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# Towards low-carbon energy systems: The case of Bolivia until 2035

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## Abstract:

Energy is vital to reduce poverty and improve social and economic development. For more than a century, modern economies have based their growth on fossil fuels, which has led to global warming, environmental pollution, and social problems. In accordance with the Paris Agreement (2015), governments have committed to evaluating their energy systems to seek appropriate solutions to support their decarbonization and keep global warming well below 2$^{o}$C. In order to achieve this objective, developing countries are making considerable efforts, among which is considered a shift to the use of renewable energy sources to satisfy their growing demand. Despite the current development and planning for the sector, there is room for improvement within the long-term planning and evaluation of energy systems. This paper analyses the difference between fossil-based and renewable-based growth in terms of economics, technical and environmental effects in Bolivia. To do so, all the country's energy sectors, including electricity, heat, and mobility, are covered and optimized through the open-source energy system modeling framework EnergyScope. Results showed a sustainable energy scenario in 2035, which accounted for 66% of renewable share and 44.64 €/t$CO_{2\text{-eq.}}$ related to a compensation value for the difference with the business-as-usual scenario based on future government plans. This work demonstrated that a Bolivian energy system with a high share of renewable resources is possible, leading to energy sovereignty addressing climate change.

## Keywords:

Bolivia, Sustainable growth, Renewable energy, Energy system modeling, Energy development.

## 1. Introduction

Poverty reduction, industrial activities, and improvement of education and healthcare services are strongly related to the energy a society can consume. Nonetheless, the availability of energy supply is not the only objective, but also to achieve sustainability to maintain an ecological balance, social equity, and economic vitality [1]. The use of fossil fuels has led to global concern about the emissions of greenhouse gases (GHG). Therefore, one hundred and ninety countries have pledged to the Paris Climate Agreement to limit the global average temperature increase to 1.5℃ or well below 2℃ and have established clear goals to be fulfilled by the years 2030 and 2050 [2]. Decarbonization exploits pressure on all nations globally, but even more low and middle-income countries, which in most cases, have planned to rely on fossil fuels to achieve development [3]. Although Bolivia possesses a relatively low contribution to global GHG emissions (0.21% of the total 48.6 Gton$CO_2$eq registered in 2021) [4], it was the 43th country with the highest emissions per capita in 2021 (9.6 ton$CO_2$eq/person) [5]. Thus, Bolivia has signed the agreement and is putting significant efforts to meet the commitment and also become a primary net exporter of electricity in South America [6].

According to the information provided by the Ministry of Hydrocarbons and Energy (MHE), Bolivia's total primary energy supply (TPES) in 2021 was 202.9 TWh, based mostly on fossil fuels (80.7% and 11.9% of the energy coming from fossil gas (FG) and oil, respectively). From this value, 58% corresponded to gas export (117.4 TWh) [7]. Related to other sources, such as biomass, hydro, solar, and wind energy, reached 7.4%. Similarly, the power sector has relied heavily on fossil gas for the last two decades. The Bolivian power grid is divided into the National Interconnected System (SIN) and the Isolated Systems (SAs). For instance, the country's total installed electricity generation capacity was 3.72 GW for 2021, of which 71.03% comes from thermoelectric power plants, 20.36% from hydropower plants, and 8.60% from other renewable sources such as wind energy and photovoltaic systems [6]. Moreover, fossil fuel-based electricity generation is subsidized by approximately 46.63 €/MWh for diesel [8], and 3.95 €/MWh for FG (Supreme Decree No. 29510) [9]. In this context, the government has established policy guidelines, including universal electricity access, reducing the consumption of petroleum derivatives, and increasing renewable energy use for electricity generation [10].

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Nevertheless, most of Bolivia's energy objectives and projections are based on 2007 statistics and extend until 2030. Recent expansion plans for the sector are described in the Patriotic Agenda for 2025 [11] and the update of the Intended Nationally Determined Contribution (INDC) [2]. For instance, the Electrical Plan of the Plurinational State of Bolivia (PEEBOL2025) presented by the MHE stipulated the installation of 183 MW of renewable energy by 2025 [12], and the Alternative Energy Development Plan (PDEABOL2025) included a simple estimation of the renewable energy potential of the country [13]. Recent projections from the National Electricity Company (ENDE) indicate that 74% of the newly installed and existing capacity will be hydropower (Hydro dam and hydro run-of-river), 4% other renewable, 12% combined cycle plants, and 10% thermal power plants. Nonetheless, only the SIN is accounted for in these forecasts. So, electrification plans for rural communities that cannot be included in the SIN are also required [12].

Furthermore, Bolivia aims to become an electricity exporter to neighboring nations. With the new large hydropower capacity inclusion, the electricity exports could account for up to 21% of total electricity exports in South America [14]. Besides the estimated hydroelectric potential of 39.86 GW related to the watercourses of the large rivers that surround Pando, Beni, and the strip that goes from the Yungas of La Paz in the north of the country to Tarija in the south, Bolivia holds a high RE potential, which is distributed throughout its territory. Thus, the country has a high solar energy potential due to its position south of the equator line and high altitude above sea level (higher than the international solar radiation average). Practically, 97% of all the national territory is suitable for solar energy, and the remaining 3% have been identified as areas of dense cloudiness located to the east of the Andes region [15]. According to Bolivia's Atlas of global solar radiation, the existing solar radiation in the country's lowlands (Santa Cruz, Beni, Pando, and north of La Paz) reaches a maximum of 5.1 kWh/m$^2$/day. At the same time, in the sector of the valleys (Cochabamba, Chuquisaca, and Tarija), this value can vary between 5.1 and 6.7 kWh/m$^2$/day and in the Altiplano (La Paz, Oruro, and Potosí), the radiation is between 6.7 and 9.5 kWh/m$^2$/day [16]. The most robust wind resource is located in the southern and western regions of the department of Santa Cruz, in the southwestern sector of the department of Potosí, in a strip to the west and south of La Paz and Cochabamba [17]. Furthermore, twenty-one potential geothermal resources have been detected in the country's western mountain range, eastern mountain range, and Altiplano, near the departments of Potosí, Oruro, and La Paz [15]. Significant biomass resources are available in the country, likewise. For instance, forest biomass such as firewood and logs can be extracted in the Amazon region principally. In 2005, Bolivia possessed a wood stock of 317 million m$^3$ in its forested area. It was estimated that the sustainable production capacity of the Bolivian forest was 20 million m$^3$ of wood stock per year [15, 18]. Due to the country's unique natural circumstances, Bolivia produces various agricultural products. According to the agricultural census conducted by the National Institute of Statistics, the six most important crops grown in Bolivia are sugarcane, soy, sorghum, corn, rice, and sunflower, with the Department of Santa Cruz being the primary producer [19]. Morató et al. estimated that approximately 3.7 Mton/year of sustainable biomass on a dry basis is available in Santa Cruz [20]. Even though agricultural and forest residues are abundant in Bolivia, they are not utilized as a low-cost energy source to increase the proportion of renewable energy in the energy mix and reduce fossil fuel consumption.

