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Contribution to the energy transition in Bolivia

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Abstract

Contribution to the energy transition in Bolivia

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This thesis aims to assess the data provided by the long-term energy planning model OSeMOSYS with the short-term power dispatch and unit commitment model, Dispa-SET. This assessment lies in the more significant project, "Contribution to the development of solar hybrid micro-grids for rural electrification in Bolivia". First, three scenarios of the Bolivian energy system are developed in OSeMOSYS, the Business-As-Usual model, a model representing the Bolivian energy mix as it is now and how it will evolve. The Mixed Policies scenario is a scenario taking into account various energy policies made to lower Bolivia's greenhouse gases (GHG) emissions and reduce its dependence on fossil fuels. The last scenario, Carbon Neutral, pushes the BES to zero GHG emission by 2050. The results given by OSeMOSYS are introduced as inputs in the Dispa-SET model through a soft-linking process. It consists of the transfer of outputs from one model to the other. In this case, the OSeMOSYS data is transferred to Dispa-SET. Multiple years are simulated in Dispa-SET to assess the adequacy of the data of the proposed system. The results reveal that OSeMOSYS lacks installed power capacity in the short term, leading to a significant amount of energy not served on the modelled energy system. However, its results can be improved by using multiple mechanisms in Dispa-SET, such as the flexible demand. Implementing a bi-directional automated soft-linking may provide more sensible data from OSeMOSYS.

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Contents

Nomenclature

BAU: Business As Usual

BES: Bolivian Energy System

CHP: Combined Heat and Power

CN: Carbon Neutral/Carbon Neutrality

$CO2_{eq}$: CO2 equivalent

COP: Conference Of the Parties

CTI: Carbon Taxing Implementation

DSM: Demand Side Management

ENS: Energy Not Served

GHG: Greehouse Gases

GLPK: GNU Linear Programming Kit

IPCC: Intergovernmental Panel on Climate Change

LP: Linear Programming

MILP: Mixed Integer Linear Programming

MP: Mixed Policies

MW: Mega Watts

MWe: Mega Watts electricity

NOx: Nitrogen oxides

PV: Photovoltaic panels

RES: Renewable Energy Sources

VRES: Variable Renewable Energy Sources

Chapter 1

Introduction

1.1 Context

For the past twenty years, global warming has been increasing at an alarming rate. Its effects are worldwide and are already having irreversible impacts on Humanity. The IPCC, The Intergovernmental Panel on Climate Change, the United Nations body for assessing the science related to climate change, publishes reports that assess the possible future impacts and risks of global warming and pave the way in terms of GHG reduction to guide governments and countries to reduce their $C02_{eq}$ emissions to avoid future risks. To counter global warming, "carbon neutrality" must be achieved by each country by 2050. It means that every country should have ruled out their GHG emitting sources by then or have compensated with complementary technologies [1].

As shown the figure 1.1, the majority of the GHG emissions emanate from fossil fuel-powered technologies, which originate from the energy sector for the vast majority. By 2010, this sector represented 76% of the global GHG emissions worldwide, corresponding to around 32 Gton$CO2_{eq}$ [2]. Transitioning from an energy mix relying on fossil fuels to a renewable and sustainable energy system is complex since the energy sector is strongly connected to other sectors such as the economy, society, and even politics [3]. Many countries and academic institutes have turned to this field to study and come forth with ideas and solutions. While there exist various points of view from which to study the energy transition, there are however recurring themes among all the works regarding this

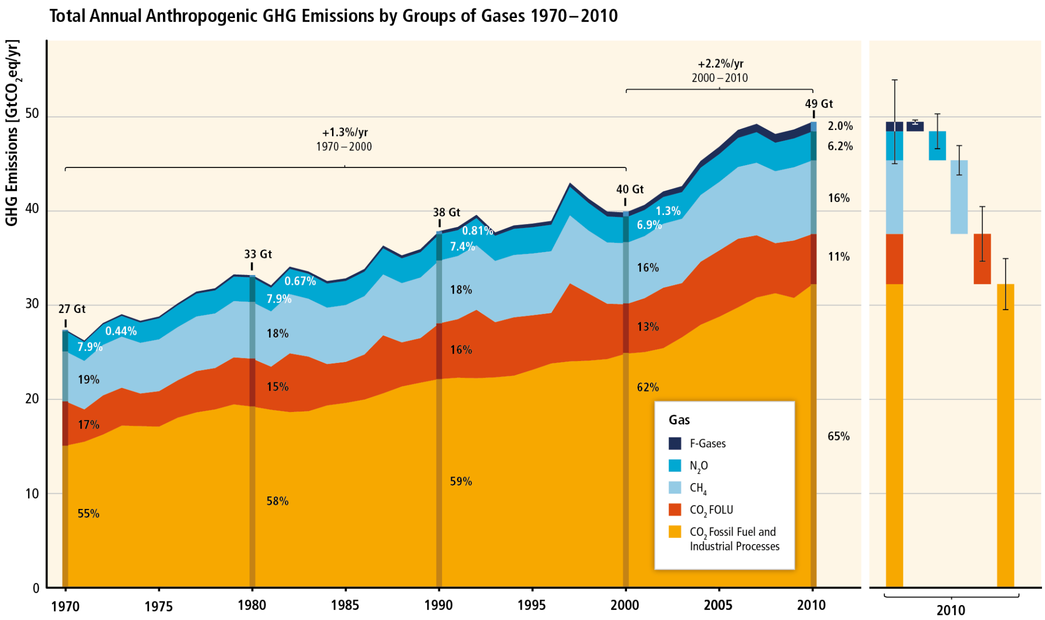

Figure 1.1: CO2 emissions by sector, World 1990-2019 [2]

subject to verify the overall feasibility of the transition:

- Optimal composition of the energy system
- Investments for the implementation of a solution [4]
- Local limitations and policies required [5]

1.2 The Bolivian case

Bolivia, officially the Plurinational State of Bolivia, is a landlocked country in the centre of South America, located both in the Andes region and the tropical region, covering 1,098,581 km^2 of land. Bolivia's population amounts to 11.83 million inhabitants as of 2022 [6]. Bolivia exhibits a variety of climates, from the lowlands having a very tropical climate with humid air and monsoon to Andean and Sub-Andean regions experiencing a great range of weathers [7].

On the energy level, Bolivia forged itself a name in the South American energy market thanks to its large natural gas reserves, exchanging with its neighbouring countries. However, natural gas export is not the primary use for that fossil fuel; instead, the Bolivian energy system uses natural gas to produce energy [8]. As of 2020, natural gas power plants represent roughly 80% of the energy mix, with hydroelectricity making up 1.5%, biomass for 6% and oil 12% of the energy mix, the wind and solar power plants represent 0.16%. The Bolivian government has implemented VRES (solar and wind) in the mix since 2014. The Bolivian energy sector's $CO2_{eq}$ production has been steadily increasing along with its energy demand [9], due to its heavy reliance on fossil fuels, as stated earlier. As of 2022, Bolivia also has invested in the geothermal energy generation [10, 11].

Due to the COP21 decision to reach carbon neutrality by 2050, countries worldwide, including Bolivia, have started planning and studying their future energy transition. As the first assessment in an energy transition, it is necessary to understand and qualify the potential of renewable energy penetration in a country. For Bolivia, Severino Alejandro Quispe Ramos et al. showed this potential in the report for the Minister of Hydrocarbons and Energy [12]. Following the multiple studies on the energy transition of Bolivia, the

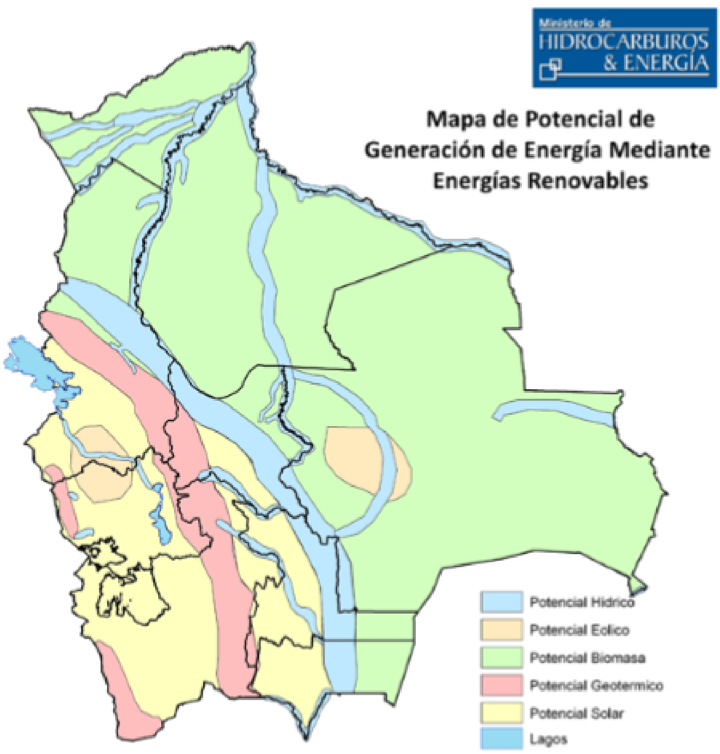

Figure 1.2: Map of power generation potential through renewable energies [12]

Universidad Mayor de San Simon de Cochabamba, along with academic institutes from various countries, including the Université de Liège have started a joint project to model the energy transition.

Concerning the works that have been done for Bolivia, different approaches can be noted: Navia et al. have studied the expansion of the generation capacity of the Bolivian energy system (BES) for the year 2025 using the short-term energy planning model, Dispa-SET [13]. Lopez et al. assessed the realization of sustainable energy systems for Bolivia across multiple sectors [14]. In the long-term planning, Fernandez et al. have analyzed the impact of carbon emission scenarios on the Bolivian electricity sector [15]. Then, using OSeMOSYS, they realized different scenarios to define the general trend of Bolivian energy mix until 2040 and 2050 and point to the techno-economical requirements for the different defined trends; also taking into account the political and social impacts of such a transition [16, 17]. Overall, multiple aspects of the Bolivian energy system were studied, from a large-scale perspective to the study of one single component [18].

1.3 Problem specification

1.3.1 Energy system modelling

The principle of modelling can be defined as the transposition of a problem from reality to an abstract representation; usually, computer models that help to solve the original problem thanks to conventions and mathematics [19]. Energy modelling is thus the process of transposing an actual energy system to a simplified representation of that energy system and analyzing it. Energy modelling is used in developing and developed parts of the world. Its purpose is generally to help economic commitment or to qualify policies' impact and serve as guidelines.

1.3.2 Types of energy modelling

The energy system models are based on numerical optimization. The optimization problems are most of the time written in linear programming (LP) or mixed-integer linear programming (MILP). They usually follow a bottom-up resolution; they build a more complex and in-depth solution from simple inputs. Energy system models usually have their characteristics concerning the time window resolution, precision level or studied sectors. They can also be more demand-side or generation-side oriented. However, two major distinctions can also be made for the existing energy system models:

- Optimal power dispatch models, which are generally short-term, high precision optimization models. They often work with small simulation timesteps and historical time series. They produce solutions that can forecast renewable energy penetration and their high variability. An example of such a model is Dispa-SET which runs with an hourly simulation timestep [20].
- Long-term energy planning models, which provide a view of the evolution of an energy system and the capital investment over the studied range of years by supplying the average data per year. They usually work with a long simulation timestep while providing precision in that timestep, such as day and night cycles, seasons and yearly data. OSeMOSYS [21], LEAP [22] and TIMES [23] are examples of long-term energy planning models.

Regarding energy system modelling, a complaint repeatedly heard is that the models lack transparency on their structure and data treatment [24]. In that regard, for this thesis, two open-source models were used; OSeMOSYS and Dispa-SET.

1.4 Scope of this work and framework

1.4.1 Scope

Multiple works have already been realized with the energy planning model OSeMOSYS concerning the Bolivian energy transition [15, 16, 17]. OSeMOSYS is a long-term energy planning model that only provides annual, seasonal data or clustered daily variances outputs at best and does not perform an in-depth analysis. It is therefore uncertain if the data provided by OSeMOSYS can serve as a baseline for future works. This work aims at assessing the feasibility and adequacy of OSeMOSYS results by combining OSeMOSYS with the short-term power dispatch model, Dispa-SET, thanks to a uni-directional soft-linking. This work will pave the way for further studies regarding the use of OSeMOSYS in the scope of the Bolivian energy transition.

1.4.2 Framework

This work starts by defining the scenarios explained by Carlos A. Fernandez et al. The scenarios focus on the BES and its evolution with respect to constraints over 36 years, from 2014 to 2050, to comply with the objective in the IPCC's reports. For this thesis, the years 2020, 2030, 2040 and 2050 will be studied; they spread over the range of years well enough to sufficiently capture the evolution and changes of the Bolivian Energy System.

There are three different scenarios. The first one is the Business-As-Usual (BAU) scenario. The BAU introduces an energy system that heavily relies on fossil fuels to produce energy. That system is the current Bolivian energy system. By simulating the Business-As-Usual scenario in OSeMOSYS, the goal is to display the evolution of the BES during the studied period.

From the BAU's results, a list of policies aiming at reducing the GHG emissions induced by fossil fuel power plants will be made. A second scenario called Mixed Policies (MP) scenario is based on these policies to visualize their impact. The goal of the MP scenario is to shift away from fossil fuel dependency.

A final scenario will be defined, the Carbon Neutral (CN) scenario. This scenario's goal is to obtain net zero GHG emissions by 2050.

For these scenarios, only electricity generation was considered because there is no centralized heating system in Bolivia. Therefore, there is no use for power plants to work on other modes besides electricity generation.

The OSeMOSYS' lack of depth results in annual data that do not cover essential topics for power grids, such as peak demand or seasonality. With those issues in mind, Dispa-SET is used to assess the quality of the data provided by OSeMOSYS and the feasibility of the scenarios. Dispa-SET can produce results that carry information relevant in the short term for power grids. This assessment is performed by using the OSeMOSYS outputs as Dispa-SET inputs.

Chapter 2

Models description

2.1 OSeMOSYS-MoManI

OSeMOSYS is an open-source optimization model for energy systems used for long-term energy planning developed by a collaboration of institutions to provide research centres from developing countries with an open-source energy modelling tool. OSeMOSYS has a block structure that quickly adds specific elements to the essential components. OSeMOSYS's code is written in GNU MathProg, an algebraic modelization system. GNU also provides, for resolutions of linear systems, the open-source solver GNU Linear programming kit - GLPK, destined to solve large linear programming problems. It is said to be relatively beginner-friendly. Later versions were updated to work with GAMS and Python as well [25, 26, 27] With its block structure and easy-to-pick-up nature, OSeMOSYS represents an interesting energy modelling tool for developing countries whose research resources are sometimes sparse, given the importance of energy planning in the current world [25]. It is being used worldwide by many international institutions and universities such as UCL of London, KTH Stockholm, IRENA, and WWF[21].

This model is used to produce the results presented in chapter 3

2.1.1 Block structure

As mentioned prior, OSeMOSYS has a characteristic block structure. When the core code was first released, it was centred around seven blocks [27]:

- Objective function
- Costs
- Storage
- Capacity adequacy
- Energy balance
- Emissions
- Constraints

All these are defined yearly or with respect to defined timeslices, the temporal parameter used in OSeMOSYS to segment years. Combined, these blocks measure the feasibility of a system with annual input data. Later on, in the development of OSeMOSYS, new blocks were introduced to bring more depth to the resolution that OSeMOSYS provides [27].

