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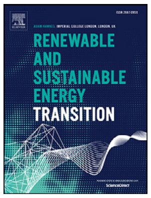

Analyzing carbon emissions policies for the Bolivian electric sector

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ABSTRACT

A transition of the Bolivian power sector towards a renewable energy dominated system has been inhibited by a series of laws and policies including heavy subsidies for power generation using domestic natural gas. Within this context, alternative techno-economic scenarios are designed based on key characteristics of the system, and a series of six policy levers are used to analyze impacts on the development of the power sector. The energy-system optimization modeling framework OSeMOSYS is utilized to analyze power sector transition pathways. Techno-economic characteristics and policies are combined to develop bracketing scenarios for the future energy system, contrasting business-as-usual with an ambitious renewable energy policy scenario.

Results from the analyzed scenarios show that achieving significant reductions of GHG emissions in the Bolivian electric system will heavily depend on:1) reducing the artificial competitiveness of thermal power plants through subsidies, but also a price on carbon emissions; 2) banning high impact power plants (mainly very large hydropower plants); and 3) defining clear long-term objectives for the participation of renewables in the system, starting with objectives in current short-term plans. By examining several scenarios, relative system costs as a function of emissions reductions are determined as well. For high penetration of variable renewable energy, addition of storage will eventually be needed as dispatchable renewable resources are limited.

Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
APS	Ambitious Policy Scenario
AETN	Autoridad de Electricidad y Tecnología Nuclear
BAU	Business as Usual
BEN	Balance Energético Nacional (National Energy Balance)
BES	Bolivian Electric System
CNDC	Comité Nacional de Despacho de Carga
CTS	Carbon Taxing Scenario
DS	Diesel
DS_SC	Diesel Simple Cycle
EL_Cons	Electricity for consumption
EL_Dist	Electricity distribution
EL_Trans	Electricity transmission
ENDE	Empresa Nacional de Electricidad
EUR	Enhanced use of renewables
GHG	Greenhouse Gas
GT_SC	Geothermal Simple Cycle
HY_L	Large Hydroelectric > 50MW
HY_LL	Mega Hydroelectric > 500MW
HY_S	Medium Hydroelectric<50MW
HY_SS	Small Hydroelectric <10MW
INE	Instituto Nacional de Estadistica
IPCC	Intergovernmental Panel on Climate Change
NG	Natural Gas
NG_SC	Natural Gas Simple Cycle
NG_CC	Natural Gas Combined Cycle
NSR	Natural Gas Subsidy Reduction
OSeMOSYS	Open Source Energy Modelling System
PGP	Programmed Generation Plants
PV_C	Photovoltaic Plants
PV_R	Residential Photovoltaic
RES	Reference Energy System
SI	Supplementary Information
SIN	Sistema Interconnected Nacional (Interconnected National System)
WT_L	Wind Turbines Large
WT_S	Wind Turbines Small
YPFB	Yacimientos Petrolíferos Fiscales Bolivianos

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Introduction

Under the Paris Agreement, countries agreed to reduce carbon dioxide and other greenhouse gas (GHG) emissions consistent with efforts to limit the global average temperature increase to well below 2 °C compared to pre-industrial levels and striving for a limit of 1.5 °C [1], a goal that requires net-zero CO_2 emissions globally by about 2050 [2].

In this context, Bolivia, despite being a country making a relatively low contribution to global GHG emissions, 0.26% of the total 48.9 $GtonCO_2eq$ registered in 2018 [3], has ratified the Paris Agreement and presented its Nationally Determined Contributions (NDC) to the UNFCCC [4]. With this document Bolivia acknowledge the severity of climate change and provided its overview of national adaptation goals and mitigation efforts to combat global warming [5].

Currently, 71% of the global GHG emissions come from the energy sector, mainly electricity and heat production [6, 7]. In the case of Bolivia, according to the last official GHG inventory, the energy sector is the second most relevant sector, after Agriculture, Forestry and Other Land Use (AFOLU), in terms of contribution to total national emissions [8, 6]. A more recent official GHG inventory has not been published, but from other data sources it can be seen that both consumption of energy and emissions in the energy sector have increased significantly over the past decade [6].

This characteristic, coupled with the inherent relevance of the electricity sector in the development of emergent economies such as Bolivia, makes the planning of the energy sector a national priority. However, mostly due to political implications, official sectorial development plans are quite scarce and most of them have a short to medium temporal scope, such as: Optimal Expansion Plan of the National Interconnected System [9], Electricity Plan of the Plurinational State of Bolivia 2025 [10], Sectoral Integral Development Plan For Living Well (PSDI) - Energy Sector 2016–2020 [11]. The vacuum of information must be addressed if the electricity sector is to continue expansion and development without risking unnecessary economic losses or suboptimal operation of systems due to a lack of analysis of conditions for long-term scenarios.

To analyze the evolution over time of the power sector in Bolivia under different scenarios and policies, the Open Source Energy Modelling System (OSeMOSYS) was chosen, considering its techno-economic approach, flexibility for long-term analysis for the energy sector, availability and transparency as an open source modeling tool and its capacity to introduce GHG emissions accounting as a relevant variable in the model [12]. The model constructed for Bolivia has as its main objective to cover a specified demand over time with the minimum cost set of technologies. However, techno-economic parameters are only one part of an energy system transformation, and therefore techno-economic scenarios are closely linked in the present work to policies, both current and proposed, that impact the trajectory of the sector.

Literature review

Energy models can be categorized as either bottom-up or top-down approach, depending on the emphasis on supply technologies or on macroeconomic drivers of energy demand. In addition, models may differ in the time frame that is considered (long-term, medium-term, or short-term) or the modeling technique (accounting or optimization) [13].

In this paper the focus is on analyzing the impacts of various policies on the electricity system, including expected carbon (GHG) emissions in the long-term. Since the Bolivian electric sector is currently governed by an economic dispatch rule [14] which can be simulated as an objective function, OSeMOSYS was selected as the modeling tool. Effectively, the approach of the present work is (except for the Business-as-Usual scenario) to use policies or technological potentials serve as guidance for setting boundaries on the electricity system, and then to use OSeMOSYS to find optimal solutions under those policy-dictated boundary conditions.

Although previously published studies may have some overlap in their analysis of the Bolivian electric sector, such as using the same modeling tool [15], analyzing similar characteristics of the electric system [16, 17] or applying similar policies for carbon emission management [18], the present study considers a particular mix of all these characteristics.

For instance, the Bolivian case study based on the OSeMOSYS SAMBA model [15] is focused on the capacity of electricity export from potential large hydropower projects. While this study represents the electrical system in the same optimization model, it gives less detail to how local demands are covered, and most importantly, lacks an emphasis on emissions mitigation pathways.

Another study of the Bolivian power sector analyzes the high penetration of renewable energy in the electrical grid, and although using an optimization model, considers a dispatch model to simulate short-term variations [17] and not long-term changes in the electric system. At the opposite end of the spectrum, one previous study evaluates the long-term variations of the electrical system due to the implementation of specific measures, however, the model is based on an accounting model and the analyzed variations are the result of demand side management measures [16].

Finally, OSeMOSYS was used as the modeling tool in an analysis of the electrical system in a long-term framework and applies a carbon taxation policy to reduce the emissions from the power generation system [18]. The study focuses the impact of one specific policy and how it could allow a low-carbon development for the Bolivian electric system. However, by exploring only the carbon taxation measure, the comparison of different policy-based scenarios and their effectiveness on the electric system is not considered. In this context, it is expected that the current work can add to the literature by considering an array of different potential scenarios, not only technoeconomical, but also based on characteristics of the national context (*i.e.* potential social conflicts) which in turn could provide input to proposed locally defined policies.

Background information

Bolivia's energy and electricity systems have undergone significant changes over the years. The Electricity Law of 1994 [14] was developed to establish general operation conditions for the electric industries in Bolivia, while the "Capitalización" Law [19] made it possible for state companies to be transferred to the private sector. Both laws, in conjunction with the regulations in the Supreme Decree 24043 [20], aimed at promoting intensive use of natural gas (NG) as the main energy source for electricity generation in the country. Previously, approximately 70% of electricity had been hydroelectric and large volumes of NG were unused at that time (approximately 1/3 of total production of NG was vented, 1/3 was consumed internally and 1/3 was exported, according to the national energy balance of 1994 [21]).

Simultaneously, the Electricity Law of 1994 also introduced the concept of "economic dispatch" *i.e.* according to the increasing order of generation costs. In this context it seemed reasonable to promote the intensive use of NG to generate electricity, and thus a heavily subsidized prices were established to be used in thermal power plants. In 2000 a fixed price was defined by Supreme Decree [22] and this value was reaffirmed in 2008 [23]. Since then, with a price of NG of 1.3 USD/Mcf, new hydroelectric and other renewable energy projects have not been economically competitive.