The Bolivian energy sector is the second largest contributor to the country's GHG emissions (After agriculture, forestry, and other land uses). Although the country lacks rigorous emissions reduction targets, the INDC, presented by the authorities to United Nations Framework Convention on Climate Change (UNFCCC), projected a decrease in GHG emissions from 0.41 ton$CO_2$eq/MWh in 2015 to 0.04 ton$CO_2$eq/MWh in 2030 in the country's power sector [2, 21]. Additionally, the Global Climate Risk Index (IGRC) of 2021 ranked Bolivia as the most affected and the tenth most vulnerable country in the world [2]. This highlights Bolivia's need for strategic energy policies and carbon reduction goals to protect its most vulnerable communities and rich biodiversity. Thus, the energy system will allow renewable energy (RE) to be competitive, cope with subsidies, and deal with the absence of negative GHG emission pricing. Therefore, the focus of this study is to model a fully sustainable transition for Bolivia across all energy sectors and assess the feasibility of such a transition in terms of economics, technical and environmental effects to help shape future Bolivian society's energy behavior and reach the objectives for a long-term sustainable energy system with low-carbon emissions. The remainder of the paper is structured as follows. Section 2 describes the methods of the EnergyScope model. Section 3 presents the current Bolivian energy system and information about resources, demand, and technologies. Section 4 provides results by sector for each scenario. These results and main limitations are discussed in Section 5. The main conclusions are summarised in Section 6, then recommendations for future works are made.

## 2. Methods

The present research relies on *EnergyScope TD*, a bottom-up linear programming modeling framework for the long-term planning of energy systems, including a high share of RE and representing the heating, mobility, and electricity sectors equally [22]. It has already been applied to develop energy transition scenarios for European countries such as Switzerland [22, 23], Belgium [24], Italy [25], as well as Uganda [26]. Given demands in the different sectors and resources, the model identifies a design and an hourly operation optimisation of

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the conversion technologies to minimize the overall system cost, considering a constraint on greenhouse gas emissions. The main input data of EnergyScope TD are founded on three elements: resources, technologies (energy conversion, storage and infrastructure), and demand, as depicted in Fig. 1. Furthermore, it involves typical days (TD) to reduce the computational time (around one minute on a personal laptop) while keeping a simple and straightforward formulation. The reconstruction method by Gabrielli et al. enables consideration of seasonal phenomena [27]. In this application, twelve TDs have been used, which was shown to be a good trade-off between accuracy and computation time [24]. Moreover, the version utilized is the one that corresponds to Limpens' thesis [26]. Even though the original model accounted already for more than 100 options for technologies, resources and demands, an adaptation was required for the present study. The main additions were:

- Resources: Liquefied petroleum gas (LPG).
- Demand: Heat demand for cooking.
- End-use categories: Cooking and mobility freight air.
- Technologies: Open cycle gas turbine (OCGT), diesel genset, biomass combustion power plant, syngas combustion power plant, firewood stove, LPG stove, FG stove, oil stove, electric stove, aircraft, biomass fermentation to bioethanol, esterification to biodiesel, diesel engine, LPG burner and gasoline bus.

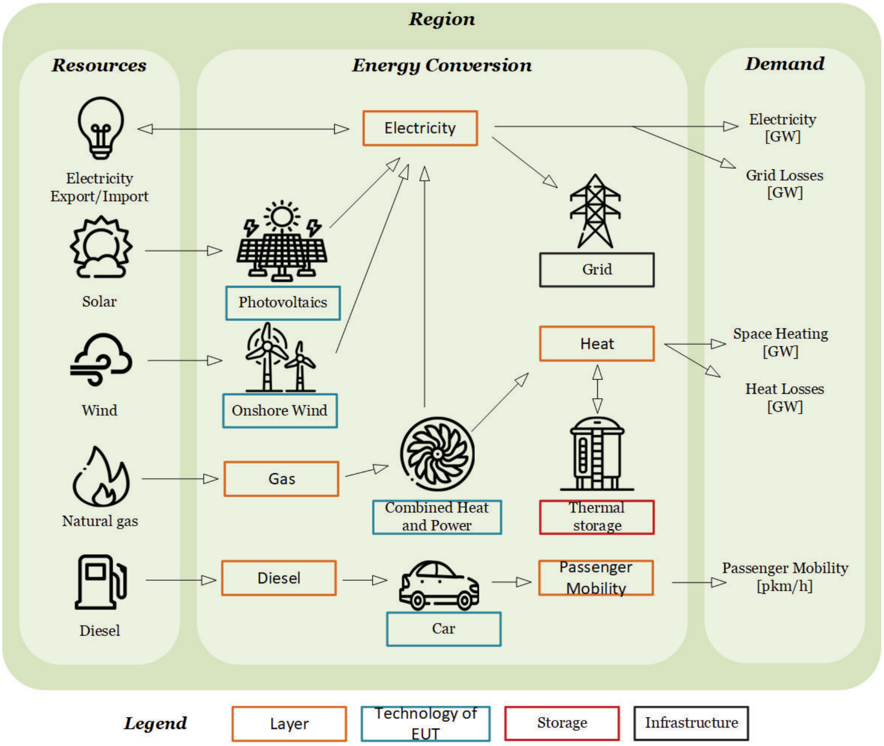

**Figure 1**: Conceptual representation of an energy system: Resources are converted by technologies to supply end-use type (EUT) demands related to electricity, mobility, and heating. Layers, such as *Electricity and Heat*, require to be balanced in each period. This figure is inspired from [22].

## 3. Case study: Bolivia

This section presents an overview of the Bolivian energy system based on the last national energy balance presented by the Ministry of Hydrocarbures and Energy (MHE) for the year 2021 [28,29], and the main techno-economic information to perform the optimisation for the year 2035.

### 3.1. Demonstration for the year 2021

Primary energy consumption in Bolivia for the year 2021 reached 94.28 TWh, with an approximate population of 11.84 million inhabitants [30]. Regarding sources, fossil fuels (FG, diesel, gasoline, LPG, and light fuel oil (LFO)) represented 87.0% of the country's final energy demand. In this context, the participation of renewable energy sources was limited to less than 14% of the total: wet and woody biomass with 9.1%, hydropower with 3.4%, and others (solar and wind) with a proportion of 0.5%. This data was assembled and summarized in a Sankey diagram, Fig. 2.

