Energy Transition in Bolivia. Modelling of the Bolivian energy sector to achieve carbon neutrality by 2050

Carlos A. A. Fernandez Vazquez*
Centro Universitario de Investigaciones en Energías
Universidad Mayor de San Simón, Cochabamba, Bolivia
e–mail: carlosfernandezvazquez1992@gmail.com

Thomas Vansighen
Thermodynamics Laboratory
University of Liège, Belgium
e–mail: thomas.vansighen@student.uliege.be

Miguel H. Fernandez Fuentes
ENERGETICA, Cochabamba, Bolivia
e–mail: miguel@energetica.org.bo

Sylvain Quoilin
Faculty of Engineering Technology
KU Leuven, Leuven, Belgium
e-mail: sylvain.quoilin@kuleuven.be

ABSTRACT

The 2018 IPCC special report on global warming indicates that by 2050 all CO_2 emissions on the planet must be neutralized, not to not exceed the 1.5°C global warming. In this context, Bolivia is making efforts in its electric sector, such as increasing the share of renewable energy and decommissioning inefficient power plants. However, these efforts remain limited when compared to the total national energy demand. Currently, more than 80% of internal energy consumption in Bolivia is of fossil origin.

Under these conditions and in the face of the global climate emergency, how should Bolivia respond to the challenge of decarbonizing its energy sector?

To better answer this question, a long-term optimization model of the Bolivian energy sector was developed with OSeMOSYS, considering the national energy demands, disaggregated by fuel and type of consumer. The model has a bottom-up approach focusing on techno-economic variables and aims to determine the most cost-efficient solution to cover the projected energy demands until 2050.

Results show that, in a Business as Usual scenario (BAU), by 2040, CO_2e emissions from the energy sector will practically double compared to 2020 and 96% of energy sources will be fossil fuels. To analyse potential deviations from this trend, four policy-based scenarios are modelled: 1) electrification of energy demands (EED); 2) introduction of carbon taxation (CTI); 3) gradual reduction of fossil fuel subsidies (NSR); 4) implementation energy efficiency measures (EEM).

* Corresponding author

While each of these scenarios have limited effects over the energy system, a synergistic effect is achieved when a simultaneous implementation of their measures is analysed (MP). In this scenario the participation of the electricity in the Bolivian energy consumption reaches 87% by 2050, of which over 96% is produced by renewable sources, and emissions are reduced by 74% in 2050 compared to the BAU scenario. However, while this scenario starts a transition process in the energy sector, it would still not become emission-free by 2050.

Achieving carbon neutrality in the energy sector by 2050 (CN) would require a large investment just to cover capital costs of new powerplants, close to a yearly investment between 2020 and 2050 of 10% of the current national GDP of Bolivia. Given that this value would represent 22 times the investments required in a BAU scenario, complementary measures with other sectors or technologies need to be explored to find more feasible and cost-effective solutions.

KEYWORDS

Energy modelling, Energy systems, Bolivia, Energy Transition, GHG Emissions, Energy policy, Carbon neutrality.

INTRODUCTION

Global warming is the main problem to be solved by humanity in the timeframe of one generation. The relevance of this problem is given by two key factors: (1) the source of the problem are human activities that release a surplus of Greenhouse Gases (GHG) to the atmosphere [1]; (2) the direct impact of this problem is global and will represent the alteration of climate patterns all around the world [2].

IPPC's report "Global Warming of 1.5°C, 2018" exposes the current situation and the imperative necessity to limit the GHG emissions as soon as possible to avoid a situation where the impacts have irreversible effects over the planet [3]. Even though multiple scenarios, the most accepted pathway to limit the increase of the global temperature is based on achieving "carbon neutrality" by 2050 [4]. In such scenario all nations should phaseout their GHG emissions by 2050 or be able to compensate their emissions with alternative technologies [5].

As shown in IPPC's special report, most of the emissions are derived from the use of fossil fuels, which in turn are mainly used in the energy sector [3]. In 2018 the energy sector was responsible for over 76% of the global GHG emissions in the world corresponding to 48.9 $GtCO_2e$ [6]. Therefore, it is imperative that each country takes appropriate measures to ensure the decarbonization of their energy systems. This problem of achieving the energy transition, from fossil fuel sources to renewable technologies, has gained attention and is being studied both in developed countries [7] and developing countries alike [8].

While the approaches used to study the subject can vary widely, the technical viewpoint [9], the economic impacts [10] and the political aspects [11] tend to be the most discussed. These 3 aspects have to be studied in each country to guaranty the feasibility of the transition process and will often tend to find/understand: 1) the optimal technology mix required to get to net-zero emissions; 2) the local conditions and policies needed to facilitate the transition process [12]; 3) and the expected costs of implementation [13].

For the case of Bolivia, depending on the approach, different models have been used to study its energy sector. Short-term dispatch models such as the one developed by Rojas et. al. in 2018 (Dispa-Set) analyse, from a technical point of view, the capabilities of the electrical system to cope with increasing levels of variable renewable energies [9]. Long-term accounting models like the one proposed by Peña et. al. in 2017 (LEAP) explore how national energy demands can develop over time by implementing energy saving and fuel substitution policies [14].

Optimization models, like OSeMOSYS, are based on a techno-economic optimization minimizing total system costs. For particular case of Bolivia, they have been used to analyse opportunities of exporting electricity to bordering countries [15]; to simulate mid-term scenarios of energy transition for Bolivia [16]; or to evaluate the implementation of policies and their impacts on reducing emissions derived from the production of electricity [17].

This paper builds upon these previous studies by extending the scope of the optimization model to other non-electrical sector that would require its electrification. It includes energy demands for various fuels, in addition to electricity, and analyses the implications of including demand-side and generation-side management policies to reduce GHG emissions until 2050 [17].

METHOD

The Bolivian energy sector

Bolivia, located in the centre of Latin America, has a population of approximately eleven million inhabitants and is a net exporter of energy at the regional level, mainly due to its large natural gas reserves [18]. According to data from the latest national inventory of carbon emissions [19] and the third national communication [20], the energy sector is the second largest contributor to total greenhouse gas emissions in Bolivia after the Agriculture, Forestry and Other Land Use (AFOLU) sector.

The maximum primary energy production reached 150 kboe in 2014, year in which the Natural Gas (NG) exports were highest. These exports are currently decreasing due to the depletion of the natural gas reserves [21]. In 2020, NG exports were 60% of the national energy production and NG, in general, represents a total of 80.2% of the national primary energy production. The rest of the primary energy production is attributed to petroleum derivatives (12.4%) and renewable energy (7.4%) [18].

Total energy consumption in 2020 in Bolivia was of 43 kboe, of which shares were 24.2% for Diesel (DS), 22.0% for NG, 29.4% for gasoline and other fuels / Heavy Fuels (HF), 12.4% for Biomass (BM) and 12% for electricity (EL) [18]. When expressed by sectors, the transport sector is the main energy consumer in Bolivia with a share of 49.0%, followed by industry 25.3%, residential 17.3%, commerce and services 3.8% [18].

In 2020, the power generation system in Bolivia (National Interconnected System or SIN) had a total 3318.8 MW installed capacity. This capacity was composed by a share of 72.8% of thermal power plants, mainly NG simple (steam) cycles and combined cycles, and 27.2% of renewable power plants, mainly hydraulic with small quantities of wind and solar energy [22]. For the same year a total amount of 8897.3 MWh was generated, of which 63.3% was provided by conventional NG plants, 32.3% was provided by hydroelectric power plants and the rest by a mix of solar, wind and biomass power plants [23].

To this date, the electrical sector has been the one making the most efforts to reduce the dependency on fossil fuels. These efforts have been considered and planned in national development plans, such as the “Optimum Expansion Plan of the National Interconnected System 2012-2022” [24] and the “Electricity Plan of the Plurinational State of Bolivia 2025”

[25], ratified by international documents such as the Bolivian Nationally Determined Contributions (NDC) [26] and presented to the United Nations Framework Convention on Climate Change (UNFCCC) in order to comply with the Paris Agreement [27]. However, most of these plans are now outdated and require revisions accounting for the recent changes in the energy sector.

Currently, an update of the NDC under development and will be presented in 2022, together with a new expansion plan for the electrical sector. The latest planning document available for the development of the sector is the "Economic and Social Development Plan 2021-2025" [28]. Even though this document presents a short-term planning horizon, it provides some interesting goals for the energy sector that are expected to be continued overtime:

- Industrialization of production plants of Hydrotreated Vegetable Oil, biodiesel and synthetic diesel to replace up to 43% of diesel imports (goal 2.1.2.1);
- Implementation of train lines and other electric transport systems (cable-cars) to improve transportation of passenger and commercial loads (goals 3.3.3.1, 3.3.5.1, 3.3.5.2) across Bolivia;
- Exploration and exploitation of new hydrocarbon fields to provide internal and external demands (goals 4.1.1.1, 4.1.1.2, 4.1.2.1);
- Increase up to 75% the share of renewable in electricity production (goal 4.3.1.1).

These goals and trends for the future are sensible but need to be supported by longer-term planning efforts and by quantitative analyses ensuring proper energy balances in all sectors. The present work is a first attempt in that direction.

General characteristics of the model

The Open-Source Energy Modelling System (OSeMOSYS) [29] is used as the modelling tool for this analysis and builds upon previous works more focused on the electricity sector [17]. In this study, the Model Management Infrastructure (MoManI) and the open-source solver GLPK were used to develop the model structure, solve the linear programming problem in each scenario and to visualize the results [30].

The model is expressed as a linear programming problem, with its objective function, sets, parameters, constraints and variables. The short-code equation used as the objective function in the model (OF) is presented below:

$$Minimize\ OF_{Cost}:$$

$$\sum_{y,r,t}^{YEAR,REG,TECH} \left(\begin{array}{c} \frac{\left(\left(\sum_{YY}^{YEAR} NC[r,t,yy] + RC[r,t,y] \right) * FC\,[r,t,y] \right)}{\left((1+DR[r])^{(y - min(yy) + 0.5)} \right)} + \\ \frac{\left(\sum_{l,m}^{TS,MO} RA[r,l,t,m,y] * YS\,[l,y] * VC\,[r,t,m,y] \right)}{\left((1+DR[r])^{(y - min(yy) + 0.5)} \right)} + \\ CC[r,t,y] * \frac{NC[r,t,y]}{\left((1+DR\,[r])^{(y - min(yy))} \right)} + \\ DEP[r,t,y] - DSV[r,t,y] \end{array} \right) \quad (1)$$