2.1.2 Objective function

The OSeMOSYS objective function tries to minimize an energy system's net present cost (NPC) while under constraints. A specificity in OSeMOSYS requires the user to choose which objective function and equations to use for a particular project. There are 2 different objective functions, the Long-term objective function (OFLcost) and the Short-term objective function (OFScost), and 3 categories of constraints equations, the *common* set of equations, the *long code* equations and the *short code* equations. The difference is that the long-code version, long-term objective function, the *long code* and *common* equations was the first version developed in OSeMOSYS. However, with the ever-increasing penetration of renewable energy in an energy system and, therefore, the increase of their share, the original code lacked precision in the time resolution to consider the high variability of renewable energy sources. Consequently, the short-code version, short-term objective function and *short code* and *common* equations were made to come up with a finer assessment of the penetration of VRES in an energy mix than the long version [27]. Moreover, the short version provides lower computational time by merging some equations from the long version. The long-term version was then labelled "long-term" in opposition to the newer equations, named "short-term" with respect to their design.

In essence, the "short" version of the objective function of OSeMOSYS is a long-term energy planning function combined with short-time windowed equations to capture renewable technologies' erratic behaviour.

The short-version objective function writes as follows:

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

where r, t, y respectively correspond to Region, Technologies and Year. The variables that can be found in the expression of the objective function are the following:

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

2.1.3 OSeMOSYS set

In OSeMOSYS, running a simulation for a scenario requires having defined a set beforehand. The set represents the physical, spatial and temporal background for this scenario. There are different parameters to build a set. They can be handpicked with respect to what is needed by the user. Here is the list of the parameters to build the set in the scope of this work:

- EMISSION: the emission to be accounted for. For example, CO_2 or NO_x. The emissions can also be defined as "$CO_{2,eq}$", which means that whatever the nature of the emissions, they will be labelled as such.
- FUEL: this data contains every fuel required by the model. Fuels have to have a source and an end to exist in the model.
- MODEOFOPERATION: it represents the variability of a technology regarding the types of fuels it can use. For example, a CHP plant may use different fuels to generate electricity or heat. The mode of operation allows switching between these modes.
- REGION: the geographical region in which the model is located.
- TECHNOLOGY: It includes every single type of technology present in the system that generates, transports, or consumes a fuel.
- TIMESLICE: fractions of the year. Each fraction has its respective specific load and supply characteristics.
- YEAR: represents the time frame of the model.

Once these data are entered, multiple scenarios can be defined with the help of the simulation parameters.

2.1.4 Simulation parameters

OSeMOSYS takes as exogenous data a large variety of parameters such as technologies and fuels as well as their technical, economic, and environmental aspects. These represent the backbone of the computations to come. The parameters can be split into four different categories:

- Demand
- Technology
- Emissions
- Auxiliaries

These categories represent the data used for the model and are required for the model to run.

The values can be given to the program via files with the `.csv` format or implemented manually. For each parameter, it is possible to set a default value that will be used unless a value is specified.
Depending on the analysis the user wants to carry out on the results, some model characteristics will have a higher significance than others. In this case, below is the list of the critical parameters, which were split into categories for clarity.

Demand

Regarding the variables related to the demand, there are only three parameters, each of which is of pivotal necessity.

- AccumulatedAnnualDemand: For each commodity, the demand is given for one specific year for each year of the time frame.
- SpecifiedAnnualDemand: It allows the demand to be modelled through the different end-user electricity consuming sectors, namely
  1. Industry
  2. Residential
  3. Services
  4. Transport
  5. Others

  It is to note that the transmission and distribution sectors are not considered because they are transition sectors and not primary consuming sectors.
- SpecifiedDemandProfile: For each commodity, for each year, the demand is split in fractions between the different existing timeslices specified in the parameters of the defined set. For each year, the input should then sum up to 1.

Technology

The technology scenario parameters are the technologies through which technical specifications are entered.

- AvailabilityFactor: the available capacity at each timeslice which corresponds to a fraction of the annual available capacity. In the case of OSeMOSYS, they can be compared to the outage factor that shows the percentage of time where the generation technologies are in maintenance and cannot intervene in the generation, expressed as a percentage.
- FixedCost: fixed cost of a technology, such as operation and maintenance costs, is expressed in dollars per unit of capacity.
- InputActivityRatio & OutPutActivityRatio: rate of input/output of a fuel (commodity) by a technology. The ratio of these variables defines the efficiency of a technology.
- OperationalLife: the lifetime of a technology, expressed in years.
- ResidualCapacity: it is the capacity left over from a period prior to the modelling period, expressed in power units.
- TotalAnnualMinCapacityInvestment: minimum investment required in a defined year for the capacity installation of a particular technology, expressed in power units.
- VariableCost: cost of a technology for a given mode of operation (Variable O&M cost), per unit of activity.

The parameters above are common to conventional energy sources and renewable energy sources. However, the RES have some unique scenario variables attached to them. These unique variables model the uncertainty of RES and the potential target production through RES. These variables are the following:

- CapacityFactor: it is used to convert annual capacity to the capacity available for each timeslice.

- RETagFuel & RETagTechnology: they allow the model to understand which fuel and technologies are renewable.

Storage

In this scenario, no storage is considered because the storage data available did not have enough precision. Therefore, introducing unreliable storage data could impact the results and give irrelevant solutions.

Emission

Regarding emissions, the different variables model the impact of these and how emission limits can be imposed on the model.

- AnnualEmissionLimit: annual upper limit for a specific emission generated in the whole modelled region.
- EmissionActivityRatio: emission factor of a technology per unit of activity, per mode of operation.
- EmissionsPenalty: penalty per unit of emission, such as taxes.

Auxiliairies

The auxiliary variables are the variables that are not related directly to anything stated previously.

The parameters above are defined for the three scenarios used for this work. While most of them remain the same throughout the multiple scenarios, some are the parameters that allowed to implement the differences between scenarios and thus have to assume different values depending on the context. The entire list of input parameters and constraints can be found in appendix A or on the dedicated website of OSeMOSYS [21].

2.2 Dispa-SET

Dispa-SET is an open-source unit-commitment and optimal power dispatch model developed in a collaborative effort by the Joint Research Centre of the EU Commission, the KU Leuven, and the University of Liège. Dispa-SET's purpose is to model the short-term operations on power systems at any scale: micro-, region-, country- or continent-scaled power grids, with acute precision while being subjected to multiple constraints. It was first developed with the intent to serve at a European level and was rapidly applied to other regions and projects. [28, 20]
Dispa-SET is expressed as a Mixed-Integer-Linear-Program (MILP) based on `Python` and `GAMS`, the General Algebraic Modelling System. `Python` performs the pre- and post-processing of the data, and `GAMS` is used to perform and solve the optimization problem. The file format used for data handling is `csv`. There is also another configuration than the MILP, such as Linear Programming (LP). This allows for an option to trade-off between computational complexity and accuracy [29]. The entire model can be found in a `Github` repository [1].

This model is used to produce the results presented in the chapter 5

The official Dispa-SET documentation inspires the next subsections. It can be found online or on the JRC technical report [20, 29]

2.2.1 Dispa-SET inputs

Technologies

Technologies are used to distinguish the different ways in which a fuel can be transformed. Dispa-SET differentiates conventional technologies and renewable technologies, as well as technologies that can store energy. There are a great number of technologies recognized by Dispa-SET. The table 2.1 below displays the technologies used in the scope of this thesis:

Fuels

Fuels in Dispa-SET are used to distinguish the different fuels a technology can transform.

[1] https://github.com/energy-modelling-toolkit/Dispa-SET

Technology	Description	VRES	Storage
COMC	Combined cycle	N	N
GTUR	Gas turbine	N	N
HDAM	Conventional hydro dam	N	Y
HROR	Hydro run-of-river	Y	N
PHOT	Solar photovoltaic	Y	N
STUR	Steam turbine	N	N
WTON	Onshore wind turbine	Y	N
BATS	Stationary batteries	N	Y

Table 2.1: Dispa-SET technologies used for Bolivia

Dispa-SET considers the most common fuels types. The fuels used in Dispa-SET are listed below:

- BIO: Biomass
- GAS: Gas
- GEO: Geothermal heat
- SUN: Solar energy
- WAT: water energy
- WIN: wind energy

Zones

Dispa-SET allows splitting a system into different geographical regions. In this case, four regions split Bolivia, namely central (CE), northern (NO), oriental (OR), and southern (SU). These zones will define the demand as well as power plants.

Demand

The electricity demand is split between all zones. Initially, the demand is assumed to be inelastic, although a flexible demand feature exists in Dispa-SET. This feature requires a percentage of peak load to be defined and some days. The percentage specified will be spread over the defined days.

Power plants

Power plants are defined firstly by combining one technology and one fuel. The fuel GAS and technology COMC define a gas combined cycle powerplant. They also have a lot of other characteristics attached to them. Power capacity, CO2 intensity, ramp up and down rates. The exhaustive list can be found in appendix C

Interconnections

There are two cases of interconnections:

- Net Transfer Capacities: the capacities of the transmission between the internal regions of one model in Dispa-SET.
- Historical physical flows: energy flows between the inner regions of one model and external regions.

In the scope of this thesis, only the former is considered. The interconnections are always defined as positive. Therefore, there always exist two NTC values between two regions.

Renewable Generation

Variable renewable generation represents the power produced by RES that cannot be stored; it is either consumed or curtailed.

To define the variability of these technologies, it is necessary to provide data on their time-dependency. The availability factors display this dependency through availability factors. These factors represent the percentage of the installed power capacity available at each hour for the variable renewable energy source technologies.

Conventional power technologies are also assigned availability factors. It is equal to one.

Outage factors

The outage factors model the power outages for technologies over the years. Plant outages occur when power plants are shut down or disconnected from the grid. Outage factors represent the time the power plants remain shut down or disconnected. The nominal power multiplied by (1-Outage factors) gives the power capacity for power plants.

2.2.2 Dispa-SET model description

This model aims to represent, with a high level of detail, the short-term operation of large-scale power systems solving the so-called unit commitment problem. To that aim, a central operator with complete information on the technical and economic data of the generation units, the demands in each node, and the transmission network manages the system.

The objective of this model is to represent large-scale power systems on a short-term basis, emphasizing the operations in that system with unit commitment and power dispatch. To do so, the model is given economic and technical information about the power system, the demand in each region, and the transmission system data.

The unit commitment is a simplified version of the bid-clearing operation in the wholesale day-ahead market. The fact that it is clustered at each node and the transport problem between nodes represents the transmission system simplifies the operation. Dispa-SET does not optimize the power flows.

The unit commitment problem is practically split into two steps:

- Scheduling start-ups, operations, and shut-downs of the available power units.
- Minimizing the overall power system cost by allocating the total power demand among the available power units.

The former contains a lot of binary variables to model the start-up and shut-down decisions, as well as the consideration of constraints linking the commitment status of the units in different periods.

Therefore, given all the features of the problem mentioned above, it can be naturally formulated as a mixed-integer linear program (MILP). However, the problem can also be relaxed to a linear program (LP).

As Dispa-SET models large-scale power systems, the formulation of the model was made tight and compact. Compactness implies the quantity of data the solver will process and thus the speed with which it will search for the optimum. The smaller the amount of data, the greater the compactness. Tightness, on the other hand, is related to the space between relaxed and integer solutions of the MILP and, therefore, to the space the solver will search through. When tightness is increased, usually by adding constraints, the size of the problem increases, leading to an increased amount of data to be processed by the solver and therefore decreased compactness. The idea is to compromise between the two to reach an optimum for tightness and compactness.

Objective function

The goal of the unit commitment problem is to minimize the total power system cost, which is defined as the sum of different cost items:

$$
\begin{aligned}
\min \Bigg[& \sum_{u,i} \text{CostFixed}_u \cdot \text{Committed}_{u,i} \cdot \text{TimeStep} \\
& + \sum_{u,i} \big(\text{CostStartUpH}_{\ u,i} + \text{ CostShutDown } H_{u,i} \big) \\
& + \sum_{u,i} (\text{ CostRampUpH } H_{u,i} + \text{ CostRampDown } H_{u,i}) \\
& + \sum_{th,i} \text{ CostHeatSlack}_{\ th,i} \cdot \text{ HeatSlack } k_{th,i} \cdot \text{ TimeStep} \\
& + \sum_{i,n} \text{VOL}\, L_{\text{Power}} \cdot (LL_{\text{MaxPower },i,n} + LL_{\text{MinPower },i,n}) \cdot \text{ TimeStep} \\
& + \sum_{i,n} 0.8 \cdot VOLL_{\text{Reserve}} \cdot (LL_{2U,i,n} + LL_{2D,i,n} + LL_{3U,i,n}) \cdot \text{ TimeStep} \\
& + \sum_{u,i} 0.7 \cdot VOLL_{Ramp} \cdot (LL_{RampUp,u,i} + LL_{\text{RampDown },u,i}) \cdot \text{ TimeStep} \\
& + \sum_{s} \text{ WaterValue } \cdot \text{ WaterSlack } k_s \Bigg]
\end{aligned}
$$

where the sets u, i, l, and n respectively represent the power generation units, the simulated hours, and the interconnection lines between zones and the zones. s, th, and chp represent the storage technologies (without heat units), thermal units, and combined cycle units. It is possible to break down the costs as follows:

- Fixed costs: depending on whether the unit is on or off.
- Variable costs: stemming from the power output of the units.
- Start-up costs: due to the start-up of a unit.
- Shut-down costs: due to the shut-down of a unit.
- Ramp-up: emerging from the ramping up of a unit.
- Ramp-down: emerging from the ramping down of a unit.
- Load shed: due to necessary load shedding.
- Transmission: depending on the flow transmitted through the lines.
- Loss of load: power exceeding the demand or not matching it, ramping and reserve.
- Spillage: due to spillage in storage.
- Water: cost of water coming from unsatisfied water level at the end of the optimization period.

The model allows voluntary load shedding. Load shedding reduces the demand to relieve stress off the system. Additionally, to allow for a clear assessment of simulation errors or system inadequacy, the model also considers some variables representing the capacity the system cannot provide when the minimum/maximum power, reserve, or ramping constraints are reached. These losses of load (LL) are an extremely costly last resort of the system used when no other choice is available. The different lost loads are assigned very high values (for any other costs). This allows simulating without infeasibilities, thus helping to detect the origin of the load loss. In a typical model run, without errors, all these variables are expected to be equal to zero.

The objective function of OSeMOSYS presented in section 2.1.2 and the objective function of Dispa-SET help visualize the crucial difference between the two models. OSeMOSYS computes its objective function with the smallest timestep being the year. The costs, capacities, and other parameters are computed for their region, their technologies, and the current year of the simulation. Whereas Dispa-SET considers much more details about the optimized cost, the optimized cost is determined for each hour of the simulation.

Day-ahead market equation The main constraint to be met is the grid power balance for each period and each zone in the day-ahead market. It means that the sum of all the power generated by all the power units in one node (including storage and imports) is equal to the demand in that node plus the stored power as well as shedded and lost load.

$$\begin{aligned}\sum_u (\text{ Power }_{u,i} \cdot \text{ Location }_{u,n}) + \sum_l (\text{ Flow }_{l,i} \cdot \text{ LineNode }_{l,n}) \\ = \text{ Demand }_{DA,n,h} \\ + \sum_s \left(\text{ StorageInput }_{s,h} \cdot \text{ Location }_{s,n} \right) \\ - \text{ ShedLoad }_{n,i} \\ + \sum_{p2h} \text{ PowerConsumption }_{p2h,i} \cdot \text{ Location }_{p2h,n} \\ - L_{\text{MaxPowern }, i} + \text{ LL }_{\text{MinPower } n,i}\end{aligned}$$

2.2.3 Rolling Horizon

Dispa-SET can model the hourly variation of the availability and production of power plants and compute hourly costs. In the end, compute a minimum hourly cost for the power system. Realizing these operations is theoretically feasible for an entire year. However, the dataset that needs to be processed to model a year is of consequent size and thus increases the dimensions of the problem, leading to increased computation times. To limit that increase, the problem is split into more minor optimization problems run recursively throughout the year. This approach is shown in figure 2.1. The optimization period is two days. The look-ahead period is one day. This means that days j-1 and j are optimized, then the day j is dropped, and the optimization starts again for days j and j+1. The look-ahead period is modelled to avoid issues related to the end of the optimization period, such as emptying the hydro reservoirs or starting low-cost but non-flexible power plants.

