A TWO-STEP CASCADE MODELLING BETWEEN ENERGYSCOPE PATHWAY-BO AND PYPSA-BO FOR ENERGY TRANSITION PLANNING. PART A: IMPACTS OF DEMAND SCENARIOS

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ABSTRACT

As the transition of energy systems becomes more urgent worldwide, countries and communities are searching for pathways toward sustainable energy systems, which involves developing long-term energy plans and deciding on the key resources and technologies required to meet their future energy needs. In this context, bottom-up models are commonly used to analyze scenarios that assess the development of energy systems. Nevertheless, the technical, temporal, and spatial detail levels vary as systems and cases become more complex.

Various modelling tools are currently available, each tackling issues using distinct approaches or addressing specific aspects of the system's behavior. Thus, considering a common objective and structure, redundancies among models could be used to check consistency across models and provide an additional validation layer. Alternatively, models can be enriched by including inputs or supplementary information from other tools, considering the aspects each tool focuses on.

This research is split into two parts and addresses the coupling and comparison between two models. The first part, detailed in the current article, focuses on optimizing the investment strategy path from 2021 to 2050 (EnergyScope Pathway), while the second concentrates on optimizing the electrical network and dispatch (PyPSA-Earth). Within the scope of this paper, a critical gap in the literature was addressed by comprehensively characterizing energy demand patterns and evaluating the trajectory of the Bolivian energy system across various sectors—electricity, heat, cooling, and mobility—under three scenarios (business-as-usual (BAU), conservative effort towards transition (CET) and net zero emissions (NZE)) based on historical data for 2021 and energy demand projection of consumer groups until 2050. Prior to this investigation, no detailed analysis of energy demand had been conducted for Bolivia, leaving uncertainties regarding its evolution and impact on the country's commitment to achieving carbon neutrality.

The analysis, utilizing the open-source *EnergyScope Pathway* model, identified electrification, synthetic fuels, efficiency improvements, and renewable integration as key to a sustainable transition. The NZE scenario reveals a 3% reduction in primary energy demand (due to energy efficiency) and a path to decarbonize the Bolivian energy system, emphasizing the importance of electrification, which grows to reach 135.23 TWh and a 48% share of energy consumption by 2050. At the same time, the total system cost (106.03 billion €$_{2021}$) represents a lower value than the BAU and CET scenarios and emphasizes the necessity of dispatch & electricity network reinforcement in future endeavors (Part B).

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1 INTRODUCTION

Transitioning to decarbonized energy systems by 2050 is a global priority to address climate change and meet the goals established in the Paris Agreement. This transformation necessitates a profound and enduring change in current energy systems, which must be analyzed and tailored specifically for each country, taking into account their unique economic, social, and environmental characteristics. Consequently, numerous studies have emphasized the critical need for formulating long-term pathways for energy transition (Rogelj et al., 2018).

In this context, bottom-up energy system models have emerged as indispensable tools for facilitating the strategic planning and analysis of energy systems at various scales, from local to global. These models, by design, integrate various energy sources, technologies, and demand scenarios to identify cost-effective and efficient solutions, taking into account environmental constraints and policy goals. For instance, renowned models belong to this category, such as MARKAL/TIMES, MESSAGE, EnergyPLAN, LUT Energy System Transition Model, OSeMOSYS, Temoa, and EnergyScope Pathway (Prina et al., 2020). Nonetheless, not all of these possess the capability to identify optimal transition pathways. This limitation often stems from their simulation horizon, the granularity of data they can process, and also their adaptability to rapidly evolving energy technologies and price dynamics (DeCarolis et al., 2017).

Within this collection of models, only a few consider end-use demands as inputs for the optimization process. For instance, OSeMOSYS adopts a final energy consumption (FEC) methodology that emphasizes the overall need for fuels or energies, leading to a pre-optimization fixed fuel consumption. This approach influences technological aspects and affects resource availability, fuel supply chain costs, the scale of demand, potential alternative fuel uses across sectors, and emissions reductions (Jacquemin, 2023). On the other hand, the end-use demand strategy deeply breaks down energy demand, assessing the energy used by end-users for specific purposes (Alajmi et al., 2020). Such disaggregation provides a nuanced view of energy requirements, enabling the integration of various energy consumptions and conversion technologies, including non-energy demands often neglected in traditional energy models. Additionally, this method facilitates the identification of sectors or processes where efficiency measures could have the most significant effects.

Regarding the progress and challenges of long-term energy planning in Bolivia, the country's approach to energy transition has been predominantly analyzed through the lens of its electrical system, primarily concentrating on short-term and medium-term targets (Candia et al., 2019; Jimenez Zabalaga et al., 2020). However, few studies were published regarding energy demand projection and potential pathways for the country's energy mix. One publication projected energy demand by sectors from 2012 to 2035 and analyzed three energy efficiency and electrification scenarios, utilizing LEAP, a tool to develop forecasts of energy consumption of a given area (Peña Balderrama et al., 2017). Another research explored Bolivia's energy pathway up to 2040 using the OSeMOSYS model, which led to a great increase of PV and hydro primary energy for the national system (Fernandez Vazquez et al., 2020), while a further study extended the analysis to 2050, examining the system's adequacy and flexibility through a soft-linking methodology that linked OSeMOSYS and the Dispa-SET dispatch model (Fernandez Vazquez et al., 2024).