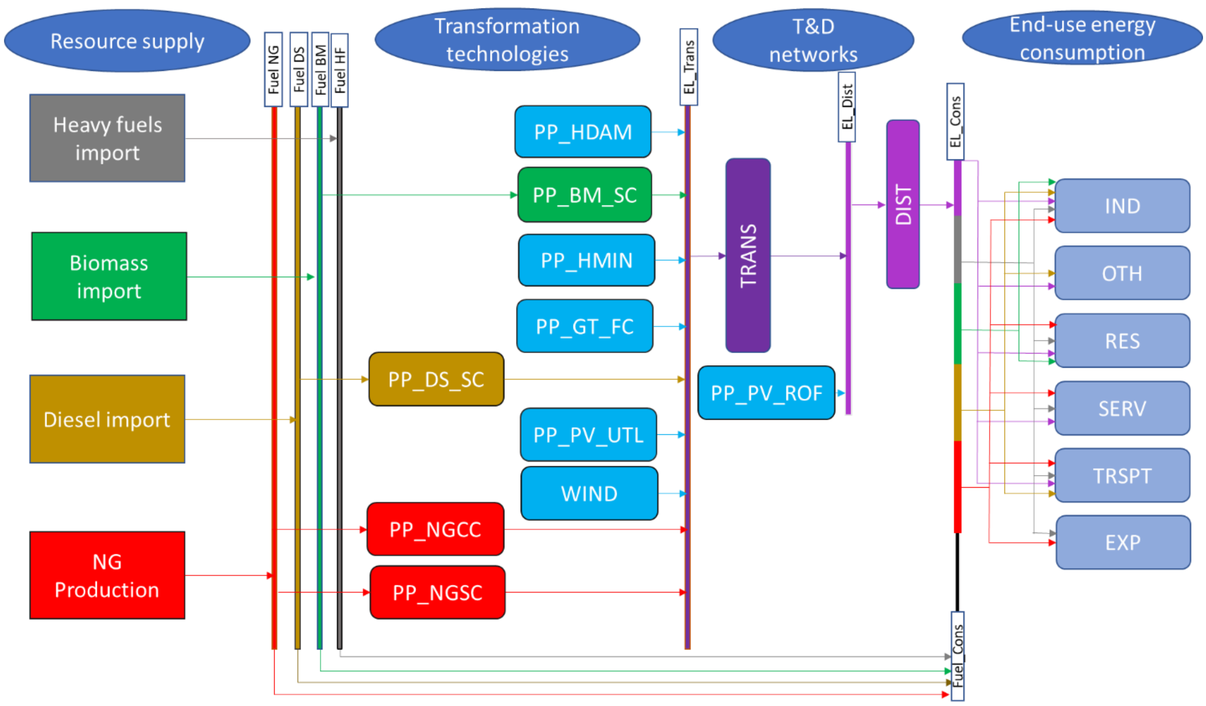
OperationalLife = OL	FixedCost = FC	VariableCost = VC
NewCapacity = NC	RateOfActivity = RA	ModeOfOperation = MO
ResidualCapacity = RC	YearSplit = YS	TimeSlice = TS
DiscountedTechnologyEmissionsPenalty = DEP	DiscountedSalvageValue = DSV	CapitalCost = CC

The objective function is the total accumulated costs required to satisfy exogenous energy demands in each defined time period. Costs in the objective function include capital costs linked to new investments, fixed and variable operation costs of technologies and costs related to emission penalties. For the sake of transparency and reproducibility, the model and the input data are released under open licenses and are in Zenodo (doi: 10.5281/zenodo.6419675).

Model structure and referential energy system

The model developed Bolivia as one single node, isolated from other countries in terms of electrical connections, which is currently the case. A long-term analysis (up to 2055) is run with a yearly time step. Additionally, each year subdivided into 6 time slices corresponding to seasons (summer and winter, 3 months each, and intermediate seasons, 6 months); and day (6:00-17:59) and night (18:00-5:59) cycles. This time resolution configuration is defined based on the results obtained in previous work [16] in order to represent changes in availability of resources, such as hydropower (seasonal) and PV or Wind (daily), and limit the solving time of the model now that additional technologies and fuels are included.

The baseline model for Bolivia is built upon the characteristics of the national energy demands [18] and the current power generation system [31]. Figure 1 presents the relations between fuels (lines) and technologies (boxes) considered in the model.



Power Generation Technologies

PP_NG_SC	natural gas simple cycle	PP_PV_UTL	PV plants
PP_NG_CC	natural gas combined cycle	PP_PV_ROF	PV roof
PP_DS_SC	diesel simple cycle	WIND	wind farms
PP_BM_SC	biomass simple cycle	PP_HDAM	dam hydropower
PP_GT_FC	geothermal flash cycle	PP_HMIN	Run-off hydropower

Figure 1. Referential energy system for Bolivia - Relations between fuels and technologies.

In the first phase "Resource supply" 4 technologies that provide the availability of fuels in the system are defined. These technologies are all producing specific fuels and are connected to either the end-of-use sectors or to energy conversion technologies. The second stage

“Transformation technologies” considers the technologies (power plants) used to produce energy in the form of electricity divided as conventional and renewable technologies. The electricity is then transmitted and distributed in the third stage “T&D networks”. Finally, the “End-use energy consumption” stage represents all the consumer sectors in the energy system and their energy demands.

For each of these technologies a set of parameters is defined to describe their operational characteristics and cost-competitiveness. Technical parameters include power plant efficiencies, operating lifetimes, capacity factors and availability factors. Economic variables consider the capital cost of new investments and operating costs (fixed or variable) for each technology. These values are estimated based on historical data of projects, executed [32], under development [33] or under study [34], from ENDE, the national electric company in charge of generation and transmission of electricity. In the case of fossil fuel supply technologies, NG production is defined by exploitation and production process presented by Chavez et. al. [21] and the values used in previous models [17]. For DS and HF, given that they are mostly imported [18], and BM, with no formal large-scale production, costs are reflected directly by their prices at the end-use consumption level.

In addition to these variables, the model also considers GHG emissions in the form equivalent carbon dioxide (CO_2e). The model considers life-cycle emission activity ratios for the technologies that emit during operation, and technologies that indirectly produce a surplus of GHG emissions, such as hydropower [35]. For the fossil fuel-based technologies, these emission activity ratios are based on the carbon emissions factors from the IPCC guidelines [36]. For the hydroelectric plants, a literature review was conducted to define values of GHG emissions linked to these technologies [37], especially in tropical reservoirs [38], where emissions are expected to be higher [39]. While values can vary between ranges of 0.5 - 152 gCO_2e/kWh to 1300 - 3000 gCO_2e/kWh [40], for this study, in order to be conservative, values in the lower range for plants were used, based on plants on Brazil, given that in Bolivia there is still a lack of local studies that can give more precise information.

Energy demand projections

The model considers the end-use consumptions for Transport, Residential, Industry, Commercial and Others. For each sector, 5 key fuels are defined based on their representativeness: Electricity, Biomass, Natural Gas, Diesel and Heavy Fuels (other liquid hydrocarbon-based fuels such as Gasoline, GLP, Kerosene, etc.).

Projections of energy consumption in Bolivia used information contained in the national Energy Balance Reports from 2000 – 2020 [41], [18]. A Simple Moving Average calculation on the yearly increments, with a time frame of 20 years, was selected to project the energy demands for each fuel in each sector from 2021 to 2055. These projections are consistent with international data bases [42], prospective energy demands for Latin America until 2040 [43], the short-term Bolivian projections [44] and projections in previous work [16].

An incremental trend can be expected in all the energy demands, however slightly different growth rates are expected for each sector and fuel based on the historical data. These energy demands are introduced to the model as the main exogenous input and characterize the development of the energy system in a Business-as-Usual (BAU) scenario where no additional changes are made after 2020.

For the model a time horizon from 2014 up to 2055 is considered with 3 specific periods: 1) An historical period corresponding to available observations, between 2014 and 2020. 2) The analysis period of 30 years, between 2021 and 2050 3) A look-ahead period which corresponds to an additional 5 years projection, between 2051 and 2055, included in the model to avoid end-of-horizon effects.

BAU and alternative scenarios

The BAU scenario is constructed based on the current conditions of the system [22], its expected development over time if no additional changes are made [16] and the current development plans, which are expected to be implemented [28].

To examine deviations from the BAU, a mix of policy-driven scenarios focused on generation-side and demand-side management measures [17], as well as goal-based scenarios to achieve carbon neutrality [16], are defined and compared:

- Two generation-side management scenarios are analysed assuming policies for NG Subsidy Reductions (NSR) and Carbon Tax Implementation (CTI).
- Two demand-side management scenarios are defined, one assuming the implementation of Energy Efficiency Measures (EEM) and the other achieving a complete Electrification of Energy Demands (EED) in Bolivia.
- One scenario with Mixed Policies (MP), based on the implementation of both generation and demand-side policies.
- One goal-based scenario based on the MP scenario and emission limits to achieve Carbon Neutrality (CN) in 2050.

EEM Scenario. Based in on international experiences, this scenario considers changes in the energy intensity of different sectors. This is considered as the first measure that should be implemented in any energy system and aims to achieve a general reduction in the demand for energy. In Ecuador, an energy efficiency program was carried out [45] proposing changes in the residential, industrial and public sectors achieving quite encouraging results [46]. In European countries, the report of the United Nations European Economic Commission [47] presents a summary of the main practices and measures related to energy efficiency and their results, in households, transport and businesses. In Asian countries, there is a list and agenda of energy efficiency policies that propose both the reduction of consumption and the inclusion of minimum operating standards in the different consumption sectors [48].

The study conducted by Peña et.al. in 2014 evaluates the development of energy demands in the Bolivian energy system over time in LEAP [14]. Its results show that an “energy savings scenario” could reduce the overall consumption by 8.5% in relation to a reference scenario projection, between 2012 and 2035. However, it also proposes that this achieved reduction does not encompass the complete potential of energy efficiency measures and there are a wide array of additional technologies and processes that can be exploited. Building upon these results, efficiency implementation goals are set to achieve a reduction of 20% of energy consumption in every sector until 2050.

EED Scenario. This scenario assumes a rapid electrification process for all sectors, taking into account that, in many cases, electrical alternatives are already available. In most cases, switching from fuels to electricity is a matter of cost-reduction and/or applying incentives that make electric appliances more attractive than conventional alternatives [49]. Such is the case of Norway and its policies to implement electric vehicles [50], which positioned them as leaders in the electrification of the transport sector [51].

However, it is important to note that this scenario is relatively optimistic since some sectors, such as the steel production, cement industry or aviation, remain hard to electrify. To simulate the electrification of the energy demands, given the complexity and variability of end-use technologies, a simplified replacement of fossil fuel demands with electricity based in consumption rates es considered. It is expected that until 2050 all the fossil fuels demands will be replaced with electricity.

To represent each demand in the sectors and estimate the replacement rates, based on their energy consumption, the technology with the largest participation to the overall demand is considered and replaced by their electrical counterparts: For the Transport sector, conventional private cars based on NG, DS and HF are considered as the main consumers [52], replaced with standard electric cars [53]; For the Industry sector, the energy demands are mostly related to heating requirements, replaced with their equivalent electrical technologies (heat pumps, boilers, electrical ovens, etc.) [54]; For the Residential demands, cooking represents the main energy demands both in NG and HF, replaced by electrical stoves [55]; For the Commerce and Service sector the main energy demand of NG and HF are heating systems, replaced by electric heating [56]; For the Others sector DS demands are mostly defined by its use in vehicles used for productive process or large transport and are considered to be replaced by their electric counterpart [57].

NSR Scenario. Natural gas is currently heavily subsidized in Bolivia. The electricity sector benefits from a differentiated price defined in the electricity law [58] of 1.3 US$/Mbtu [24], well below international prices [59]. This price difference represents a loss of up to 216.4 million US$ in 2018, taking the form of an opportunity cost [60] and an artificial high competitiveness of NG-based powerplants [17]. In other countries, technologies such as coal-fired power plants or hydroelectric plants can compete with natural gas and in most regions of the world, renewable energies such as solar or wind are already more competitive [61].

This scenario evaluates the impact of removing fossil-fuel subsidies in the country, gradually increasing NG prices until they reach the ones on international markets. To simulate the reduction of NG subsidies in the model, the variable costs of the NGSC and NGCC technologies were altered based on the projected changes of the NG prices. The model assumes a linear increase of the prices reaching the expected international prices by 2040 [62].

CTI Scenario. This scenario assumes the inclusion of a tax on GHG emissions as an incentive to decarbonize the energy system [63]. This measure is extensively justified in the literature, to the point of existing handbooks on the subject [64], and is usually recommended as one of the most effective measures when regulating and penalizing the environmental impact of large emitters [65]. A reference case is Sweden, with a consistent high carbon tax over time [66] and achieving 137 \$US/tCO_2eq in 2021 [67].