2.2.4 Mid-term Scheduling

Because of the rolling horizon approach, yearly storage levels (e.g. for hydro dams) must be provided to the optimizer. Storage levels are usually forecasted based on historical data. The lack of such data also impacts the accurate modelling of such scenarios. Moreover,

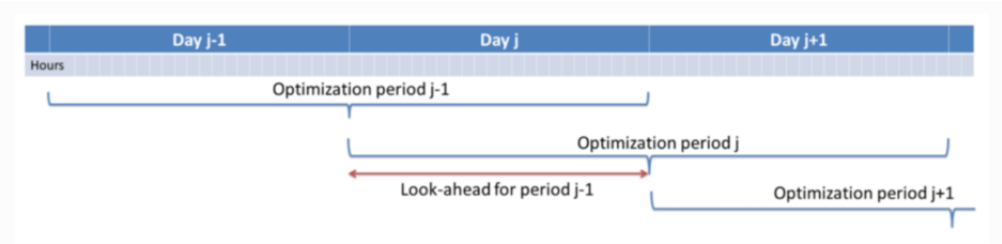

Figure 2.1: Rolling horizon visual representation

the storage levels are forecasted based on historical data for future scenarios. The lack of precision thus impacts the results of these scenarios, especially with Bolivia's high share of hydroelectric power plants. To prevent the results from being flawed by this lack of precision, Dispa-SET possesses a Mid Term Scheduling (MTS) module. This module provides a precise forecast and allocation of the storage resources for the whole year based on a simplified set of equations and linear optimization. The simplification means that all equations concerning unit commitment are not considered, and the binary variables Committed, StartUp, and ShutDown are defined as linear. The time step is set to one day. The Mid Term Scheduling also allows for a lower computation time of the simulation.

2.3 Uni-directional soft-linking

With OSeMOSYS only providing annual, seasonal or clustered daily variances outputs at best, it does not allow to fully discern the smaller scale variations of the energy demand and generation even though the most suitable version of OSeMOSYS is chosen specifically with that objective in mind. Moreover, a long-term energy planning model cannot possibly consider every single detail of an energy system. The computation time and complexity would be needlessly high. The opposite goes for Dispa-SET; having detailed data about power plants such as ramp up and down times and an hourly simulation step does not allow for simulations over multiple years. Therefore, Dispa-SET is not suited for long-term economic investments.

The ideal energy planning model would, of course, be a mix of high precision and small simulation steps but suited for long-term energy forecast so that it can be used for investments. Although such a model does not exist, it is possible to figuratively build a bridge between a short-term and a long-term energy planning model to get the advantages of both models and have the disadvantages counterbalance each other. Such a link is called *soft-link* [30].

There exist two types of soft-links, uni-directional and bi-directional. A bi-directional soft-linkage such as the one between the EnergyScope model and Dispa-SET model realized by Matija Pavicĕvić et al. allows for improving both models' results through iterations in which the two models repeatedly vary each other's inputs until their solutions converge [31]. As for uni-directional soft-linking, one model influences the other without the latter having any form of influence on the former [32]. It can be assimilated to a master-slave relation as one model imposes the input on the other. In the scope of this work, OSeMOSYS and Dispa-SET are uni-directionally linked, with OSeMOSYS being the model that imposes its outputs as some of the inputs of Dispa-SET.

The soft-linking takes into account the processing of the data structure. Indeed, it is highly likely that these two models do not have the exact needs in terms of data structure, simply due to the simulation step, for instance. The script realizing the soft-linking reshapes the data from one model to the other, in that instance, from OSeMOSYS to Dispa-SET.

The figure 2.2 represents the explanatory block diagram of the soft-linking between OSeMOSYS and Dispa-SET.

2.3.1 Data from OSeMOSYS used in Dispa-SET

To shape these data from one model to the other, it is important to discern one of the main differences between the formulations of the scenarios in OSeMOSYS and Dispa-SET Bolivia. In the latter, Bolivia is split into four regions, namely central (CE), northern (NO), oriental (OR), and southern (SU) regions. OSeMOSYS scenarios do not have such geographical segmentations. Therefore, it was necessary to define those limitations and then consider them for soft-linking. The figure 2.4 represents the four regions defined by the *Viceministerio de Electricidad y Energías Alternativas* in their report [34]. The piecing of Bolivia for Dispa-SET in the scope of the work followed this figure. All historical data available was already disaggregated into four. This segmentation allows a clearer view of the procedure required to transfer data from the OSeMOSYS structure to that of

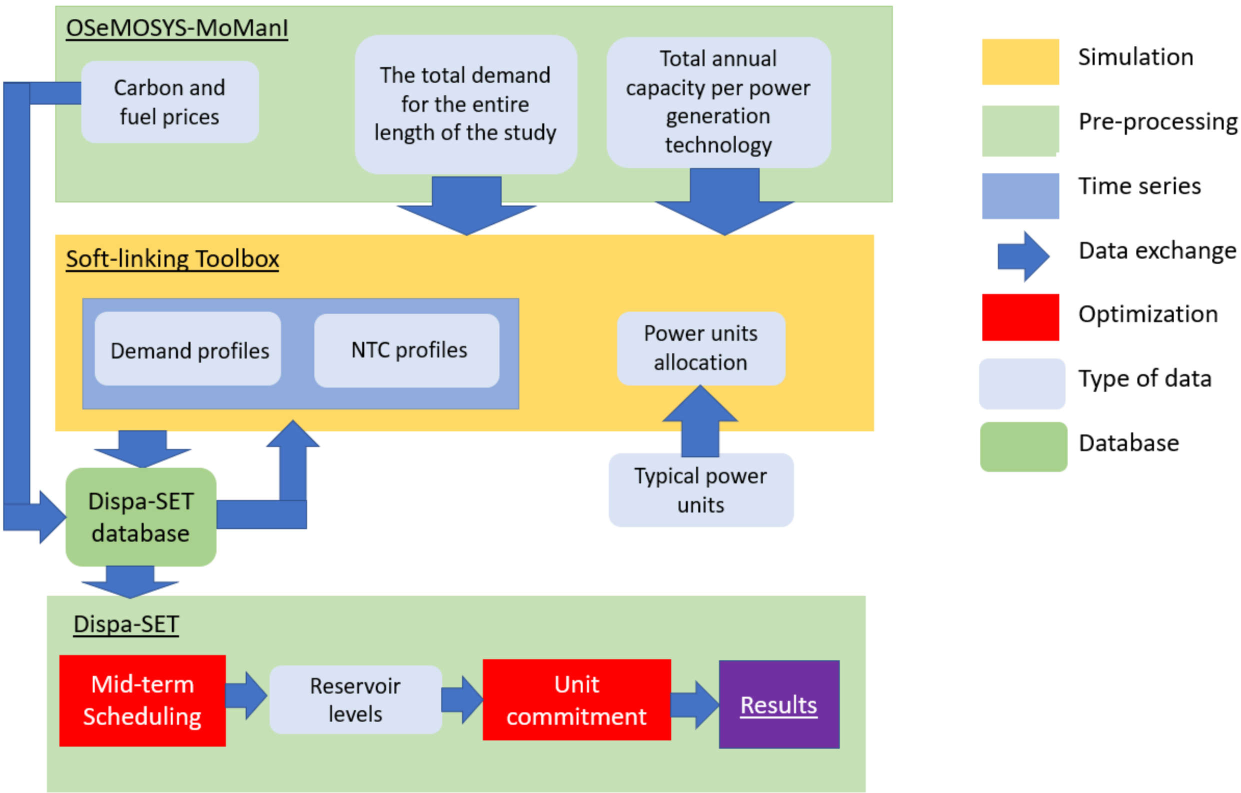

Figure 2.2: Explanatory block diagram of the soft-linking between OSeMOSYS and Dispa-SET. Inspired from [33]

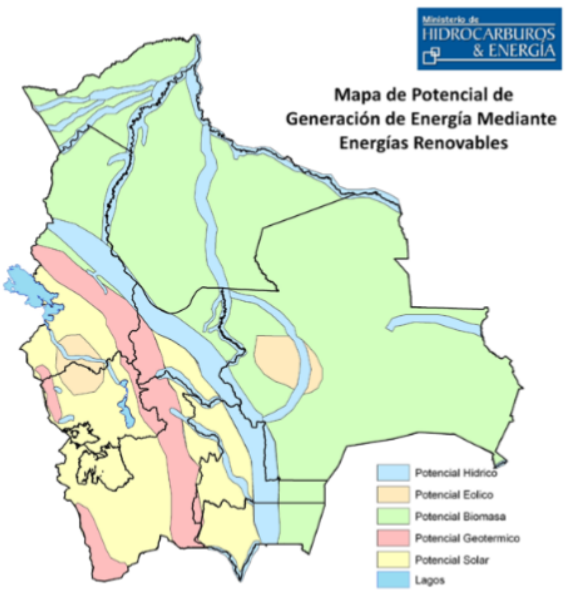

Figure 2.3: Map of power generation potential through renewable energies

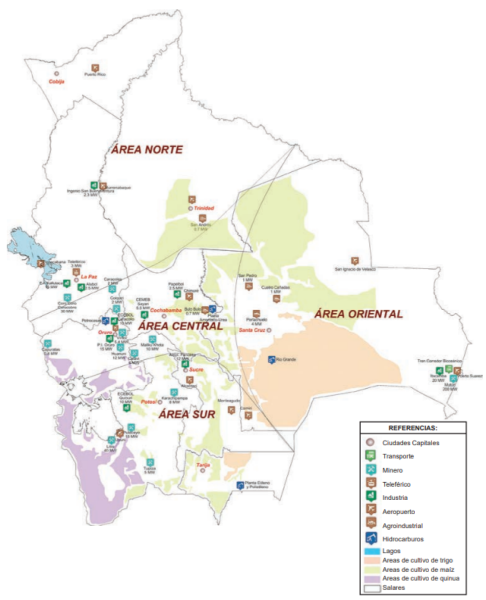

Figure 2.4: Definition of the different zones in Bolivia [34]

Dispa-SET.

Regions / RES	CE	NO	OR	SU
WIND	21.62	9.45	58.11	10.81
GTFC	0	0	0	100
HDAM	35.69	20.52	17.1	26.67
HMIN	66.58	23.77	0	9.65
PVUTL	57.52	5.06	0	37.42
BMSC	0	11.06	88.94	0

Table 2.2: Percentage of renewable energy sources capacities per technology as of 2025.

The variables transferred from OSeMOSYS to Dispa-SET are:

- The total demand for the entire length of the study
- Total annual capacity per power generation technology
- Carbon and fuel prices
- Demand

Total annual capacity per powerplant

The total annual capacity for power plants is split amongst each region based on the current repartition provided by historical data on the BES power plants.

However, as the demand rises from 2014 to 2050, an assumption is made regarding the RE share. Based on the historical data and Navia et al.'s work, the projected share of installed RE capacities in the regions as of 2025 is determined. These values are assumed to represent the RE potential of each region, according to what was demonstrated by Severino Alejandro Quispe Ramos et al. in the Minister of Hydrocarbons and Energy report [12]. The table 2.2 shows the repartition of installed capacities for RES per region:

Therefore, as the demand in the RE increases through the different scenarios, so are the installed capacities for the different technologies. For the simulations, the geographical repartition of the installed capacity for the RES follows the map of power generation potential through renewable energies 2.3. This means that new capacity is installed where it can physically be installed. No solar is installed in the OR region because it is highly likely that there would already be some power installed in that region by 2025 if it was possible or efficient. However, there is one exception. As shown in table 2.2, the total installed capacity of the geothermal steam turbine technology is located only in the SU region. Based on the figure 2.3, new capacity is added to the regions that supposedly have the geothermal capacity, such as the NO and CE regions, as shown in the figure 2.4. It avoids having 100% of the capacity of one technology installed in a single region, and it considers the physical limitations of the resources region-wise.

The total capacity from OSeMOSYS is reshaped to form power plants per region. It is a required input in Dispa-SET. OSeMOSYS is less detailed regarding the characteristics of the power plants than Dispa-SET, which is why a database with typical power units is used to generate these techno-economic characteristics. The gaps are, for instance, the ramp-up and down rates, start-up cost, CO2 intensity.

Carbon and fuel prices

The carbon and fuel prices are imported from OSeMOSYS. They are defined as exogenous input in Dispa-SET. It is essential to know that the simulation was performed before the Russo-Ukrainian war and the ensuing crisis.

Demand

OSeMOSYS provides annual demand output; the annual data does not correspond to the hourly format Dispa-SET uses. It is, therefore, necessary to slice that annual demand into an hourly resolution.

Although it is best to limit the influence of Dispa-SET on OSeMOSYS output, it is necessary to use the demand time-series Dispa-SET to shape the annual demand so that it is usable.

The historical demand time series available are the years 2016 and 2020. The latter proved to have been heavily impacted by COVID-19. Therefore, the demand curve relative to the year 2016 has been considered for the present analysis.

In order to slice the annual demand into hourly demand, firstly, the total 2016 demand is computed. Then, the total demand for 2016 and the annual demand for the studied years are compared. The ratios obtained by dividing the annual demand for the studied years by the annual 2016 demand gave the general load increase between those years. The 2016 demand time series is then multiplied by those ratios to obtain hourly demand for each year.

2.3.2 Dispa-SET transmission lines capacities requirements

Transmission line capacities, known in Dispa-SET as Net Transfer Capacities or NTC, are not defined in OSeMOSYS and are required for Dispa-SET to run correctly. Even so, no data can be transferred over to help determine these capacities related to a studied year. However, there is historical data for NTC from 2016 to 2021. It is trivial that, as the demand increases with the years, so should these capacities to allow the energy to flow as best as possible from region to region. With that objective in mind, a first extrapolation was made to obtain data for 2025 in the scope of Navia's work [13]; itself basing its results on R.A. Rojas Candia's work [35].

Nonetheless, this increase in the NTC values for 2025 is not suited to withstand the increase in demand and generation planned for years after 2030. Therefore, the NTC values are adjusted to be adequate with the rest of the Bolivian energy system. Two solutions are considered to forecast the future development of the grid and the NTC:

- Upscaling the NTC according to the peak load
- Upscaling the NTC according to the total installed generation capacity

The generation upscaling represents more precisely the repartition of the generated energy. It can be set as a fraction of the total installed capacity for each region. It can, however, be spoiled by the influence of the peak generation of the photovoltaic panels. The photovoltaic panels' capacity is defined based on their peak power capacity, which can fail the results.

In the first instance of the simulation, the load upscaling is implemented.

Chapter 3

Long-term energy scenarios for Bolivia

3.1 Bolivian Reference Energy System

One goal of the Bolivian energy transition is to phase out the GHG emitting technologies to achieve the IPCC goals by 2050. In that regard, various energy plannings have been done. They rely on the current structure of the Bolivian energy mix as the reference point. In this case, a reference system was defined.