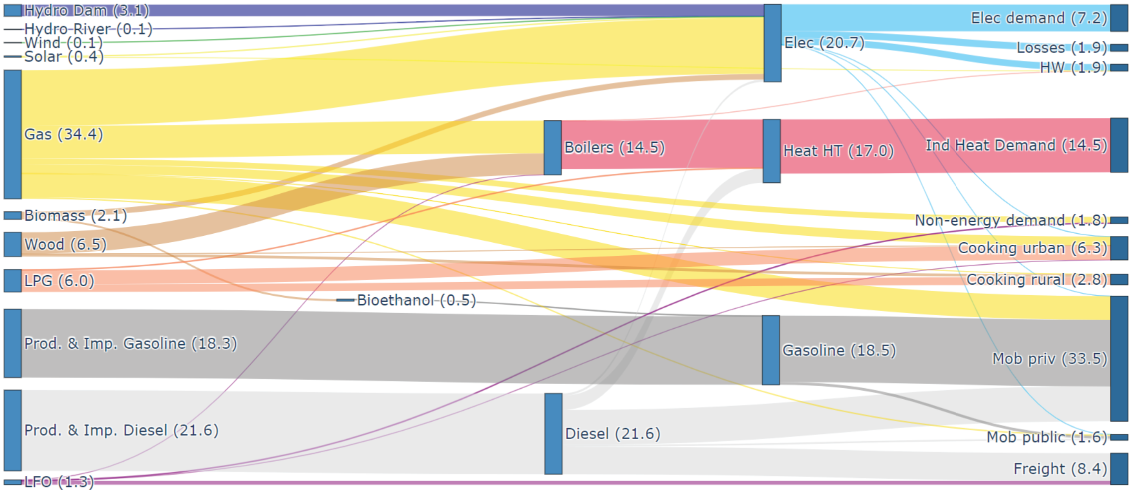

**Figure 2**: Energy flows of the modeled Bolivian energy system for 2021 (Units: TWh). The left side integrates all the resources while the right side retrieves the final energy consumption. The conversion technologies are in between. Energy exports are not represented. Abbreviations: mobility (mob), private (priv), electricity (Elec), liquefied petroleum gas (LPG), light fuel oil (LFO), industrial (Ind), domestic hot water (HW), low temperature (LT), high temperature (HT), importation (Imp), production (Prod).

As shown in Fig. 2, the present landscape of energy utilization in Bolivia could be divided into electricity, transport, and heat. The electricity generation was mainly covered by gas turbines (open-cycle and combined-cycle technologies), which represented around 59.7% of the total amount, followed by hydropower (29.7%), biomass (4.2%), photovoltaic (3.2%), diesel gensets (2.1%), and wind (1.1%) [6,29]. The mobility sector was split into public transport with diesel, gasoline, gas buses, and electric aerial tramways. On the other hand, private transport comprised light vehicles fueled by gasoline, diesel, fossil gas, and electricity [31,32]. Trucks contributed the most to freight transportation. Still, there were also rail, boat, and air transport options. Heat use was subdivided into three major demands: cooking, domestic hot water (HW), high-temperature heat (HT) from industrial processes such as manufacturing (foods and beverages, textiles, no metallic, and metallic), cement production, mining, and quarrying [31]. Residential and commercial cooking demand in Bolivia was mainly based on LPG (approximately 73.6%), followed by fossil gas (23.2%), woody biomass (2.5%), electric (0.4%), and LFO stoves (0.3%). A division between cooking in rural and urban areas was made, as the gas network does not cover the entire country. Likewise, the industry also relied on FG [28]. Overall, the EnergyScope TD model accurately portrayed the final energy consumption (FEC) of the Bolivian energy sector and its associated GHG emissions for the year 2021. The assessment of the present state of the system revealed 94.19 TWh/y in terms of primary energy consumption, differing only 0.1% from the country's energy balance [28]. Similarly, regarding $CO_2$ emissions related to the energy sector and waste, the model calculated 24.51 MtCO$_{2\text{-eq.}}$/y whereas CAIT country greenhouse gas emissions reported 23.17 MtCO$_{2\text{-eq.}}$/y [4,33,34].

## 3.2. Scenario in 2035

Due to a vast array of modern technologies and a rapid expansion of the economy, the energy system of Bolivia may undergo significant changes. So, this section presents the resources and technology potentials and forecast demands for Bolivia in 2035, a period that allows for substantial transformations yet close enough to know the available technologies at that time.

### 3.2.1. Energy resources

The resources available for the Bolivian energy system could be divided into fossil and renewable.

*3.2.1.1 Fossil resources*

Bolivia holds FG reserves (2 729, 1 009, and 1 485 TWh of proven, probable and possible reserves in 2018) [29]. Furthermore, the economy of the country relies to a great extent on fiscal revenues and tax collection from FG exports. In 2021, nearly 72% of its total FG production was exported (75.45 and 48.22 TWh of FG to Brazil and Argentina, respectively). Those accounted for 20.5% of Bolivia's total exports (around 1 924

M€) [35]. Nonetheless, oil extraction is limited (14.09, 89.00, and 220.25 TWh of crude oil, natural gasoline, and condensate proven reserves in 2018, respectively) [29]. Consequently, the government has to import diesel, gasoline, and other oil-based products. Since 2001, Bolivia has subsidized those fuels in the energy sector, intending to pass on affordable prices (46.63, 53.48, 35.45, 3.95 €/MWh related to diesel, gasoline, LFO and FG subsidized prices, respectively) [36]. For comparison, the prices used in this article correspond to the ones without the subsidy (Table 1). Moreover, the estimated prices of fossil fuels for the horizon of 2035 in Bolivia are based on the projection of the U.S. Energy Information Administration (EIA), expressed in the reference case of the Annual Energy Outlook 2022 (153.91, 163.21, 139.10, 15.03, 33.27 €/MWh for diesel, gasoline, LFO, FG, and LPG, respectively) [37].

#### *3.2.1.2 Renewable resources*

Renewable energies are essential to the energy transition; consequently, their deployment is crucial. Real weather data and scaled inflows were used to model solar, wind, and hydro resources to account for temporal variations in availability. For each hour, average capacity factors for wind and solar were computed using the open-source Renewables Ninja database [38–40]. For hydropower plants, hourly water inflows were used. The Electric Load Dispatch Committee (CNDC) supplied these hydrological data; values are publicly available in [41]. The biomass and waste yearly resources could be summarized as follows: 17.81 TWh of wet biomass from agricultural residues [42], 5.2 TWh of wet biomass from the 2010 approximated value of organic municipal solid waste [30, 43], 4.5 TWh of wet biomass used to generate electricity in 2021 [29], 5.7 TWh of wet biomass used to reach the maximum volume mentioned in the agreement by the government and the bioethanol producers until 2025 [44], 1.2 TWh of wet biomass from elephant grass of the two future biomass power plants planned by the government [45] and 28.6 TWh of wet biomass from the three future biodiesel production facilities planned to be built until 2025 [46]. Unfortunately, no information about woody biomass resources such as forest residues has been reported. So, only firewood for cooking was considered in this article, accounting for the sustainable production of wood as a limit [18]. The potential geothermal estimates were determined according to Gawell et al. [47], besides the planned Laguna Colorada geothermal power plant, which is currently a pilot plant [48]. Table 1 summarizes the resource potential described previously.