Although market mechanisms such as quotas are preferred in many other countries [68], those implementing such policies currently witness carbon prices varying between 1 and 150 $/tonCO2eq [69]. In the present scenario a carbon tax of 10 \$US/tCO_2eq is imposed starting in 2026, with a yearly increase of 10 \$US/tCO_2eq.

MP Scenario. The MP scenario is built upon all the aforementioned cases and assumes the simultaneous implementation of all the individually-simulated measures: Implementing energy efficiency measures, achieving the electrification of fossil fuel demands, removing the current subsidy on NG and including a carbon tax.

CN Scenario. This scenario builds upon the MP scenario and assumes a maximum limit for emissions in the system instead of a carbon tax. Emission limits are introduced in 2025 and are reduced each year following a linear trend in order to reach 0 emissions in 2050 and onwards.

RESULTS

BAU Simulation

The BAU considers the development of the energy system under the current conditions of the sector, the expected energy demands cost-optimal pathway principle. To characterize the results of the BAU scenario, 3 key parameters are analysed: the evolution of the total energy consumption by fuel; the electrical energy generation mix; the total annual emissions in the energy sector.

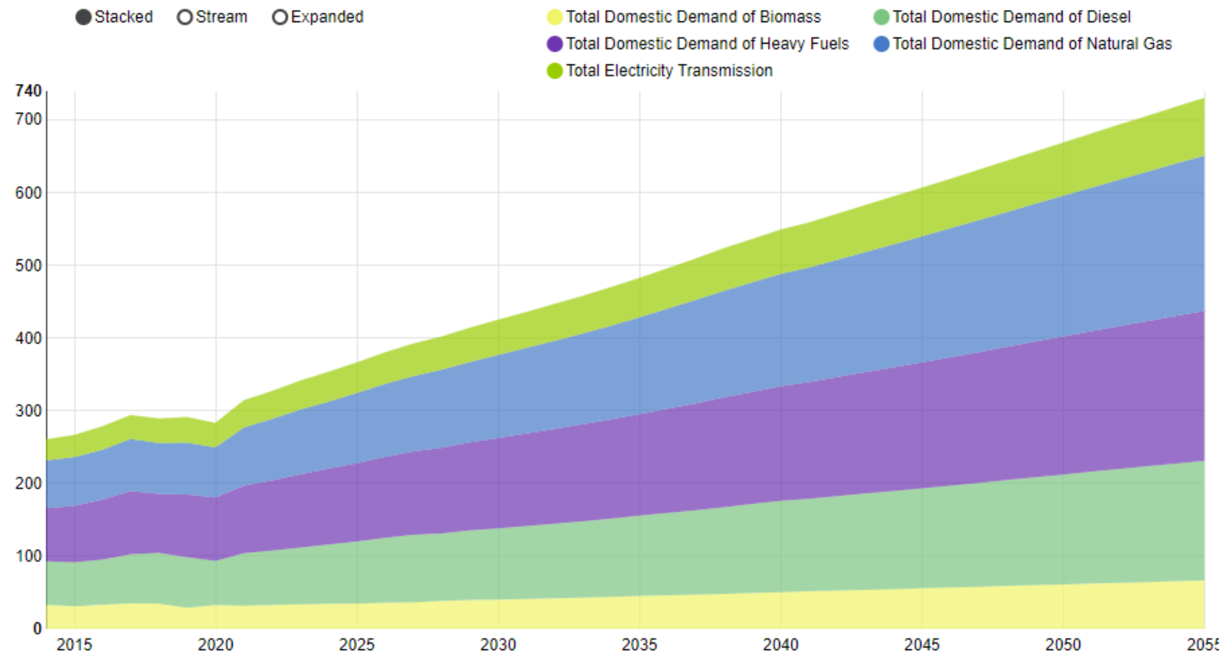


Figure 2. Total energy consumption in Bolivia by fuel in the period 2014-2055 (expressed in PJ).

Figure 2 shows a stable growth over the years as a result of the growth rates used to forecast energy demand and the lack of unexpected events such as the economic turndown caused by the sanitary crisis in 2020. It is also worth noting that the energy demand in the energy sector practically doubles in 20 years and reaches a value of 669 PJ in 2050. From the accumulated energy demand, electricity accounts for 12% in 2020 and 14% in 2050.

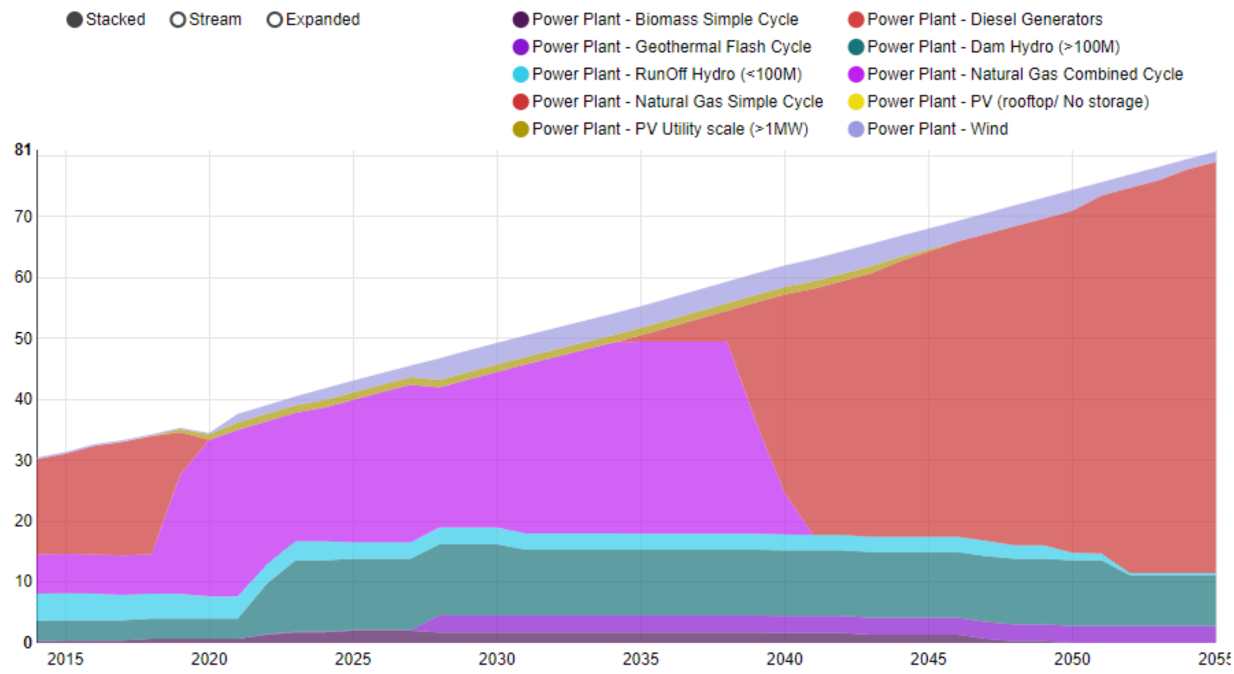


Figure 3. Electrical energy generation mix in Bolivia by technology in the period 2014-2055 (expressed in PJ).

Figure 3 shows the participation of the different generation technologies used to supply of the electricity demand. According to the results, the majority of the demand is covered by simple cycle and combined cycle natural gas thermoelectric plants, leaving a smaller share to hydroelectric plants and a marginal participation to the remaining generation technologies. This behaviour reflects the current situation of the system, when considering the subsidized prices of local fuels for use in electricity generation.

Renewable technologies that are planned or already available in the power generation mix are used at their full capacity but are not considered as for new investments overtime because of their low competitiveness compared subsidized gas. Among the thermoelectric plants, the model has a preferential use for the available and planned combined cycle powerplants, given their higher efficiency and lower operation costs. However, as soon as these powerplants are decommissioned (before 2040), simple cycle plants powerplants are preferred as new investments and take over the generation mix. This is another consequence of current subsides, which are high enough to favour older, less efficient gas generation technologies, due to lower investment costs.

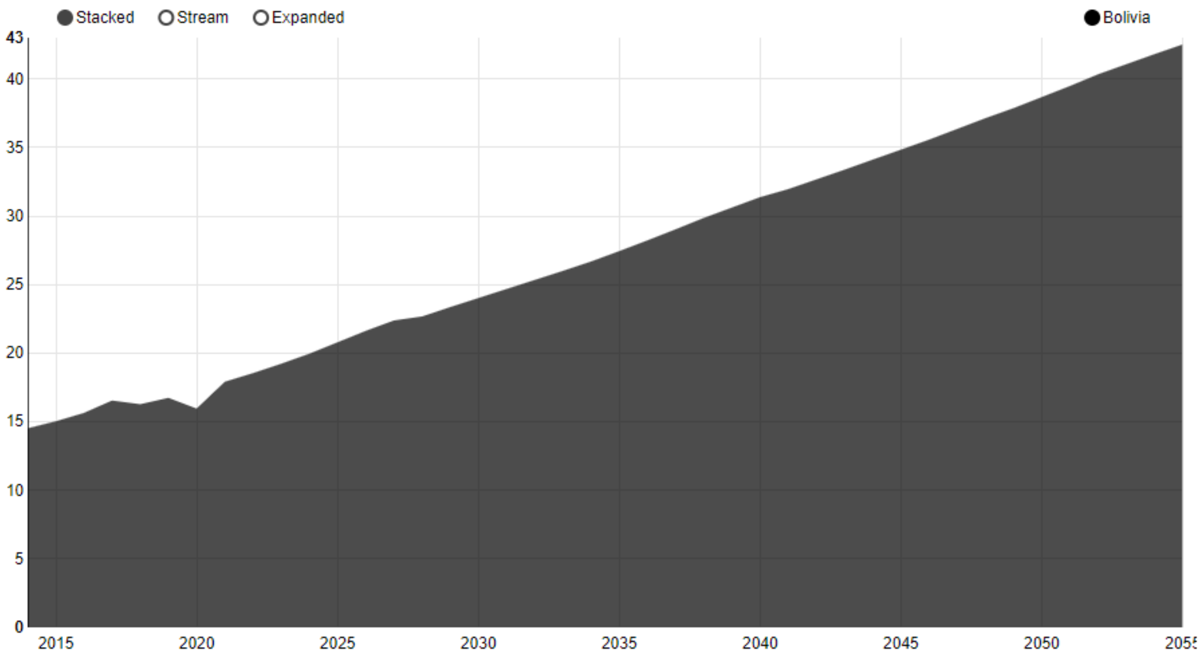


Figure 4. Total annual emissions linked to energy consumption in Bolivia in the period 2014-2055 (expressed in $MtCO_2e$).

Finally, the carbon emissions associated with internal demand of the energy system are shown in Figure 4. The results show a clear trend of sustained growth throughout the analysed period, with a total of 15 $MtCO_2e$ in 2020 and almost 39 $MtCO_2e$ by 2050, consistent with the trend of sustained use of fossil fuels. To estimate these values, the emission factors associated with the consumption of fuels available in the 2006 IPCC Guidelines for National GHG Inventories were considered [36].

Alternative scenarios

Each of the proposed scenarios is based in a particular set of measures or conditions that modify characteristics of the BAU scenario. By analysing specific modifications in each case (energy demands, fuels used, variable costs or additional penalties), it is possible to represent them as "implemented policies", understand their effects over the system and quantify their impacts.