The reference energy system of the BES represents its current structure. The Bolivian reference energy system is a state-of-the-art model to help visualize the energy system in its entirety.
This system represents how each fuel and technology will be connected in the model. How variables will be labelled as "fuels" or "technologies" is coherent with the labelling of the variables in the OSeMOSYS planning model.

The structure of the Bolivian Reference Energy System will now be reviewed. In the BRES, four stages contain fuels and technologies. They mark the stages of energy production to consumption. These four stages are:

- Resources Supply

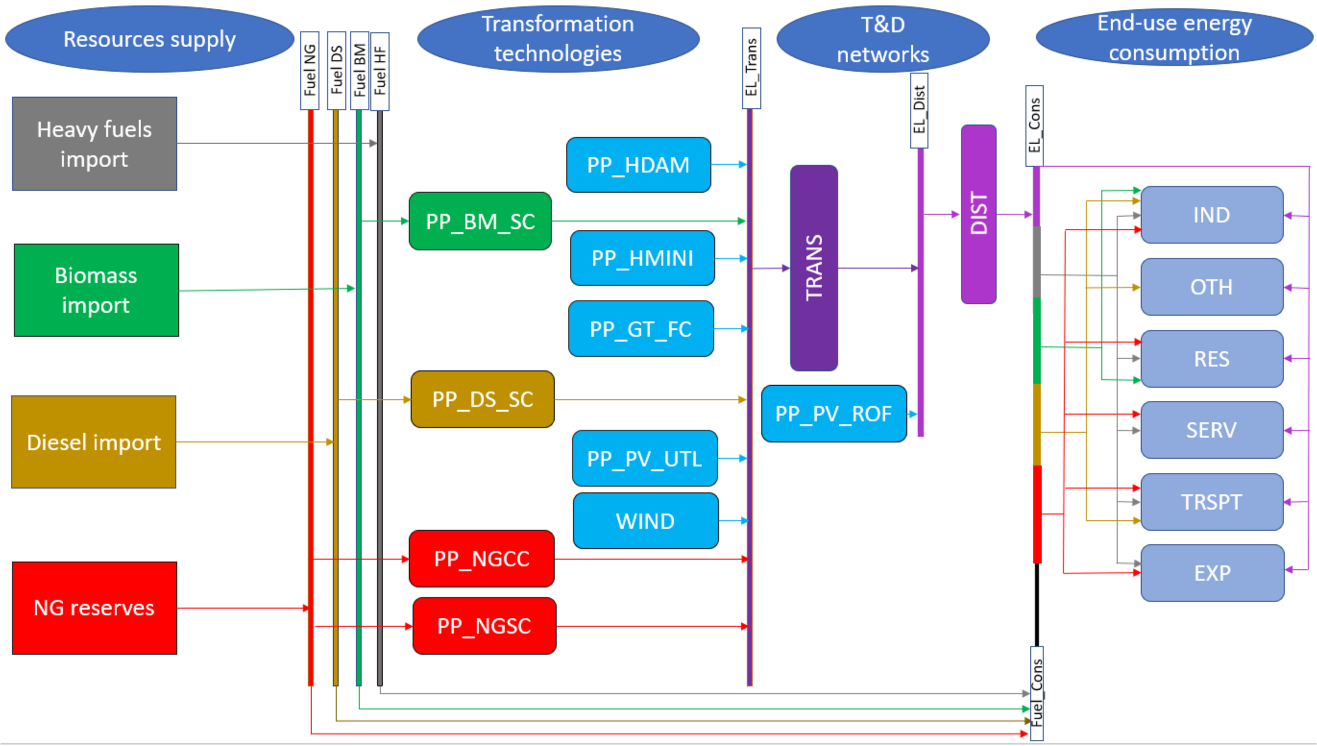

Figure 3.1: Bolivian Reference Energy System

- Transformation technologies
- T&D networks
- End-use energy consumption

The variables involved in those two stages relate to fuels or technologies. The following list contains the various fuels that can be found in BRES:

- Fuel_DS: Diesel fuel
- Fuel_BM: Biomass
- Fuel_HF: other Heavy Fuels (Gasoline, Kerosene, ...)
- Fuel_NG: Natural gas
- EL_Trans: High voltage electricity on the transmission level
- EL_Dist: Medium voltage electricity on the distribution level
- EL_Cons: Low voltage electricity on the distribution level

These fuels represent the majority of the fuels in Bolivia. The three last fuels are related to electricity. The transmission level receives high voltage electricity coming out of the power plants. Afterwards, through its progress to the consumption sectors, the voltage is reduced little by little. These last three fuels specify the voltage level of the electricity.

Technologies transform, use, and produce fuels. The main category is the power plants generating power, mostly located in the "Transformation technologies" stage. This stage contains the power plants generating power at the transmission level. There are two categories of power plants:

- Conventional power plants [1]:
    1. Natural gas simple cycle (PP_NG_SC)
    2. Natural gas combined cycle (PP_NG_CC)
    3. Diesel simple cycle (PP_DS_SC)
- Renewable power plants:
    1. Biomass simple cycle (PP_BM_SC)
    2. Geothermal flash cycle (PP_GT_FC)
    3. Photovoltaic power plants at transmission level (PP_PV_UTL)
    4. Wind farms (WIND)
    5. Hydropower of small and large capacities (PP_HMIN and PP_HDAM respectively)

The last power generation technology is installed on the distribution grid level :

- Photovoltaic power plants at the distribution level (PP_PV_ROF)

The second category of technologies are the ones bringing the fuel to the consumers:

- TRANS & DIST: they model the usual electric network. In practice, these technologies reduce the high voltage electricity coming out of the power plants to lower

[1] also referred to as fossil fuel power plants, or thermoelectric power plants

voltage electricity that can be transmitted to the consumer level.

- CONS: it models the interface between the demand on a country level to demand on an individual/per unit level, such as a gas station for heavy fuels or diesel, for instance.

One last type of technology represents the origin of the primary fuels used. OSeMOSYS requires all fuels (other than hydro, solar, and wind) to have an origin. Therefore, the following

- NG reserves
- DS Import
- BM Import
- Heavy fuels import

represent the importation and extraction systems.

Consumers are considered by sectors. This allows knowing how and where the energy was consumed. There are five considered sectors for energy consumption which are the following:

- Industry: the energy consumption for the industrial sector.
- Residential: the electricity that Bolivia's households consume.
- Services: the energy consumption of the tertiary sector: retailers, restaurant industry, telecommunication, transport.
- Transport: the vehicles' energy consumption. Transport belongs to the tertiary sector, but other scenarios will require hypotheses on this sector [8].
- Others: other sectors such as Agriculture, Forestry.

These sectors were chosen because they are directly linked to the power sector. For example, the agriculture sector is important regarding fossil fuel consumption but is lightly dependent on electricity production and therefore was left aside [8]. Although the transport sector is currently negligibly dependent on electricity, it was chosen because of its relevance in some of the later explored scenarios, which make use of hypotheses regarding the electrical dependency as efforts should be made to electrify that sector.

In conclusion, the BRES model can be understood as follows:

Firstly, the primary fuels are imported into the BRES in various ways. Afterwards, the path forks. Either the fuels are used as raw materials or consumed by the power plants and transformed into electricity.

The electricity produced by the power plants, the fuel "ELTrans", high voltage electricity, is then transmitted and distributed in the third stage ", TD networks". Finally, the electricity from the distribution level is ready to be consumed by the various sectors.

3.2 OSeMOSYS scenarios

The BRES defined in the section 1.2 is used as the backbone of the scenarios built with the OSeMOSYS model.
First, a Business As Usual (BAU) scenario is developed. It represents the current BES and its evolution from 2014 to 2050. A scenario is based on the results and analyses from the BAU, the Mixed Policies (MP) scenario. The last scenario derived from the MP scenario results is focused on Bolivia's carbon neutrality.

3.2.1 Simulation code version

The code version in OSeMOSYS used for these scenarios is the short-version objective function of OSeMOSYS. Supposedly, with the phasing out of the fossil fuel-powered thermoelectric power plants, there will be penetration of RES in the BES. As explained in the section 2.1.2, the short-code version is a long-term energy planning function combined with short-time windowed equations to capture the erratic behaviour of renewable technologies. It is an apt choice in this case.

3.2.2 Model set parameters definition

Referring to the section 2.1.3, the set data needs to be defined for each scenario and is common to all scenarios. Here is how they are defined:

- EMISSION: the only specified emission is the CO2 emission. If there is no other type of emissions than CO2, it can be considered as CO2 equivalent emissions. Therefore every data related to emission is scaled to equivalent emissions.
- FUEL & TECHNOLOGY: as the scenarios are based on the BRES, see figure 3.1, the fuels and technologies used are already specified in the section related to the Bolivian Reference Energy System, section 1.2.
- MODEOFOPERATION: for these scenarios, only a single mode of operation is specified because the CHP potential of power plants is not considered.
- REGION: the region specified is Bolivia, given that the model considers the entire Bolivian energy system.
- TIMESLICE: the year is split into three different periods, each split day and night. They are the following:
  - Intermediate season;
  - Summer season;
  - Winter season

  The intermediate season represents autumn and spring. It represents fifty per cent of the year, which means that day and night both represent a quarter. The summer and winter seasons represent a quarter of the year, meaning day and night represent an eighth of a year.
- YEAR: The studied years span from 2014 to 2055. The range goes to 2055, but the results are studied for 2050. These extra five years are added as a look-ahead period to buffer the end-of-horizon effects.

3.2.3 Scenario parameters

Each scenario used the parameters listed in the section 2.1.4. However, only a few changed from scenario to scenario, so the parameters that received changes will be defined in each scenario's respective section.

3.3 Business As Usual Scenario

This first scenario represents a template model. It aims at describing the current Bolivian energy mix and system, to project the energy and $CO2_{eq}$ productions to 2055 to understand how the energy mix will evolve later on and to modify its input to decrease or possibly nullify the $CO2_{eq}$ emissions by 2050 as suggested by the IPCC with other scenarios. From the BAU's results and analysis, policies will be assessed to minimize Bolivia's $CO2_{eq}$ emission.

3.3.1 BAU inputs and hypotheses

The BRES allows having the frame of the system in mind. This structure will be used in OSeMOSYS. With that structure come the parameters of the different technologies and fuels.

The fuel inputs will be represented as the demand for each fuel. Based on the historical data [8]. From the figure 3.2 displaying a linear growth, a realistic view of the trend of the fuel share is extracted and scaled linearly to the demand up until 2055 for the BAU scenario. This should show a constant growth in the results. It is imposed as a steady growth with respect to energy consumption before 2020. As shown in 3.4, the energy consumption has steadily progressed since 2006, except for 2020. This dip in energy consumption can be attributed to the COVID pandemic. The total energy demand curve will follow the trend of figure 3.4.

Regarding the technologies, there are a few key parameters:

- power plants operational variables: Capacity factors, efficiencies, available factors.
- power plants economic variables: Operation costs, fixed costs, capital cost, cost of

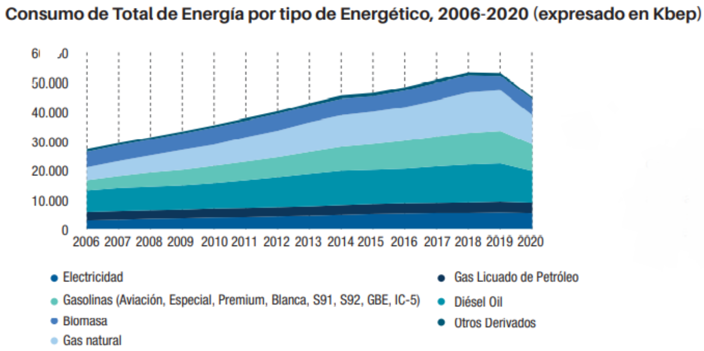

Figure 3.2: Fuel consumption trend

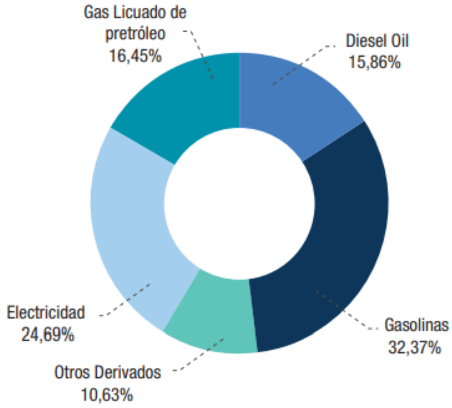

Figure 3.3: Share of fuel consumption per fuel

investment.

- power plants $CO2_{eq}$ emissions factors

The table 3.1 shows the current installed capacity in MW in Bolivia for each technology on the transmission level:

For the BES, these values are estimated based on historical data from ENDE, the national electric company in charge of the generation and transmission of electricity. The economic data are also extracted from ENDE's databases [36]. Moreover, it is necessary to know that Bolivia is one of the poorest countries in South America [37, 38], and it has significant natural gas reserves. Consequently, the Bolivian government established a "natural gas subsidy" that allows the natural gas and the energy generated with natural gas to be cheap [39], compensating for the low average income of Bolivia. These subsidies have as a consequence that the variable cost of the natural gas power plants is maintained relatively low when compared to other technologies, therefore putting them at an advantage, disrupting the "usual" merit order in which the renewable energy sources produce the energy with the lowest cost .

As for the $CO2_{eq}$ emissions, direct and indirect emissions are considered. Direct $CO2_{eq}$ emissions relate to the technologies that produce $CO2_{eq}$, such as power plants, and indirect emissions relate to technologies that produce $CO2_{eq}$ as a by-product, such as hydro

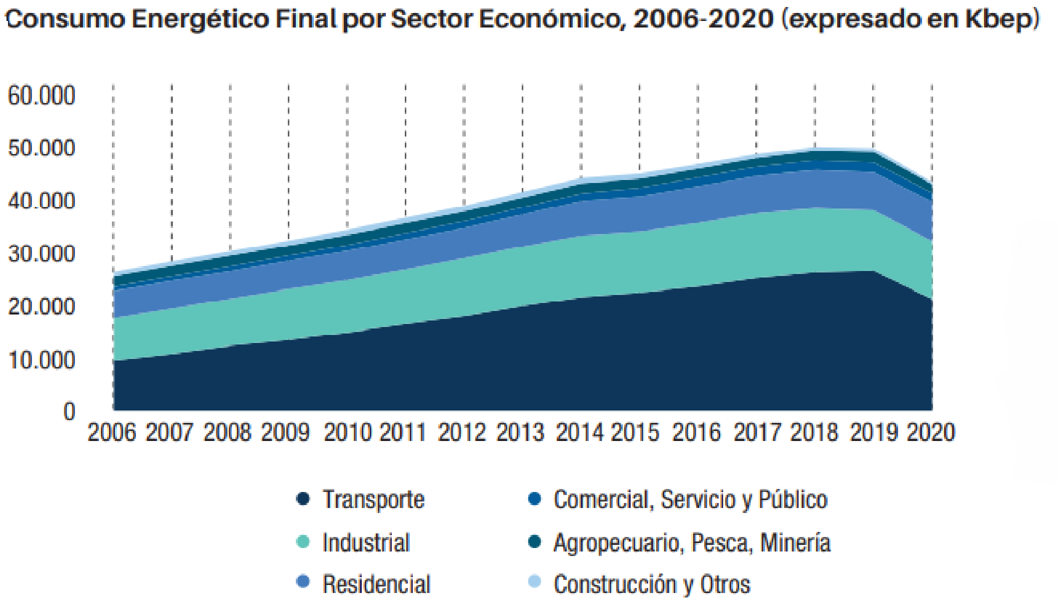

Figure 3.4: Bolivia's energy consumption from 2006 to 2020 [8]

Technologies \ Regions	CE	NO	OR	SU
NGCC	497.36	0	580.65	306.4
NGSC	554.68	56	440.13	221.46
DSSC	0	31.58	0	0
WIND	28.6	12.53	77.04	14.32
GTFC	0	0	0	5
HDAM	174.13	100.11	83.38	130.12
HMIN	130.88	49.58	0	20.08
PVUTL	93.98	8.26	0	61.12
BMSC	0	10.91	87.9	0
TOTAL	1479.63	268.97	1269.1	753.5

Table 3.1: Current installed capacity in MW in Bolivia for each technology on the transmission level

dams. As shown by R. Almeida et al. [40], lowland dams in the amazon forest have higher GHG emissions than fossil fuel-fired power plants. The emission activity ratios of the conventional power units are based on data from the IPCC guidelines [41]. For the carbon emission of hydro dams, the values are established through a literature review [41, 42, 43].