**Table 1**: Energy resources and their potential.

| | Sources | TPES in 2021 (TWh) | Availability (TWh/y) | Price in 2021 (€/MWh) | References |
|---|---|---|---|---|---|
| **Fossil fuels** | Gasoline | 18.54 | (no limit) | 124.12 | [29] |
| | Diesel | 21.72 | | 111.31 | |
| | LFO | 1.07 | | 85.12 | |
| | FG | 34.43 | | 10.66 | |
| | LPG | 6.03 | | 21.58 | |
| **Biomass** | Woody | 0.78 | 150 | 16.98 | [18, 29] |
| | Wet | 2.07 | 63 | 10.32 | [29, 30, 42–46] |

### 3.2.2. Energy demand

The Latin American Energy Organization (OLADE) published a report offering future energy projections of the Andean zone. Those numerical values included the yearly FEC by fuel based on future expansion plans of the energy sector, energy balances, and gross domestic product (GDP) growth of Bolivia, Colombia, Ecuador, Perú, and Venezuela until 2050 [49]. The yearly end-use demand (EUD) was estimated and used as an input parameter in the model based on this final energy demand. Besides, cooling demand was not specified due to the lack of information on the consumption of residential, commercial, and industrial subsectors. Nonetheless, as in other developing countries, refrigeration, food conservation, and air conditioning (AC) requirements in Bolivia are usually covered by electricity [50]. Therefore, it is already included in electricity demand. For instance, AC is seldom used in the households of the Altiplano and the valley regions. On the other hand, electric fans and AC systems utilizing liquid refrigerants are commonly employed in the country's lowlands urban areas. These can account for up to 40% of the total energy demand in an urban household in Santa Cruz during a hot summer day [51, 52]. Moreover, commercial and home refrigerators and other complex industrial systems in the country usually comprise electric compressors [50]. Table 2 illustrates the differences between the end-use demand in 2021 and 2035.

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**Table 2**: Comparison of energy end-use demand for 2021 and 2035. Abbreviations: temperature (Temp.), passenger (pass.), tons(t).

| | | Units | 2021 | 2035 | Δ | References |
|---|---|---|---|---|---|---|
| **End-use demand** | Electricity | (TWh) | 7.2 | 10.1 | +2.9 | [28, 49] |
| | Heat High-Temp. [a] | (TWh) | 14.5 | 19.9 | +5.4 | |
| | Heat Low-Temp. [a] | (TWh) | 1.8 | 2.5 | +0.7 | |
| | Cooking [a] | (TWh) | 5.1 | 6.9 | +1.8 | |
| | Mobility pass. [a] | (Gpass.-km) | 73.7 | 101.0 | +27.3 | |
| | Freight [a] | (Gt-km) | 15.5 | 21.2 | +5.7 | |
| | Non-energy [a] | (TWh) | 1.8 | 2.4 | +0.6 | |

[a] In [49], the FEC is provided instead of the EUD; hence own calculations were performed to estimate these values.

The forecast given in Table 2 shows an increase in all types of demands of around +37%. Electricity increase was the most important (+42%). The increase in energy demand was related to the projected economic growth of the country at an average annual GDP growth of 2.7% since 2024 [49] and the population growth with an average rate of 1.33% for the 2020-2040 period [53]. In addition to yearly demands, an hourly time series is used to dispatch the variable demand over the year. Thus, the electricity demand series was obtained from CNDC [54], and the mobility demand was adapted from [55].

### 3.2.3. Energy technologies

The technologies utilized in this study can be divided into three categories: conversion, storage, and network. Conversion refers to transforming one energy carrier into another with conversion efficiency. Storage devices can store energy over time, characterized by input/output efficiency and losses. Lastly, networks permit the transport of certain energy carriers across the nation, such as the gas or electrical grid. The networks are characterized by transmission losses. In this case, the one for the electricity grid is set at its historical value of 17.2% [28, 29]. Future technologies were based on local commercial availability [51, 53], government plans, and trends in Bolivia, so hydrogen-based, carbon-capture, heat pumps, and seasonal storage technologies were not considered. Table 3 shows different technologies' installed capacity and potential.

# 4. Results

In the following section, the model was applied to prospect the energy system at the horizon of 2035. The data used were listed in Section 3.2. First, the Business As Usual (BAU) projected scenario based on the future power plants [12] and biodiesel production facilities [61], planned by the government until 2025 was presented 4.1.). Then, a renewable-based scenario was proposed and compared to the BAU one (see 4.2.).

## 4.1. Business As Usual (BAU) case

The Business As Usual case was based on the characterization of the Bolivian energy system without GHG constraints, leading to a scenario without considering major changes in consumption trends or policies that alter the behavior of the system components. Hence, a minimum capacity for power plants, the technologies for producing biodiesel and bioethanol, and the share between the different mobility technologies were maintained.

### 4.1.1. Major trends in energy consumption

Optimisation results stated a FEC of 142.08 TWh per year, representing an increase of 50.8% compared to the year 2021. Figure 3 illustrates the energy balance over the year 2035 from primary to final energy consumed for this solution. As can be seen, the system still relied heavily on FG (around 42.9% of the total demand), which was consistent with the regional policies of extraction, production, and use of this resource. Furthermore, the national reserves were sufficient to supply the mentioned demand besides the significant growth and the export volumes of the current contracts (Approximately 2 619.1 TWh of total gas demand from 2021 to 2035). Related to renewable resources, there was a massive increment of biomass to produce biodiesel and bioethanol in this scenario according to the government plans. Regarding GHG emissions, the system produced 25.74 MtCO$_{2\text{-eq.}}$ (around 1.81 tCO$_{2\text{-eq.}}$ per capita), during its yearly operation, which represented a 5.0% increase compared to the system of 2021, and 66% smaller than the Belgian cost optimum BAU scenario for 2035 [24].

### 4.1.2. Power sector

Electricity generation was dominated by hydro dam power plants (6.24 TWh), followed by combined cycle gas turbines (3.34 TWh), Photovoltaic plants (PV) (1.75 TWh), geothermal plants (0.80 TWh), wind turbines (0.61 TWh), hydroelectric run-of-river power units (0.30 TWh), open cycle gas turbines (0.27 TWh), and bioenergy steam turbines (0.51 TWh). Aside from the planned power plants established in PEEBOL2025, only one