In all the cases, whereas the models were used to explore different scenarios and analyze various alternatives for the energy system, some demands, certain technical attributes, and technologies were neglected or oversimplified, which enhanced the uncertainties in determining the optimal configuration of the system. Specifically, the heating, cooling, and mobility sectors only considered fuel and electricity consumption. In addition, none of the evaluated study scenarios reached carbon neutrality before 2050. Thus, this study aims to assess the pathway for the Bolivian energy system using an end-use demand model framework, *EnergyScope Pathway*, to achieve a sustainable transition based on the CO_2 emissions across electricity, lighting, heat, cooling, driving force, and mobility sectors for three scenarios based on forecasts of the energy demand of consumer groups according to expected growth in the population and industries. Moreover, the work represents the first national-level open-source energy demand projection model for Bolivia until 2050. The remainder of the paper is structured as follows. Section 2 describes the

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methods for forecasting energy demand, scenario creation, and pathway optimization. Section 3 provides information about the estimated demand, resources, and technologies of the Bolivian energy system, while Section 4 presents and discusses the results. Finally, Section 5 summarizes the concluding remarks.

2 METHODS

The methodology employed in this research encompassed three stages: first, a long-term forecast of energy demand was performed. Second, different scenarios were created. Two of these focused on the potential replacement of fossil fuel technologies and the implementation of previously identified efficiency measures. Finally, the pathway optimization and analysis were performed, focusing on cost, technical, and environmental effects.

2.1 Characterization and projection of energy demand

The end-use energy consumption in Bolivia was modeled and forecasted till 2050 using a combination of bottom-up and top-down approaches, depending on the availability of data. The energy demand model utilized a hierarchical tree structure to categorize various consumers into five levels: Sector, subsector, class, type of usage, and technology. Additionally, each of the eight sectors, as categorized by the National Energy Balance reports (Ministerio de Hidrocarburos y Energías (MHE), 2022), was modeled independently and separately due to the absence of interaction between them. This process included reviewing and compiling data from public reports, articles, and other relevant literature. The structure of the energy demand system is depicted in Figure 1 through a radial tree diagram. In the spirit of the project, the model was developed in a Jupyter Notebook, which includes data, comprehensive references, and the methodologies employed, and is entirely open-source [1]. Table 1 summarizes relevant information used for the mentioned model.

Table 1: Methodology approach by sector, subsector, and class. References of the parameters and data can be found in [1].

Sector	Subsector	Class	Methodology approach	Unit of consumption
Residential	All	All	Bottom-up	Households
Public Lighting	All	All	Bottom-up	Public Lighting
Commercial	All	All	Top-down	Persons
Industrial	LEs LEs MSMEs	Cement All others All	Bottom-up Bottom-up Top-down	Tonne of production Industries Energy consumption
Transport	Passenger Passenger Freight	Public Private Freight	Bottom-up Bottom-up Bottom-up	Passenger-km Passenger-km Tonne-km of freight
Agriculture	All	All	Bottom-up	Cultivated area
Mining	All	All	Top-down	Tonne of production
Fishing & Others	All	All	Top-down	Energy consumption
Non-energy	All	All	Top-down	Energy consumption

The projection of energy demand was based on three primary factors: population growth, which was used for seven sectors, future trends in mineral production, and the increase in the sales volume index of the manufacturing industry. The former was determined using projections from the National Statistics Institute (Instituto Nacional de Estadística (INE), 2020), while the latter two relied on linear growth projections [1].

1 Jimenez Zabalaga, P. and C. A. Fernandez Vazquez (2024). *Bolivian energy demand*. URL: https://github.com/CIE-UMSS/EnergyScope_Pathway_BO/tree/main/Characterization_and_projection_of_Bolivian_energy_demand

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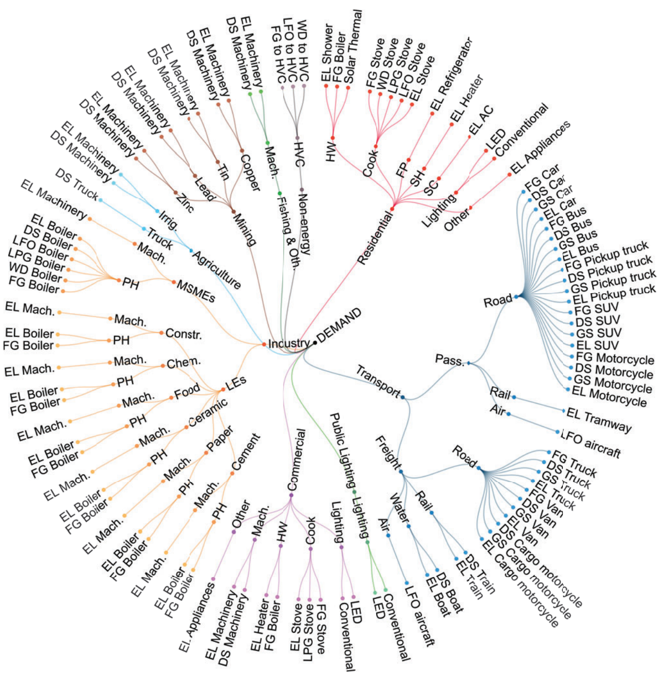

Figure 1: Radial tree representation of the energy demand model. The abbreviations are: DS: Diesel, EL: Electricity, FG: Fossil gas, GS: Gasoline, HW: Hot Water, Irrig: Irrigation, LEs: Large enterprises, LFO: Light fuel oil, LPG: Liquefied petroleum gas, Mach: Machinery, MSMEs: Micro, small and medium-sized enterprises, Pass: Passenger, PH: Process Heat, SUV: Sport utility vehicle, WD: Biomass, Fishing & Oth.: Fishing & Others, HVC: High Value Chemicals.