As for the parameters, the Business-As-Usual scenario follows the current trend of the Bolivian Energy System. Therefore, the natural gas subsidy is implemented.

3.4 Mixed Policies Scenario

From the BAU model, one particular thing can be pointed out: natural gas represents the vast majority of the Bolivian energy mix. In Bolivia, the government provides subsidies [44] to natural gas power plants such that, in a dispatch, these power plants have a meagre cost and a high availability factor. Therefore, they are prioritized on merit order energy markets [45].

It was necessary to find a counter-measure to the domination of natural gas in the Bolivian energy mix to minimize the $CO2_{eq}$. In other words, to reduce the dependency of Bolivia on natural gas. Those counter-measures policies are the following

- Carbon tax;
- Reducing or even nullifying natural gas subsidy;
- Energy Efficiency Measures (EEM);
- Electrification of Energy Demands (EED).

These policies will be introduced in the model in order to quantify their possible impact. The first scenario modelled to meet that objective was the "Carbon tax" scenario. Its purpose is to shift the electricity dependence from a natural gas majority to a greener mix. These policies implemented together form the Mixed Policies scenario.

3.4.1 Carbon Taxing Scenario

This policy was first declined in multiple versions; the difference was the value of the tax imposed. It was decided that the taxes would be imposed from 2025 onwards. Indeed, the Bolivian government approved the plan to initiate the energy transition in the Bolivian energy mix by 2026 [46]. The taxes are not fixed throughout the studied timeframe; the idea was to perform an evolution so that the taxes would see their value steadily increase from 2026 to 2050. The initial values in 2026 are \$10/t of $CO2_{eq}$ with a yearly increase value from \$2/y to \$40/y. There is also a "Swedish" version which is an adaptation of the Swedish tax carbon plan which consists in a \$5.5/y increase with a value of \$126/t$CO2_{eq}$ in 2020, \$137/t$CO2_{eq}$ in 2022 and of \$159/t$CO2_{eq}$ in 2026 with the same yearly increase, resulting in a \$318/t$CO2_{eq}$ carbon tax by 2055 [47] which was considered as the harshest version for this policy. Given Bolivia's poor economic background [37, 38], it is only normal to take this factor into account and avoid implementing high-value taxes. The objective of these first scenarios is the establish a general behavior for the carbon taxing impact and afterward to optimize the carbon tax value so that the energy mix is or tends to be in line with the objective of the Carbon Taxing Scenario. A sensitivity analysis was conducted to point out the value that offers the best mix possible. The figures B.3 and B.4 show the typical results obtained with carbon taxing policy. These figures were

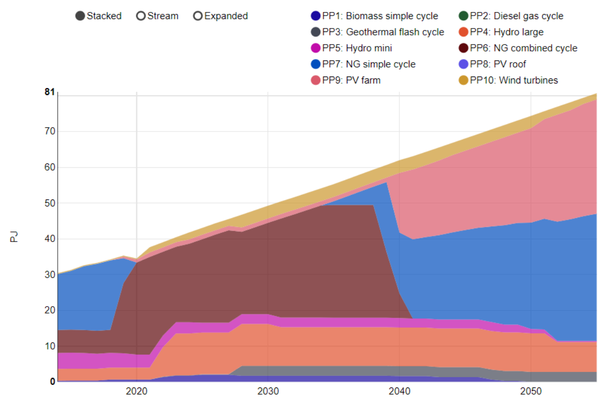

Figure 3.5: Typical generation mix with CT

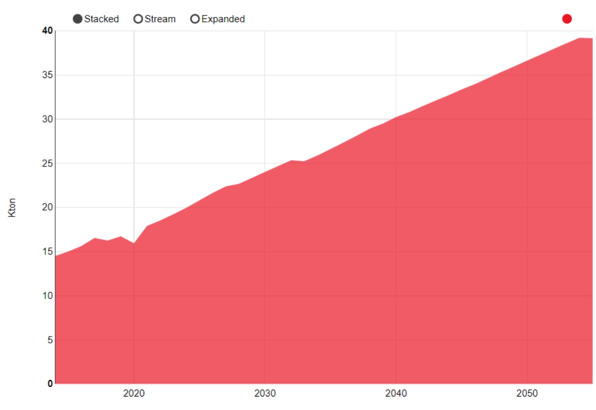

Figure 3.6: Typical emission with CT

performed with a \$10/t$CO2_{eq}$ CO2 with a yearly increase value or\$10/y. The figures also show that the impact of carbon taxing is relatively low as, although there is a big solar penetration in the mix, natural gas still possesses the greatest share in the generation mix.

The "Swedish" version was then studied, it was noted as the highest policy admissible in Bolivia but appeared to display poor influence on the energy mix and was then ruled as unsatisfying. As stated earlier, Sweden has the world's highest carbon tax, it was only legitimate to wonder why this version did not work for Bolivia. Sweden has been investing in RES from the 1990's - the early 2000's, their energy mix is also different from the Bolivian [48] [9] and low carbon energy sources (hydro, bio waste, nuclear, wind,

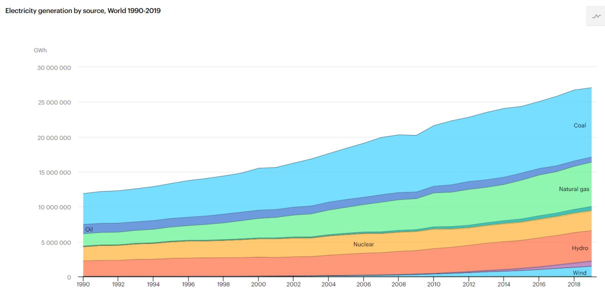

Figure 3.7: Swedish energy mix

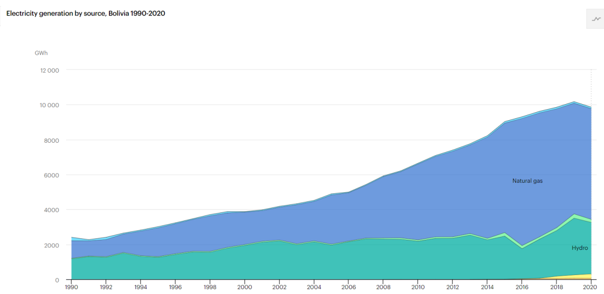

Figure 3.8: Bolivian energy mix

solar) make up for 72.9% of the total energy supply. Therefore, their evolution towards carbon neutrality is in a more advanced state concerning Bolivia. To reach this same objective, Bolivia needs a harsher carbon taxing scenario to catch up to Sweden, as it will be starting close to 20 years later.

With the Swedish version failing to provide a satisfying result for Bolivia, other values through a further sensitivity analysis were studied. However, these values were deemed infeasible due to their value which was much greater than the highest admissible value for Bolivia, excessing the Swedish version by hundreds of dollars.

The carbon taxing policy proved to be bringing insufficient impact on the BES with less than 10% carbon emission reduction. This can be explained by the fact that, in Bolivia, most of the emissions can be found outside the electricity production sectors [12].

The entire Carbon Taxing study can be found in appendix B.

3.4.2 Energy Efficiency Measures

These measures take into account the evolution of the energy demand from the different sectors. Increasing the efficiency with which resources are transformed, and energy is

transported and consumed is a priority regarding the rational energy consumption in an energy system of any scale.
All the energy sectors, all around the world, are affected by these measures. Studies have been conducted about EEM in the residential sectors and the industrial sectors, it is a subject that has been studied all around the world and is of paramount importance [49] to challenge global warming. In Europe, the United Nations Economic Commission for Europe has published a report summarizing the best policy practices and their results in different sectors to promote energy efficiency[50].

In Bolivia, these measures have already been studied. Peña et al. have shown that such measures could significantly reduce energy consumption when applied to the current Bolivian energy system. From 2012 to 2035, the simulated measures show 8.5% of energy saved compared to the current consumption trend [51]. They also note that much larger energy savings are possible through complementary technologies and processes that were not considered in their paper. This combination of complementary technologies and processes could lead to a 20% reduction of $CO2_{eq}$ emission for each sector by 2050. Peña et al. display this potential in their scenario "Combined scenario" where energy consumption reduction plans and fuel consumption reduction plans are aggregated, resulting in a 9.4% reduction in the energy demand, leading to an amount of avoided $CO2_{eq}$ emissions of 25.84 million tons by 2050 in Bolivia[51].

3.4.3 Electrification of Energy Demands

This policy assumes a rapid electrification process for all sectors, switching from fossil fuels to electricity in terms of demand.
It is important to note that this policy is optimistic since there are sectors where the idea of electrifying the demand is clear, such as transport for example but there are other sectors where it would be harder to put in place electrification of their energy demand, such as aviation or cement industry. The sectors' electrification also implies that every fossil fuel will be ruled out of the energy mix by 2050.

To represent the demand shift from fossil fuel to electricity dependency sector-wise, there were specific considerations for some sectors:

- Residential: every appliance that required gas or heavy fuels such as stoves or heating systems should be electrified.
- Industrial: apart from irreducible fossil fuel demand, the heating/cooling systems and their equivalents in the industrial sector are a major component of energy consumption.
- Transport: the Bolivian transport sector is majorly made of fossil fuel vehicles and they represent the largest sector in terms of energy consumption and $CO2_{eq}$ emissions.

These considerations list practices of good measure that should be put in use in the listed sectors to decrease fossil fuel dependency.

3.4.3.1 Industry & residential sector electrification

For these two sectors, the percentages were estimated roughly. In the model, the residential demand was fully electrified as the fossil fuel dependency was majorly on heating and cooking. As for the industrial sectors, the electrification followed the results obtained by Elmegaard. B et al. [52]. These results display the potential of electrification of the industrial sector in Denmark, providing the percentage of possible electrification.
However, the EED and EEM measures cannot achieve the goals of carbon neutrality and fossil fuel dependence. They will increase that dependence as they have no impact on the energy mix composition per se. Increasing the energy demand by electrifying it will increase the load and, therefore, the generation. With the natural gas thermoelectric power plants representing more than 65% of the generation, the emissions can only increase with the EED measures. As for the EEM measure, it can reduce the emissions as it should reduce by 20% the consumption of each sector in 2050 according to Peña et al. [51]. Nevertheless, the composition of the BES will remain the same.

3.4.3.2 Transport sector electrification

As for the transport sector, with regards to the carbon taxing scenario, it was shown that trying to influence the Bolivian's CO2eq emission through a carbon tax on the conventional power production unit proved to be ineffective, with an impact of less than 10% regarding the reduction of the $CO2_{eq}$ emissions. As shown previously [8], the Bolivian energy consumption repartition was studied. It is suggested and shown in figure 3.4 of this work that the transport sector might represent the most significant part of energy consumption in Bolivia. This sector is the only sector among all (residential, industrial, services, others & transport) not to be using the conventional power production unit, explaining the weak impact of the CTI scenario. As hinted earlier, the plan of the section 3.4.3.2 is to model the electrification of the transport sector in Bolivia.

What is the Bolivian transport sector made of?

Bolivia's transport sector is made of various types of vehicles and has three types of fuel: diesel, natural gas, and gasoline, with absolutely no electrification. Moreover, due to heavy taxes on the new cars, Bolivia's transport sector is made of old cars and trucks. Hence, most of the cars found in Bolivia are relatively old and not suited for environmental criteria, such as those enforced in Europe.

The electrification of the Bolivian transport sector would heavily decrease the CO2eq emission of the country. However, this is not a simple feat. Gradually replacing every car, truck, or SUV with electric vehicles would monopolize plenty of resources. Bolivia also has harsh meteorological conditions that are unforgiving for electric vehicles, such as in the Uyuni desert or the highlands with little to no access to electricity and replacing the SUV journeying in those regions, transporting necessary equipment, food, and supplies by electric vehicles is not a matter quickly tackled

Assumptions

The assumption is made that it is possible to realize a 100% electrification of the transport sector to provide results for potential large-scale electrification. The assumption that the grid can withstand this new load is also made. No total electrification of the transport sector has been realized yet, and studies can only predict how the total electrification of the transport sector can impact the grid. M. Blonsky et al. stated about transport electrification that "The increase in electricity consumption will likely make most of these activities (peak demand changes, voltage regulation, integrated resource planning, and distribution upgrades) more challenging in the coming decades; however, many existing and new solutions are available to address these challenges." [53] making this assumption realistic albeit to a certain extent.

Electrification factors

Conversion factors were needed to scale 1 kWh of conventional fuel-powered vehicles to electric-powered vehicles to perform the electrification. Conversion factors help quantify the efficiency difference between internal combustion and electric engines. To compute these factors, the yearly average energy consumption was computed to have reference fossil fuel consumption. A linear projection for 2023 to 2055 was performed to obtain the data. The data was split into 3, one for each fuel, namely gasoline, natural gas, and diesel.

Secondly, references were needed for light- and heavy-duty electric vehicles. For the light-duty, different types of electric cars are chosen as a base for electric energy consumption with regards to the worldwide electric vehicles markets with a particular emphasis on the South American EV/HEV market with the latter currently booming [54]. Here are the different types of EV/HEV that are taken into account [55]. They are the two best-selling electric vehicles for each continent as of 2021:

- North America: Mustang Mach-e and Chevrolet Bolt EV/EUV
- Europe: Tesla Model 3 and Volkswagen ID4
- Asia: Wuling Hongguang Mini EV and BYD Qin
- South America: Renault Zoe and Toyota Corolla

This data provides an average electric consumption of 16.24kWh/100km.

For the conventional fuels, the average L/100km per fuel is computed for the Bolivian transport sector [56]. For the Natural gas vehicles, specific vehicle datasheets are used in order to compute an average energy consumption [57]. The results for the conversion factors can be found in the table 3.2. The conversion factors for diesel are higher than

Gasoline	Diesel	Gasoline
57.8kWh/100km	520kWh/100km	50.32kWh/100km

Table 3.2: Average energy consumption per fuel in Bolivia [57, 56]

expected due to the composition of the diesel-powered vehicle fleet in Bolivia. The majority of diesel vehicles are trucks and buses/minibuses. Therefore, the greater the engine cylinders, the higher the fuel consumption [58], greatly impacting the average energy consumption. With this in mind, it is agreed to compute an average energy consumption for heavy-duty electric vehicles [59], Z. Gao et al. [60] state that a battery electric vehicle would have an energy consumption of around 1.9-19.7kWh/mile (118-123kWh/100km) while K. Kivekäs et al. found that, in warm weather, electric buses would have an energy consumption of around 1.14kWh/km [61]. Other key components such as the heating, ventilation, and air conditioning will not be studied due to the complexity of such a work.Consequently, the average energy consumption for heavy-duty electric vehicles is computed and is equal to 117.25 kWh/100km.