**Table 3**: Installed capacity of technologies and their potential.

| | **Technology** | **Capacity in 2021** | **Initial capacity in 2035** | **Max. Potential** | **References** |
|---|---|---|---|---|---|
| **Electricity generation** ($GW_{elec.}$) | Combined cycle gas turbine | 1.05 | 1.05 | (no limit) | [6] |
| | Open cycle gas turbine | 1.06 | 1.06 | | |
| | Diesel genset | 0.47 | 0.47 | | |
| | Photovoltaic | 0.17 | 0.18 | 40 000 | [6, 12, 56] |
| | Onshore wind | 0.13 | 0.21 | 260 | |
| | Hydro run-of-river | 0.03 | 0.07 | 39.9 | [6, 12, 57] |
| | Conventional hydro dam | 0.71 | 2.34 | 39.9 | |
| | Biomass steam turbine | 0.15 | 0.19 | 0.85 | [6, 45] |
| | Syngas steam turbine | 0.001 | 0.001 | 0.32 | |
| | Geothermal | 0 | 0.10 | 0.89 | [12, 47, 48, 58] |
| **Heat generation** ($GW_{thermal}$) | Boiler gas (Industry) | 0.97 | 0.97 | (no limit) | [6, 28] |
| | Boiler woody biomass (Industry) | 0.63 | 0.63 | | |
| | Boiler oil (Industry) | 0.002 | 0.002 | | |
| | LPG burner (Industry) | 0.02 | 0.02 | | |
| | Diesel engines (Industry) | 0.18 | 0.18 | | |
| | Boiler gas (HW) | 0.005 | 0.005 | | |
| | Electric shower (HW) | 0.20 | 0.20 | | [6, 52] |
| | Solar thermal (HW) | 0.007 | 0.01 | | [6, 28, 59] |
| **Cooking** ($GW_{thermal}$) | Firewood stove | 0.01 | 0.01 | (no limit) | [6, 28] |
| | LPG stove | 0.42 | 0.42 | | |
| | FG stove | 0.13 | 0.13 | | |
| | Oil stove | 0.002 | 0.002 | | |
| | Electric stove | 0.01 | 0.01 | | |
| **Mobility** (Gpass.-km) (Gt-km) | FG bus | 1.3 | 1.3 | (no limit) | [29, 32, 60] |
| | Diesel bus | 1.5 | 1.5 | | |
| | Gasoline bus | 2.5 | 2.5 | | |
| | Aerial tramway | 0.4 | 0.4 | | |
| | Electric car | 0.05 | 0.05 | | |
| | FG car | 16.5 | 16.5 | | |
| | Diesel car | 19.6 | 19.6 | | |
| | Gasoline car | 32.0 | 32.0 | | |
| | Diesel train freight | 0.2 | 0.2 | | |
| | Diesel boat freight | 0.02 | 0.02 | | |
| | Diesel truck | 13.2 | 13.2 | | |
| | LFO aircraft | 2.1 | 2.1 | | |
| **Storage** (TWh) | Battery of electric vehicles | 0.01 | 0.01 | (no limit) | [29] |

energy technology represented a cost-effective solution and experienced an increment. PV installed capacity rose from 0.18 GW to 0.88 GW.

### 4.1.3. Heat sector

Heating demands (HW, HT, and cooking) were projected to increase from 21.40 TWh in 2021 to 29.32 TWh in 2035. Regarding HT demand, gas-based heating remained nearly the sole technology (Almost 99.9% of total demand). HW demand was provided by gas boilers (with 99.2%) and solar thermal (around 0.8%). The latter's share was based on the current installation ratio of these technologies in Bolivia (500 systems/y), according to Noël [59] and Fernandez [52]. Finally, the cooking demand was covered by FG (68.4%), electric (16.2%), and LPG stoves (15.4%) in the urban areas and by FG (81.7%) and LPG (18.3%) in rural areas. Moreover, biomass and kerosene stoves were reduced from the solution, covering only 0.1 MWh of the cooking demand. The share of the different fuels used for cooking was projected based on the information presented by the National Statistics Institute of Bolivia (INE) in 2021 [62].

### 4.1.4. Transport sector

The final energy demand for public and private passenger transportation was based on FG (42.5%), gasoline (34.1%), diesel (20.9%), and electricity (2.4%). Moreover, electric tramways for public transport showed an

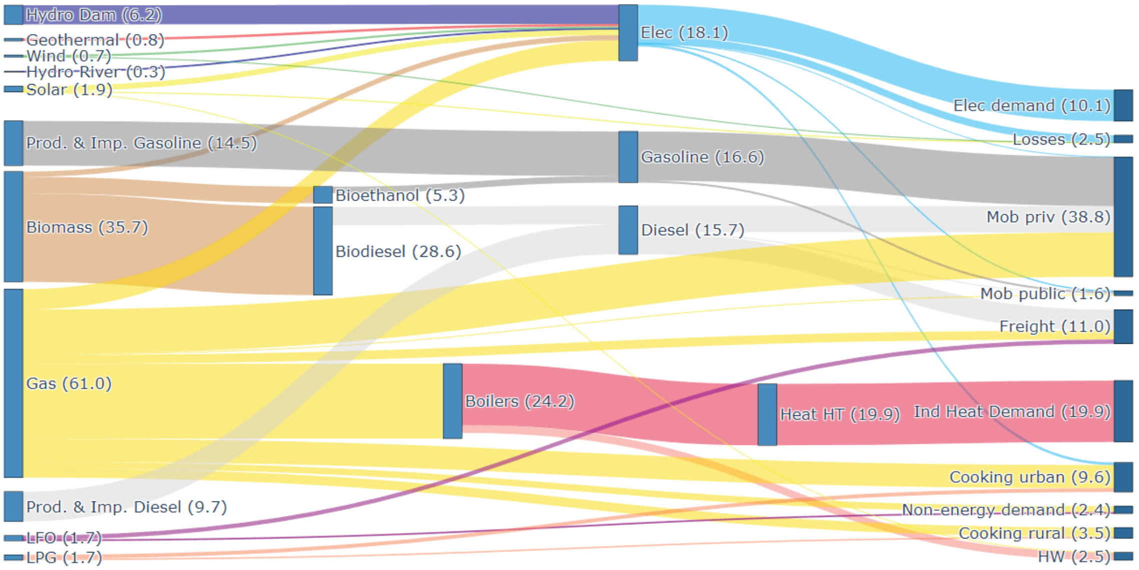

**Figure 3**: Energy flows of the modeled Bolivian energy system for 2035 BAU scenario (Units: TWh). The left side integrates all the resources while the right side retrieves the final energy consumption. The conversion technologies are in between. Energy exports are not represented. Abbreviations: mobility (mob), private (priv), electricity (Elec), liquefied petroleum gas (LPG), light fuel oil (LFO), industrial (Ind), domestic hot water (HW), low temperature (LT), high temperature (HT), importation (Imp), production (Prod).

increase. Those technologies resulted in an installed capacity of 0.81 GW. On the other hand, fossil fuels technologies (FG, diesel, and LFO) almost completely covered freight transport demand (63.2%, 23.0%, and 13.8% of diesel vehicles, FG vehicles, and aircrafts, respectively). Furthermore, freight share was 85.0% of transportation by road, 13.8% of transportation by air, 1.1% of transportation by rail, and 0.1% of transportation by boat. Even though the demand for liquid fossil fuels was considerable, approximately 12.7% of all gasoline and 38.3% of all diesel were produced from biofuels such as bioethanol and biodiesel.

## 4.2. Renewable energy (RE) case

In this scenario, the system was simulated considering the minimum GHG constraint that allowed finding a feasible optimisation solution, determining whether total growth based on renewable resources was achievable, and seeking a low carbon emission case.