2.2 Scenario creation and assumptions

Three scenarios were created: The business-as-usual (BAU) scenario assumes that technologies' share will remain the same for the different sectors throughout the years, except for the medium-term power plants approved by the Electric Load Dispatch Committee (Comité Nacional de Despacho de Carga (CNDC), 2022). The conservative effort towards transition (CET) scenario considers a constant linear increase until 2050 based on the update of the Nationally Determined Contributions (NDCs) (Ministerio de Medio Ambiente y Agua (MMAyA), 2022), which outline specific ratios for the transport and lighting sectors up to 2030. The net zero emissions (NZE) scenario set the goal of achieving a 100% reduction in green house gases (GHG) emissions by 2050 through a linear decrease, including a greater variety of technologies to examine their potential roles in a future decarbonized energy system. Table 2 summarizes the principal features of these scenarios.

2.3 Pathway optimization and analysis

The optimization of the future pathway relied on *EnergyScope Pathway*, a bottom-up linear programming modeling framework for the long-term planning of whole-energy systems (high share of renewable energy and representing the electricity, heating, cooling, mobility, and non-energy sectors equally). This tool is an extension of the open-source and documented *EnergyScope TD*, which is a snapshot model that provides a detailed analysis of an energy system for individual years and, therefore, cannot comprehend the intricacies involved in investment strategies throughout the decades (Limpens et al., 2024). The approach for the enhanced model segments the transition into five-year periods, optimizing the energy system for one specific year each, yielding seven EnergyScope TD representative years from 2021 to 2050 (Figure 2). For these representative years, limitations were included to capture investment changes between periods, account for societal inertia, and evaluate the transition's cost and emissions (Limpens et al., 2024). Moreover, a perfect foresight approach was employed for this work, and the original code

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Table 2: Summary of assumptions considered for the BAU, CET, and NZE scenarios.

	BAU	**CET**	**NZE**
Power sector	Maximum renewable capacity reached in 2030	From 2030, it is not limited by government plans	From 2030, it is not limited by government plans
Water heating	Solar share based on historical trends	Solar share based on historical trends	Not limited
Lighting	Same proportions of current technologies	LED share defined in NDCs	Not limited
Transport sector	Same proportions of current technologies	Public electric buses share defined in NDCs	Electric, hydrogen and hybrid vehicles
Bioenergy	Not considered	Bioethanol and biodiesel production	Biofuels and synthetic fuels production
Emission limits	Not considered	Not considered	Linear decrease

was extended to include phases outside the optimization window (2015-2050), accounting more precisely for the end-of-life of power generation technologies.

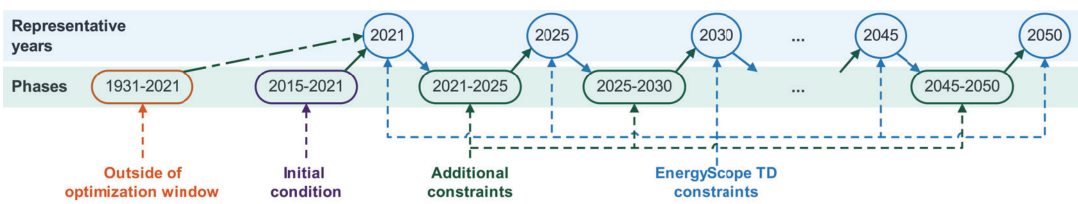

Figure 2: The methodology for the pathway is based on representative years (indicated by blue circles), during which the EnergyScope TD model is utilized. Additionally, the approach incorporates linking constraints (highlighted in green boxes), an initial condition (purple box), and the phases outside the optimization window (orange box).

3 CASE STUDY

The *EnergyScope Pathway-BO* model became a customized version of the original one by incorporating specific end-use categories and technologies, and utilizing enhanced data from a prior snapshot analysis focused on defossilizing Bolivia's energy system for 2035 using *EnergyScope TD* (Jimenez Zabalaga et al., 2023). In 2021, Bolivia's reliance on fossil fuels was substantial, with these sources constituting 92.6% of its energy mix (Ministerio de Hidrocarburos y Energías (MHE), 2022), making the transition challenging. Despite the limitation of the one-cell spatial resolution for the pathway model, the Bolivian energy system can be, to a certain degree, applied and extrapolated to the situation in other developing countries of the global south that rely significantly on non-renewable resources. In this specific case study, a total of 17 demand categories were considered, along with 15 resources and 86 technologies. The adapted version of the model for Bolivia is available online at [2]. A simplified representation of the model is proposed in Figure 3.