The corrected conversion factors are the following:

EV/HF	EV/DS	EV/NG
0.28	0.22[2]	0.32

Table 3.3: Conversion factors between internal combustion engines and electric engines

These values for the conversion factors mean that electric vehicles are 3 to 4 times more fuel efficient than vehicles equipped with conventional thermal engines. With the electrification of the Bolivian transport sector, it is expected that the emission of the latter will considerably decrease.

3.5 Carbon Neutral Scenario

The objective of the CN scenario is to have zero net $CO2_{eq}$ emissions by 2050, as required by the IPCC in their report. In this case, every previous limitation on technologies or enforced values is relaxed. The only specified objective was the maximum admitted $CO2_{eq}$ emissions by 2050, which is equal to 0.

Conventional and hydropower technologies are expected to be completely ruled out from production. Carbon neutrality requires that every emitting technology will exit the mix, whatever its emission intensity.

Chapter 4

OSeMOSYS simulation results

4.1 Results and analysis of the BAU scenario

The results of the OSeMOSYS simulations for the Business-As-Usual scenario are the following: From the figure 4.1, it is possible to visualize the evolution of the BES under

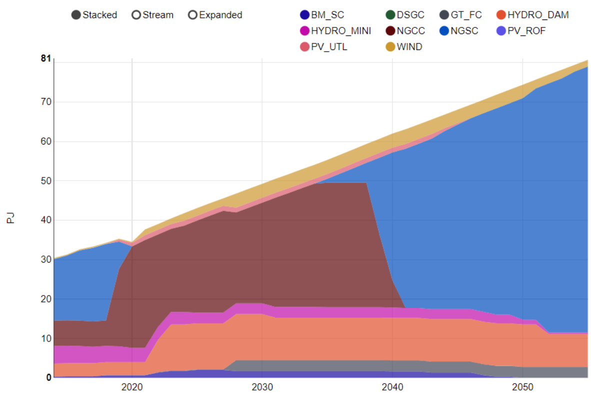

Figure 4.1: BAU energy production

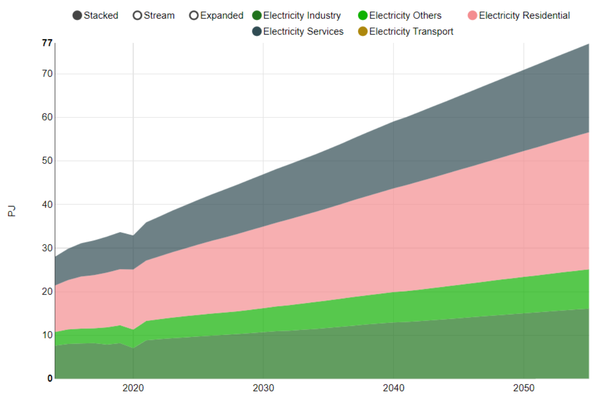

Figure 4.2: BAU energy consumption/ sector

the current conditions. Three key parameters are analyzed to assess the policies that will be put in place for the other scenarios; the electricity demand, the power production, and the $CO2_{eq}$ emission. These factors are all scaled on an annual level in the years of the study. According to the current status of the energy sources, the BES is composed, in the majority, of natural gas power plants, adding to it the hydropower plants.

From figure 4.3, renewable energy sources already available in the BES provide power

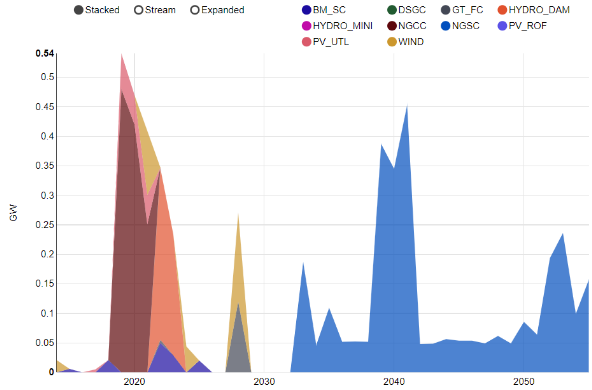

Figure 4.3: BAU capacity investment

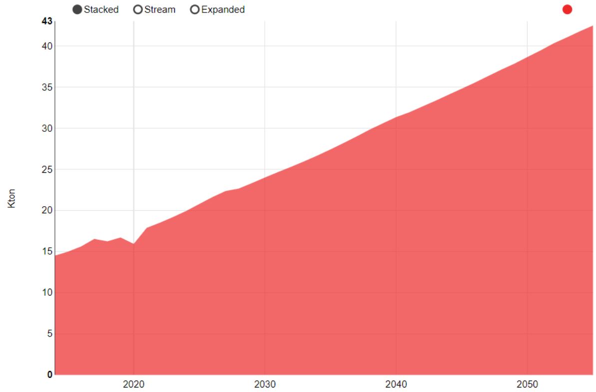

Figure 4.4: BAU $CO2_{eq}$ emissions

with their total capacity but, given their low competitivity, are not invested in by the optimization model. Due to their efficiency and operating costs advantages, the available combined cycle thermoelectric plants are primarily preferred by the model. Nevertheless, it can be seen that they are being replaced by natural gas simple cycles from 2037 on. This is a consequence of decommissioning the Natural Gas Combined Cycles (NGCC) power plants. Afterwards, Natural Gas Simple Cycles (NGSC) became the favoured investment technology. The fact that renewable energies are not chosen for investment and that this same investment goes to the natural gas-fired thermoelectric plants are direct consequences of the natural gas subsidies.

As for the figure 4.2, it represents the stable growth over the years as it is initially computed. The primary electricity consuming sector is the residential sector with more than 40% of the total consumption by 2055. The pandemic consumption dip is apparent in this figure.

Regarding the $CO2_{eq}$ emissions on figure 4.4, the BAU produced for 2018 16.26 kton; for 2021 produced 17.90 kton of $CO2_{eq}$ and by 2055 will have produced 42.51 kton.

As for the renewable energy share, by 2050, it amounts to 34.3%. This means that with the current BES and based on the current power plants and future works for RES installations, the RE share would still increase from 2022 to 2050. The point, however, is to show that their $CO2_{eq}$ emissions are still relatively high and that the BES is still heavily fossil fuel reliant.

Additionally, as proven by Robert P. Echazú [12], Bolivia is a country with plenty of resources, and, to fit the IPCC goal of carbon neutrality by 2050, the current state of the energy system cannot be kept as such. That is why different policies were inferred from the BAU and the method of best practices in energy use worldwide to head toward this carbon neutrality and reduce the Bolivian fossil fuel reliance.

4.2 Results and analysis of the MP scenario

The results of the OSeMOSYS simulations for the Mixed Policies scenario are the following: Each policy working on its own does have enough weight to change the BAU. The

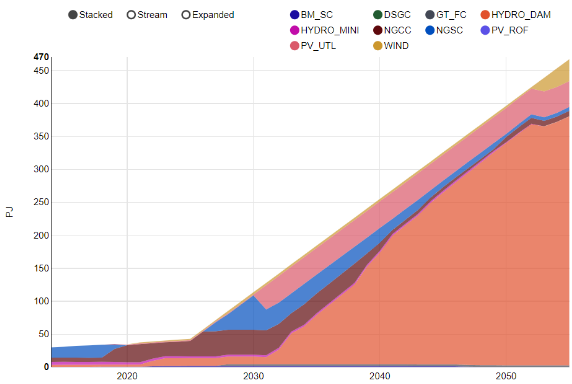

Figure 4.5: MP energy production

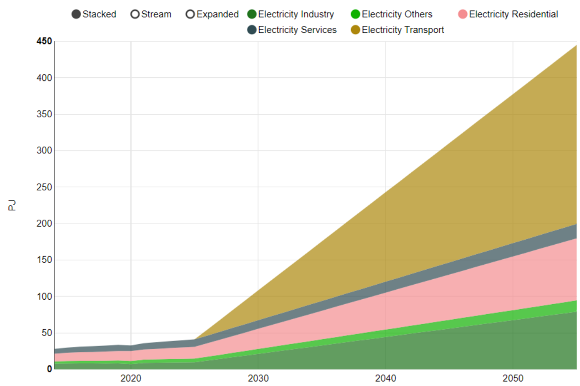

Figure 4.6: MP energy consumption/ sector

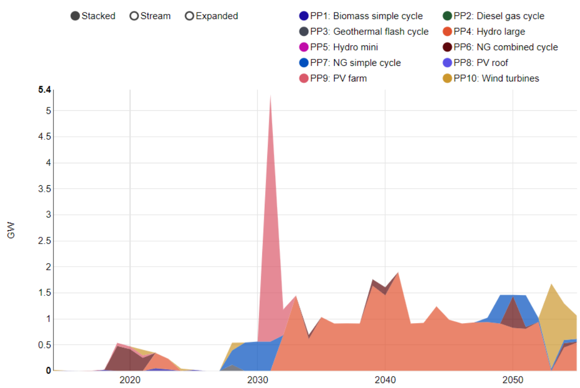

Figure 4.7: MP capacity investment

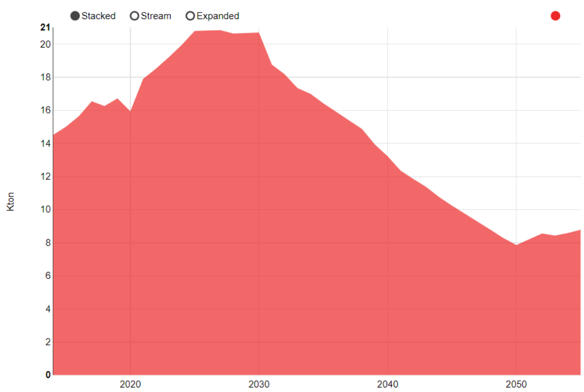

Figure 4.8: MP $CO2_{eq}$ emissions

CTI could reduce the dependence on fossil fuels but does not remarkably influence the $CO2_{eq}$ emission. The EEM and EED can reduce fuel consumption and improve energy transmission but do not impact the energy mix. The effect of electrification on the transport sector can also be noticed in the figure 4.6. With this sector's energy consumption now being passed onto the power grid, the Carbon Tax Implementation scenario is more impactful as what was holding it back was the raw fuel consumption of the transport sector. Now that this consumption is solely focused on the power grid, the CTI has a greater influence on the mix composition.

Together, the policies provide complementary effects when combined. The carbon tax implementation and the natural gas subsidy reduction impose heavier restrictions on the $CO2_{eq}$ emitting technologies, thus allowing renewable technologies to enter the energy mix while the EED measure electrifies the demand of the different sectors. The outstanding results can be seen in the figures 4.8 and 4.5, where the emissions are reduced by 79.7% and the BES drastically shifts from fossil fuels to renewable energies. By 2050, the RE shares amount to 96.7%, marking the consequences of the policies.
The Bolivian Energy Mix obtained with the simulation performed in OSeMOSYS is composed of mostly hydropower with solar and wind power and a small share of natural gas power plants to fill the demand.

4.2.1 Economic impact of the Mixed Policies scenario

The figure 4.7 provides an insight into the capacity investment over the studied years, transitioning from the current energy mix dominated by fossil fuels to a renewable and sustainable energy mix oriented towards a lower carbon emission.
This shift in the energy mix has to be followed by economic investment. Moreover, as the demand increases, the capacity in the energy mix needs to be amplified fivefold to cover the now almost fully electrified demand.
As a reminder, the figure 4.3 showed the installed capacity per year was replacing the power plants coming to the end of their lifetime. The total capacity installed by 2050 was 3.39 GW, and the total investment cost of the capacity installed over 2030 to 2050 equals roughly US$ 2 billion.

Whereas for the Mixed Policies scenario, the total installed capacity in 2050 amounts to 28.66 GW, and the total investment cost of the capacity installed over 2030 to 2050 equals US$ 56.248 billion. An investment 28 times higher than for the BAU. This result symbolizes the energy transition's impact on the Bolivian economy.

4.3 Results and analysis of the CN scenario

The results of the OSeMOSYS simulations for the Carbon Neutral scenario are the following: Hydropower is completely ruled out of the mix by 2050. As stated prior, every

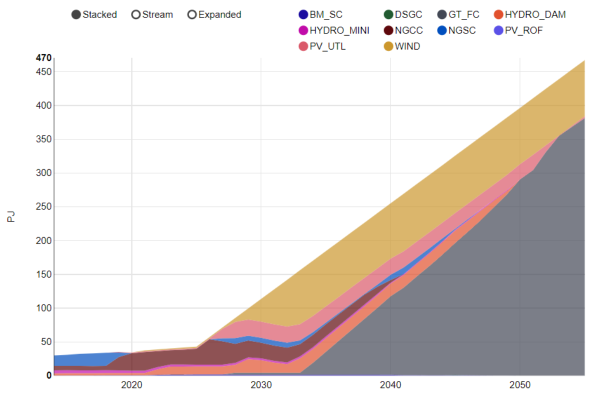

Figure 4.9: CN energy production

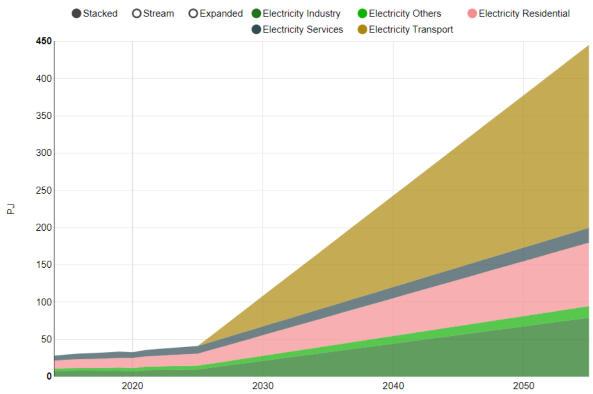

Figure 4.10: CN energy consumption/ sector

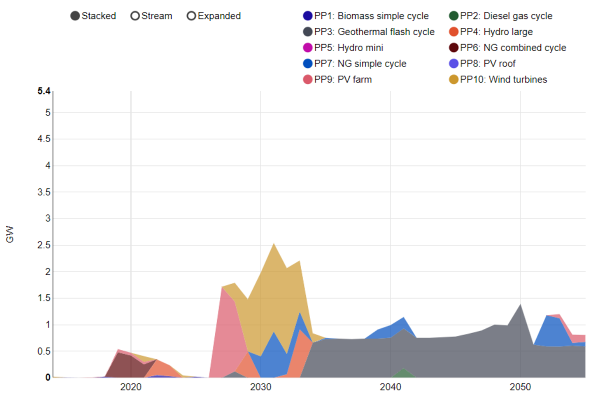

Figure 4.11: CN capacity investment

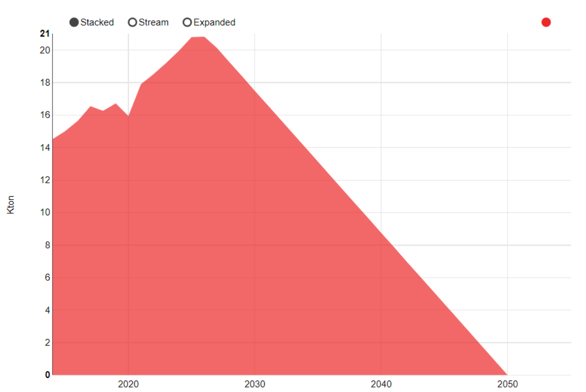

Figure 4.12: CN $CO2_{eq}$ emissions

$CO2_{eq}$ source will be ruled out, and it is possible that, under certain circumstances, hydropower emits $CO2_{eq}$, circumstances that are met in some places in Bolivia as R. Almeida

et al. stated in their article [40]. The authors also mention that the emissions are due to the decomposing organic matter found in the hydro reservoir, organic matter that was either brought there by rivers or produced inside that reservoir. Their decomposition leads to CH_4 being emitted into the atmosphere. It is supposed that, in the near future, hydropower installation will be a booming sector in developing countries. The Amazon, one of the world's largest hydro mass, will be the core of hydropower in South America. This is why it is necessary to factor in the possible $CO2_{eq}$ emissions of this technology [40].
To make up for the absence of hydropower, geothermal, solar, and wind are the three major technologies present in the energy mix by 2050, leading to a zero-emission energy mix by 2050, as can be seen in figure 4.12. The variations between the BAU, the MP, and CN scenarios can be found in the table: The low renewable energy share in the MP scenario

	2030			2050		
	BAU	MP	CN	BAU	MP	CN
Total energy demand [PJ/year]	46.94	108.39	108.39	70.89	377.85	377.85
Renewable electricity share [%]	42.58	14.94	73.16	24.2	96.7	100
Emissions [MtCO2e/year]	24.01	20.70	17.5	38.67	7.86	0
Installed Capacity [MW]	4239.63	5623.43	10938.12	3334.13	28673.76	29243.75

Table 4.1: Comparison between OSeMOSYS BAU, MP and CN scenarios for different years

is explained by the fact that the year 2030 is the threshold year. In 2030, the demand is being increased while the renewable energy technologies are spooling up, leaving the BES in a transition spot full of fossil fuels with increasing demand.
Meanwhile, although the MP scenario provides, as a result, an energy mix that shifts away from fossil fuels and with low emissions, it still does not achieve carbon neutrality by 2050, a primary IPCC goal. Hence, a third scenario, "Carbon neutral", is implemented in OSeMOSYS to achieve this aforementioned goal.