### 4.2.1. Major trends in energy consumption

In contrast to the BAU scenario, the system depended on biomass as the principal primary energy source (40.5 TWh and nearly 29.5% of TPES). Nonetheless, biofuel production remained the same due to a lack of information on the maximum production limit. For instance, the government created a program in 2022 to promote oil production of oil species such as African palm, jatropha, macororó, and soybean (Supreme Decree No.4764). Those energy crops are expected to be farmed, reaching an approximate production of 638 344 $m^3$/y of biodiesel [63]. Moreover, an agreement with local ethanol producers has established a maximum purchase of 380 000 $m^3$/y of bioethanol by 2025, an amount which will be used as blended fuel with gasoline (Law No. 303/2017-2018) [44]. As shown in Figure 4, FG was still present but reduced (around 78.7 % less than the BAU scenario). Regarding $CO_2$ emissions, the system produced 12.50 $MtCO_{2\text{-eq.}}$/y, representing a 49% of decrement compared to the 2021 case.

### 4.2.2. Power sector

Electricity generation was dominated by PV (25.03 TWh), followed by wind turbines (15.75 TWh), hydro dam power plants (6.54 TWh), geothermal plants (2.38 TWh), bioenergy steam turbines (1.93 TWh), and hydroelectric run-of-river power units (0.31 TWh), and limited production of combined cycle and open cycle gas turbines (2.66 MWh). In terms of total installed capacity, PV arrays reached 12.70 GW, wind power 4.98 GW, bioenergy steam turbines 0.65 GW, and geothermal plants 0.30 GW.

### 4.2.3. Heat sector

The energy supply for the heat sector was extensively electrified. To illustrate, HT demand was based on direct-electric heating (around 77% of total demand), followed by gas boilers (23%). Also, the HW demand

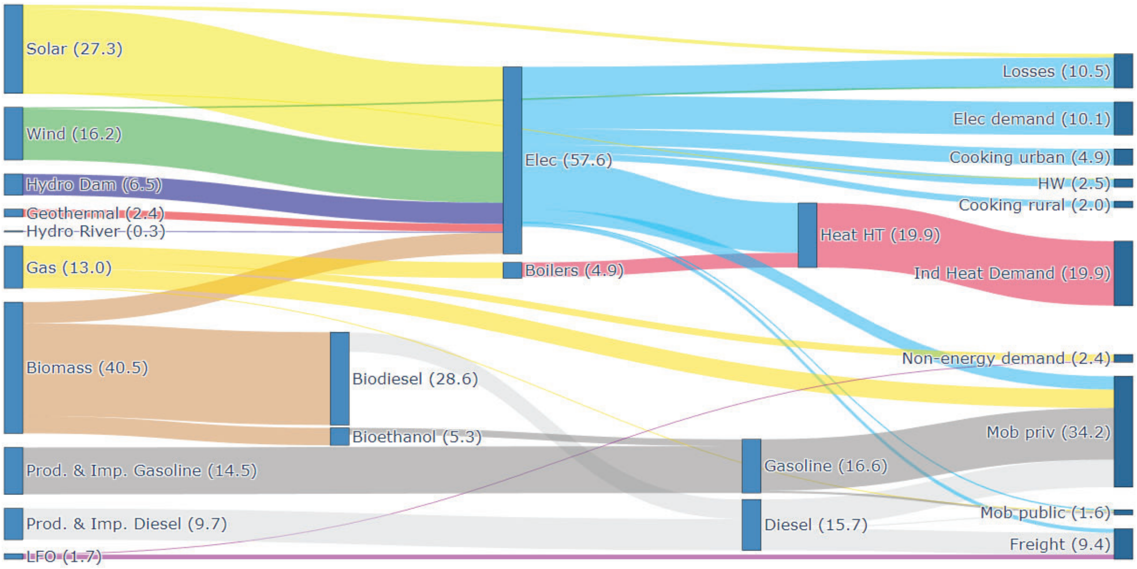

**Figure 4**: Energy flows of the modeled Bolivian energy system for 2035 RE scenario (Units: TWh). The left side integrates all the resources while the right side retrieves the final energy consumption. The conversion technologies are in between. Energy exports are not represented. Abbreviations: mobility (mob), private (priv), electricity (Elec), liquefied petroleum gas (LPG), light fuel oil (LFO), industrial (Ind), domestic hot water (HW), low temperature (LT), high temperature (HT), importation (Imp), production (Prod).

was provided by electric heating (99.2%), and the rest corresponded to solar thermal (around 0.8%). Finally, the cooking demand was almost completely covered by electricity in urban and rural areas.

### 4.2.4. Transport sector

Regarding the transport sector, there was a limited electrification share. The mobility demand for public and private passenger transportation was covered by gasoline (34.1%), electricity (27.4%), diesel (20.9%), and FG technologies (17.6%). Similar to the BAU scenario, electric tramways ended up with an installed capacity of 0.81 GW. The demand for freight transportation was covered by diesel-based vehicles (63.2%), electric trucks (23.0%), and aircraft (13.8%). The share between rail, boat, road, and aviation freight transport remained the same as the BAU scenario.

## 5. Discussion

This section highlights key insights and trends from the preceding sections. Finally, the limitations of the work were enumerated.

### 5.1. Comparison of scenarios

In 2035, according to the BAU scenario results, the Bolivian energy system is still fossil-based, with traditional fuels accounting for 62% of the TPES. Most of the primary energy goes to mobility (51.4 TWh), whereas heating and industrial processes are the second sector (24.2 TWh), electricity the third one (18.1 TWh), and cooking the last one (13.0 TWh). In contrast, the RE scenario is only 28% fossil-fuel dependent on the TPES. Moreover, the electricity sector represents 56.5 TWh in terms of primary energy due to the high electrification of the scenario, followed by the mobility sector with 45.1 TWh, heating and industrial processes with 22.7 TWh, and cooking with 6.9 MWh. Regarding the system's annualized total cost, the BAU scenario shows a lower value than the RE scenario (6 925 and 7 516 M€ per year for BAU and RE scenarios, respectively). Nonetheless, the RE solution reduces 49% of GHG emissions from 2021 (51% fewer emissions than the BAU scenario), which is equivalent to 44.64 €/tCO$_{2\text{-eq.}}$ of compensation. Moreover, it is essential to highlight that the mobility sector is a main constraint to the system transition, as the majority of the vehicles throughout the 14 years of analysis remain in the system due to the permissive laws and regulations in Bolivia. Nearly 8% of the total vehicle fleet in 2021 was composed of vehicles manufactured in 1885 or below, according to INE [62]. Moreover, the importation of new vehicles is still under the Euro II emissions standard [64].

### 5.2. Limits of the study

The energy system optimisation model was intended for developed economies with well-established networks and accounting for all users with electricity access. Moreover, more studies are required to confirm the dispatchability of various resources, such as agricultural and industrial residues, municipal solid waste, biofuels, or power for cooking. Furthermore, decentralized energy systems like microgrids, a significant component of Bolivia's power sector, should be accounted for. Additionally, a model for cooling demand could be determined and evaluated to estimate this consumption and associated technologies. Also, a more thorough market analysis is required to evaluate the costs of the existing technologies, their evolution, and the introduction of others. Energy policies could be evaluated especially for the transport sector and account for an increase in the share of public mobility. Finally, this study does not address the socioeconomic effects of the transition based on fossil fuels or renewable energy.