3.1 Demands

Demands were defined by annual quantities that needed to be met and hourly time series. The annual end-use demand (EUD) across all sectors was determined using the previously described methodology, and Table 3 summarizes these consumption levels. In this context, the increase in energy demands shown

2 Jimenez Zabalaga, P. (2024). *EnergyScope Pathway-BO*. URL: https://github.com/CIE-UMSS/EnergyScope_Pathway_BO

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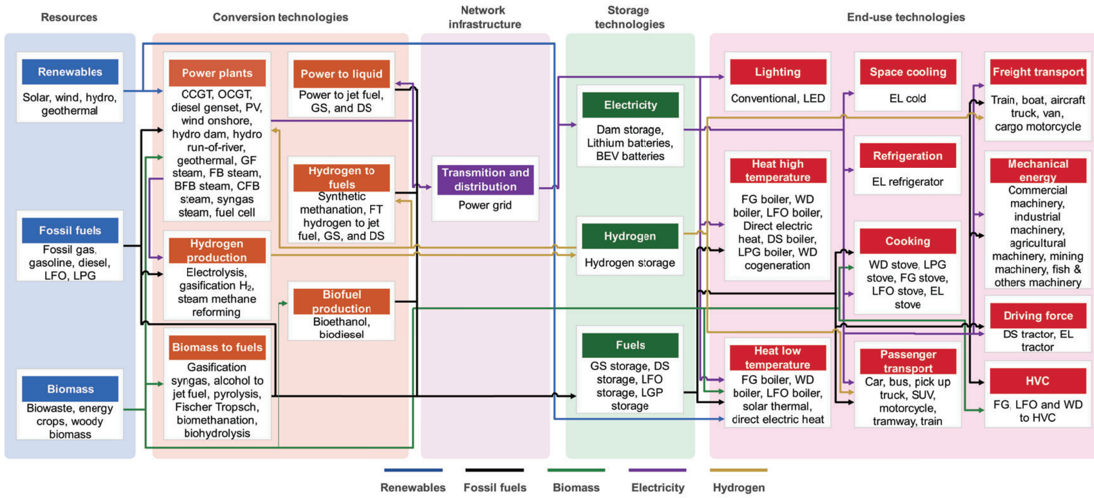

Figure 3: Simplified representation of energy system model.

was related to the projected population growth (1.06% average per year) (Instituto Nacional de Estadística (INE), 2020), increase in ore production (1.81% average per year) (Instituto Nacional de Estadistica (INE)., 2023) and the rise in the sales volume index of the manufacturing industry (1.74% average per year) (Instituto Nacional de Estadistica (INE), 2019) for the 2021-2050 period. The analysis used time series data to evaluate the system's operability by optimizing hourly dispatch across typical days. These time series drew on historical data from 2021 for electricity (Comite Nacional de Despacho de Carga (CNDC), 2021), space cooling, and space heating demands (Staffell et al., 2023). For passenger mobility, a daily time series was utilized (McGuckin et al., 2017), while freight mobility time series was assumed to remain constant throughout the year.

Table 3: End-use demands from 2021 to 2050.

Sector	End-use demand	2021	2025	2030	2035	2040	2045	2050
Residential	Cooking (TWh)	4.74	5.00	5.32	5.63	5.91	6.17	6.41
	Water heating (TWh)	1.17	1.23	1.31	1.38	1.45	1.52	1.58
	Refrigeration (TWh)	0.34	0.36	0.38	0.41	0.43	0.44	0.46
	Lighting (GWh)	48.13	50.78	54.01	57.09	59.97	62.64	65.07
	Space cooling (TWh)	0.10	0.10	0.11	0.12	0.12	0.13	0.13
	Space heating (GWh)	21.25	22.42	23.84	25.20	26.47	27.65	28.72
	Other electronics (TWh)	0.82	0.86	0.92	0.97	1.02	1.07	1.11
Commercial	Electricity (TWh)	1.16	1.22	1.30	1.37	1.44	1.51	1.57
	Cooking (TWh)	0.30	0.32	0.34	0.36	0.38	0.40	0.41
	Water heating (TWh)	0.14	0.14	0.15	0.16	0.17	0.18	0.19
	Mechanical energy (GWh)	77.00	81.24	86.40	91.33	95.95	100.22	104.10
	Lighting (GWh)	30.14	31.80	33.82	35.74	37.55	39.22	40.74
Industrial	Process heat (TWh)	13.19	14.36	15.82	17.28	18.74	20.19	21.65
	Mechanical energy (TWh)	1.58	1.72	1.90	2.07	2.25	2.42	2.60
	Lighting (GWh)	26.43	28.77	31.69	34.61	37.54	40.46	43.38
Transport	Passenger (Tkm-passenger)	0.35	0.36	0.39	0.41	0.43	0.45	0.47
	Freight (Gkm-ton)	15.24	16.08	17.10	18.08	18.99	19.84	20.61
Agriculture	Mechanical energy (TWh)	0.23	0.24	0.26	0.27	0.29	0.30	0.31
	Driving force (GWh)	50.12	52.88	56.24	59.44	62.45	65.23	67.76
Mining	Mechanical energy (TWh)	1.55	1.71	1.92	2.13	2.34	2.54	2.75
Fishing & Others	Mechanical energy (TWh)	0.45	0.47	0.50	0.53	0.56	0.59	0.61
Public Lighting	Lighting (GWh)	54.13	57.11	60.74	64.20	67.45	70.45	73.19
Non-energy	Process heat (TWh)	1.76	1.86	1.97	2.09	2.19	2.29	2.38