On the demand side, as a developing economy, electricity consumption in Bolivia has been steadily increasing, as shown in Fig. 1. Peak power demand is currently about 1600 MW. Fig. 1 also shows the composition of electricity produced in Bolivia over the past decade; the share of fossil-fuel generation reached a maximum of 80% in 2016, rising from 65% in 2010 and dropping back to that same level more recently.

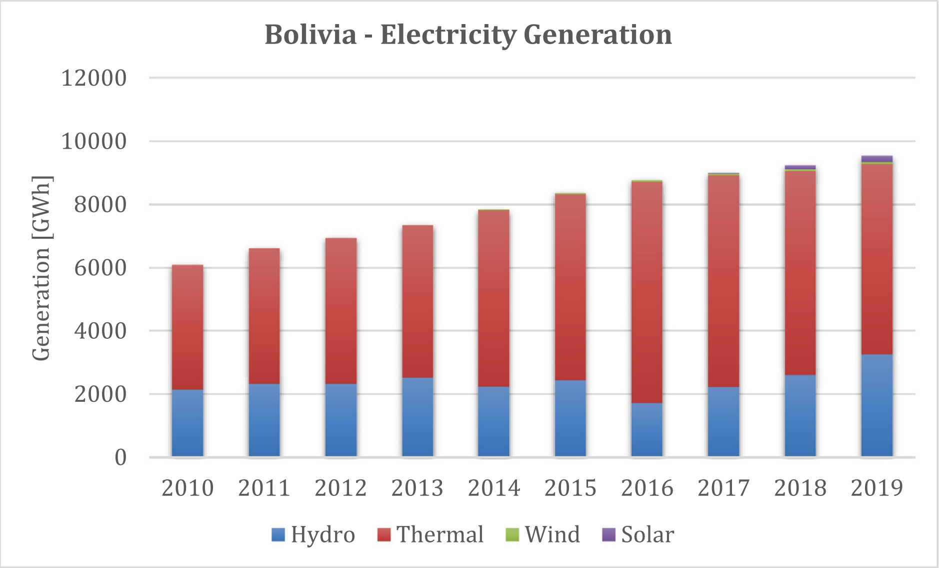
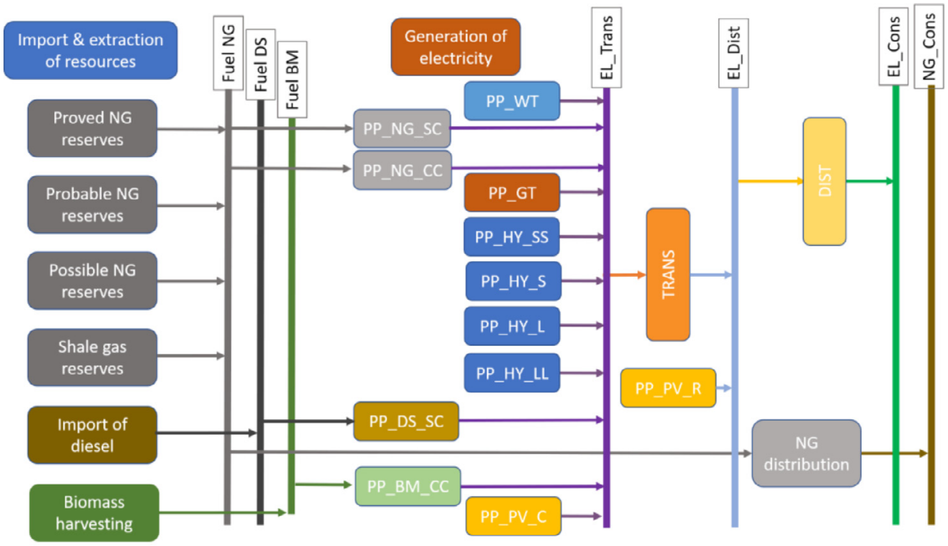


Fig. 1. Historical behavior of the demanded energy in Bolivia 2010–2019 (GWh). Energy produced by source is differentiated by colors (blue bars for hydro, orange bars for thermal plants, gray bars for wind power plants and yellow for solar). Data extracted from “Comité Nacional de Despacho de Carga, https://www.cndc.bo/estadisticas/anual.php.



Relevant acronyms for the Bolivian reference model

NG – Natural Gas
DS – Diesel
BM – Biomass

PP – Power Plant
SC – Simple Cycle
CC – Combined Cycle

WT – Wind Turbine
GT – Geothermal
HY - Hydro

SS – Very Small
S – Small
L – Large

LL – Very Large
PV_C – Photovoltaic Central
PV_R – Photovoltaic Roof

TRANS – Transmission
DIST – Distribution
EL – Electricity

Fig. 2. Reference model used to represent technologies, energy carriers and their relations in the Bolivian Electric System (BES).

Given its geographical location and climatic diversity, Bolivia has a high potential for taking advantage of renewable resources, with solar potential much higher than the world average [24], areas with winds of considerable speed, high biomass productivity in the Amazon area, and regions for geothermal exploitation and hydropower potential across the entire country [25].

Characterization of the Bolivian electric system

A Reference Energy System (RES) to be used as the basis for the development of the model for the Bolivian Electric System (BES) is shown in Fig. 2. The RES guides the selection of information necessary to parameterize the model. A review of available literature and information was carried out, giving priority to national information sources and official databases (summarized in the Supplementary Information), to produce a database for the different techno-economic characteristics of the electrical generation matrix in Bolivia. Historical time-series data linking electricity demand and GDP were used in econometric models to produce a long-term projection of energy consumption as summarized in the SI and Ref. [26].

The RES considers 4 stages of transformation to obtain electricity as a final service, 1) extraction or import of fuels, 2) electric generation, 3) transmission and 4) distribution. In Fig. 2 boxes represent technologies and vertical lines representing fuels (including electricity and demand). Although direct consumption of NG is shown in Fig. 2, only the electricity sector is considered in what follows. A more detailed description of the natural gas production sector is given by Fernandez [26] and the SI; as input to the model results reported here, a gas costs were taken as based on international prices, with the baseline cases having input fuel costs scaled to represent the existing subsidies. This choice was made based on the fact that the effective cost of using natural gas for power generation will be an opportunity cost, or price at which the gas could otherwise have been sold on a global market. A heuristic increase in NG costs for electricity generation based on projections from the International Energy Agency (IEA) was used (2% increase per year) and mirrors increasing scarcity of resources and “fuels” represent the first stage of the model system. The fuel cost was included as one component of variable operating costs parameter in OSeMOSYS.

The generation technologies included in the model were simple-cycle and combined-cycle natural gas plants (PP_NG_SC and PP_NG_CC respectively), diesel (PP_DS_SC), biomass (PP_BM_CC), geothermal (PP_GT_SC), photovoltaic plants (PP_PV_C), residential photovoltaic (PP_PV_R), wind farms (PP_WT), and four different categories of hydropower: very small (<10 MW) (PP_HY_SS), small (<50MW) (PP_HY_S), large (PP_HY_L) and mega (>500MW) (PP_HY_LL). These technologies are defined to transform primary sources of energy, such as fuels mentioned before or renewable resources, into electrical energy which then moves (represented in a simplified fashion with overall loss factors) to the transmission system (EL_Trans), and then to the distribution system (EL_Dist) and to final consumption (EL_Cons).

Developing the Bolivian model and scenarios

OSeMOSYS minimizes the net-present-cost (NPC) of the system over the entire modeling time period such that an exogenously-defined energy demand is met during each time slice [27]. With this objective function, together with boundary conditions set by the scenarios, and using input data specific to Bolivia, a model of the system under different conditions was constructed. The open-source solver glpk is used, and solving times are on the order of 1500 seconds per scenario run. Data for scenarios were entered in a spreadsheet and a Python script used to generate the model input file. Likewise, a Python script was written to read and plot output data from model runs. These scripts and the output data are available in an open repository (https://github.com/RJBrecha/OSeMOSYS_Bolivia.git). More details on the data used can be found on the SI.

General considerations

The model presented here analyzes the BES considered as one region, in the period from 2010 to 2060. Temporal resolution is represented by one representative day each month, with three daily time periods of ten hours during the day (08:00–18:00), six hours in the evening (18:00–24:00), and eight hours during the night (24:00–8:00), for a total of 36 time slices per year. There are numerous possible approaches to aggregating time-series for both electricity demand and for supply of variable renewable energy technologies such as solar photovoltaics and wind power (see Ref. xxx and citations therein). The specific temporal resolution chosen provides a simplified but practical starting point for analyzing the main characteristics of interest to this study, key among these being to capture the daily pattern of demand, realizing that there is little seasonal variation (based on hourly data for demand for one year). One the other hand, hydroelectric power does show some seasonality, and therefore the monthly resolution was chosen. Furthermore, the time slices are arranged such that solar PV output only occurs during one of the three daily time slices. This level of temporal resolution is sufficient considering that the study is focused on long-term management in energy system without having very high penetrations of variable renewable energy. Additional daily and weekly time slices could be considered in order to more accurately represent the energy demand variations, dispatch capacities and availability of some technologies. For each scenario, the minimum-cost system configuration is found for the entire modeling period. Resulting cumulative CO_2 emissions, determined using input emissions factors, and the overall system NPC are reported for the period 2020–2050. The simulation runs longer than the period of interest to avoid end-effects from the modeling.