## 6. Conclusions

The Bolivian energy system is going to experience a transition from a fossil fuel-based supply to one with a high share of renewable resources to fulfill the commitment of the Paris Agreement and future governmental plans. Nowadays, the country is going through strong population and economic growth, which is reflected in future energy demand projections. In this context, the energy system was assessed utilizing the EnergyScope TD framework in order to gain a comprehensive understanding of its reality. The adapted version of the model for Bolivia is freely available at [65].

The case study consistency was verified by applying the energy system optimisation for the national energy balance of 2021, showing a high similarity between the reported and simulated values. Furthermore, the highest energy demand in the mentioned year was related to the transport sector, mainly supplied by gasoline (18.5 TWh), diesel (17.2 TWh), and fossil gas (6.7 TWh). This is followed by heat demand for industries, agriculture, and mining, mostly based on FG (8.7 TWh). Electricity demand was covered principally by FG (14.9 TWh), and finally, cooking demand was based on LPG (5.8 TWh), FG (2.5 TWh), and wood (0.8 TWh). The latter was more used in rural populations.

A projection of the energy system by 2035 allowed to identify difficulties and opportunities. With the current subsidies for fossil fuels, the system would economically prefer to experience growth based on fossil energies. For this reason, a optimisation was carried out including future plans, fuel prices, and technologies costs from the government's point of view. The latter scenario being called the business-as-usual scenario. It represents a share of 32% renewable sources related to the final energy consumption and a 5% rise of greenhouse gas emissions compared to the 2021 case. Furthermore, this scenario could not meet the emissions target of the INDC (0.18 $\text{tonCO}_{2,\text{eq}}$/MWh).

On the other hand, a sustainable scenario with a constraint in greenhouse gases emissions to reach a low-carbon system showed a renewable resources share of 66%. Although this latter was a bit more expensive, it showed a 49% decrement of $CO_2$ emissions during its operation from the base case, which is also equal to 44.64 €/$\text{tCO}_{2\text{-eq.}}$ of compensation. This growth driven by renewable energy required the electrification of heat and transportation systems, as well as enhancing renewable electricity generation using solar, wind, biomass, and geothermal technologies. Finally, this work has demonstrated that a Bolivian energy system with a high share of renewable resources could meet a significant increase in energy demand for all sectors at every hour throughout the year. Yet, to achieve this change, national policies must set ambitious goals for the transportation and heat sectors. Future studies should consider the pathway to assess the complete transition of the system, including more policy scenarios for different sectors.

Moreover, an improvement of the technical resolution is required, assessing the potential of microgrid systems such as PV-battery systems necessary to generate electricity, especially in remote areas, and addressing the extension of the electricity and gas network around the country.

## References

[1] Karekezi S, McDade S, Boardman B, Kimani J, Lustig N. Energy, poverty, and development. Global Energy Assessment–Toward a Sustainable Future [Johansson, TB, N Nakicenovic, A Patwardhan, and L Gomez-Echeverri (eds)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Sys. 2012:151-90.

[2] Estado Plurinacional de Bolivia. Nationally Determined Contribution (NDC) of the Plurinational State of Bolivia; 2022.

[3] Bradley S, Lahn G, Pye S. Carbon Risk and Resilience. Chatham House, London. 2018.

[4] World Resources Institute. Climate Watch; 2022. Available from: `https://www.climatewatchdata.org`.

https://doi.org/10.52202/069564-0182

[5] Jones MW, Peters GP, Gasser T, Andrew RM, Schwingshackl C, Gütschow J, et al.. National contributions to climate change due to historical emissions of carbon dioxide, methane and nitrous oxide. Zenodo;. Available from: `https://zenodo.org/record/7636699`.

[6] Autoridad de Fiscalización de Electricidad y Tecnología Nuclear (AETN). Anuario Estadístico 2021. La Paz; 2021. Available from: `https://sawi.aetn.gob.bo/docfly/app/webroot/uploads/`.

[7] Latin American Energy Organization (OLADE). Latin American and Caribbean Energy Information System (sieLAC); 2022. Available from: `https://sielac.olade.org/default.aspx`.

[8] Banco Interamericano de Desarrollo (BID). Evaluacion Financiera y Economica del Proyecto Electrificacion Rural con Energıa Renovable (BO-X1013). Cochabamba, Bolivia; 2013.

[9] Sauer IL, Escobar JF, da Silva MFP, Meza CG, Centurion C, Goldemberg J. Bolivia and Paraguay: A beacon for sustainable electric mobility? Renewable and Sustainable Energy Reviews. 2015;51:910-25.

[10] Ministerio de Hidrocarburos y Energías (MHE). Plan de Desarrollo energetico - Análisis de Escenarios: 2008-2027. La Paz, Bolivia; 2009.

[11] Ministerio de Planificación del Desarrollo. Agenda Patriótica 2025; 2014.

[12] Ministerio de Hidrocarburos y Energías (MHE). Plan Electrico del Estado Plurinacional de Bolivia 2025. La Paz, Bolivia; 2014.

[13] Viceministerio de Electricidad y Energías Alternativas. Plan para el Desarrollo de las Energías Alternativas 2025. La Paz, Bolivia: Ministerio de Hidrocarburos y Energía; 2014.

[14] de Moura GNP, Legey LFL, Balderrama GP, Howells M. South America power integration, Bolivian electricity export potential and bargaining power: an OSeMOSYS SAMBA approach. Energy strategy reviews. 2017;17:27-36.

[15] Fernandez M, Fernandez C, Rodriguez G. Situación Energética de Bolivia y Desafíos. Cochabamba; 2020.

[16] Fernandez M, Periódico Digital PIEB. Estudio sostiene que la energía solar es factible en el 97% del territorio nacional. Cochabamba; 2012.

[17] 3TIER. Atlas Eólico de Bolivia. Transportadora de Electricidad [TDE]; 2009.

[18] Malky Harb A. Sector Forestal en Bolivia; 2005.

[19] Instituto Nacional de Estadistica (INE). Censo Agropecuario Estado Plurinacional de Bolivia; 2013.

[20] Morató T, Vaezi M, Kumar A. Techno-economic assessment of biomass combustion technologies to generate electricity in South America: a case study for Bolivia. Renewable and Sustainable Energy Reviews. 2020;134:110154.

[21] Balderrama JGP, Alfstad T, Taliotis C, Hesamzadeh MR, Howells M. A sketch of Bolivia's potential low-carbon power system configurations. The case of applying carbon taxation and lowering financing costs. Energies. 2018;11(10).

[22] Limpens G, Moret S, Jeanmart H, Maréchal F. EnergyScope TD: A novel open-source model for regional energy systems. Applied Energy. 2019;255:113729.

