspect to exploit in future work would be to develop feedback loop processes between modelling tools developers, users with detailed information and online data providers. This would allow to improve capacities on all fronts at the same time as promoting the open-source philosophy, enhance contribution among researchers and transparency between users of the model and its results.

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Acronyms

SDDP	Stochastic Dual Dynamic Programming
HOMER	Hybrid Optimization of Multiple Energy Resources
OnSSET	Open Source Spatial Electrification Tool
RAMP	Remote Areas Multi energy load Profiles generator
OSeMOSYS	Open Source energy MOdelling SYStem
PyPSA	Python for Power System Analysis
NG	Natural Gas
ENDE	Empresa Nacional De Electricidad (National Electricity Company)
CNDC	Comite Nacional de Despacho de Carga (National Committee for Charge Dispatch)
AETN	Autoridad de Fiscalización de Electricidad y Tecnología Nuclear (Supervision Authority for Electricity and Nuclear Technology)
VMEEA	Viceministerio de Electricidad y Energias Alternativas (Vice Ministry of Electricity and Alternative Energies)
SIN	Sistema Interconectado Nacional (National Interconnected System)
STI	Sistema Troncal de Interconexion (Backbone Network System)
OCGT	Open Cycle Gas Turbines
CCGT	Combined Cycle Gas Turbines
Ror	Run-off river powerplants
Res	Reservoir
Onwind	Onshore wind

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