Specific input data

Total demand was given as an exogenous input to be satisfied by the combination of generation technologies, subject to constraints applied in different scenarios. For all the scenarios described here, overall demand followed the same pathway for future years to isolate the impacts of other variables. Key parameters for generation technologies (described in more detail in the SI) are the capital and operating costs, as well as availability. Power plant efficiencies, operating lifetimes, capacity factors and availability factors are exogenously determined and taken from country data. Carbon emissions factors are based on IPCC data for fuels, and on plant efficiencies, including emissions for biomass and geothermal power generation. One of the interesting features of the BES system is that, on the one hand there have been plans to develop several large hydroelectric projects to enable the transition to renewable energy; on the other hand, there are indications from the literature that tropical large-scale reservoir hydroelectric power plants may have operational specific CO_2 emissions as high or higher than even coal power plants, especially in the early years of operation. (See SI for a summary and for results of a sensitivity test to different assumed emissions factors for large-scale hydroelectric power [28]) For other renewable technologies (wind and solar PV) carbon emissions were considered to be zero as the focus here is on operational rather than life-cycle emissions.

Analyzed scenarios

The model was constrained to reproduce historical installed power capacity, energy production and carbon emissions from 2010 to 2019. The Tier One accounting methodology proposed by the IPCC was used [29] and fuel consumption of the electricity sector based on National Energy Balance records [30]; these were then used to determine average emissions factors for electricity generation, which were in turn used for future estimates based on average generation efficiencies.

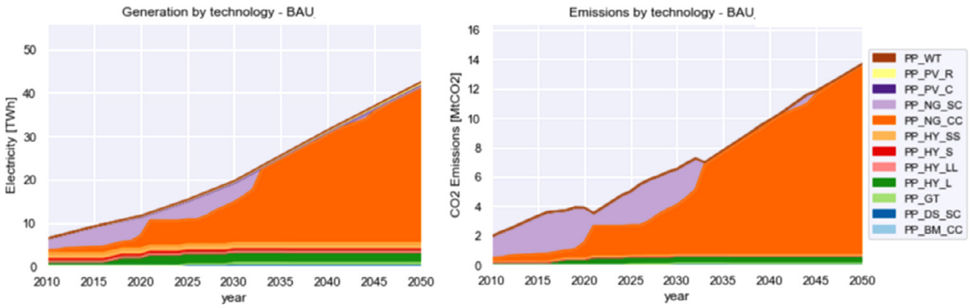
Development of the BES in Business As Usual (BAU) conditions

The BAU considers the development of the Bolivian Electric System as if no additional changes, plans or policies are included over time that could affect the system. The considerations were: NG subsidies are fixed during the modeling period; no carbon taxes are included; no growth rates for participation of renewables; only a small amount of renewable capacity already in construction are specified as inputs in this scenario.

OSeMOSYS reports a wide variety of results from the modeled system; here the focus is on the amount of electricity produced each year for each technology, as well as the total amount of CO_2 emitted. Details of total capacity and capacity additions over time, as well as system costs by year are found in the SI for the following scenarios and some additional ones.

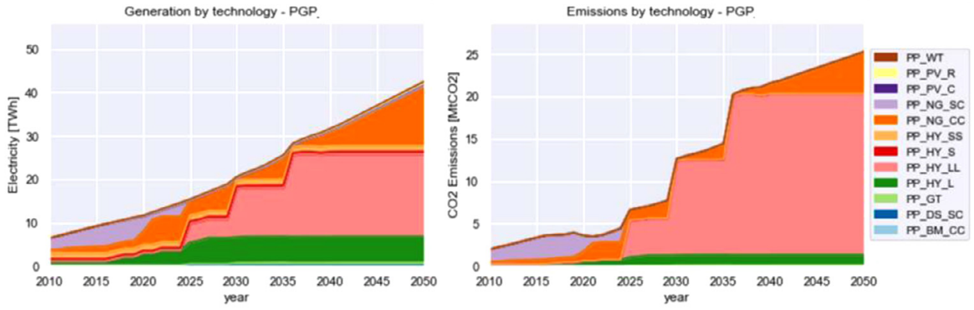
Fig. 3a shows that the model for the BAU system has an exclusive preference for the use of natural gas-based plants due to subsidies for natural gas that make that fuel available at approximately 20% of the regional market price [9]. Starting in the 2020s, simple cycle plants cease to be the main energy producers, as the participation of more efficient combined cycle plants begins to increase due to increased capacity needs and these being the best economic alternative since natural gas prices increase over time due to the depletion of the cheapest natural gas reserves because of both domestic and export demand, effect that has been analyzed by other studies [31] and is supported by national statistics that show no increase in national reserves [32,33]. Only accumulated yearly demands of natural gas for internal electricity consumption are included in the model and based on optimized demand for NG generation [26] .

In Fig. 3b BAU power system CO_2 emissions increase proportionally to natural gas consumption with changes visible due to the switch from simple-cycle to combined-cycle plants in the 2020s. Since in this BAU scenario current subsidies for natural gas are continued throughout the



a) b)

Fig. 3. BAU scenario for the Bolivian Electricity system a) Projection of the electrical energy produced [TWh] by each type of technology; b) total emissions [MtCO2].



a) b)

Fig. 4. PGP scenario for the Bolivian Electricity system a) Projection of the electrical energy produced [TWh] by each type of technology; b) total emissions [MtCO2].

period, even in the face of rising natural gas costs, combined cycle plants are inexpensive enough to keep most renewable energy technologies out of the system and therefore emissions rise by a factor of 3.5 from current levels by 2050.

Alternative premises analyzed with the model

Five alternative scenarios of the BES were developed: Programmed Generation Plants (PGP), based on implementation of the current short-term national development plans for the sector; Carbon Taxing Scenarios (CTS), which assumes the introduction of a taxing mechanism for power plants that generate GHG emissions; Natural Gas Subsidy Reduction (NSR), which considers a gradual decrease of subsidies for natural gas in thermal power plants; Enhanced Use of Renewables (EUR), which analyzes the impact of fixed rates for the introduction of new renewable power plants. Each scenario considered various changes to parameters and approaches that could, in turn, be related to specific policies.

Programmed generation plants (PGP)

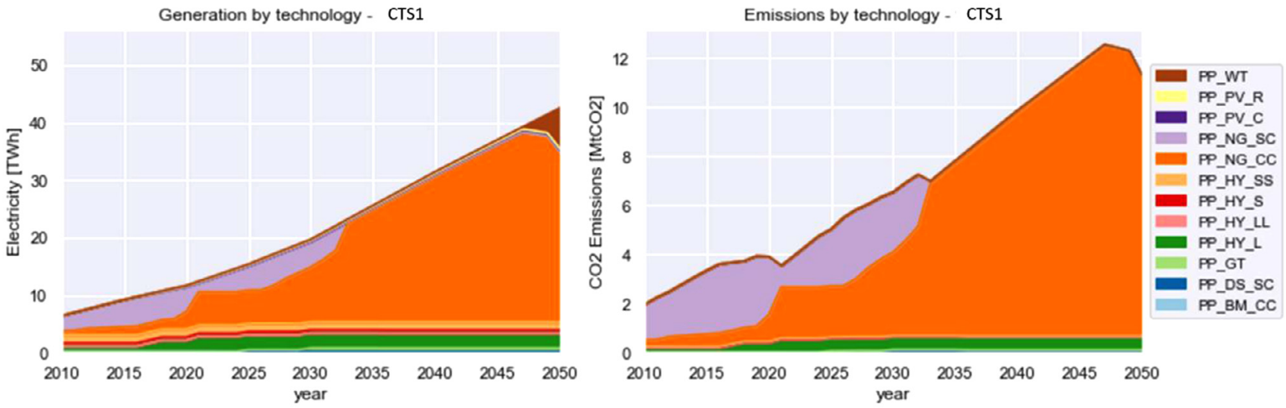
The PGP scenario considers the implementation of the plants programmed by the government until 2025 based on previously reviewed government reports and plans, mainly PEEP 2025 [10]. Adaptations to project implementation dates and adjustments to powers were made based on the official website of ENDE Corporation, including recent upgrades of simple-cycle capacity to combined-cycle plants [34]. To implement these scenarios, the parameter TotalAnnualMinCapacity was used to “force” the construction of the planned capacities. The main planned projects having an effect on the system are large (PP_HY_L) and very large (PP_HY_LL) hydroelectric power projects, as well as up to 100MW of geothermal (PP_GT) power capacity.