In all scenario it is assumed that changes are implemented, only after the year 2025, to account for the delay between the development, promotion and adoption of measures/policies in the system. Because of this, effects of the policies are also expected to have a gradual growth on the system. 0Shows a compiled version of the results for each scenario at the end of the analysed period.

Table 1. Simulation results of scenarios for 2050 compared to the baseline values in 2020.

	2020	**2050**						
	Baseline	BAU	EEM	EED	NSR	CTI	MP	CN
Total energy demand [PJ/year]	283.7	669.3	535.4	463.3	669.3	669.3	450.1	450.1
Electricity share [%]	12.0%	10.9%	10.9%	87.1%	10.9%	10.9%	86.8%	86.8%
Renewable electricity share [%]	24.1%	23.3%	28.7%	3.0%	74.8%	60.6%	96.4%	100%
Emissions [MtCO2e/year]	15.0	38.7	30.6	22.2	37.0	37.3	7.8	0.0

Energy efficiency measures result in a direct reduction of energy consumption and a proportional reduction of carbon emissions. They have an impact proportional to the efficiency goals assumed. In the case of the electricity system, by reducing the energy consumption, fewer conventional powerplants are necessary and renewable energy participation is higher because of its lower operation cost.

In the electrification scenario results provide a referential magnitude of changes required in energy system. Given the replacement of other energy demands with electricity, the electrical system undergoes a drastic increase in generation capacity, over 550% compared to the BAU. The total energy consumption is also reduced because of the replacement of conventional technologies by electrical appliances, which have higher efficiencies. Lastly, the energy mix used keeps prioritizing investments in NGSC power plants over the rest of technologies, resulting negligible percentages of renewables in 2050. While emissions still grow over time, a reduction is achieved by the shift from DS and HF demands towards NG (used in the thermal power plants that generate the electricity used).

The subsidy reduction and carbon taxing scenarios both have a null impact on energy demand compared to the BAU. However, they significantly impact the energy production mix. In both cases the power generation gradually includes renewable technologies. However, the NSR scenario shows a direct impact on the competitiveness of natural gas technologies, inducing their replacement with hydropower. The CTI impacts both conventional and hydropower technologies considering only PV plants to replace a share of the energy produced. In both cases the introduction of renewable energy allows significant reductions of GHG emissions in the power system. However, given the low participation of electric consumption in the overall demand, both measures fail to achieve significant reductions in the overall energy system.

In the MP scenario, the mix of EEM and EED measures have a cumulative effect, achieving lower demands than the ones expected individually for either of them. When analysing the electricity system, the CTI and NSR measures provide more restrictive conditions for polluting technologies and allows a higher share of renewables to be implemented. However, the real synergy can be seen in the reduction of GHG emissions. In 2050 a reduction of 79.8% compared to emissions in the BAU or a reduction of 48% compared to the baseline, representing a shift on the emissions trend.

Finally, while the MP scenario starts the transition process towards a more sustainable energy mix with decreasing emissions, it still does not achieve a complete phase-out by 2050. This condition is only achieved in the CN scenario, where a limitation for yearly emissions is fixed. In this scenario, both conventional technologies and hydropower plants will be completely removed from the generation mix. If a complete carbon neutrality is required emitting technologies will need to be replaced, independently of their carbon intensity. This is particularly important to take into account for hydropower in tropical zones where emissions can be generated due to methane emissions that accumulate biomass in their reservoirs.

Feasibility of transition

Results from the MP scenario, embody a set of conditions that would allow the energy system in Bolivia to start transitioning from conventional technologies towards a more renewable, sustainable and carbon-free energy system. However, this transition process would represent major changes in the power generation mix, which should cover an important additional demand. Figure 5 shows the changes that the electrical system should go through in the BAU and MP scenarios.

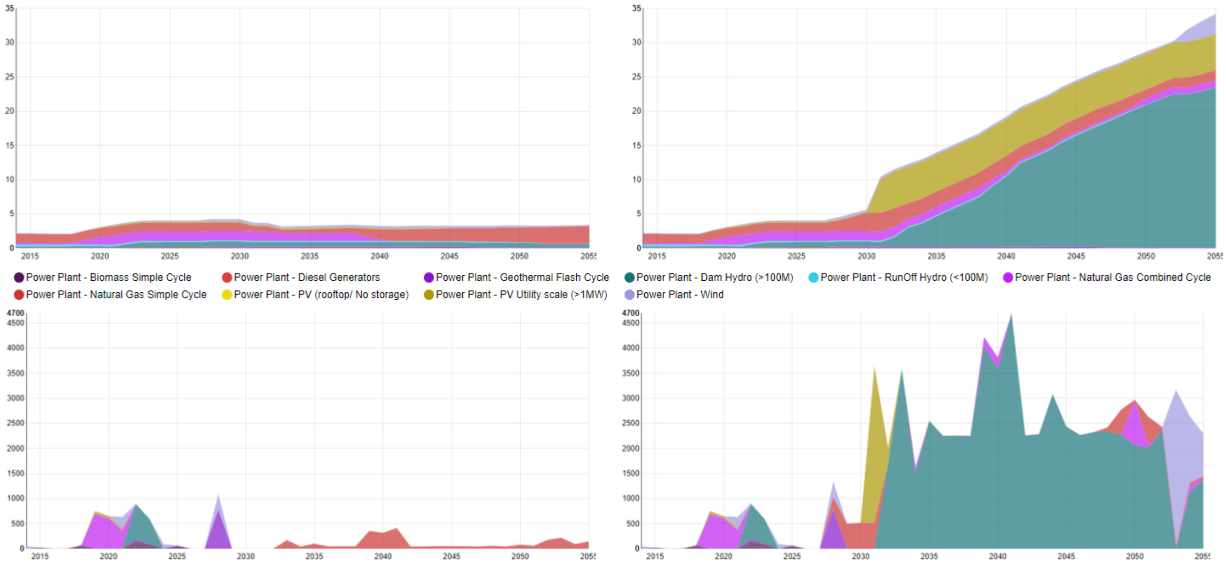


Figure 5. Modelling results of the MP scenario (right) compared to the BAU results (left) for the 2014-2055 period. Total installed capacity in Bolivia by technology [GW] (Top); Total annual capital investment in Bolivia by technology [MM$US] (Bottom).

As a reference, in the BAU the available installed capacity suffers a decrease over time due to the decommissioning old powerplants and the low increase rate of electrical energy demand, reaching a value of 3.3 GW in 2050. Because of this, limited investments in power plants, compared to the 2014-2020 historical values, would be necessary, adding to a total of 4,900 MM$US for investments in new powerplants between 2020 and 2050.

The MP scenario shows a completely different evolution, where installed capacity increases to a total of 28.6 GW by 2050 and the accumulated investments between 2020 and 2050 add up to 57,100 MM$US. This increase in the investment costs, 11 times higher than the BAU scenario, exemplifies the economic impact that the transition process would have in Bolivia and provides a magnitude to consider in future national development plans where the transition process is analysed. Complementary measures like carbon sinks, carbon capture or others should also be considered outside the energy sector to compensate the residual emissions [70].

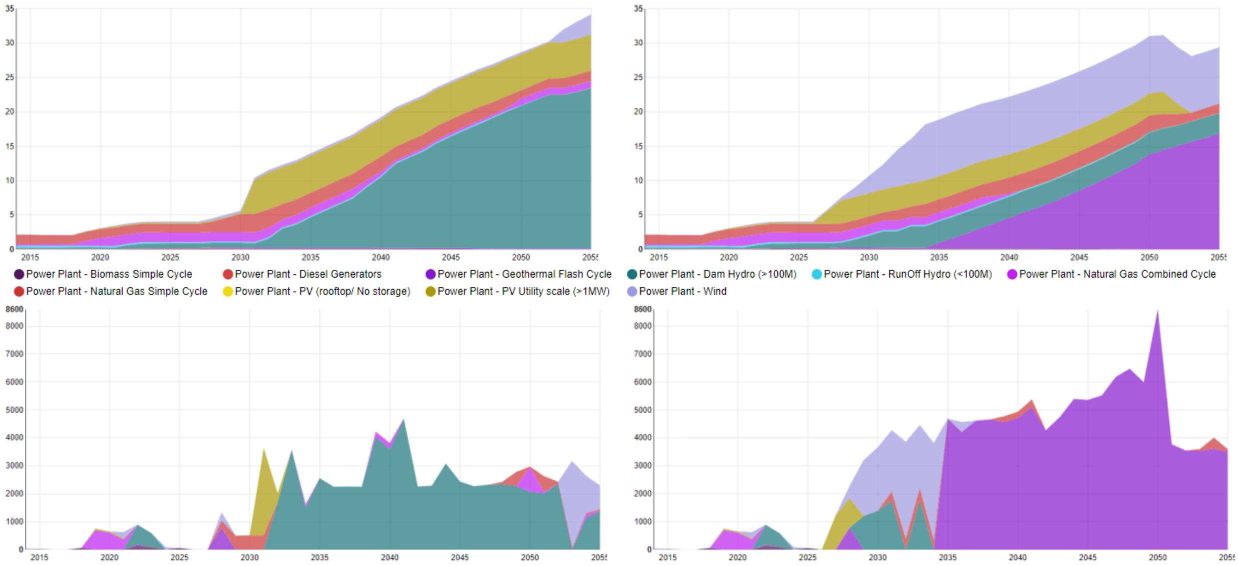


Figure 6. Modelling results of the CN scenario (right) compared to the MP results (left) for the 2014-2055 period. Total installed capacity in Bolivia by technology [GW] (Top); Total annual capital investment in Bolivia by technology [MM$US] (Bottom).

Figure 6 shows small variations between the CN and MP scenarios in regards of the total installed capacity. However, the energy mix is affected by the shift and replacement of CO_2 intensive technologies, with high (NGSC and NGCC) or small (HDAM and HMIN) emissions. These are replaced by geothermal plants for their high availability factor and PV units reduce their participation in the mix and are replaced by wind farms given their higher availability.

This change of technologies comes with a significant increase of investments given the higher costs of geothermal, compared to hydro, and wind turbines, compared to PV. The CN scenario requires an accumulated investment of 110,600 MM$US between 2020 and 2050, doubling the investment needed for the MP scenario or 22 times the amount of the BAU scenario. The differences are explained by the high upfront cost of renewables, which is partly recovered during operation thanks to lower operation costs and lower subsidy expenses for fossil fuels.

Without considering operational costs (variable or fixed), the CN scenario requires yearly investments of over 10% of the national GDP in 2020 [71]. This value represents almost the entirety of public investments for the year 2018, used for the development of infrastructure, social services and the productive sector (energy production, industry and agricultural processes) [72].

DISCUSSION

Results obtained by the model show a mix of alternatives futures of energy system in Bolivia. These are useful to understand, from a broad perspective, what can be expected from the energy sector and its development under the current national conditions (BAU) and the inclusion of popular measures to decarbonize the sector [73], defined as goals (EEM and EED), restrictions (CTI and NSR) or a mix of both (MP and CN). However, it is important to mention that these results have inherent limitations derived from the characteristics and simplifications considered in the model.

Other studies for Bolivia use a higher time resolution for the demands and the availability of resources but these focus on the electrical sector only [15]. In this work, a whole energy system is considered and a lower time resolution is used to maintain a similar CPU time while conserving seasonal and day/night cycles [17]. A low time granularity might impact the results if the simulation improperly captures the requirements for the balancing of renewables. To address this future work will verify and complement these results with a unit commitment and optimal dispatch model to confirm adequacy of the proposed power system [74].