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3.2 Resources

Resources were defined by a price (€/TWh), availability (TWh/y), and GHG intensity (kt$CO_{2\text{-eq.}}$/TWh), the latter derived from a Life Cycle Assessment (LCA) (Limpens et al., 2024). Regarding fossil fuel resources, international prices were considered, which exclude the current subsidies to quantify actual public expense (Agencia Nacional de Hidrocarburos (ANH), 2023). Moreover, future values of these were based on projections from the U.S. Energy Information Administration (EIA), expressed in the reference case of the Annual Energy Outlook 2022 (Energy Information Administration (EIA), 2022). The availability of all fossil fuels was assumed unrestricted or that they could be imported as much as needed, with the exception of FG, whose availability over the years was calculated by deducting the volumes committed under existing sales contracts with Brazil and Argentina from the proved, probable, and possible reserves (Ríos, 2023; Pike, 2008). This adjustment was necessary because Bolivia exported approximately 72% of its total FG production in 2021. Conversely, the potential for renewable energy was limited by land availability, climate, and resource allocation, which either limited the energy output (in TWh/y) for resources like biomass or the capacity for technology deployment (in GW) for solar, wind, geothermal, and hydro technologies. The potential capacities for these resources were reviewed and determined at 40 TW for PV (Cheng et al., 2022), 260 GW for onshore wind (Cheng et al., 2022), 6.09 GW for hydro dams (Comité Nacional de Despacho de Carga (CNDC), 2022), 0.91 GW for run-of-river hydro (Empresa Nacional de Electricidad (ENDE), 2015), 0.88 GW for geothermal (Jimenez Zabalaga et al., 2023), 150 TWh/y for woody biomass (Magne et al., 2024), and 28.02 TWh/y for wet biomass (Magne et al., 2024). No importation of clean fuels was allowed due to the lack of information about the exportation capacity of these resources from neighboring countries.

3.3 Technologies

Techno-economic data related to technologies included an investment cost (M€/GW), operational non-fuel variable cost (M€/y/GW), minimum and maximum deployment (GW), conversion efficiency, lifetime (years), and capacity factor. In this context, the unit of measurement varied from gigawatts (GW) for power supply technologies to gigawatt-hours (GWh) for storage technologies, million passenger kilometers per hour (Mpkm/h) for passenger transport technologies, and million-ton kilometers per hour (Mtkm/h) for freight transport technologies. Furthermore, the technologies employed in this study could be categorized into three groups: conversion, storage, and network. Conversion technologies involve the process of transforming one form of energy carrier into another. Storage technologies are capable of holding energy for later use, defined by their input/output efficiency, internal losses, and energy-to-power ratio. Network technologies enable the distribution of specific energy carriers throughout the country. Notably, the transmission losses for the power grid were maintained at its historical rate of 14.8% (Ministerio de Hidrocarburos y Energías (MHE), 2022). The selection of future technologies was guided by their commercial availability locally, governmental plans, and prevailing trends within Bolivia, leading to the exclusion of heat pumps and seasonal storage technologies from consideration.

4 RESULTS AND DISCUSSION

This section delineates the results, starting with an analysis of GHG emissions and energy consumption. It further explores the transformations across various sectors and concludes with an evaluation of the associated costs.

4.1 GHG emissions

Under the BAU scenario, the GHG emissions grow to 30.97 $MtCO_2$ by 2050, more than 1.3 times the 2021 emissions level. Furthermore, mobility and high-temperature heat, or industrial process heat, emerge as the predominant emissions contributors. This is primarily attributed to the reliance on fossil fuels for vehicles and boilers. In contrast, the NZE scenario adheres to the carbon budget outlined by the Paris Agreement's commitments, effectively ensuring the elimination of carbon emissions by the final year. The production of synthetic fuels is pivotal in offsetting non-abatable emissions from the transport sector,

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allowing for the continued use of gasoline, diesel, FG and LFO. Notably, aircraft technology, which accounts for the largest share of residual emissions, is predominantly powered by e-jet fuel. Conversely, the CET scenario falls short of achieving carbon neutrality by the target year of 2050 (19.92 $MtCO_2$ in that year). This outcome can be attributed to the current government's strategic plans until 2030, which are limited to implementing new power plants and producing bioethanol and biodiesel from energy crops. Additionally, these plans encompass an increase in the adoption of LED lighting, the electrification of industrial and mining heating requirements, and the growth of electric public transportation. These measures leave the decarbonization pathways for other sectors uncertain. Figure 4 presents a comparison of the emissions trajectories for each scenario. The mitigated GHG emissions contribute to reducing the carbon intensity, moving from 0.20 $ktCO_2$/GWh in the BAU scenario to 0.14 $ktCO_2$/GWh in the CET scenario and none in the NZE scenario.