The result of the PGP scenario shows (Fig. 4a) a dramatic change in the BES if current plans are carried out. Hydropower quickly begins to dominate the system in the mid-term, but due to the continued growth in demand, in the longer-term natural gas continues to grow. It should be noted as well that very large hydroelectric power plants in the tropics have potentially large specific GHG emissions due to the reservoir emissions, although the extent of emissions is the subject of dispute in the literature [35], ranging from 15 $kgCO_{2eq}/MWh$ [36] to 3000 $kgCO_{2eq}/MWh$ [37]. Some studies justify low emissions during operation in cold climates [38] but possible large emission in tropical climates [36]. Other studies mention that there is no sufficient information to conclude that all tropical reservoirs are large GHG emitters [39]. The discussion in this regard is centered on to the difficultly of predicting emissions from reservoirs before they are built [40], however a general trend can be find on the available literature which supports that emissions from hydropower plants are particularly significant in tropical climates [28, 41], and even in some cases with cold climates [42]. Our baseline case is to use an emissions factor of 1000 gCO_2/kWh for very large hydropower plants, assuming emission rates for tropical reservoirs from a 2012 study [37], and leads in the PGP case to a ten-fold increase in system emissions over time; of course, if emissions were even half of this amount per MWh generated, the result shown in Fig. 4b for emissions would decrease accordingly, but would still represent a significant increase. In the SI a version of the PGP scenario without large hydroelectric plants is given as well and a sensitivity check to various values of the emissions factor are given as well; in what follows, scenarios without this technology will be the focus of attention.

Carbon taxing scenarios (CTS)

Economists consider a tax to be one of the most efficient mechanisms to incorporate negative externalities of the energy system (impacts of climate change due to CO_2 emissions) [46]. Different levels of carbon tax were analyzed using the OSeMOSYS variable EmissionPenalty to consider taxes per carbon dioxide equivalent. Values used in different countries of the world cover ranges that vary from \$1 to \$150 / tCO2 [43–45].

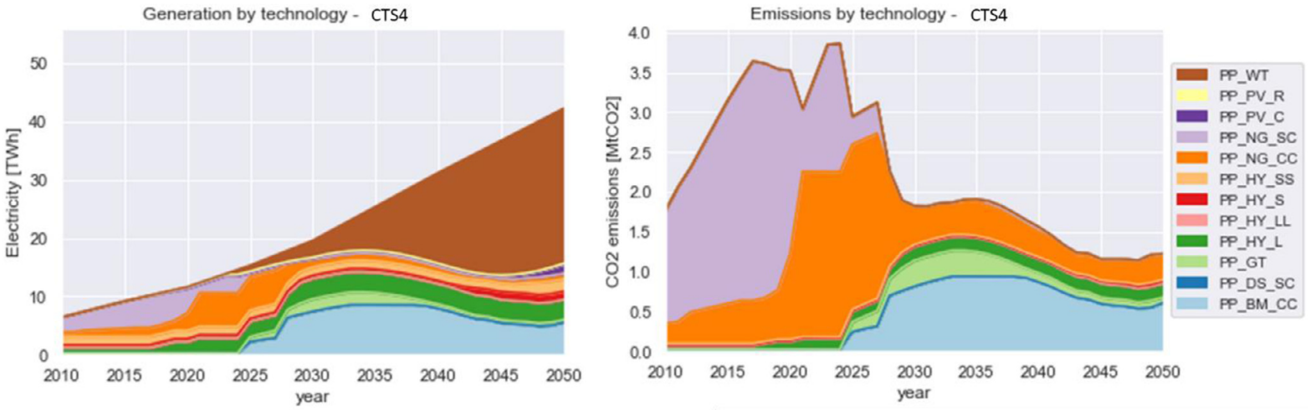
Here, four different tax cases are implemented, all starting from an initial value of US\$20/tCO_2 in 2020, with three increasing at a constant yearly rate. The first case assumes a growth rate of 3%/year reaching a value of ~US\$50/tCO_2 in 2050 (CTS1); the next two cases con-



a)

b)

Fig. 5. CTS1 scenario with a tax reaching \$50/tCO$_2$ by 2050. A) Projection of the electrical energy produced [TWh] by each type of technology; b) total emissions [MtCO2] by technology.



a)

b)

Fig. 6. CTS4 scenario with Paris Agreement 1.5 °C compatible carbon tax. A) Projection of the electrical energy produced [TWh] by each type of technology; b) total emissions [MtCO2] by technology.

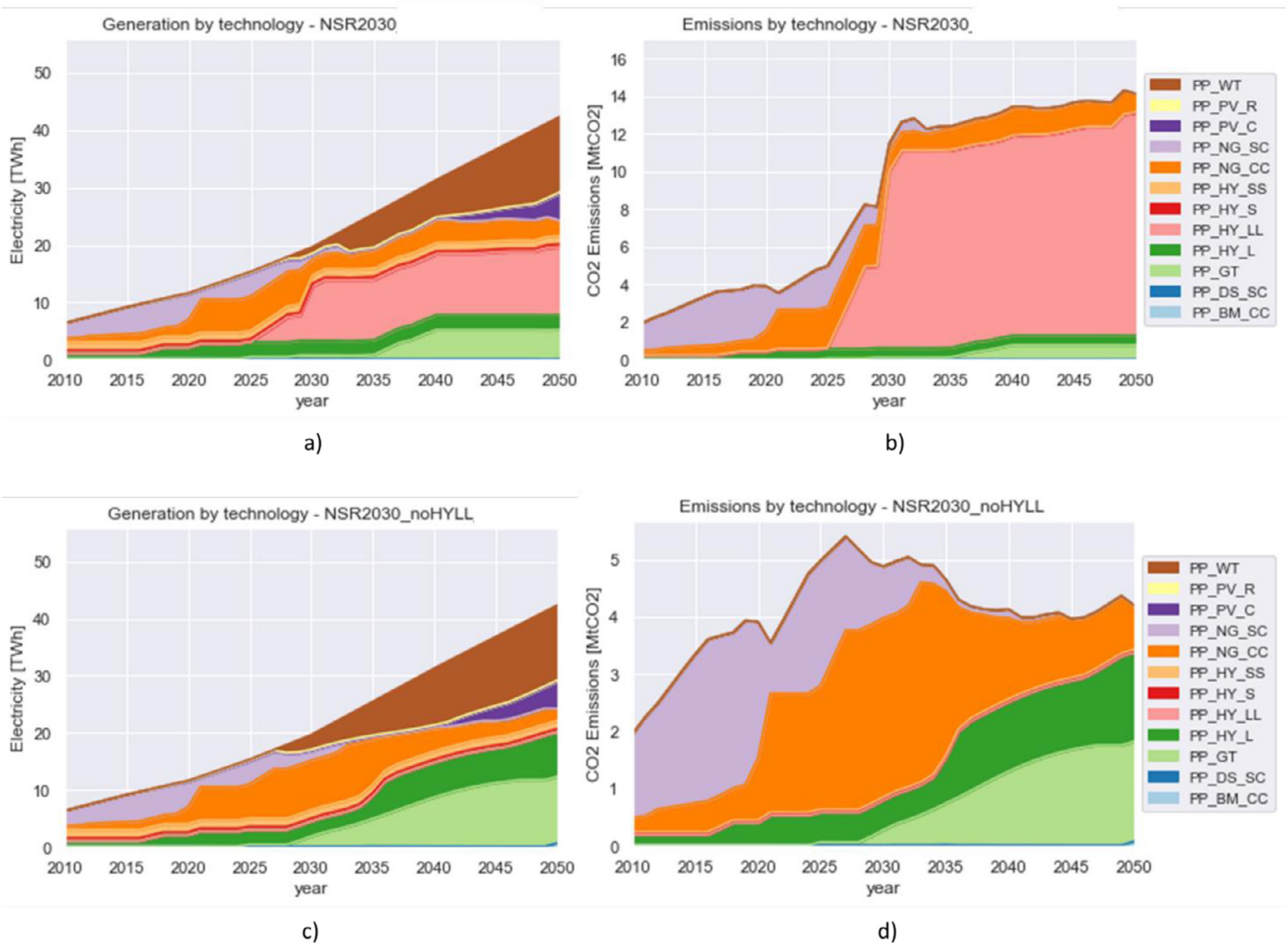
sider growth rates of 6%/year and 8%/year, reaching ~US\$100/tCO$_2$ (CTS2) and ~US\$200/tCO$_2$ (CTS3) in 2050, respectively. For the last case, a linear trend is fit to a median of Paris Agreement 1.5 °C compatible Integrated Assessment Model outputs [2]; here the tax reaches US\$240/tCO$_2$ in 2030, doubling by 2040 and reaching US\$700/tCO$_2$ in 2050 (CTS4). Details are given in the SI and the carbon tax pathways are shown in Fig. S3 in the SI.