While simple regressions were used to simulate the growth of energy demands based on historical data [75], alternative econometric models based on time-series analysis might be considered [76]. The use of this econometric models (VAR, SARIMA, VECM, etc.) could allow the inclusion of seasonal variations or explicative variables like the GDP [77] to capture the energy demands in the long-term.

At the structural level, the model allows to simulate scenarios with aggregated changes in fuel consumptions for the more relevant sectors in Bolivia. However, the proper representation of activities/services, technologies used and their energy requirements at end-user level is limited. Accounting models such as LEAP could be used in tandem to properly characterize the national demands considering them at service level, with an array of alternative technologies, costs and efficiencies, providing more detailed inputs for the model [14].

Additionally, more conversion routes and fuels, such as hydrogen and biofuels, should be included in the model in order to properly account for all possibilities in terms of sector coupling. This is particularly relevant if more disaggregated demands are provided to the model, such as aviation fuels in transport or cement furnaces in industries, which cannot be easily electrified and are generally considered hard to decarbonize [78].

CONCLUSIONS

This study presents a general overview of the Bolivian energy system and an array of potential development scenarios based on a mix of management and goal-based measures. In a BAU scenario the energy demands would doble in each sector in a period of 20 years, between 2020 and 2040. This trend is accompanied by an increase in GHG emissions, starting at a value of 16 [GgCO2e] in 2020 and reaching a value of 38.7 [GgCO2e] in 2050. Additionally, no significant development of the electrical sector is expected, maintaining a clear preference towards the use of conventional technologies. This is explained by the subsidies in place for the use of NG in electric generation.

Four policy-based scenarios are also constructed in order to simulate the impacts of demand-side management measures, such as energy efficiency goals or electrification of energy demands (EEM and EED), and generation-side measures, such as carbon taxing or reduction of national subsidies (CTI and NSR). While each scenario can achieve impacts over the primary energy demands, the mix of technologies used for electrical generation or the expected emission reductions, only when they are implemented simultaneously structural changes are perceived in the energy system. In this sense, the Mixed Policies scenario (MP) represents a development scenario in which the system transitions towards a more sustainable system, in which expected emissions drop to 7.8 [GgCO2e] in 2050, representing a reduction of 48% in relation to the year 2020 or a reduction of 80% compared to the BAU emissions in 2050.

While the MP scenario manages a significant shift in energy consumption and emissions, it does not achieve the IPCC goal of carbon neutrality by 2050. To achieve this goal, an additional scenario is considered where a yearly carbon emission limit is fixed and reaches 0 by 2050

(CN). While both scenarios are technically feasible, they are linked to very high additional investment costs in order to phaseout carbon emissions.

While the MP scenario would represent an increase of investments of 11 times compared to the BAU, the CN would represent an increase of investments of 22 times compared to the BAU scenario. Achieving carbon neutrality would require yearly investments of over 3,700 MM$US or 10% of the current GDP in Bolivia. Therefore, considering potential carbon sinks in other sectors that could compensate some of the residual emissions should represent a much more feasible and cost-effective solution.

Finally, it is important to highlight that the current model and its results present a simplified version of the energy sector and how it operates. While the presented values can provide a broad understanding of the costs linked to different scenarios, complementary studies and models are required. Econometric models can be coupled for more precise projections of the energy demands, dispatch models can be used to asses technical feasibility in the scenarios and accounting models can be used to better represent the end-use technologies and consumptions in the system. Future research in the area will focus on addressing these limitations and on the soft-linking with complementary models.

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NOMENCLATURE

AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business As Usual
BM	Biomass
CN	Carbon Neutrality
CTI	Carbon Taxing Implementation
DS	Diesel
EED	Electrification of Energy Demands
EEM	Energy Efficiency Measures
GHG	Greenhouse Gas
HF	Heavy Fuels
IPCC	Intergovernmental Panel on Climate Change
LEAP	The Low Emissions Analysis Platform
MoManI	Model Management Infrastructure
MP	Mixed Policies
NDC	Nationally Determined Contributions
NEB	National Energy Balance
NG	Natural Gas
NSR	Natural Gas Subsidy Reductions
OF	Objective Function
OSeMOSYS	Open-Source energy MOdelling SYStem
SIN	National Interconnected System
UNFCCC	United Nations Framework Convention on Climate Change

REFERENCES

[1] J. Houghton, "Global warming," Reports on Progress in Physics, p. 1343–1403, 2005.

[2] IPCC, "Climate Change 2007: Synthesis report," Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, 2007.

[3] IPCC, "Global warming of 1.5°C," IPCC, Suiza, 2018.

[4] J. Chen, "Carbon neutrality: Toward a sustainable future," The Innovation, 2021.

[5] F. Wang, J. Harindintwali, Z. Yuan, M. Wang, F. Wang and S. Li, "Technologies and perspectives for achieving carbon neutrality," The Innovation, vol. 2, p. 100180, 2021.

[6] World Resources Institute, "Historical GHG Emissions," 2021. [Online]. Available: https://www.climatewatchdata.org/ghg-emissions.

[7] G. Resch, A. Held, T. Faber, C. Panzer, F. Toro and R. Haas, "Potentials and prospects for renewable energies at global scale," Energy Policy, pp. 4048-4056, 2008.

[8] M. Venegas, "Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries," Energy Research & Social Science, p. 101716, 2020.

[9] R. Rojas, A. Araoz, S. Balderrama, J. Peña, V. Senosiain and S. Quolin, "Techno-economic assessment of high renewable energy source penetration in the Bolivian interconnected electric system," Proceedings of the 31st ECOS Conference, 2018.

[10] T. Stringer and M. Joanis, "Assessing energy transition costs: Sub-national challenges in Canada," Energy Policy, 2022.

[11] A. Carvalho, M. Rquito and V. Ferreira, "Sociotechnical imaginaries of energy transition: The case of the Portuguese Roadmap for Carbon Neutrality 2050," Energy Reports, vol. 8, pp. 2413-2423, 2022.

[12] T. Schmidt and S. Sewerin, "Technology as a driver of climate and energy politics," Nat Energy, 2017.

[13] A. Sadiqa, A. Gulagi and C. Breyer, "Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050," Energy, pp. 518-533, 2018.

[14] J. Peña, O. Broad, C. Sevillano, L. Alejo and M. Howells, "Techno-economic demand projections and scenarios for the Bolivian energy system," Energy Strategy Reviews, vol. 16, pp. 96-109, 2017.

[15] G. Pinto de Moura, L. Loureiro, G. Peña and M. Howells, "South America power integration, Bolivian electricity export potential and bargaining power: An OSeMOSYS SAMBA approach," Energy Strategy Reviews, vol. 17, pp. 27-36, 2017.

[16] WWF & ENERGETICA, "Modelamiento del sistema energetico Boliviano al 2040 segun metas del IPCC," Cochabamba, 2020.

[17] C. Fernandez, R. Brecha and M. Fernandez, "Analyzing carbon emissions policies for the Bolivian electric sector," Renewable and Sustainable Energy Transition, vol. 2, 2022.

[18] Ministerio de Hidrocarburos y Energia, "Balance Energetico Nacional 2006-2020," La Paz, 2022.

[19] Ministerio de Medio Ambiente y Agua, "Inventario de emisiones de Bolivia: 2002 y 2004," La Paz, 2004.

[20] Ministerio de Medio Ambiente y Agua, "Tercera Comunicacion Nacional del Estado Plurinacional de Bolivia," La Paz, 2020.

[21] M. Chavez Rodriguez and et. al., "Can Bolivia keep its role as a major natural gas exporter in South America?," Journal of Natural Gas Science and Engineering, pp. 717-730, 2016.

[22] AETN, "Anuario Estadistico 2020," La Paz, 2021.

[23] AETN, "Memoria Anual 2020," La Paz, 2021.

[24] Ministerio de Hidrocarburos y Energia, "Plan Optimo de Expansion del Sistema Interconectado Nacional," La Paz, 2012.

[25] Ministerio de Hidrocarburos y Energia, "Plan Eléctrico del Estado Plurinacional de Bolivia 2025," Viceministerio de Electricidad y Energías Alternativas, La Paz, 2014.

[26] Bolivia, "Contribución Prevista Determinada Nacionalmente del Estado Plurinacional de Bolivia," 2016. [Online]. Available: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Bolivia%20(Plurinational%20State%20of)%20First/ESTADO%20PLURINACIONAL%20DE%20BOLIVIA1.pdf.

[27] UNFCCC, "NDC Registry," 2016. [Online]. Available: https://www4.unfccc.int/sites/NDCStaging/pages/Party.aspx?party=BOL.

[28] Ministerio de Planificacion y Desarrollo, "Plan de Desarrollo Economico y Social 2021-2025," La Paz, 2021.

[29] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazilian and A. Roehrl, "OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development," Energy Policy, vol. 39, pp. 5850-5870, 2011.

[30] F. Gardumi, A. Shivakumar, R. Morrison, C. Taliotis, O. Broad, A. Beltramo and M. Howells, "From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS," Energy Strategy Reviews, vol. 20, pp. 209-228, 2018.

[31] CNDC, "Memoria Anual 2020," Cochabamba, 2021.

[32] ENDE, "Proyectos ejecutados," 10 January 2022. [Online]. Available: https://www.ende.bo/proyectos/ejecutados.

[33] ENDE, "Proyectos en ejecucion," 10 January 2022. [Online]. Available: https://www.ende.bo/proyectos/ejecucion.

[34] ENDE, "Proyectos en estudio," 10 January 2022. [Online]. Available: https://www.ende.bo/proyectos/estudio.

[35] L. P. Rosa and R. Schaeffer, "Greenhouse gas emissions from hydroelectric reservoirs," Ambio, vol. 23, pp. 164-165, 1994.

[36] IPCC, "2006 IPCC guide lines for National Greenhouse Gas Inventories," Institute for Global Environmental Strategies (IGES), 2006.

[37] L. Gagnon and J. van der Vate, "Greenhouse gas emissions from hydropower: The state of research in 1996," Energy Policy, vol. 25, pp. 7-13, 1997.

[38] R. Almeida and et. al., "Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning," NATURE COMMUNICATIONS, 2019.

[39] J. Rudd, R. Hecky and R. Harris, "Are hydroelectric reservoirs significant sources of greenhouse gases?," Ambio, vol. 22, pp. 246-248, 1993.

[40] W. Steinhurst, P. Knight and M. Schultz, "Hydropower Greenhouse Gas Emissions," Synapse, Cambridge, 2012.

[41] Ministerio de Hidrocarburos y Energia, "Balance Energetico Nacional 2000-2014," La Paz, 2015.

[42] Organización Latinoamericana de Energía, "Sistema de Información Energética de Latinoamérica y el Caribe," 2019. [Online]. Available: http://sielac.olade.org/default.aspx. [Accessed 01 Agosto 2019].

[43] Organización Latinoamericana de Energía, "Prospectiva energética de América Latina y el Caribe," in Panorama energético de América Latina y el Caribe 2019, Quito, OLADE, 2019.

[44] R. Landaveri, Modelización y Prospectiva del Sistema Energético Boliviano 2007 – 2025. Escenarios tendencial y de mitigación, Fundación Bariloche, 2009.