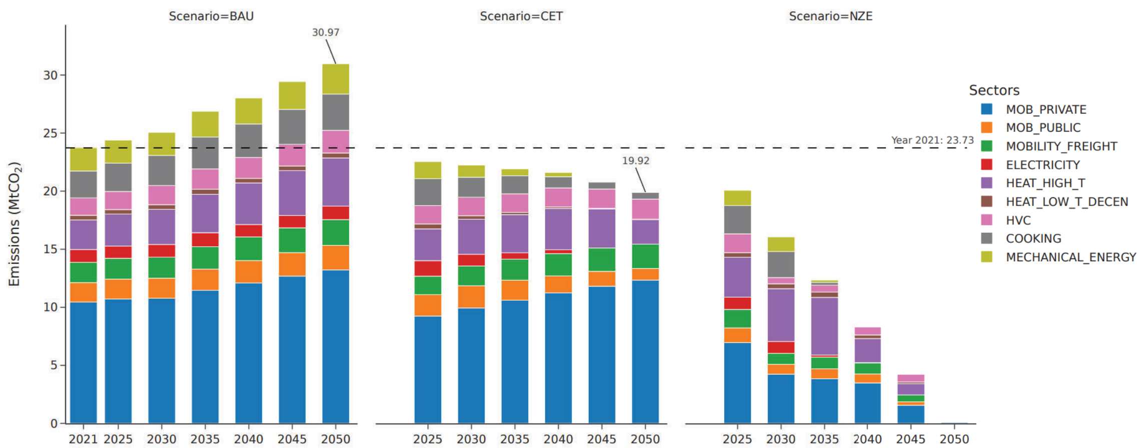

Figure 4: Anual GHG emissions per sector for the three scenarios. Only the NZE scenario achieved carbon neutrality in 2050.

4.2 Energy mix

Final energy consumption in the BAU scenario reaches 153.40 TWh by 2050, representing 1.6 times the energy used in 2021. On the other hand, the other scenarios satisfy the demands with less energy. The CET scenario requires 144.27 TWh by 2050, and the NZE scenario needs 149.41 TWh by 2050. The penetration of more efficient technologies on the supply and demand sides enables lower energy requirements and improves energy intensity in these decarbonization scenarios. The energy consumption changes to achieve GHG emissions reduction as illustrated in Figure 5. The BAU scenario continues the trend of a high dependency on fossil fuels with around 68% of its total energy in 2050. The decarbonization scenarios present five facts to be highlighted:

- The electrification of end-uses dominates the energy transition. The contribution of electricity grows from 10.88 TWh in 2021 to 37.56 TWh in 2050 regarding the CET scenario and to 135.23 TWh in 2050 for the NZE scenario. From which only 0.9% and 1.1% are related to power curtailment in the CET scenario and the NZE scenario for that final year, respectively.
- Renewable energy constitutes the largest proportion of primary energy consumption. In the CET scenario, wind energy increases from 1.1% to 23.6%, solar energy rises from 3.2% to 10.8%, hydro energy grows from 29.8% to 63.5%, and geothermal energy increases from 0% to 2.1% by 2050. While wind energy increases to 42.4%, solar energy grows to 34.0%, hydro energy represents 18.3%, and geothermal energy increases to 5.2% by the same year in the NZE scenario.
- Petroleum derivatives and FG share decreases progressively until levels of 43.7% in the CET scenario and nearly 0% in the NZE scenario by 2050.
- Furthermore, power-to-fuels and pyrolysis-to-fuels produce endogenously the full demand of gasoline, diesel, and LFO by the final year of the transition in the NZE scenario, accounting for 87% and

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13% of those fuels consumption, respectively. Nonetheless, H_2-to-gasoline technology possesses a higher share from 2030 to 2040. Regarding FG, biohydrolysis accounts for 97.5% of that fuel demand, whereas biomethanation technology accounts for the remaining 2.5% by 2050. The shift from biowaste to solar and wind energy in the final year is caused by the early decommissioning of synthetic fuel plants and the low cost of renewable power technologies by that time.

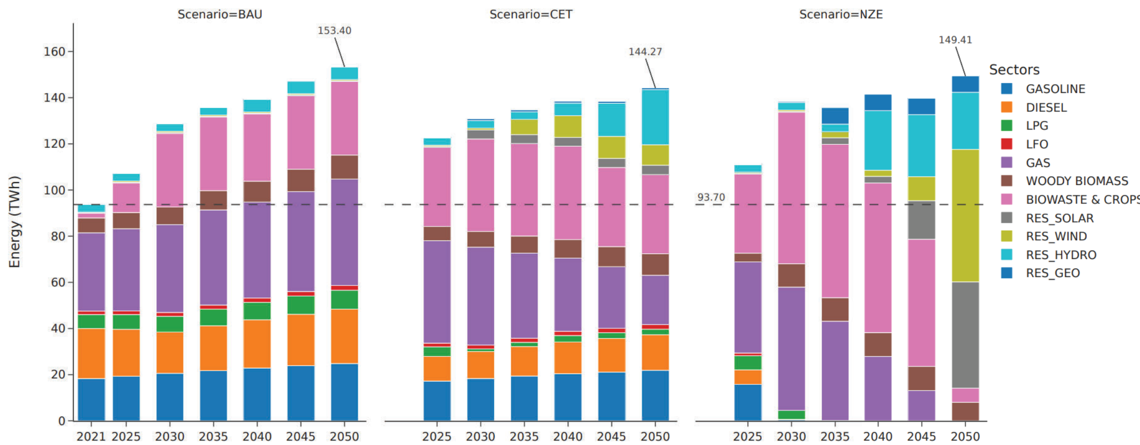

Figure 5: Final energy consumption in Bolivia by resource in the period 2021–2050.