From Fig. 5, we see that even a relatively modest carbon tax of US\$50/tCO$_2$ by 2050 (CTS1) leads to no implementation of the very large hydroelectric power plants due to their high emissions factor. Wind power begins to play a small role in the system later in the modeling period. As shown in the SI, higher taxes (CTS2 and CTS3) show similar behavior, with wind moving into the system progressively earlier as the carbon tax increases. Even in a scenario with a carbon tax consistent with what might lead to Paris Agreement compatibility, *i.e.* roughly zero emissions in the power sector by mid-century globally, in the Bolivian system this would serve to limit emissions to a constant value of around 2 MtCO$_2$/year, about current levels. With the highest taxes, however, additional technologies begin to play a role, such as small hydro, solar photovoltaics and biomass power generation, shown in Fig. 6. The impact of including storage in the system is shown in the SI, Fig. 18; with storage and under a high carbon tax scenario, the system uptake of solar PV increases greatly, and drives emissions nearly to zero by 2050. Without storage and given cost assumptions made as input to the model, the lowest-cost solution is to include biomass generation and other dispatchable technologies.

Natural gas subsidy reduction (NSR)

The NSR scenario variants consider a gradual reduction of the subsidy associated with natural gas, an idea previously studied [51, 52]. To define the scenarios, natural gas prices and therefore the cost of generating electricity, are increased to the level of international prices, with future estimates based on the IEA World Energy Outlook [45] .

Two alternative cases were considered based on the time it takes for national natural gas prices (VariableCost) to catch up with international prices. In all cases it is assumed that the increase in costs will start in 2025 and the increase will be linear until reaching the international price. The first case assumes that export prices will be equalized by 2030 (NSR2030) with an annual increase of approximately \$1.0/GJ. The second case assumes that prices are equalized in 2040 with an increase in prices of \$0.3/GJ (NSR2040). In Fig. 7 the results for generation and emissions by technology are shown for two variants of the NSR2030 case, one without (NSR2030) restrictions on the implementation of power plants and the other (NSR2030_noHYLL) assuming that no large hydroelectric plants can be installed. This latter option is included due to growing discontent over large-scale projects in the Amazon region [41] with highly impacted populations. Results for NSR2040 are included in the SI.



a) b) c) d)

Fig. 7. NSR2030 and NSR2030_noHYLL scenarios, with natural gas subsidies eliminated by 2030 a) and c) Projections of the electrical energy produced [TWh] by type of technology; b) and d) total emissions [MtCO2] by technology.

The main dynamic observed when removing the natural gas subsidies is that the optimization searches for other dispatchable renewable sources to replace natural gas. In this case, the two main technologies are very large hydroelectric plants and geothermal power due to their high capacity factors. The capital costs for each are relatively high, but operating costs are anticipated to be low. In each case, later in the modelled time period, wind power begins to play a larger role. Finally, emissions in the two variants of NSR2030 are dramatically different due to the assumed high emissions factor for tropical large reservoir hydroelectric plants, rising to above the BAU values with large hydro and decreasing to approximately one-third of BAU by 2050 in the variant without very large hydroelectricity.

Enhanced use of renewables (EUR)

These scenarios assume fixed rates of increase per year in the installation of renewable capacities, especially of wind and solar PV. Although the techno-economic optimum may only include relatively small amounts of wind and solar, many countries around the world have already seen rapid uptake of these technologies.

As shown in the maps presented in the document "Plan para el Desarrollo de las Energías Alternativas del Estado Plurinacional de Bolivia - 2025″, renewable resources are available and distributed throughout the country [25]. Targeted policies (discussed below) would allow increasing the rate of installation and reducing effective costs. To assess the impact of these presumed installation rate increases on the system, three different cases were analyzed, with different rates of increase starting from current levels, but limited in a logistic curve fashion to maximum total capacities. Initial rates of increase in the three cases are 10%, 15% and 20% per year, within the range of rates seen internationally in recent years [46]. Fig. 8 shows the results with the main point being that even at these rates, variable renewables such as wind and solar only slowly make an impact on system composition, after 2040, given their initial size (less than 100 MW of installed capacity in 2015).

Summary of scenario characteristics

Before turning to policy options for implementation of techno-economic energy system transformation strategies, a brief summary of the scenarios is presented. The results obtained from the BES simulation, based on the four alternative premises and their scenarios, show quite clearly that there is a complex interaction between subsidies, taxes, and policies for both fossil fuels and renewables. In broad terms, without reducing subsidies to natural gas, with costs less than one-fifth of international prices [47], or imposing a carbon tax, NG thermoelectric plants will continue to be the predominant technology to cover energy demand. This holds even though cost trends associated with renewable energy continue to decline globally [48, 49].

However, an unintended consequence of building large hydroelectric dam and reservoir capacity, located in the Amazon region, may be to increase significantly GHG emissions. Alternative technologies that are available as close substitutes for natural gas as a dispatchable source include geothermal or biomass power and medium size hydropower plants. Finally, another approach could be to set intentional objectives

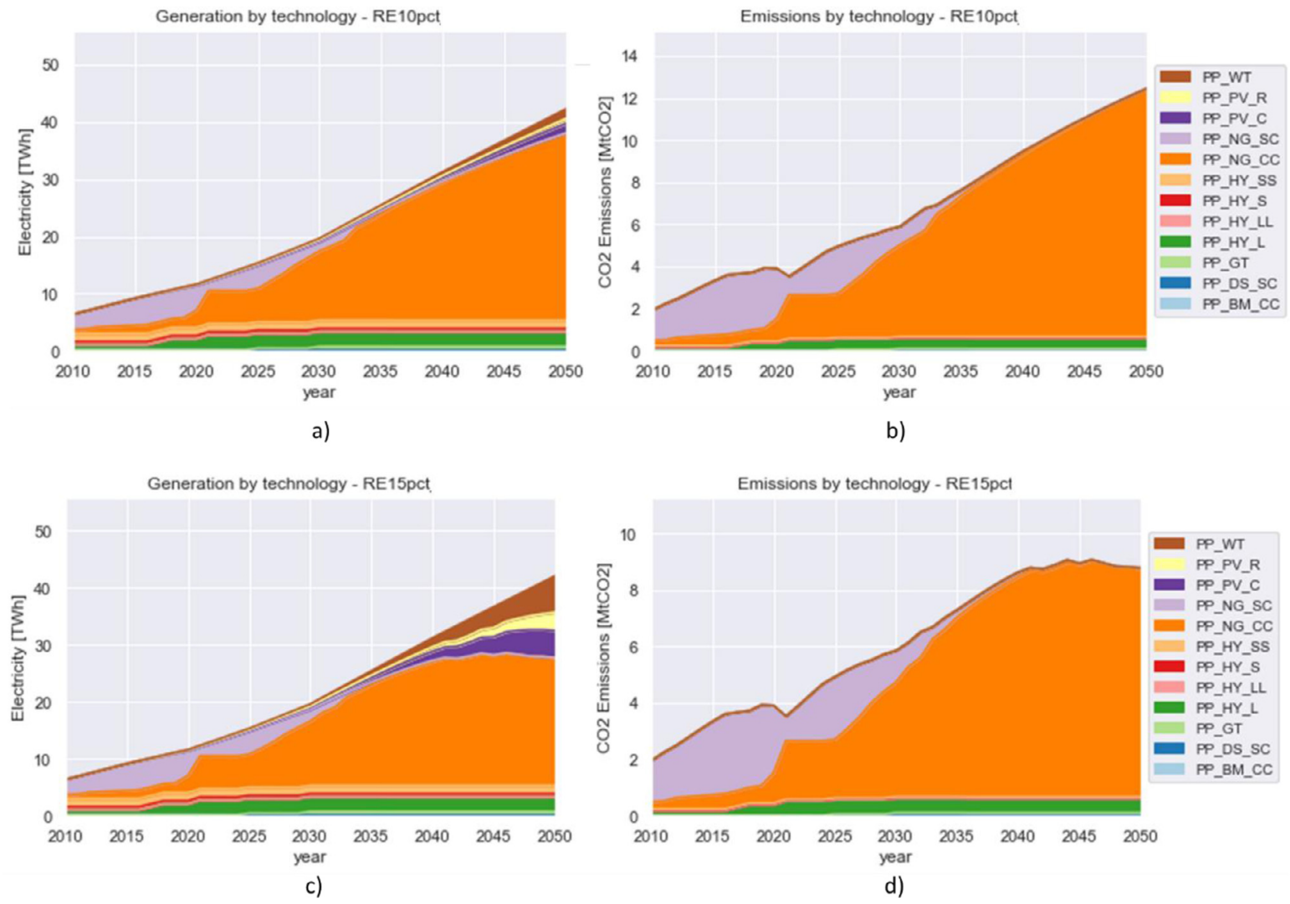


Fig. 8. Renewable growth rates of 10%/year and 15% year, up to maximum estimated potential capacities. Panels a) and c) show generation by technology [TWh] and panels b) and d) show the resulting emissions by technology.

for the growth of variable renewable energy in the system, even to 100% like European models [50, 51], or models that intend decarbonization at a global scale [52–54]. For example, private small-scale PV systems (as distributed generation) can be encouraged, shifting investment costs from the national grid operator to local consumers; here we have effectively mixed the two by including costs for rooftop PV. Higher penetrations of variable renewable energy sources will, however, require storage as well as generation capacity to be considered.

