

Supporting data and scenario assumptions for: A bi-directional soft-linking method for a Whole Energy System Model and a Power System Optimization Model.

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

The supplementary material provided here offers some additional information supporting the main findings presented in the paper. It extends the characteristics and considerations used for the scenario formulation, and complementary results of the transition aspects of the energy system. This material is intended to provide some additional insights into the analytical procedures and assumptions underlying the main text.

1. Case study

1.1. Scenarios

This study defines two distinct scenarios, including the Existing Policy Implementation (EPI) and the Net Zero Emissions (NZE). The key input parameters for this analysis, including resource prices and availability, technology costs, efficiencies and lifetime, and end-use demand trends, were adopted from a previous study [1], which established a complete database for the Bolivian energy system. The EPI scenario integrates governmental policies as outlined in the electric expansion plan of the National Interconnected System (SIN) [2] and the latest update of Bolivia’s Nationally Determined Contributions (NDCs) [3]. Nonetheless, these policy frameworks are limited to projections up to 2030 and do not establish specific targets for GHG emission reductions. The NZE scenario envisions a fully decarbonized energy system by 2050. This scenario incorporates a wide range of technologies to evaluate their potential roles in the future energy mix, assuming a linear reduction in emissions over time. Table 1 summarizes the most important assumptions for each scenario, with data sources indicated.

While both scenarios are designed to explore distinct pathways, it is important to acknowledge that the outputs of the model are sensitive to several key assumptions detailed in Table 1. The most influential of these are the future cost trajectories of low-carbon technologies, the projected prices of fossil fuels, and the maximum potentials for constrained renewable resources. For instance, the competitiveness and deployment rate of PV, wind, and battery storage are highly dependent on their investment cost projections. A more rapid cost reduction than assumed would likely accelerate their adoption in the NZE scenario. Similarly, the economic feasibility of the decarbonization pathway is sensitive to the evolution of international fossil fuel prices; higher prices would increase the cost-competitiveness of renewable alternatives. The fixed price assumption for fossil gas represents a significant uncertainty. Finally, the upper limits imposed on resources such as biomass, geothermal, and hydropower act as critical system constraints. Should these potentials be lower than estimated, the model would need to deploy other, potentially more expensive, technological solutions to meet the NZE target, thereby increasing the total system cost.

2. Results and discussion

2.1. Scenario modelling results

Results from the method implementation, independently of the scenario, show that the bidirectional linking will be capable of providing an intermediate point for the expansion of the power system, which takes into account the implications of the transition in neighboring sectors inside the energy system and the caveats of a more detailed power system representation. In this sense, the composition of the resulting

Table 1. Summary of assumptions and inputs for the EPI and NZE scenarios

Parameter	EPI scenario	NZE scenario
Energy vectors	Diesel, Gasoline, LFO, LPG, Fossil gas, biodiesel, bioethanol	EPI + H ₂ and synthetic fuels
Fossil fuel prices	Projected international values (Diesel, gasoline, LFO and LPG) and fixed historical values for fossil gas, firewood and biomass/energy crops [1]	
Discount rate	Constant 12% value for the entire period based on values considered in national reports [4]	
Historical installed capacity	Electric expansion plan up to 2026 [2], then open to optimization	
Power generation mix	CCGT, OCGT, diesel genset, biomass, solar PV, wind, hydro, geothermal	EPI + Fuel cell
Technology efficiencies	Based on Bolivian National Interconnected System [1]	
Storage mix	Fossil fuel storage, electric car batteries	EPI + lithium utility-scale batteries and H ₂ storage
Geothermal limit	Maximum capacity of 980 MW based on South American potential assessment [5]	
Biomass limit	National plans until 2026 [2]	Maximum capacity of 2470 MW based on agro-waste availability [6]
Hydro expansion	Planned expansion until 2026 (864 MW RoR, 6077 MW Reservoir), excluding exportation megaprojects [7]	
Line capacities	Brownfield expansion based on GeoBolivia [8]	
Wind/PV resource availability	From Renewables.ninja datasets [9, 10] and Copernicus Climate Change Service data sets [11]	
Hydro capacity factors	Based on historical inflows and extrapolated [12]	
Transport mix	Fossil fuel vehicles, electric cars/buses	EPI + H ₂ vehicles and electric train option
Lighting share	Regional surveys [13]	Open to optimization
Public lighting share	NDC goals [3]	Open to optimization
Low-temperature heat demand share	Based on local trends [14, 15]	Open to optimization
Bioenergy mix	Bioethanol, biodiesel plants	EPI + synthetic fuel plants
Bioenergy potential	Current production [16, 17]	Max. expected production [18, 19]
Emission factors	IPCC reference values for fossil fuels [20] and IEA values for geothermal [21]	
Emission limits	No reduction targets	Linear decrease to net-zero

power systems tends to present slight deviations compared to the modelling results if the systems are studied with an isolated model. Table 2 and Table 3 present the resulting capacity expansions and final energy production for the EPI and NZE scenarios in 2050, comparing EnergyScope-BO and PyPSA-BO runs in isolation, and the resulting mix for with the bidirectional linking method.