[45] N. Jara and C. Isaza, "Programas de Eficiencia Energética y Etiquetado en el Ecuador – Revisión del Estado Actual," in II ENCUENTRO DE TECNOLOGÍA E INGENIERIA & X SIMPOSIO INTERNACIONAL EN ENERGIAS , Medellin, 2014.
[46] R. Plaza, E. Escobar and D. Aguirre, "ANÁLISIS DE EFICIENCIA ENERGÉTICA EN LA IMPLEMENTACIÓN DE COCINAS DE INDUCCIÓN EN EL SISTEMA ELÉCTRICO ECUATORIANO," ESCUELA SUPERIOR POLITECNICA DEL LITORAL, Guayaquil, 2015.
[47] UNECE, "BEST POLICY PRACTICES FOR PROMOTING ENERGY EFFICIENCY," United Nations, Ginebra, 2015.
[48] APEC, "COMPENDIUM OF ENERGY EFFICIENCY POLICIES OF APEC ECONOMIES," ASIA PACIFIC ENERGY RESEARCH CENTRE, Tokyo, 2016.
[49] IEA, "Nordic EV Outlook 2018: Insights from leaders in electric mobility," OECD/IEA, 2018.
[50] Ecofys, "Incentives for Electric Vehicles in Norway," UKI, 2018.
[51] P. Haugneland, E. Lorentzen, C. Bu and E. Hauge, "Put a price on carbon to fund EV incentives – Norwegian EV policy success," EVS30 Symposium, 2017.
[52] S. Marañon, "Análisis de escenarios potenciales de desarrollo para el parque automotor de Bolivia y sus emisiones de gases efecto invernadero en el software LEAP para el periodo 2020-2030," Cochabamba, 2022.
[53] W. Sweeting, A. Hutchinson and S. Savage, "Factors affecting electric vehicle energy consumption," International Journal of Sustainable Engineering, 2011.
[54] F. Bühler, F. Müller and B. Elmegaard, "Potentials for the electrification of industrial processes in Denmark," ECOS 2019, 2019.
[55] S. Malla and G. Timilsina, "Household Cooking Fuel Choice and Adoption of Improved Cookstoves in Developing Countries," Policy Research Working Paper Series, 2014.
[56] J. Brenn and C. Bach, "Comparison of natural gas driven heat pumps and electrically driven heat pumps with conventional systems for building heating purposes," Energy and Buildings, pp. 904-908, 2010.
[57] J. Valero, "El camión eléctrico comienza a hacer su aparición en el mercado," 11 Mayo 2016. [Online]. Available: https://hipertextual.com/2016/05/camion-electrico-mercado.
[58] Ministerio de Energias, "Ley de Electricidad N 1604," 21 Diciembre 1994. [Online]. Available: https://www.cndc.bo/normativa/ley_electricidad.php.
[59] Index Mundi, "Gas natural Precio Mensual - Dólares americanos por millón de BTU," 16 Diciembre 2019. [Online]. Available: https://www.indexmundi.com/es/precios-de-mercado/?mercancia=gas-natural&meses=120.
[60] L. Manzaneda, "Bolivia pierde casi $us 500 millones anuales por los precios bajos de gas y electricidad," Los Tiempos, 9 Septiembre 2018.
[61] IEA, "World Energy Outlook 2021," Paris, 2021.
[62] IEA, "World Energy Outlook," International Energy Agency, 2017.
[63] J. Sumner, L. Bird and H. Smith, "Carbon Taxes: A Review of Experience and Policy Design Considerations," National Renewable Energy Laboratory, Colorado, 2009.
[64] The World Bank, "CARBON TAX GUIDE - A Handbook for Policy Makers," International Bank for Reconstruction and Development / The World Bank , Washington DC, 2017.
[65] J. Horowitz and et. al., "Methodology for Analyzing a Carbon Tax," Office of Tax Analysis, 2017.
[66] Statista, "Prices of implemented carbon taxes worldwide 2021, by select country," 1 December 2021. [Online]. Available: https://www.statista.com/statistics/483590/prices-of-implemented-carbon-pricing-instruments-worldwide-by-select-

country/#:~:text=As%20of%20April%202021%2C%20Sweden,carbon%20tax%20back%20in%201990..
[67] E. Asen, "Looking Back on 30 Years of Carbon Taxes in Sweden," 23 September 2020. [Online]. Available: https://taxfoundation.org/sweden-carbon-tax-revenue-greenhouse-gas-emissions/.
[68] CTC, "Where Carbon Is Taxed," 12 Marzo 2018. [Online]. Available: https://www.carbontax.org/where-carbon-is-taxed/.
[69] World Bank, "Putting a Price on Carbon with a Tax ," 12 Marzo 2018. [Online]. Available: https://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf.
[70] IPCC, "Global Warming of 1.5°C. Summary for Policy Makers," IPCC, Suiza, 2018.
[71] The World Bank, "GDP (Current US$) - Bolivia," [Online]. Available: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=BO. [Accessed 5 February 2022].
[72] P. Cachaga, J. Romero and J. Acho, "Evaluación de la inversión pública en Bolivia: Un análisis mediante fronteras de eficiencia," Revista de Análisis, vol. 32, pp. 169-200, 2020.
[73] Jacobson and et. al., "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," Joule, vol. 1, pp. 108-121, 2017.
[74] M. Navia, R. Orellana, S. Zarate, M. Villazon, S. Balderrama and S. Quoilin, "Energy Transition Planning with High Penetration of Variable Renewable Energy in Developing Countries: The Case of the Bolivian Interconnected Power System," Energies, vol. 15, 2022.
[75] J. Hamilton, Time Series Analysis, Princeton University Press, 1994.
[76] D. Gujarati and D. Porter, Econometría, Mexico D. F.: McGraw-Hill , 2010.
[77] E. Foster, M. Contestabile, J. Blazquez, B. Manzano, M. Workman and N. Shah, "The unstudied barriers to widespread renewable energy deployment: Fossil fuel price responses," Energy Policy, vol. 103, pp. 258-264, 2017.
[78] G. Lopez, A. Aghahosseini and D. Bogdanov, "Pathway to a fully sustainable energy system for Bolivia across power, heat, and transport sectors by 2050," Journal of Cleaner Production, 2021.
[79] F. Kern and A. Smith, "Restructuring energy systems for sustainability? Energy transition policy in the Netherlands," Energy Policy, pp. 4093-4103, 2008.
[80] J. Dixon, K. Bell and S. Brush, "Which way to net zero? a comparative analysis of seven UK 2050 decarbonisation pathways," Renewable and Sustainable Energy Transition, vol. 2, 2021.
[81] K. Gillingham, A. Keyes and K. Palmer, "Advances in Evaluating Energy Efficiency Policies and Programs," Resources for the future, Washington, 2017.
[82] BYD, 16 Diciembre 2019. [Online]. Available: https://en.byd.com/.
[83] ICCT, "Electric Vehicles," 16 Diciembre 2019. [Online]. Available: sites/default/files/BYD%20EV%20SEDEMA.pdf.
[84] ATUC, "Asociacion de Transportes publicos urbanos y metropolitanos," 16 Diciembre 2019. [Online]. Available: https://www.atuc.es/pdf/253.pdf.
[85] D. Connolly, H. Hund and B. Mathiesen, "Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union," Renewable and Sustainable Energy Reviews, 2016.
[86] K. Kavvadias, I. Hidalgo, A. Zucker and S. Quolin, "Integrated modelling of future EU power and heat systems: The Dispa-SET v2.2 open-source model," JRC technical report, 2018.
[87] H. Lütkepohl, New Introduction to Multiple Time Series Analysis, Berlin: Springer, 2005.

ANNEXES

Annex 1. Total historic (2000-2020) and projected (2021-2055) energy consumption in Bolivia

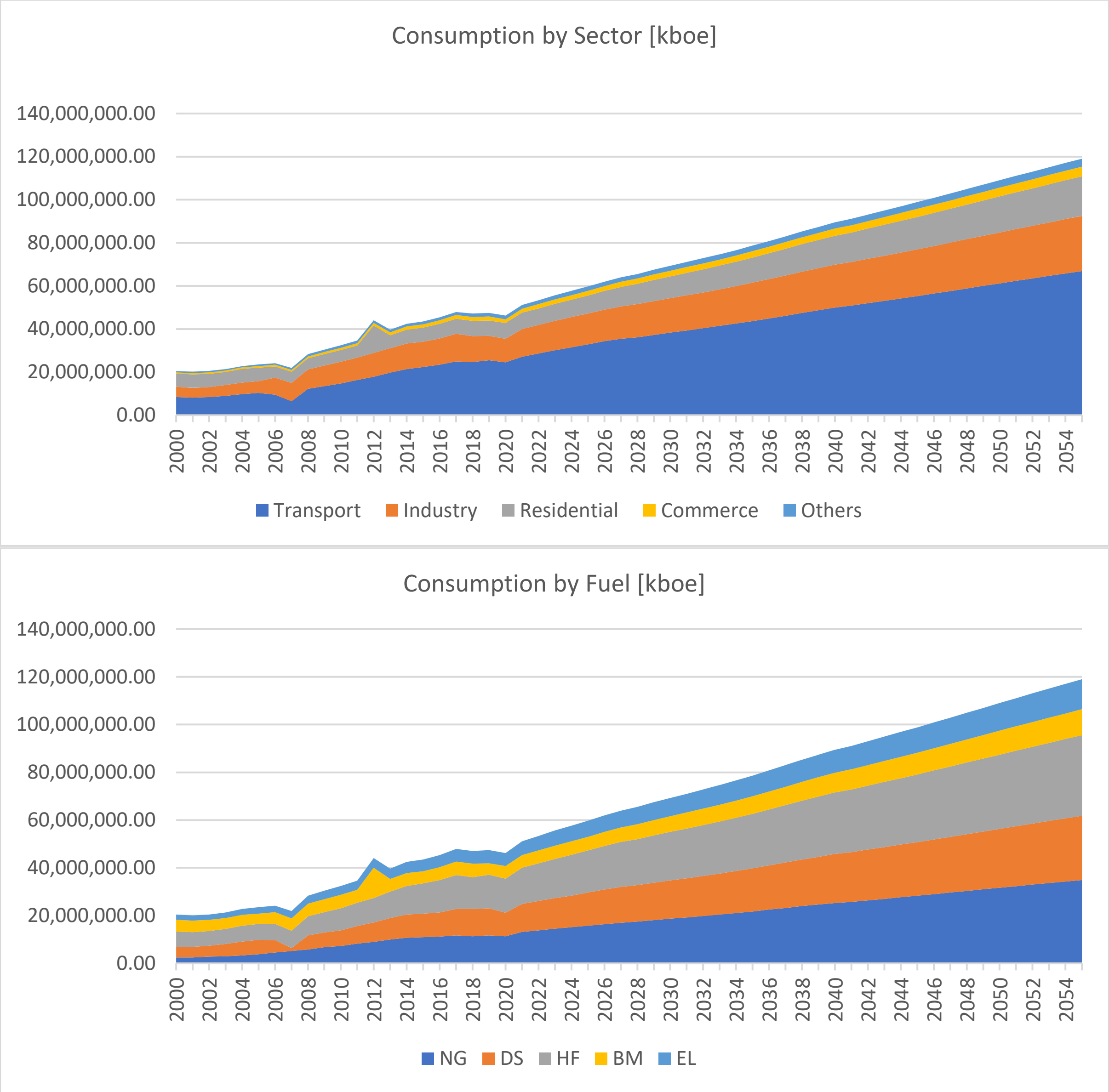

Figure 1. Total historic (2000-2020) and projected (2021-2055) energy consumption in Bolivia by sector (top) and fuel (bottom), expressed in kboe.

Annex 2. Simulation results of the EEM scenario (right) compared to the BAU results (left) for the 2014-2055 period.