Proposed policy guidelines for GHG emissions mitigation

The results shown in Section 6 represent technology "levers" for a feasible energy system transformation. In this Section, a corresponding set of GHG emissions policy guidelines will be explored.

The connection of each policy proposal to the technology scenarios from Section 6 are given and initial working guidelines were formulated to guide the development of the national electricity sector and to point out when aspects of a transition might be disruptive or unrealistic. The proposed policy guidelines considered the recommendations and information available in policy-making guides [55–57] and development goals for renewable energy [58].

Policy 1: Restriction of the introduction of high impact plants

Intent: Limit the introduction of new "high impact plants" in the BES, that contribute to global warming.

Proposed Mechanism: Implement an indicator based on the emission factor of each of the plants, estimated during pre-investment studies. Plants with annual average emission factors exceeding $1000tCO2_{eq}$/year/MW should be classified as "high impact plants". The main institutions involved would be the Bolivian Ministry of Energy, as the main manager of the electricity sector, and the dependent institutions thereof, ENDE, the CNDC and the AETN.

Technical justification: The proposed emission factor measure is based on the equivalent for a simple cycle natural gas thermal power plants with a 50% capacity factor. This policy would likely lead to restricting the inclusion of hydroelectric plants in conflict zones such as the Amazon and to the participation of simple cycle power plants in the BES. Specifying the emissions factors in this fashion instead of the more usual "kg/MWh" essentially makes explicit the limits on operational time for these plants in support of, for example, higher penetrations of variable renewable energy. If over time it becomes more economically viable to install battery or other storage, rather than using natural gas peaking capacity, then this would occur. The limitation of thermoelectric plants would be partial, allowing new plants to enter the system with the condition that their annual emission factor is below the defined limit. The importance of including this restriction is reflected in all the scenarios that allow the entry of hydroelectric plants with powers greater than 500 MW (PGP1, NSR1).

Policy 2: Long-term planning based on participation goals

Intent: Investments must be made in the medium and long term based on participation objectives for the different types of power plants in the system.

Proposed Mechanism: To achieve this, sector planning will be carried out under two parallel approaches. The first is aimed at discrete changes through an agenda of projects planned in the medium term, for example 15 years in the future. The second approach proposes the delineation of participation goals by type of technology in electricity generation in the

SIN in the long term, at least 30 years in the future and aimed at reducing emissions and therefore fossil-fuel generation. An example would be to set maximum targets for natural gas generation, decreasing over time, as well as minimum targets for renewables, increasing over time. The goal would be to move toward decarbonization in the long-term, but to leave flexibility for implementation of different technologies, including storage technologies couple with variable renewable sources. The Bolivian Ministry of Energy, as the highest authority in the electricity sector, should be in charge of promoting and implementing the goals. These participation goals are somewhat consistent with the Bolivian NDC [4], which considers a high participation of 79% of renewables in the electrical generation matrix.

Technical justification: The definition of participation targets for renewable and thermoelectric plants is used as a guide on which the growth and management of the BES should be managed, to avoid results such as those observed in the PGP scenario, even without very large hydroelectric power, in which medium-term planning achieves a significant change in the system, but in the absence of a long-term plan, the BES returns to its BAU behavior. The proposed goals were carried out considering percentages that other countries defined in periods up to 2032 [58], and the country's expectations according to PEEP 2025 [10]; proposed values are conservative in relation to countries such as Brazil, where the electric matrix is proposed with 90% based on renewables, or Denmark, which has already achieved more than 50% of its electricity generation based on wind. Although the goals proposed here do not achieve carbon neutrality by 2050, they are linked to the Bolivian NDC, which makes a case for flexibility for developing countries, considering a Climate Justice Index and the concept of the Shared but Differentiated Responsibility [4].

Policy 3: Efficient use of renewable resources

Intent: Increase the installed capacity of renewable plants by making a hierarchical designation for investment of economic resources based on technical criteria.

Proposed Mechanism: Local investments will be pushed towards the implementation of new renewable energy based power plants, considering characteristics such as costs, availability and installed capacity. These variables should allow a prioritization among different power plants based on potential benefits for the electrical system and clear indicators such as the levelized cost of electricity ($/MWh), the expected annual productivity per unit of installed power (MWh / MW / year); and the optimal physical locations for each technology. The Bolivian Ministry of Energy with the direct support of ENDE corporation are expected to define and evaluate the indicators for all the power plants considered in the national development plans and propose new projects to increment the use of renewables in the system.

Technical justification: Analysis of available energy resources [25] and the portfolio of projects under study [34] and being implemented by the government [59] show that projects are not necessarily following an efficient selection criteria. As an example, solar power plants in the north of Bolivia, such as the Riberalta or Guayamerin plants, have a solar radiation of 4.2 kWh/m^2/day; if the same funds were to be designated to an area such as Potosí (6.5 kWh/m^2/day), generation could increase by almost 55%. Additionally, overall costs for variable renewable energy in particular are dropping every year, faster than most historical projections. As will be discussed below, encouraging increased installations of variable renewable energy sources such as wind and solar PV will also eventually lead to a need for battery or other storage technologies, thus emphasizing the need for a long-term total-system low-emissions development strategy as requested through Article 4 of the Paris Agreement.

Policy 4: Incorporation of distributed generating systems

Intent: Allow and encourage the inclusion of private distributed generation systems in the SIN to displace part of the electrical generation from thermal power plants.

Proposed Mechanism: Incentives for private small-power systems and distributors to make investments to cover a portion of their own electricity demand, while remaining part of the national electricity network. The involved institutions would be INE, as the main regulatory actor in the electricity sector at the national level, and the corresponding distribution companies (DELAPAZ, ELFEC, CRE, etc.), as operating managers.

Technical justification: Based on the results of the scenarios EUR1, EUR2 and EUR3, it is seen that the introduction of distributed generation systems can have an immediate and impact on the BES, with such incentives being common internationally [60–62]. This is the case in Germany, the United Kingdom, Denmark or Spain, all of which have achieved renewable energy penetrations of 40% or more in total electricity generation. Similar regulations are beginning to be implemented at the regional level in Latin America, for example in Chile [63] and Argentina [64].

Distributed generation would also reduce the amounts of investment needed for the installation of new centralized plants and replace the use of fossil resources. These policies can also help slowly introduce the concept of distributed and interconnected generation which may be useful in the long-term with higher shares of renewables, electric vehicles and storage of energy.

Policy 5: Gradual leveling of natural gas prices for thermoelectric plants

Intent: Effectively limit the participation of thermoelectric plants in the medium and long term by allowing an increase in the price of natural gas (reduction of subsidies) used for electricity generation.

Proposed Mechanism: An annual increase of $US 1.0/mmBtu or GJ from 2025 until prices are equal to international market prices by about 2030. To achieve this the Ministry of Hydrocarbons should work with the main entities involved, YPFB, as the main company involved with the extraction and processing of hydrocarbons in Bolivia, and AETN, as the main regulatory entity in the Bolivian electrical sector.