4.3 Technology deployment

In the context of the study, the capacity for power generation increases across all cases, moving from 4.18 GW in the BAU scenario to 11.55 GW in the CET scenario and 50.31 GW in the NZE scenario, as depicted in Figure 6. As described previously, this expansion is attributed to the widespread electrification of end-uses, which elevated the role of electricity as a key energy carrier in all sectors. The ambition to fully decarbonize the national energy system by 2050 necessitates an eightfold increase in the current power generation capacity. So, in the case of the NZE scenario, the augmentation in capacity is predominantly sourced from renewable energies, comprising 22.4 GW from PV systems, 20 GW from wind turbines, 7 GW from hydropower, 0.88 GW from geothermal plants and 0.22 GW from grate-fired biomass-steam turbine. Regarding the CET scenario, which only partially mitigated emissions, electricity generation is still dependent on PV, wind onshore, hydropower, and grate-fired biomass-steam turbine, with 2.0 GW, 3.1 GW, 6.2 GW, and 0.22 GW respectively.

Carbon neutrality in other sectors also involves significant transformations. A systematic shift towards electrification is observed within the passenger transportation sector, with electric vehicles accounting for 71.1% of passenger mobility demand (mostly composed of electric buses) and 37.6% related to freight mobility demand by 2050. Similarly, direct electric heating emerges as the predominant technology for meeting high-temperature heat demands in the industrial sector, representing 99.9% of the sector's requirements, while the rest is mostly covered by FG boilers. For low-temperature heating needs, electricity and solar thermal energy are the main sources, supplying 98.6% and 1.4% of the demand, respectively. The commercial sector also relies heavily on electricity for cooking, water heating, and mechanical energy demands. Significant shifts are also noted in sectors such as agriculture, mining, and fishing, where there is a transition from diesel-powered machinery to electric alternatives. The non-energy sector's needs are predominantly met by biomass (72.1%) and LFO (27.9%). Moreover, the widespread adoption of high-efficiency LED lighting across all sectors marks a crucial step toward enhancing energy efficiency.

4.4 Cost assessment

The cost assessment considers the investment cost, fixed operational and maintenance (O&M) cost, and fuel cost. Figure 7 shows these values per scenario. The total expenses for the BAU, CET, and

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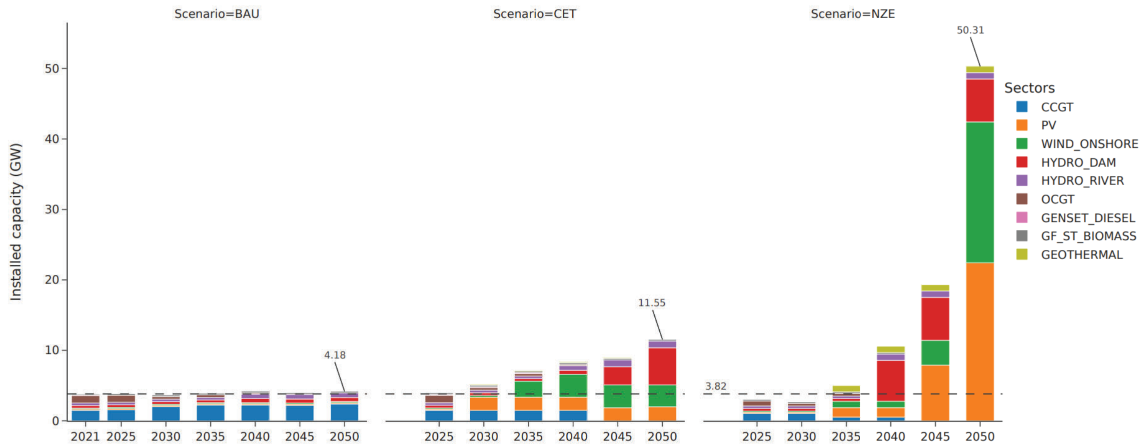

Figure 6: Installed power capacity by technology in the period 2021–2050. Electricity generation experiences an expansion of renewable technologies in the CET and NZE scenarios.

NZE scenarios are estimated at 148.59 billion €$_{2021}$, 145.70 billion €$_{2021}$, and 106.03 billion €$_{2021}$, respectively. Investment costs account for the largest share of total costs in all scenarios: 71.89 billion €$_{2021}$, 76.21 billion €$_{2021}$, and 65.47 billion €$_{2021}$, respectively. Fuel costs are the second largest expense. The BAU scenario has the highest fuel purchases with 45.07 billion €$_{2021}$, while the CET and NZE scenarios present costs equal to 36.88 billion €$_{2021}$ and 14.62 billion €$_{2021}$, respectively. Regarding the O&M costs, the CET scenario leads to a higher expense (32.61 billion €$_{2021}$), and the BAU and NZE scenarios require reduced operating costs (31.63 and 25.94 billion €$_{2021}$, respectively). The lower total costs during the transition from the CET and NZE scenarios are related to the inclusion of bioenergy in the system, which saves money from importing fossil fuels, especially gasoline and diesel. Moreover, using more efficient technologies across different sectors reduces energy requirements and, consequently, less fuel and resources.