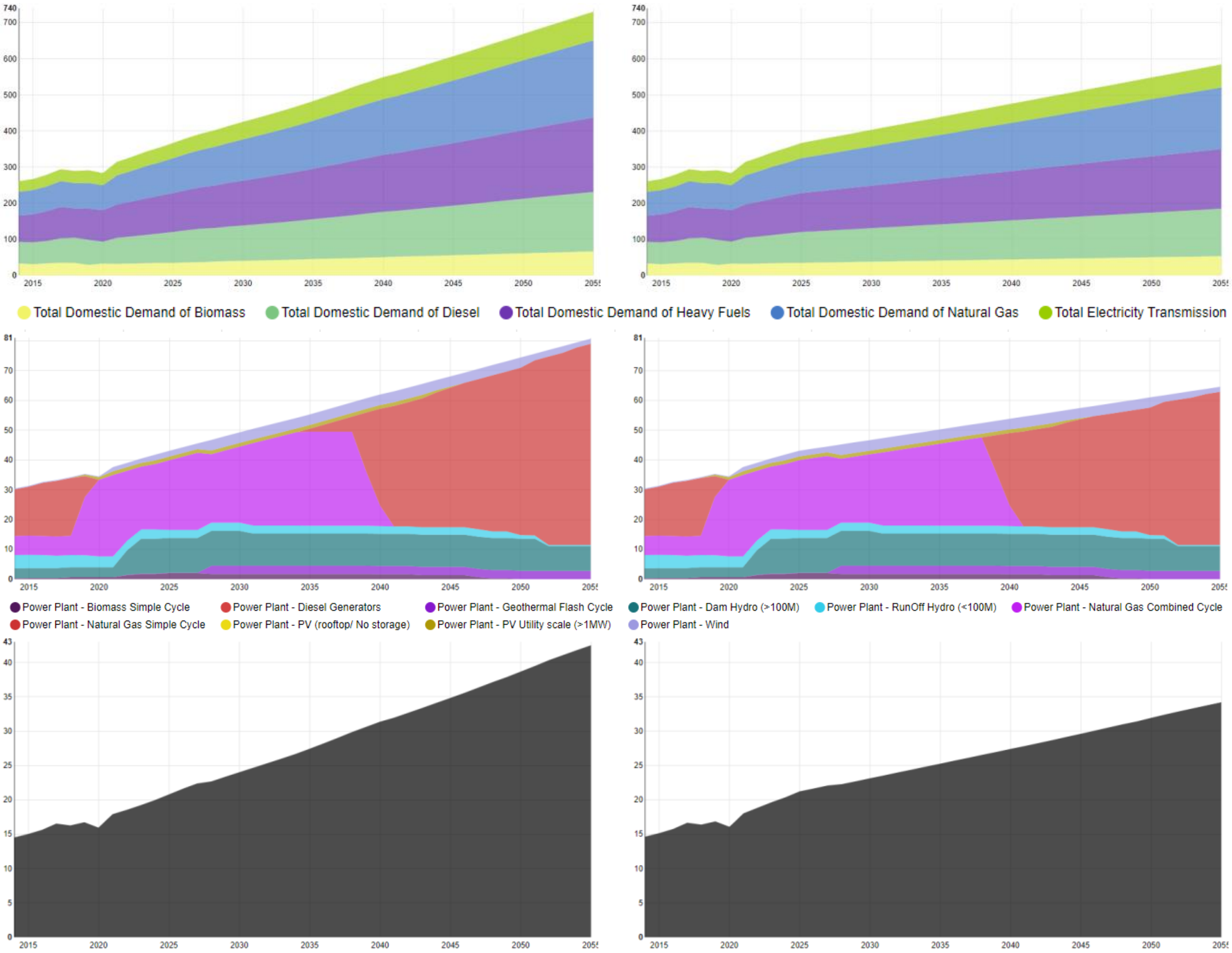

Figure 1. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).

Annex 3. Simulation results of the EED scenario (right) compared to the BAU results (left) for the 2014-2055 period.

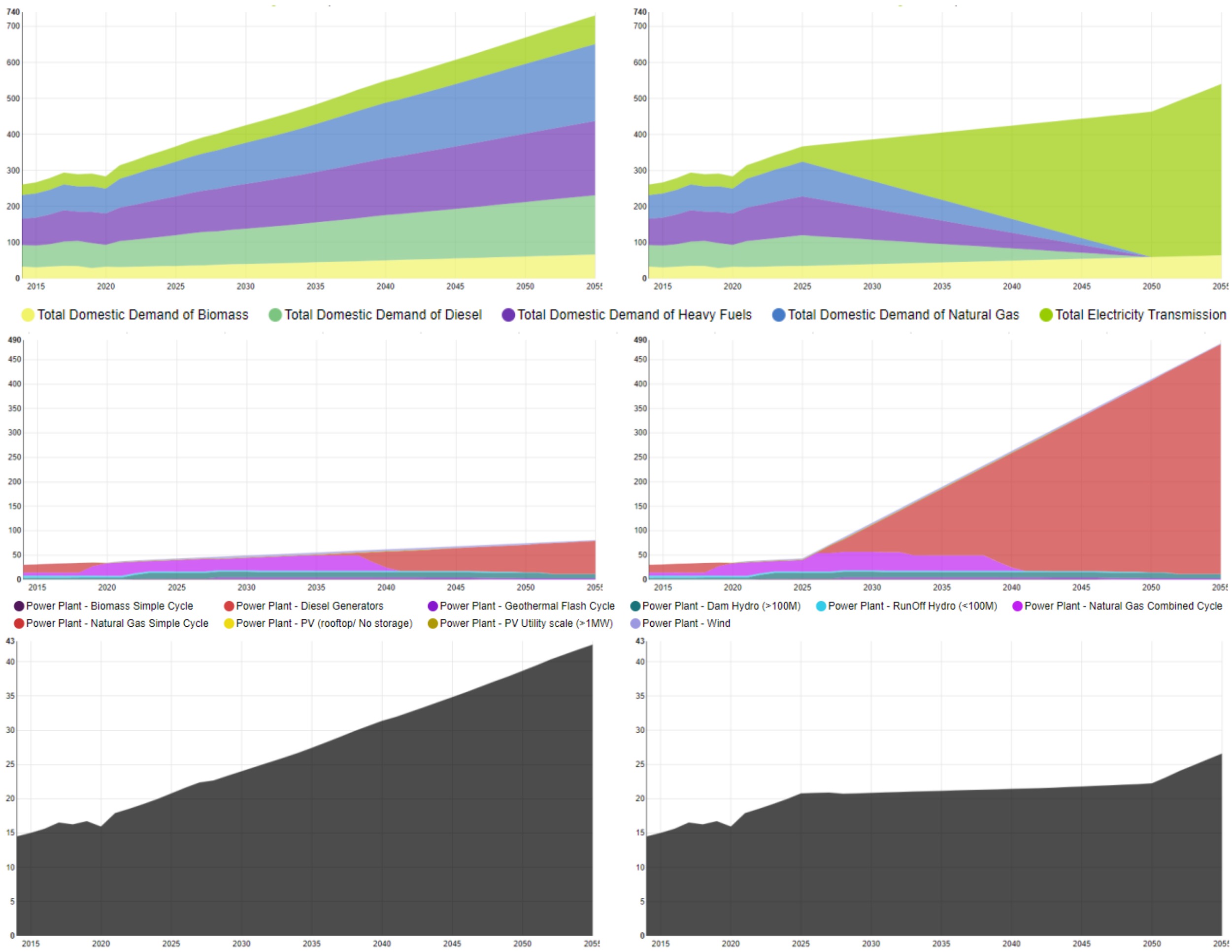

Figure 2. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).

Annex 4. Simulation results of the NSR scenario (right) compared to the BAU results (left) for the 2014-2055 period.

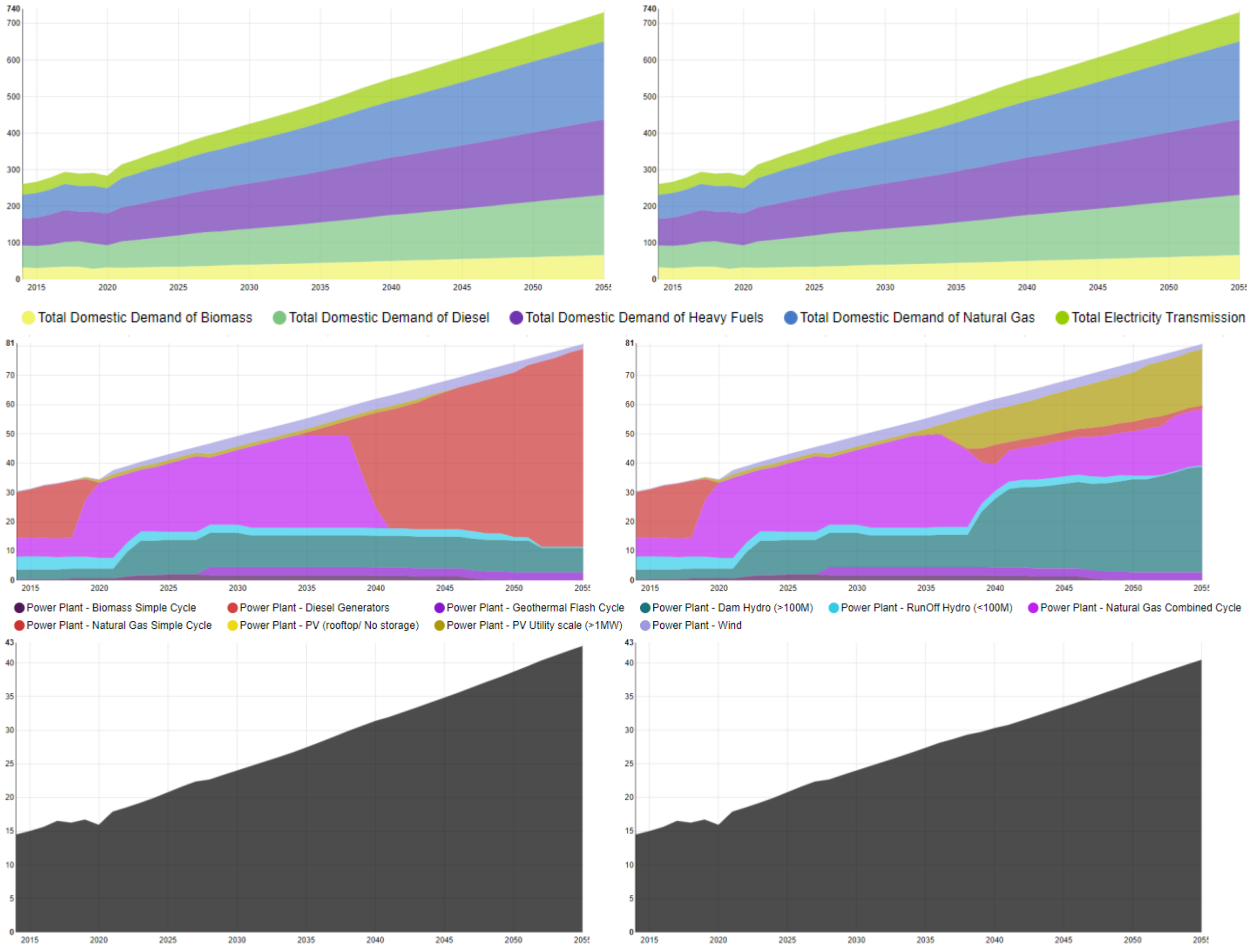

Figure 3. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).

Annex 5. Simulation results of the CTI scenario (right) compared to the BAU results (left) for the 2014-2055 period.