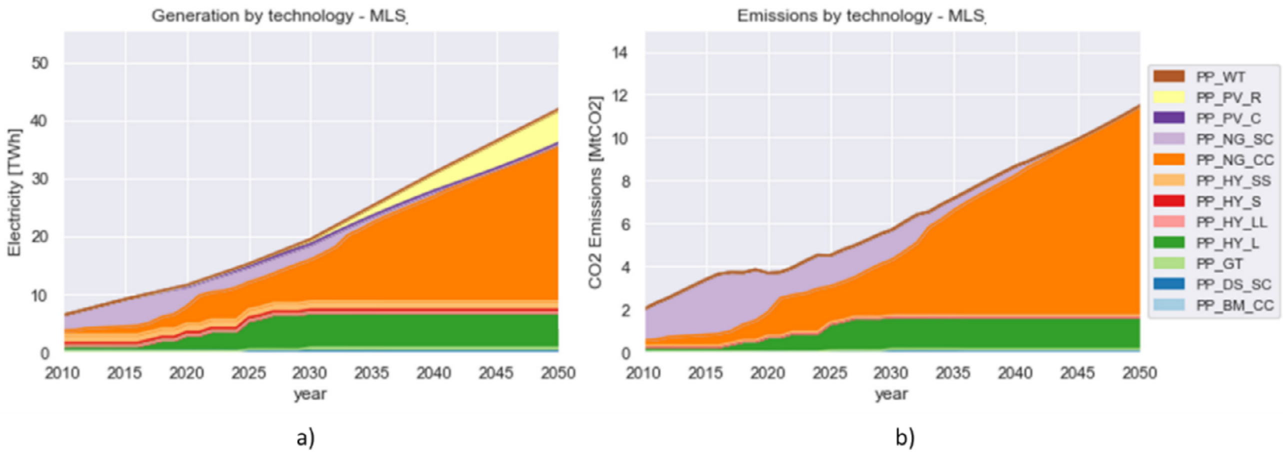
Technical justification: Because the BES is highly dependent on natural gas thermoelectric plants, measures that alter costs can be controversial. However, clear policies that consider increases in prices (reduction of subsidies) starting in 2025 would allow enough time for current thermoelectric plants to adjust to the new operating conditions, changing their current condition as baseload power plants to load regulators in the system, and limit the introduction of new plants. The impact on the system will be to encourage a faster build-out of renewable energy sources as these begin to compete on a level playing field. A secondary effect of the increase in natural gas fuel costs would be the reduction of opportunity costs that the state incurs by designating the use of natural gas, whose value in the international market is greater, to local consumption. To correctly apply this mechanism, detailed consideration of the evolution of international prices, as well as other impacts of the increase in regulated prices must be considered [65].

Policy 6: Taxes on carbon emissions from generation plants

Intent: Reduce the participation of polluting plants in the BES through the implementation of taxes on GHG emissions.

Proposed Mechanism: The collection of taxes linked to carbon emissions should be carried out annually, taking effect as soon as practicable, with an initial value of US$20/tCO$_{2eq}$. The tax will increase over time according to a plan that can be revisited and adapted as circumstances require. With many different approaches in operation around the world Bolivia can learn from the experience of other countries and regions. Power-plant-specific emissions factors can be determined in a straightforward fashion using volumes of fuel consumed. To regulate this policy it is proposed that the Ministry of Hydrocarbons, the Ministry of Energy and the Plurinational Authority of Mother Earth should work together. One key aspect of the carbon-pricing mechanism is that it should be open and transparent, enabling planning certainty for generating entities.

Technical justification: The implementation of taxes on carbon emissions is one of the most effective mitigation measures due to the direct relationship between the emissions made and the tax imposed [66]. In spite the theoretical efficiency of imposing carbon taxes, it is necessary to consider the local conditions of Bolivia and social justice issues when fixing a goal for the tax in the long term; the tax should be high enough



a)

b)

Fig. 9. MLS scenario for the Bolivian Electricity system a) Projection of the electrical energy produced [TWh] by type of technology; b) total emissions [MtCO2] by technology.

to have the desired impact on emissions, but not as high as to become an unviable measure that will be discarded. Results shown above indicate that even the most modest tax rising to US\$50/tCO_2 starts to have an impact. Supplementary policies could be used to distribute at least a portion of the carbon tax revenues to ameliorate potentially higher electricity costs for consumers.

Potential policy and technology scenarios for the future of the BES

The above techno-economic pathways and potential policy prescriptions can now be considered in tandem. Several of the proposed scenarios are limited for clarity of exposition in varying only some aspects of the model, whereas there could be interesting synergies between the measures considered in the scenarios as well as the policy options. Two combined “bracketing” scenarios were designed to evaluate the cumulative impacts on combinations of certain cases would have on the system.

Most Likely Scenario (MLS)

Beyond the BAU it is possible to take into account a minimal mix of conditions for the development of the BES that would require the least amount of modifications to the current expansion plan and the characteristics of the system. This scenario considers a loose implementation of Policy 1 (NG, some geothermal, but no mega-hydroelectric plants), as mentioned in the NSR cases in Section 6. Finally, the inclusion of distributed generation photovoltaic systems from the private sector to the grid is incorporated as well.

At the start of the model simulation, as shown in Fig. 9, thermoelectric plants assume 69% of generation, which drops to 50% in 2025, its lowest value in this scenario, increasing in the long term, from 2025 onwards, until they become responsible for 68% in 2050. This is due to the low costs associated with natural gas power plants, the lack of long-term planning objectives and the fact that no measure was taken to limit the competitiveness of thermoelectric plants. Overall emissions are slightly less than in BAU by about 20% in 2050.

An interesting consequence of this scenario is that it represents a short-term bridge using dispatchable renewables such as hydropower and potentially geothermal. In the medium-term this could provide space for future flexibility in designing a much lower-emissions system, while in the long term the incorporation of large shares of other renewable sources such as wind and solar, needs to be complemented by energy storage with batteries, pumped hydro plants or production and use of hydrogen, which are not included in our model. This can only be achieved if there is motivation of the government to consider investments outside this optimization criterion to heavily promote renewables.

Ambitious policy scenario (APS)

This case assumes that the Bolivia is willing to make large efforts to reduce GHG emissions, combining the conditions from the scenarios that consider the programmed generation plants until 2025 and carbon taxing (\$200/tCO_2 by 2050) to their abilities to reduce BES emissions. Reductions in natural gas subsidies were also used to 2030, gradually regulating the entry of thermoelectric plants enabling all renewables to be promoted in parallel. No very large reservoir hydroelectric power plants would be installed given the societal controversies and potential for large-scale disruption of ecosystems in the Amazon. Finally, it was assumed that policies would be in place to encourage a relatively rapid build-out of solar PV and wind, at a 15%/year rate of growth.

Under this scenario much of the current system would be replaced relatively quickly. Between 2020 and 2025, hydroelectric plants would play a central role as the base power of the system, and in the following years the other renewables such as large wind farms and even biomass plants would enter the system. Installed capacity of wind and, especially, solar PV is limited due to flexibility issues [67]; thermoelectric and geothermal plants are implemented to function as dispatchable energy resources, complementing variable renewables. Geothermal power plants are favored in the system because of their relatively low emissions [68, 45].

By the year 2050, wind power represents 38% and distributed and utility solar 11% each of electricity generation, with biomass and geothermal power plants contributing about 10% and 15%, respectively. Hydroelectric plants have a share of 9%. Fossil fuel thermoelectric plants cover the remaining 5% of generation in this scenario.

The increase in the price of natural gas causes thermoelectric plants to be relegated to a flexibility role competing with hydroelectric plants that also have significant, but lower, CO_2 emissions in our parameterization, which has a direct effect when considering carbon taxes. In the SI an extension of this case is shown in which battery storage is included in the model; that result shows two main conclusions – first, the remaining natural gas generation can be eliminated from the system by about 2040 with the increase in variable renewable energy generation coupled with storage. Second, the amount of wind capacity can be decreased, and substituted with increased solar PV generation, with storage serving to bridge the diurnal change in solar PV generation.

The cumulative effect of the cases reduces emissions significantly after the historical period, peaking after 2025 and then falling below current levels, although electricity generation continues to increase. Total emissions in the APS are between 2.0 MtCO_{2eq} and 3.0 MtCO_{2eq} each year, only 20% of what was expected in BAU. However, as shown in Fig. 10 emissions reach a minimum in the 2040’s before beginning to