[23] Limpens G, Moret S, Guidati G, Li X, Maréchal F, Jeanmart H. The role of storage in the Swiss energy transition. In: Proceedings of the 32nd International Conference On efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Wroclaw, Poland; 2019. p. 23-8.

[24] Limpens G, Jeanmart H, Maréchal F. Belgian energy transition: what are the options? Energies. 2020;13(1):261.

[25] Borasio M, Moret S. Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the Italian energy transition. Renewable and Sustainable Energy Reviews. 2022;153:111730.

[26] Limpens G, Thiran P, Lara E, Pavičević M, Quoilin S. Competitiveness of economic growth based on renewable energy: the case of Uganda to 2035. In: 2022 IEEE PES/IAS PowerAfrica. IEEE; 2022. p. 1-5.

[27] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. Optimal design of multi-energy systems with seasonal storage. Applied Energy. 2018;219:408-24.

[28] Organización Latinoamericana de Energía (OLADE). Sistema de Información Energética de Latinoamérica y el Caribe (OsieLAC); 2021.

[29] Ministerio de Hidrocarburos y Energías (MHE). Balance Energético Nacional 2006 – 2021; 2022.

[30] Instituto Nacional de Estadistica (INE). Proyección de Población Total e Indicadores Demográficos, 2012-2022. La Paz, Bolivia: Instituto Nacional de Estadistica (INE); 2023.

[31] Balderrama JGP, Broad O, Sevillano RC, Alejo L, Howells M. Techno-economic demand projections and scenarios for the Bolivian energy system. Energy strategy reviews. 2017;16:96-109.

[32] Instituto Nacional de Estadistica (INE). Estadísticas del Parque Automotor 2003-2021; 2022.

[33] Gütschow J, Jeffery ML, Gieseke R, Gebel R, Stevens D, Krapp M, et al. The PRIMAP-hist national historical emissions time series. Earth System Science Data. 2016;8(2):571-603.

[34] Gütschow J, Pflüger M. The PRIMAP-hist national historical emissions time series v2.4 (1750-2021); 2022.

[35] Instituto Nacional de Estadistica (INE). Exportaciones según actividad económica y Producto por Año y Mes, 1992-2022; 2022.

[36] Agencia Nacional de Hidrocarburos (ANH). Precios Internacionales de Hidrocarburos 2010-2020; 2021.

[37] Energy Information Administration (EIA). Annual energy outlook 2022. Washington: US Energy Information Administration. 2022.

[38] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy. 2016;114:1251-65.

[39] Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. Energy. 2016;114:1224-39.

[40] Pfenninger S, Staffell I. Renewables Ninja;. Available from: `https://www.renewables.ninja/`.

[41] Comité Nacional de Despacho de Carga (CNDC). Datos Hidrólogicos Previstos; 2021. Available from: `https://www.cndc.bo/estadisticas/index.php`.

[42] Morato T, Vaezi M, Kumar A. Assessment of energy production potential from agricultural residues in Bolivia. Renewable and Sustainable Energy Reviews. 2019;102:14-23.

[43] Dirección General de Gestión Integral de Residuos Sólidos. Diagnóstico de la Gestión de Residuos Sólidos en Bolivia. La Paz, Bolivia: Ministerio de Medio Ambiente y Agua (MMAyA); 2010.

[44] Kempff Bacigalupo R. Los biocombustibles pueden ayudar a mejorar la economía. La Paz, Bolivia; 2020.

[45] Fundación Solón. Biomasa: Del bagazo de caña al pasto de Uganda; 2020.

[46] Agencia Boliviana de Información (ABI). Planta de Biodiésel 1 se construirá con Sus 40 millones y prevén que inicie operaciones en 2023. La Paz, Bolivia; 2022.

[47] Gawell K, Reed M, Wright PM. Preliminary report: Geothermal energy, the potential for clean power from the earth. Washington, DC: Geothermal Energy Association. 1999.

[48] Empresa Nacional de Electricidad (ENDE). Proyecto: Construcción Planta Piloto Geotérmica Laguna Colorada; 2023.

[49] Organización Latinoamericana de Energía (OLADE). Panorama energético de América Latina y el Caribe 2022. Quito, Ecuador: Organización Latinoamericana de Energía (OLADE); 2022.

[50] Villarroel Schneider J. Combined energy solutions applied to dairy farming in Bolivia and Latin America. KTH Royal Institute of Technology; 2023.

[51] Proyecto EnDev Bolivia. Guía de Eficiencia y Ahorro Energético para el Área Rural de Bolivia; 2020.

[52] Fernández Fuentes M. Tecnología Termosolar Situación en Bolivia. ENERGÉTICA; 2011.

https://doi.org/10.52202/069564-0182

[53] Fernandez Vazquéz C, Rodriguez Cáceres G, Fernandez Fuentes M. Modelamiento del Sistema Energético Boliviano al 2040 según metas del IPCC: Un Primer Enfoque a los Modelos de Transición y las Políticas de Gestión de Emisiones de Carbono. Cochabamba, Bolivia: ENERGÉTICA; 2020.

[54] Comité Nacional de Despacho de Carga (CNDC). Despacho de carga realizado; 2021.

[55] McGuckin N, Fucci A. Summary of Travel Trends. National Household Travel Survey, Washington DC USA. 2017.

[56] Cheng C, Gutierrez NP, Blakers A, Stocks M. GIS-based solar and wind resource assessment and least-cost 100 % renewable electricity modelling for Bolivia. Energy for Sustainable Development. 2022;69:134-49.

[57] Organización Latinoamericana de Energía (OLADE), Empresa Nacional de Electricidad (ENDE). Evaluación de los Recursos Hidroenergéticos de Bolivia. La Paz, Bolivia; 1984.

[58] Jorquera C. Avanza construcción de primera planta geotérmica de Bolivia; 2022.

[59] Solar Platform America Latina (SOPELIA). Solar Thermal Bolivia; 2016.

[60] Instituto Nacional de Estadistica (INE). Estadísticas del Parque Automotor 2017. La Paz, Bolivia: Instituto Nacional de Estadistica (INE); 2017.

[61] Flores Y. Con la planta de biodiesel se prevé reducir 100 MM de dólares en importación de diésel. La Paz, Bolivia; 2023.

[62] Instituto Nacional de Estadistica (INE). Bolivia: Hogares según área y tipo de combustible usado para cocinar, 2011-2021. La Paz, Bolivia: Instituto Nacional de Estadistica (INE); 2021.

[63] Agencia Boliviana de Información (ABI). Biodiésel: Bolivia apunta a importar plantas aceiteras de tres países y tiene identificadas zonas de potencial producción. La Paz, Bolivia; 2022.

[64] Ministerio de Obras Públicas SyVM. Comunicado 16-08-2021. La Paz, Bolivia; 2021.

[65] Jimenez Zabalaga P, Thiran P, Limpens G, Jeanmart H. Bolivian EnergyScope TD Model;. Available from: `https://github.com/pablojimenezzabalaga/EnergyScopeBOL/`.