4.3.1 Economic impact of the Carbon Neutral scenario

As well as for the Mixed Policies scenario, the increase in the demand and the change in the composition of the mix implies substantial costs. The total investment costs amount to US$ 104.1 billion, about 50 times the capital investment required for the BAU. This value represents the entirety of the budget used in public investments in Bolivia for the year 2018 [62]. Achieving this scenario seems unrealistic, and including more techologies in the model will likely result in a more reasonable total cost for net zero carbon energy system. It can be noted as well that the entirety of the hydropower was ruled out when only the oriental region would be affected by the greenhouse gas emissions in the Amazon region. Moreover, the problem could be the energy source. Geothermal technology represents the largest energy source by 2040 and 2050. Bolivia has potential for geothermal energy in the northern, central, and especially southern regions. However, evaluating the geothermal energy potential in Bolivia revealed that Bolivia only has three of forty-two geothermal manifestations that are suitable for geothermal energy production [63]. Henceforth, planning on geothermal resources to fill the demand appears as an unsound solution.

Chapter 5

Dispa-SET simulation results

5.1 Dispa-SET scenarios

This chapter provides the results obtained through the uni-directional soft-linking from OSeMOSYS to Dispa-SET. In Dispa-SET, each scenario is run for 2025, 2030, 2040, and 2050. The combination of these scenarios allows to fully measure the changes in the composition of the Bolivian power generation mix. In this case, the goal of Dispa-SET is to qualify a scenario's feasibility and quantify the misalignment between the two studied models.

Some simulations have to be specified in Dispa-SET. They will remain the same for every simulation so that computation variations do not to induce differences

First, the simulation time step was chosen equal to 1 hour, the lowest time step admissible in Dispa-SET. As the goal is to assess the data from OSeMOSYS, it was essential to have the highest precision possible, implying the lowest simulation time step. Secondly, the horizon length was put to 4 days, and the look ahead to 1. This means that, in the data, four days will be optimized, and one will be discarded.

Dispa-SET also provides a set of indicators that help assess the quality of an energy system.

- Curtailment: as defined by L. Bird, "Curtailment is a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis" [64]. Hence, it is a loss of useful energy. It can occur in different situations. [64]. In Dispa-SET, red areas in the energy flow graph represent the curtailment.

- Load Shedding: it is the action of discarding a percentage of the load because it is impossible for the energy system to cover that load. In Dispa-SET, black and white hashed areas represent the load shedding.

- Capacity Margin: it represents the margin by which the capacity exceeds the demand. The data is split into hourly steps. It helps assess the availability of the power plants relative to the time of the day.

- Loss of load: loss of load usually represents the point where the energy grid cannot match the demand, meaning that the grid power balance is greatly disturbed and a blackout occurs. In Dispa-SET, there exist two types of loss of load, 'MaxPower' and '3U', which represent the loss of load in the reserves. Loss load means that a system is not feasible. However, in Dispa-Set, the system still provides a result. The loss of load is represented by a large amount of money added to the kWh price. That way, it is possible to visualize where it happens instead of having an infeasible solution. It is represented by whited-out areas.

These indicators are what is looked for in the results. For the two first indicators, their presence signifies a problem in the system, but it remains feasible, although not under the best circumstances. The capacity margin of one region is positive if it can clear its demand. If it is negative, it must import energy from other regions to meet the demand. The system cannot cover the demand if the overall capacity margin is negative. This implies a loss of load." If loss of load appears, then the problem is infeasible and requires changes because, in its current state, it does not satisfy the power balance. The addition of loss of load and load shedding represents the Energy Not Served, as known as ENS. ENS represents the amount of energy in MWh that can not be delivered to a region, usually due to a lack of resources to match the demand. For clarity, in this case, the ENS will be expressed in a percentage of the total demand.

5.2 Scenarios analyses

The analyses are based on the whole year. Nonetheless, to ease the visualization, a snippet of the load and generation profiles is displayed for the same period of each year of each scenario. The snippet begins on the first days of January. The related section display seasonality, generation, and load profiles related to each season. The scenarios were studied for the years 2025, 2030, 2040, and 2050. The year 2025 serves as a starting point for the analysis, ensuring that the data were correctly transferred for the scenario.

5.2.1 Business-As-Usual scenario

This subsection contains the results and analyses for the different simulations performed for the Business-As-Usual scenario in Dispa-SET.

2020 & 2030

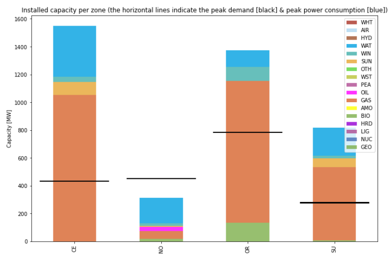

Figure 5.1: Capacity Installed for the BAU in 2020

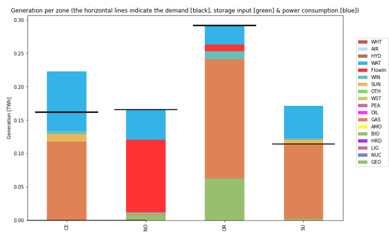

Figure 5.2: Generation per zone for the BAU in 2020

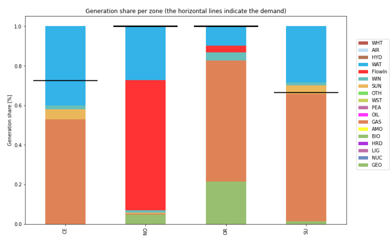

Figure 5.3: Generation share per zone for the BAU in 2020

The figures 5.1, 5.2 and 5.3 show no sign of any of the indicators mentioned before, the current BES is relatively well designed and falls into the feasible category. It can also be seen that three regions have more capacity installed than demand. However, the northern region (NO) has less capacity than demand and cannot cover its peak demand. This implies that more power flows from other regions to the NO one. This power inflow can be seen in the figure 5.3 specifically where the inflow represents around 67% of the total energy "generated" the significance and frequency of power inflows in the NO region are shown in the figure 5.4. There is also inflow in the oriental region (OR), although it can

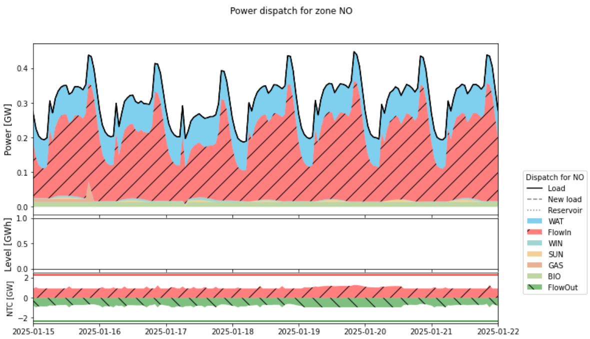

Figure 5.4: Northern region generation and load profile for BAU in 2020

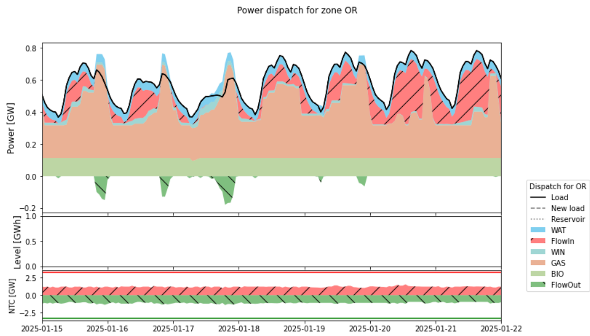

Figure 5.5: Oriental region generation and load profile for BAU in 2020

cover the demand. It can be seen in figure 5.5 that the power inflows occur when the natural gas power plants seem to reduce their power generation and that the hydroelectric power plants cannot fill in that gap. The reduction in power generation from natural gas thermoelectric power plants probably comes from an outage for maintenance. The figures

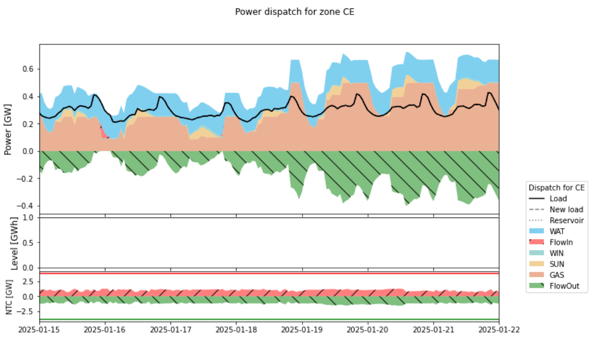

Figure 5.6: Central region generation and load profile for BAU in 2020

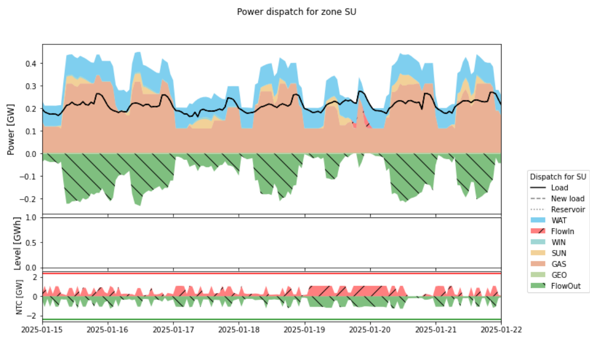

Figure 5.7: Southern region generation and load profile for BAU in 2020

5.6 and 5.7 represent the generation and load profiles of the CE and SU regions.

The year 2030 for the Business-As-Usual is highly similar to the year 2020. The analysis is the same for those two years. For 2020 and 2030, the ENS is relatively low, with 0.43% for 2020 and 0.96% for 2030.

2040

In 2040, the BES has load shedding and loss of load as shown in figure 5.9 and 5.10. The NO region demonstrates it cannot match its total demand, and figure 5.8 exhibits a lack

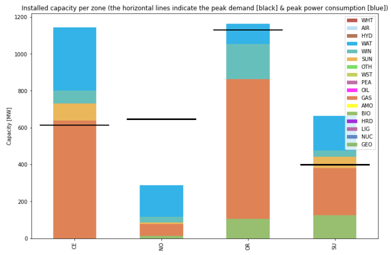

Figure 5.8: Capacity Installed for the BAU in 2040

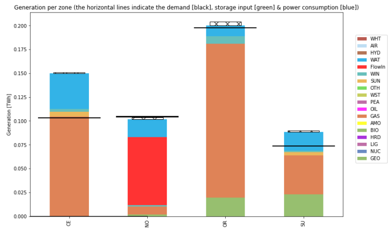

Figure 5.9: Generation per zone for the BAU in 2040

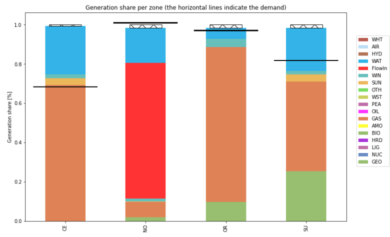

Figure 5.10: Generation share per zone for the BAU in 2040

of capacity in that same region to meet its peak demand which implies that it heavily relies on power in-flows.

The data shows that the system lacks capacity from 4 pm to 11 pm daily. This corresponds to the period where the solar power decreases and drops to 0, as well as the wind resource, which seems to tone down as it is shown in the figures 5.11 and 5.12. Therefore, the loss of load and load shedding occurs daily. Moreover, the flow graph that illustrates the flow transfer between regions shows congestion of the lines between NO and OR, from SU to OR, and from OR to CE, OR and NO being the regions needing the most power in-flows. Hence there is a lack of capacity combined with a lack of net transfer capacity. This leads to a system load loss as the generation cannot match the demand. 49704 MWh of the load are lost during the year. The shedded load represents 0.16% of the total load. The

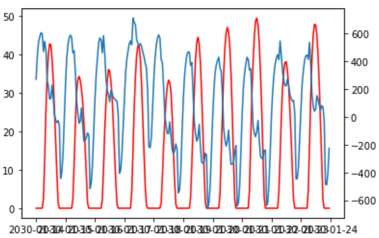

Figure 5.11: Capacity Margin and solar power production for the BAU in 2040

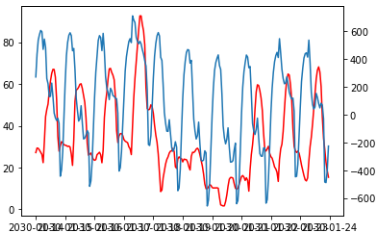

Figure 5.12: Capacity Margin and wind turbines power production for the BAU in 2040

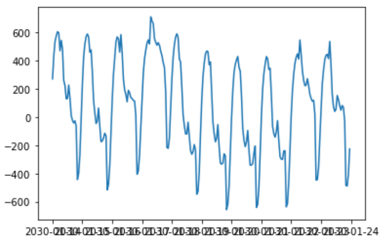

Figure 5.13: Capacity Margin in winter for the BAU in 2040

mismatch of demand and generation can be exacerbated with seasons as well. The graph exposes the summer season, the system lacks capacity, but in winter, the hydropower is impacted as the reservoir levels tend to drop. CE loses about 10 MW of output power from its hydroelectric plants in winter compared to summer, OR region loses 5 MW, Su 8MW, and NO 6MW, which does not help the already flawed system. In winter, The frequency of the loss of load increases along with its amplitude.

2050

In 2050, the problems determined for 2040 are aggravated. The system drifts away from feasibility. The lack of capacity drops from 600 MW to 800 MW, and the frequency and amplitude of loss of load increase. The load lost amounts to 157 848 MWh. The shedded load amounts to 2.7% of the total load.