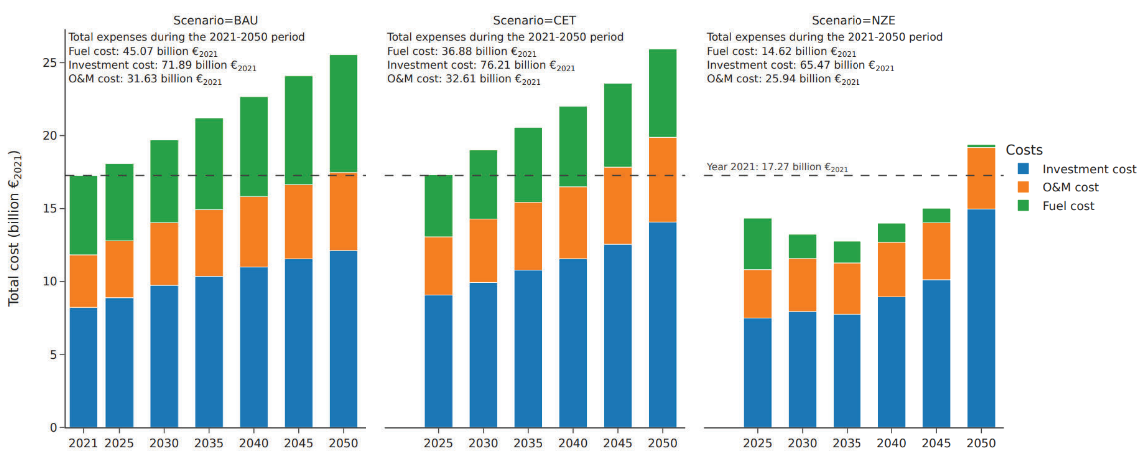

Figure 7: Total costs by scenario by category in the period 2021–2050. The yearly system cost shows the shift from non-renewable to renewable resources in the NZE scenario.

5 CONCLUSIONS

The study has presented long-term transition pathways toward a decarbonized energy system in Bolivia using an open-source optimization methodology. First, a characterization of the energy demand was performed in order to disaggregate and project the end-use demands, that were used as input for the

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model. Then, three scenarios over 2021–2050 were built, representing the business-as-usual state, a decarbonization pathway based on the few planning strategies presented by the government, and a net zero emissions scenario. Finally, the *EnergyScope Pathway-BO* model was implemented to assess these scenarios and analyze the outcomes in terms of emissions, energy mix, technology deployment, and costs. The detailed description of the modelling framework, input data, and assumptions provide a baseline for further research in Bolivia or other developing countries.

The findings revealed that transitioning to a decarbonized energy system in Bolivia offers multiple benefits over maintaining the status quo. Notably, the NZE scenario established that the adoption of more efficient processes could reduce energy demand by approximately 3%, thereby improving the nation's energy intensity. Additionally, reducing GHG emissions lowers carbon intensity, aligning Bolivia with its Paris Agreement obligations. The replacement of fossil fuels can strengthen national energy sovereignty by eliminating the need for diesel and gasoline imports. Moreover, this transition can yield cost savings across fuel, O&M, and investments.

The CET scenario showed the necessity of an integrated policy as huge transformations through all energy sectors must happen to materialize to reach a low-emissions society. Therefore, stakeholders should extend and enhance their studies for long-term planning, considering renewable power generation, electrification of end-uses, new technologies, synthetic fuels, and energy efficiency measures, which are critical for the decarbonization pathways.

In order to effectively tackle the challenges and seize the opportunities identified in this research, part B further refines the scenarios described in this paper by using the *PyPSA-Earth* model to describe the electricity sector's transition accurately. Its approach enables a detailed examination of the hourly generation dispatch and the transfer capacity of the transmission lines using the electricity demand.

Future research endeavors should prioritize the improvement of the geographical and technical detail of the other sectors, and the quantification of uncertainties that significantly impact energy system planning and analysis to improve the accuracy and reliability of the model. These uncertainties include but are not limited to, the costs associated with emerging and existing technologies, fluctuations in fuel prices, the inertia in adopting electrification processes in the different sectors, and the availability of technologies in the market. Additionally, to enhance the robustness of energy system optimization in developing countries, it is imperative to incorporate a comprehensive assessment of additional parameters beyond conventional metrics. These parameters should include land use, job creation, and other key factors that directly influence the feasibility and impact of implementing energy conversion pathways. Such a multifaceted approach, grounded in multicriteria decision analysis and multi-objective optimization, ensures a holistic evaluation of potential strategies, taking into account the socio-economic and environmental dimensions critical to sustainable development in these regions.

NOMENCLATURE

Abbreviations

BAU	Business-as-usual
CET	Conservative Effort Towards Transition
DS	Diesel
EL	Electricity
FG	Fossil gas
GS	Gasoline
HW	Hot Water
Irrig	Irrigation
O&M	Operation and maintenance
LEs	Large enterprises
Mach	Machinery
MSMEs	Micro, small and medium-sized enterprises
NZE	Net Zero Emissions
SUV	Sport utility vehicle
WD	Biomass

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