Table 2. Resulting capacity expansion and final energy production for the EPI scenario in 2050

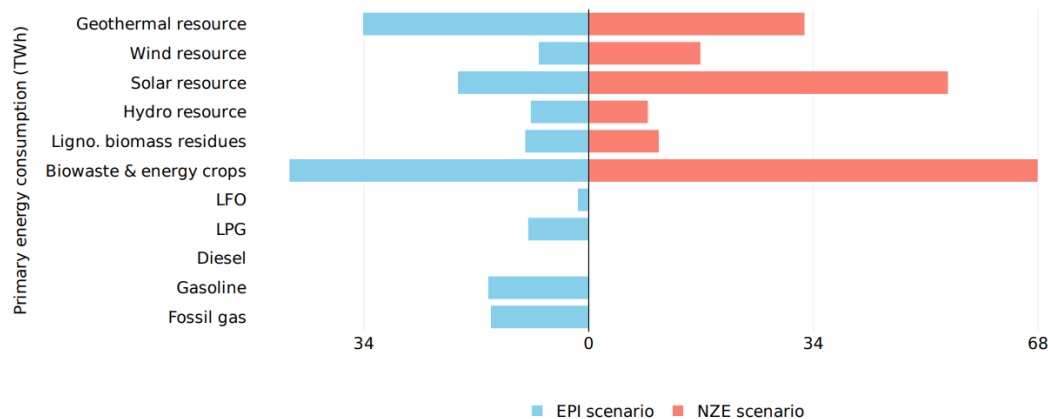
EPI	EnergyScope-BO - First run (no feedback from PyPSA-BO)		PyPSA-BO - First run (no restrictions from EnergyScope-BO)		Linking method - Final run (after convergence - 5 loops)	
	Capacity [MW]	Generation [MWh]	Capacity [MW]	Generation [MWh]	Capacity [MW]	Generation [MWh]
Biomass	744	1581393	2490	19768804	2220	3220242
Diesel	637	27069	1944	83902	545	7249
Geothermal	935	7884702	261	2116142	935	8171720
CCGT	118	73549	161	319786	608	30202
OGCT	25	9786	1512	898917	252	7352
Wind onshore	6108	15973939	147	463942	3297	7594288
PV	8666	17762468	9939	18870421	10788	19730314
Hydro dam	1295	4149898	1295	4499410	1295	4500097
Hydro ror	864	4477703	864	4860011	864	4765837
Total	19392	51940507	18613	51881335	20804	48027301

Table 3. Resulting capacity expansion and final energy production for the NZE scenario in 2050

NZE	EnergyScope-BO - First run (no feedback from PyPSA-BO)		PyPSA-BO - First run (no restrictions from EnergyScope-BO)		Linking method - Final run (after convergence - 2 loops)	
	Capacity [MW]	Generation [MWh]	Capacity [MW]	Generation [MWh]	Capacity [MW]	Generation [MWh]
Biomass	99.6	15161	6015	46190900	4708	5913941
Diesel	0.3	73	3233	147584	18	159
Geothermal	935	6506515	55	436329	935	7820235
CCGT	118.4	114	389	418393	125	518
OGCT	0.1	65	2178	1042947	4	200
Wind onshore	9053	27894016	149	466453	7044	16879349
PV	24746	52002557	18344	37047682	28657	53969661
Hydro dam	1295	4720138	1295	4499248	1,295	4498893
Hydro ror	864	4477693	864	4849738	864	4638272
Total	37112.6	95616410	32522	95099274	43650	93721228

2.2. Policy implications and transition bottlenecks

Results of the coupled analysis show that primary energy consumption in the EPI scenario reaches 165.92 TWh by 2050, approximately 1.8 times the energy used in 2021. On the other hand, the NZE scenario requires 191.06 TWh to meet the different demands by the same year. While both scenarios exhibit changes in energy sources, the EPI scenario maintains a 25% dependency on fossil fuels by 2050, as illustrated in Figure 1. The absence of diesel consumption in the EPI scenario is attributed to the adoption of biodiesel production under governmental plans. In comparison, the NZE scenario relies on nearly 53% more renewable energy than the EPI, to provide the additional conversion demands required for the production of synthetic fuels or e-fuels used in hard-to-electrify sectors such as industry or transport.