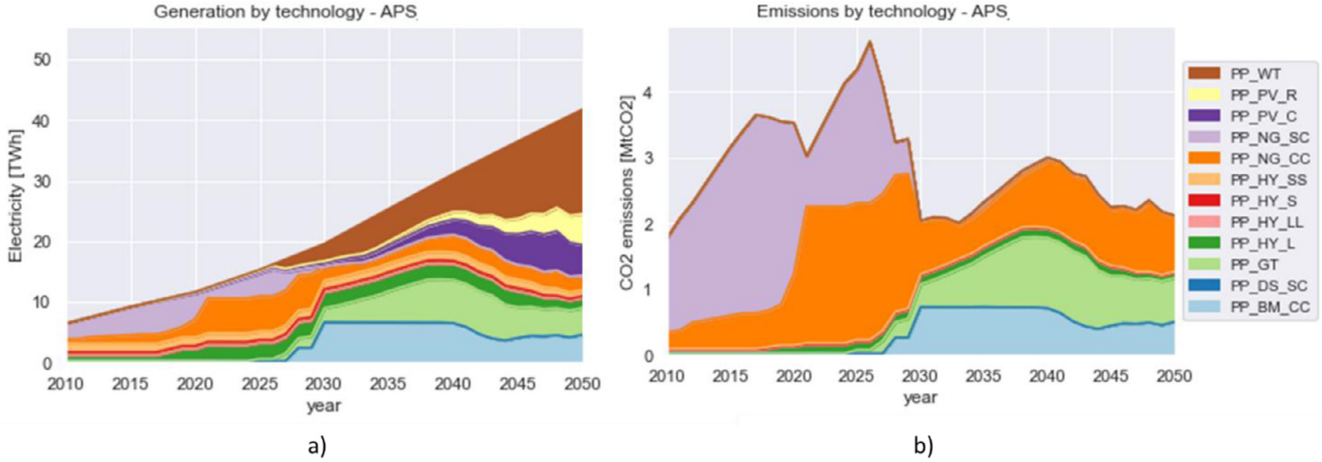


Fig. 10. Ambitious policies scenario for the Bolivian Electricity system a) Projection of the electrical energy produced [TWh] by type of technology; b) total emissions [MtCO2].

rise again later, now due to increasing amounts of geothermal, biomass and hydroelectric power, all of which still have some significant CO_2 emissions that must be taken into account. One final example is shown in the SI as well, in which the IAM 1.5 °C compatible carbon tax pathway (CTS4 above) is coupled with the availability of storage. In that case, the very high carbon prices lead to a decrease in total emissions toward zero by 2060, as increases in rooftop and utility PV along with storage are enough to drive even the biomass and geothermal power out of the system.

All of the aforementioned shows the synergistic effect of the measures considered in the reduction of GHG atmospheric emissions in the BES. Of course, between these two combined technology and policy cases lies a spectrum of other options for decreasing emissions while still satisfying electricity demand.

Conclusion and policy implications

The focus of this work is on the long-term transformation of the electrical system of Bolivia using the cost-based optimization model OSeMOSYS. The emphasis is on not only developing scenarios, but on proposing concrete measures, policies and guidelines that can enable that transformation.

The reference BAU scenario with subsidized natural gas leads to a further increase in natural gas thermoelectric plants over the modeling period to 2050, resulting in a nearly five-fold increase in CO_2 emissions. To investigate alternatives to BAU technological options were investigated, including scenarios based on current plans for future generation capacity (PGP), on the introduction of a carbon tax or reductions in subsidies to natural gas to force a technology shift, and on limits of encouraging installation of renewable energy technologies such as wind and solar PV.

Bracketing scenarios using techno-economic considerations as well as policy prescriptions were developed considering proposed policies, in various degrees of implementation for each case, designated as MLS (Most Likely Scenario) and APS (Ambitious Policies Scenario).

The results show that measures easily achievable (MLS), such as following the current plan of development of the electric system and banning large hydropower plants in the Amazon, would have only a short term impact on the system, since, aside from some short-term changes, the trends of the BAU scenario are continued after 2025. This is particularly important when discussing the implementation of large hydroelectric plants, since their impacts are not easily measured and quite controversial in the literature in terms of GHG emissions and could potentially result in higher emissions than relatively efficient natural gas combined-cycle thermoelectric plants.

On the other hand, if every policy were to be implemented (APS) a strong reduction, and later stabilization, of the carbon emissions would take place, reaching a maximum of ~2.5 $MMtonCO_{2eq}$ each year. This reduction of emissions and therefore participation of NG thermal plants, is limited by the maximum amount of potential available geothermal, biomass and medium-size hydroelectric capacity. Actual emissions factors for geothermal plants [69] and specific hydroelectric plants should be carefully investigated to be certain that locally relevant emissions factors of GHG in each of the different size and types of hydroelectric plants in Bolivia. Although challenging to achieve, the APS can serve as a guideline for energy system transformation toward zero emissions.

To summarize, the transformation will require a focus on 1) reducing the artificial competitiveness of thermal power plants (subsidies), 2) banning high impact power plants (mainly large hydropower plants) and 3) define clear long-term objectives for the participation of renewables in the system, based on the objectives of the current short-term plans. These measures have to be taken considering the current conditions of the electrical system and the potential or limitations of each renewable technology available, such as being able to serve as a flexibly dispatchable complement to variable renewables. Geothermal, biomass and hydropower can serve that role, and especially as the penetration of wind and solar power increase, battery (or other) storage will become necessary.

Although the optimization model in the OSeMOSYS framework is based on finding a lowest cost for the energy system over the modeling period, we have not focused on the relative costs of the various policies with respect to the BAU case. In Table 1 a summary of costs and relative costs for each scenario is shown. Since the overall purpose of this exercise is to examine the potential for reducing carbon emissions from the energy system, the marginal cost of mitigation for each scenario with respect to the percentage reduction achieved is also given in Table 1. Both quantities are referenced to the period 2020–2050, although the model was started in 2010 to include historical trends and ran until 2060 to avoid any artifacts in the results from end effects of the modeling. Overall, mitigation costs increase linearly with respect to amount of reduction at marginal cost of approximately $\$10/tCO_2$ reduced. Reductions become more difficult and therefore more expensive when attempting to achieve net-zero emissions, at least without significant electricity storage.

There are still areas in need of further research in the Bolivian energy system. A few recommendations for subsequent work can be suggested. In terms of planning, more detailed (and time-resolved) modeling of the system will be necessary, especially if the penetration of variable renewable sources increases significantly, and with a full range of potential technologies included. Energy storage will increasingly be nec-

Table 1
Changes in the BES's NPV in relation of their overall reduction of emissions for the period 2020–2050.

Scenario name	Emissions in 2030 [MtCO2]	Emissions in 2050 [MtCO2]	Present value 2020–2050 [million USD]	Emissions 2020–2050 [MtCO2]	Change in emissions wrt BAU	Change in PV wrt BAU	% change in emissions wrt BAU	% change in PV wrt BAU
BAU_final_2	6.5	13.8	1833	257				
BAU_PGP_final	12.6	25.3	2738	476	219	905	85.2%	49.4%
tax50_final	6.5	12.6	2279	255	-2	446	-0.8%	24.3%
tax100_final	6.5	7.9	2465	227	-30	632	-11.7%	34.5%
tax200_final*	6.1	2.4	2632	145	-112	799	-43.6%	43.6%
taxIAM_final_2*	1.8	1.2	3793	63	-194	1960	-75.5%	106.9%
NSR2030_withHYLL_final	11.5	14.1	2819	331	74	986	28.8%	53.8%
NSR2030_noHYLL_final	4.9	4.2	2911	137	-120	1078	-46.7%	58.8%
NSR2030_noHYLL_final_2*	4.6	4	2785	130	-127	952	-49.4%	51.9%
RE10pct_final	5.9	12.5	1833	244	-13	0	-5.1%	0.0%
RE15pct_final	5.9	8.8	2202	216	-41	369	-16.0%	20.1%
RE15pct_final_2*	6	6.7	2151	202	-55	318	-21.4%	17.3%
RE20pct_final	5.9	7.3	2598	189	-68	765	-26.5%	41.7%
MLS_final	6	12.1	2156	236	-21	323	-8.2%	17.6%
APS_final_4	3.8	1.8	3417	98	-159	1584	-61.9%	86.4%
APS_final_5	3.3	1.5	3371	86	-171	1538	-66.5%	83.9%

essary and is also increasingly becoming economically viable to support variable renewable energy technologies. The issue of greenhouse gas emissions from tropical reservoirs and other large hydroelectric plants is an important one to consider. Aside from important sustainability and societal impacts, it would be particularly tragic to invest in such major projects if they do have emissions similar to fossil fuel power generation as the literature tends to suggest. Demand-side management policies could be included in modeling in the future as well, although as a developing country, sufficient energy access that is reliable and affordable is clearly a priority as well. Finally, over the longer term the incorporation of additional sectors in a complete energy system model would be desirable; this would include more explicitly industry and mining sector energy consumption, more end-use resolved residential energy sources including direct combustion, and perhaps most importantly, inclusion of transportation as another main energy consuming sector.

Author Contributions

Carlos A. A. Fernandez Vazquez - Conceptualization; Methodology; Data curation; Formal analysis; Roles/Writing - original draft; Writing - review & editing.

R.J. Brecha - Formal analysis; Data curation; Methodology; Writing - review & editing.

Miguel H. Fernandez Fuentes - Conceptualization; Methodology; Supervision.

Data availability

Output results and model data are available in Zenodo's webpage. Information is available in the link: https://zenodo.org/record/5,823,510. The repository information has the DOI number: 10.5281/zenodo.5823510.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2022.100017.

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