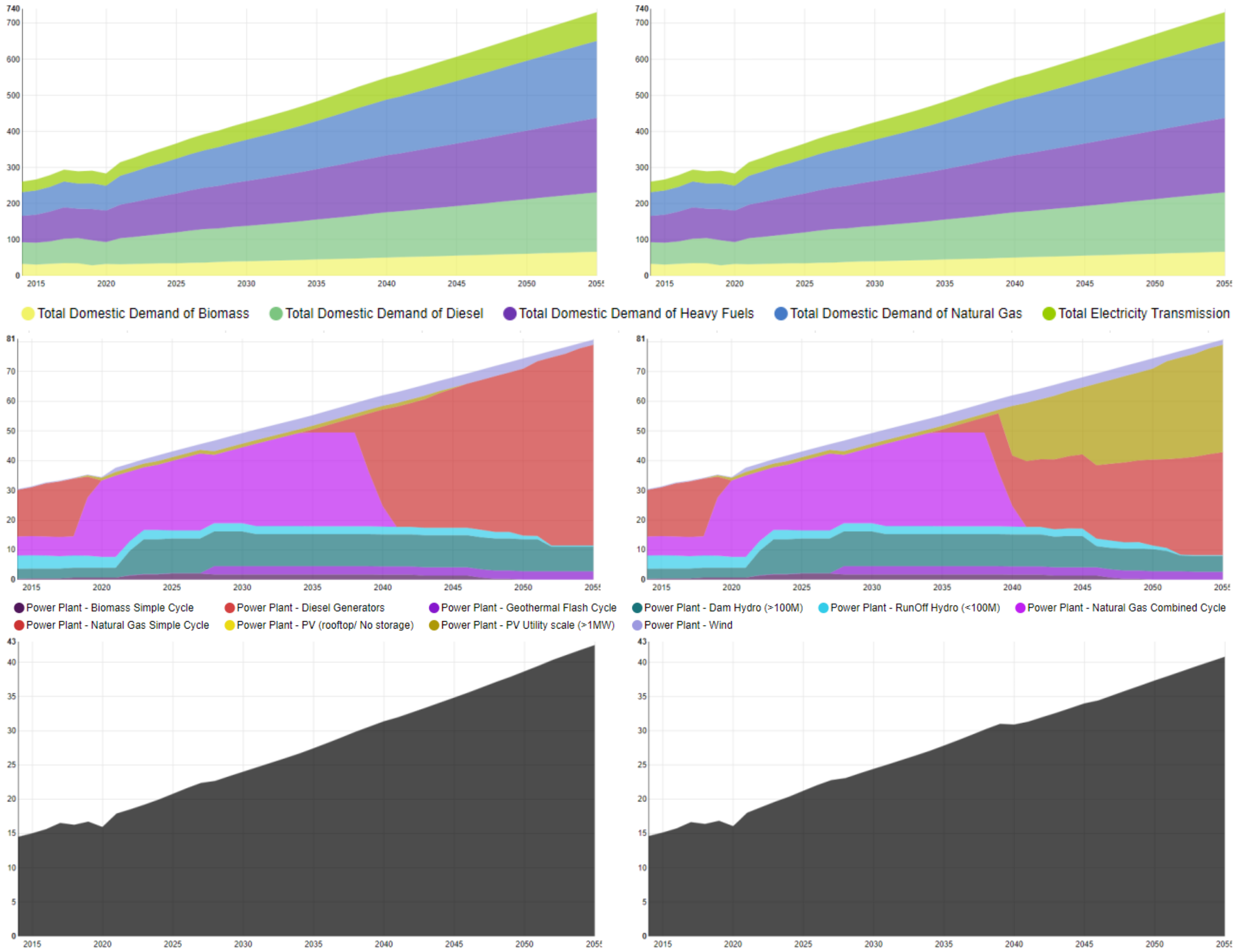

Figure 4. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).

Annex 6. Simulation results of the MP scenario (right) compared to the BAU results (left) for the 2014-2055 period.

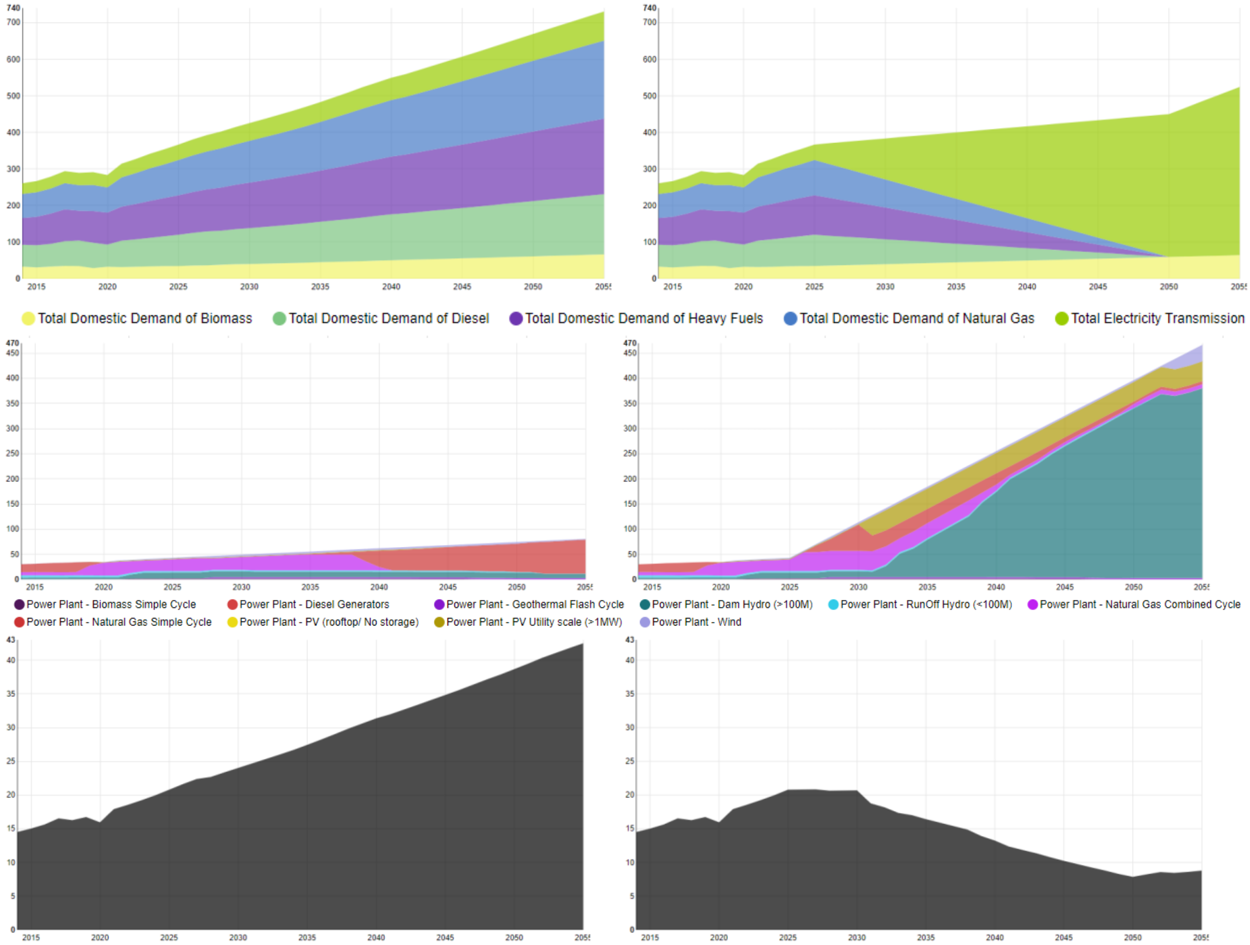

Figure 5. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).

Annex 7. Simulation results of the CN scenario (right) compared to the BAU results (left) for the 2014-2055 period.

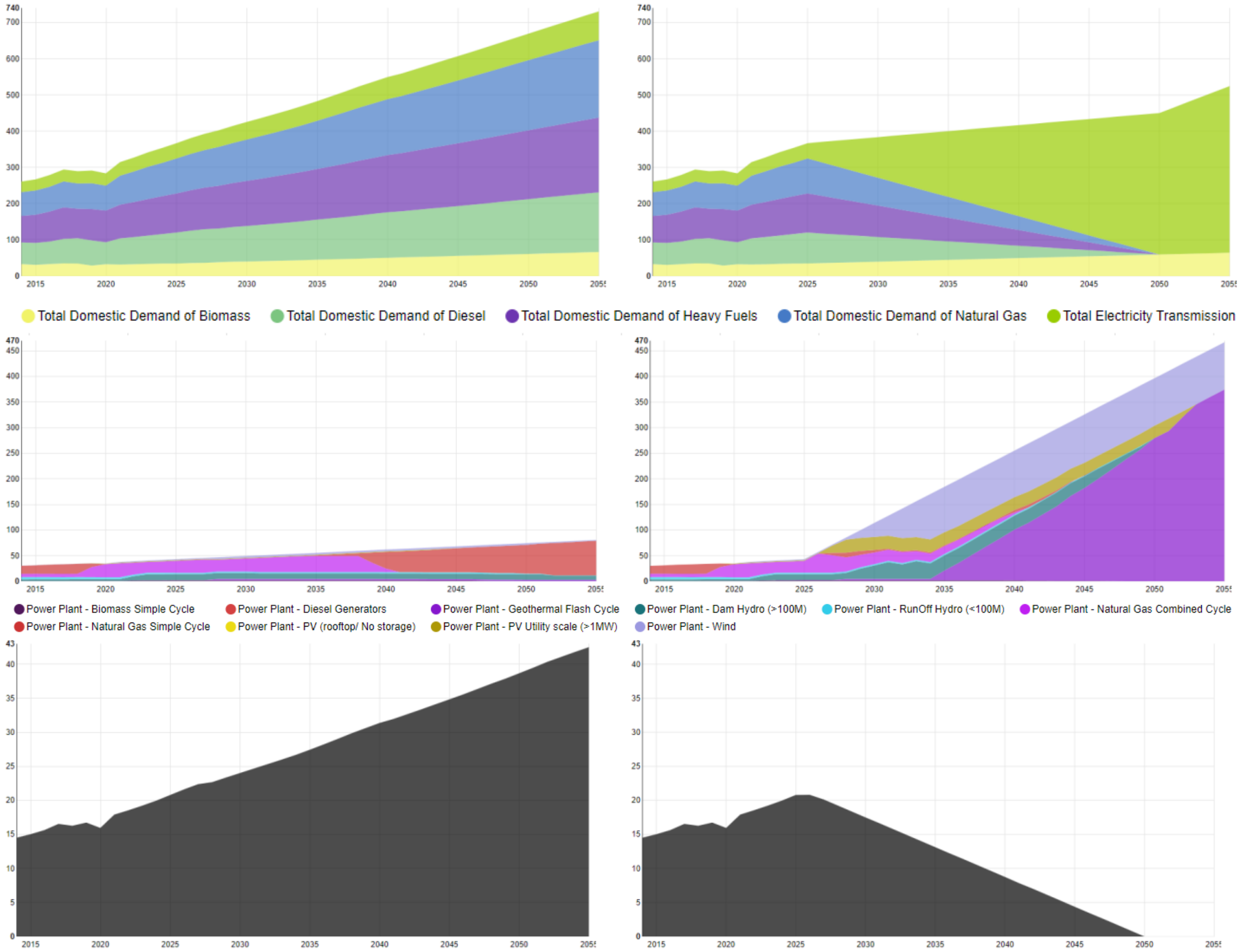

Figure 6. Total energy consumption in Bolivia by fuel [PJ] (Top); Electrical energy generation mix in Bolivia by technology [PJ] (Middle); Total annual emissions linked to energy consumption in Bolivia [MtCO2e] (Bottom).