**Figure 1.** Primary energy consumption by energy carrier in the Bolivian energy system in 2050 under the EPI and NZE scenarios. Total demand is 166 TWh for EPI and 191 TWh for NZE

An analysis from the end-use demands and energy carriers, depicted in Figures 2 and 3, highlights significant shifts in energy consumption patterns under the NZE scenario, driven by electrification and renewable energy deployment. In the cooking

end-use, the NZE scenario achieves a 30% reduction in final energy demand compared to the EPI scenario (10.3 TWh) as a result of the electrification in the sector, which uses more efficient technologies. Electricity dominates the energy mix, accounting for 93.5%, complemented by lignocellulosic biomass (4.5%), with minimal contributions from LPG (1.3%) and renewable light fuel oil (LFO) (0.7%). By contrast, the EPI scenario remains predominantly reliant on LPG, which constitutes 85.9% of the energy mix, with electricity and biomass contributing 10.9% and 3.2%, respectively.

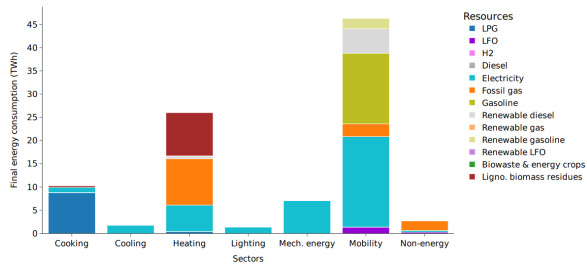


Figure 2. Final energy consumption by end-use and carrier in the year 2050 under the EPI scenario. The total final energy consumption is equal to 96 TWh

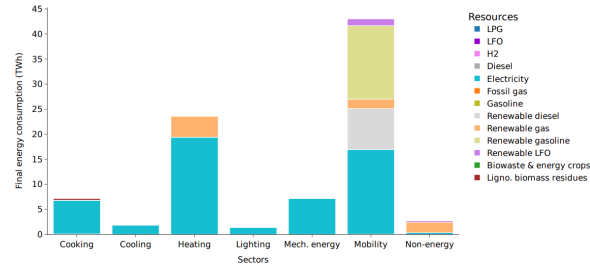


Figure 3. Final energy consumption by end-use and carrier in the year 2050 under the NZE scenario. The total final energy consumption is equal to 87 TWh

The heating services also transition to cleaner energy sources under the NZE scenario, with total energy consumption decreasing by 9.2% compared to the EPI scenario (26 TWh). Electricity accounts for 82.2%, followed by biomethanation biogas (17.7%), and renewable LFO reduced to 0.1% in NZE's energy mix. In contrast, the EPI scenario is dominated by fossil gas (38.3%), with lignocellulosic biomass residues (35.8%), electricity (22.0%), biodiesel (2.1%), LPG (1.4%), biogas (0.2%), and LFO (0.1%) playing secondary roles. The cooling and lighting sectors remain stable in both scenarios, relying entirely on electricity.

Regarding mechanical energy demands, the NZE scenario achieves a modest 0.6% reduction in energy consumption compared to EPI scenario (7.2 TWh), with electricity increasing to 99.8% and renewable diesel representing 0.2%. Under the EPI scenario, electricity comprises 98.0%, while renewable diesel (biodiesel, pyrolysis, and power-to-fuels) accounts for 2.0%.

The mobility service shows a 7.1% reduction in energy use under the NZE scenario in comparison to the other one (46.3 TWh), with a more diversified energy mix: electricity (39.3%), renewable gasoline (34.1%), renewable diesel (19.0%), biogas (4.3%), renewable jet-fuel (3.2%), and hydrogen (0.1%). By contrast, the EPI scenario relies primarily on electricity (42.0%), followed by gasoline (32.8%), biodiesel (11.4%), fossil gas (5.9%), bioethanol (4.8%), and fossil jet-fuel (3.0%).

In the non-energy demands, energy consumption decreases by 0.9% under the NZE scenario compared to the EPI scenario (2.8 TWh), with biogas dominating the mix (76.4%), followed by electricity (13.0%) and renewable light fuel oil (LFO) from biowaste

(10.6%). This is a stark contrast to the EPI scenario, where fossil gas accounts for 76.2%, with electricity (12.9%), LFO (10.5%), and biogas (0.4%) making up the remainder.

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