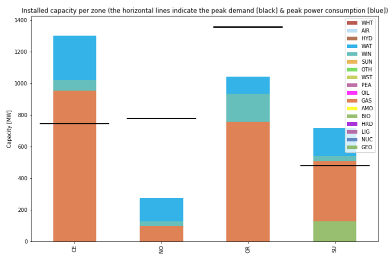

Figure 5.14: Capacity Installed for the BAU in 2050

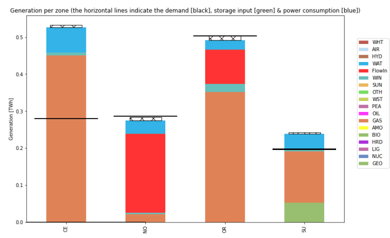

Figure 5.15: Generation per zone for the BAU in 2050

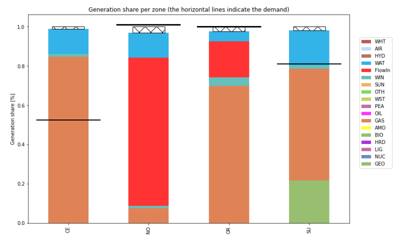

Figure 5.16: Generation share per zone for the BAU in 2050

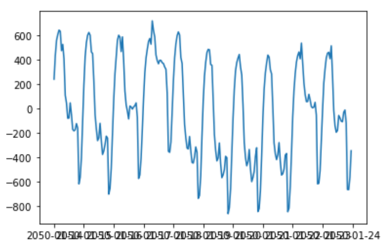

Figure 5.17: Capacity Margin for the BAU in 2050

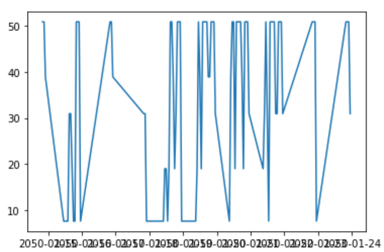

Figure 5.18: Loss of load for the BAU in 2050

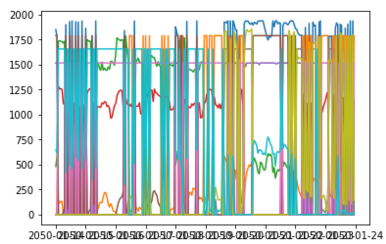

Figure 5.19: Congestion on transmission lines for the BAU in 2050

5.2.1.1 BAU conclusions

The data for the years 2040 and 2050 for the BAU are inadequate for multiple reasons and thus lead to an infeasible system. It is tried to understand the effect of load shedding on the system. In Dispa-SET, it is possible to specify the percentage of the load that is admissible to shed. The initial value is 5%, when it is doubled, the amount of load lost decreases, and the frequency of it decreases as well. It could be used as a means of alleviation for a short period, but load shedding is not a sustainable solution for a power system.

In 2030, there is 0.96% of Energy Not Served. In 2040, 143872.59 MWh are lost, 2.7% of the total consumption and the maximum load shedded 181.915 MW. And for 2050, 143872.59 MWh are lost, and the maximum shedding at once is 181.91 MW

5.2.2 Mixed Policies scenario

For the Mixed Policies, the demand increases, the natural gas subsidies are reduced, and a tax on $CO2_{eq}$ emissions are put in place.

2020

In 2020, the results for the Mixed Policies are very similar to the BAU results for the same year. This was expected because the changes do not appear that early in the mix, as the figure 4.1 shows.

2030

For 2030, the system starts to show load shedding and loss of load in the NO and OR

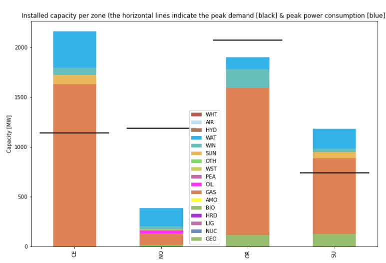

Figure 5.20: Capacity Installed for the MP in 2030

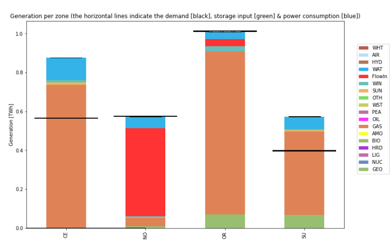

Figure 5.21: Generation per zone for the MP in 2030

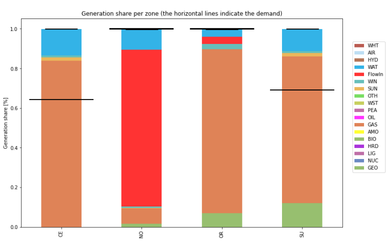

Figure 5.22: Generation share per zone for the MP in 2030

regions as they fail to match their demand. The NTC, on figure 5.25, for the lines between NO and OR regions, as well as OR to CE and SU to OR, are fully congestioned most of

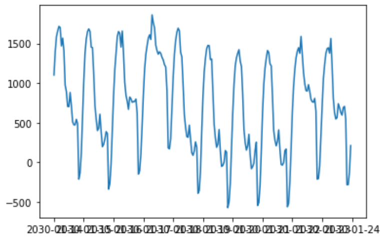

Figure 5.23: Capacity Margin for the BAU in 2030

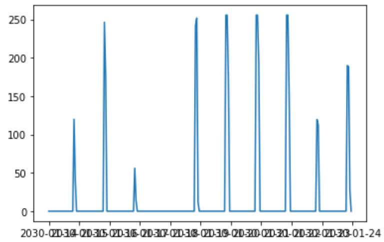

Figure 5.24: Load shedding for the MP in 2030

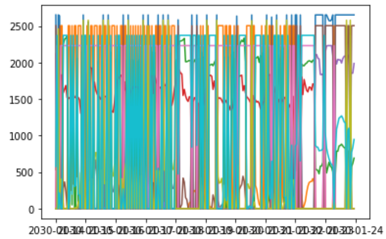

Figure 5.25: Congestion of transmission lines for the MP in 2030

the time. Therefore, it is not possible to transfer more power to this region than what is currently done. There is loss of load because of the insufficient capacity, as shown in figure 5.23. This figure shows the system's capacity margin for one week. There is a daily lack of capacity.

For the composition, there is little to no RES penetration. This is the consequence of all the policies being activated simultaneously. In 2030, the system is trying to match increasing demand, and, as the taxes are hitting, it is starting to install RE capacity. However, these changes take time to impact the system, which is why it matches the demand mainly with natural gas power plants and hydroelectric power plants, like the BAU. The MP scenario does not differ from the BAU scenario except for the demand increase. This year's Energy Not Served (ENS) amounts to 0.37% of the total load.

2040

In the year 2040, the mix starts to show significant changes in its composition. Natural

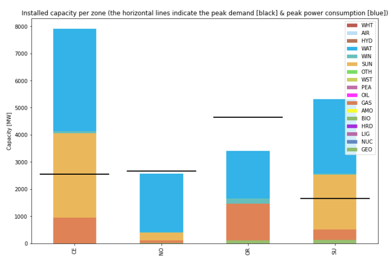

Figure 5.26: Capacity Installed for the MP in 2040

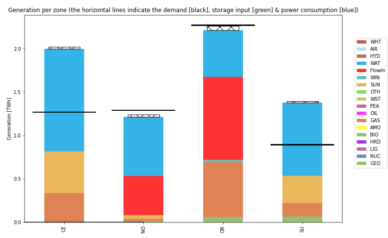

Figure 5.27: Generation per zone for the MP in 2040

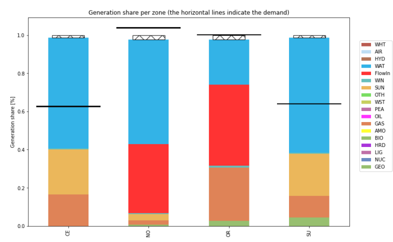

Figure 5.28: Generation share per zone for the MP in 2040

gas tones down to be replaced by RES and VRES with high penetration of hydro and solar power plants. Figure 5.29 shows the change in the energy sources with respect to the figure 5.6. However, the region OR in the figure 5.30 does not show the same trend. Although its natural gas capacity is relatively high, its demand is even higher, and the penetration of hydroelectric power plants in the region does not make up for the demand increase leading to the need for energy in-flow and load shedding. However, along with

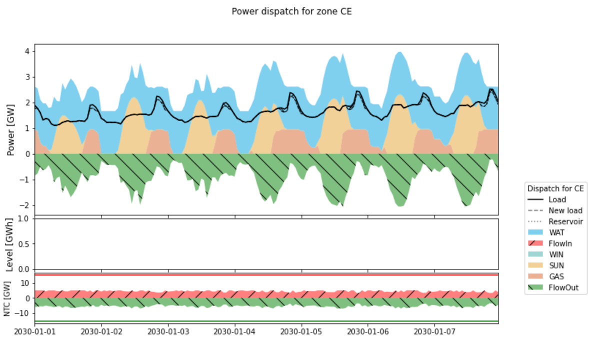

Figure 5.29: Central region generation and load profile for MP in 2040

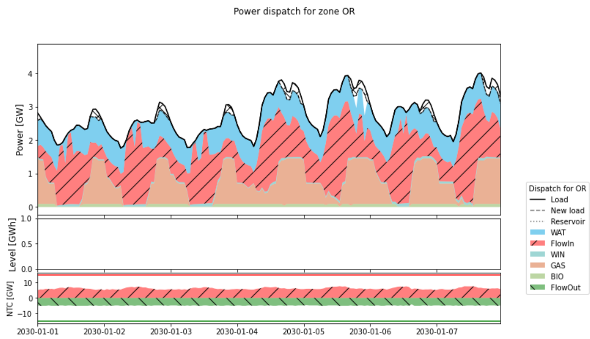

Figure 5.30: Oriental region generation and load profile for MP in 2040

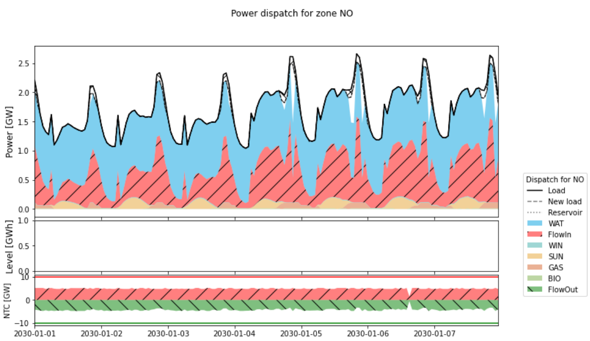

Figure 5.31: Northern region generation and load profile for MP in 2040

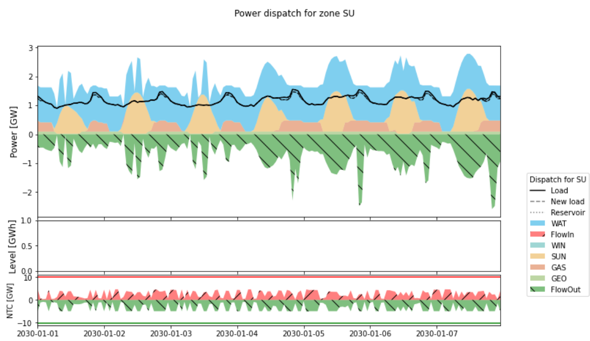

Figure 5.32: Southern region generation and load profile for MP in 2040

the load shedding, there is also loss of load, which makes the system effectively inadequate. The main reason for this loss load is recurring. With the power capacity of the NO region being so low compared to its demand, as shown in figure 5.26, a lot of energy inflow is required. However, there is enough capacity to cover the demand theoretically with flow between regions. The peak demand occurs at 8 pm. Therefore as the historical data are the same for this scenario and the BAU scenario, the solar power plants and the wind turbines in the NO region can hardly produce power at this point of the day. Hence other regions try to transfer power to NO. Due to the high value of the power transferred, the transmission lines are immediately congestioned, and in the end, the system cannot fill in that gap, leading to a loss of load in the system. The ENS represents 8.8% of the total load. In contrast with the year 2030 of the MP, it is much greater, emphasizing the infeasibility of this system for the year 2040. The ENS's relatively high percentage can also be explained by the congestion of the transmission lines that can be seen in figures 5.31 and 5.30.

2050

The year 2050 continues on the same trend as 2040, the system maintains the same VRES penetration increase, but there is also more loss of load and load shedding in the system. The ENS represents 9.7% of the total load.

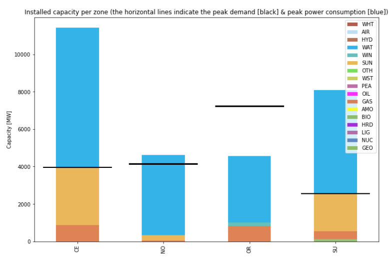

Figure 5.33: Capacity Installed for the MP in 2050

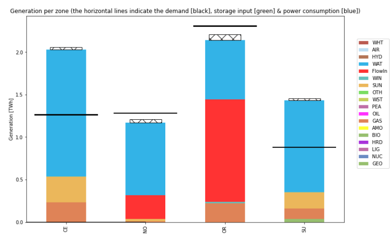

Figure 5.34: Generation per zone for the MP in 2050

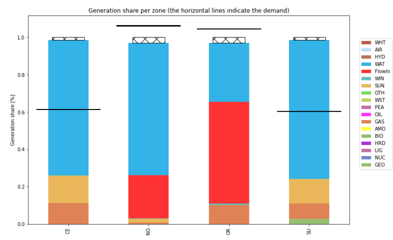

Figure 5.35: Generation share per zone for the MP in 2050

5.2.2.1 MP conclusions

The same problems faced in the BAU scenario, where the system can not withstand the relatively low demand increase, are found again in the MP scenario. However, the high penetration of the RE for 2040, for instance, shows that the scenario impacts the mix composition.

5.2.3 Carbon Neutral scenario

The Carbon Neutral scenario aims to reduce GHG emissions to 0 by 2050.

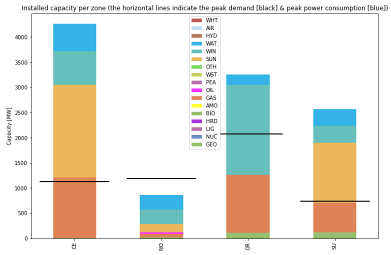

Figure 5.36: Capacity Installed for the CN in 2030

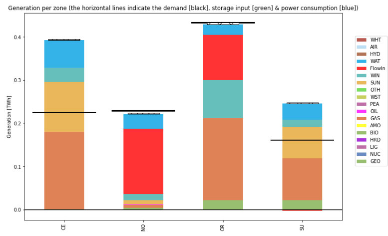

Figure 5.37: Generation per zone for the CN in 2030

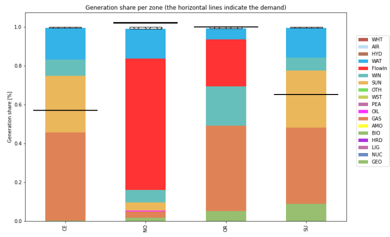

Figure 5.38: Generation share per zone for the CN in 2030

2020

The year 2020 still corresponds to the year 2020 in the BAU, as expected.

2030

The high VRES penetration leads to the first curtailment noticed in the system. Though there is more than enough installed capacity, the variability of the solar and wind energy resources leads to curtailment, load shedding, and loss of load. The system is unbalanced again on the power level.

The wind and solar power are again low, leading to a negative capacity margin and an inability for the system to meet its requirements as shown in the figures 5.39 and 5.42. Their peak production and lowest production are in line with the capacity margin. It shows the impact VRES has on the ability of a system to match its demand. The system is dependent on the VRES and, therefore, on the weather.

The seasonality, in this case, has a great impact on the system's capacity. A 20 MW is lost in the SU region for the hydroelectric power plants, 8 MW in OR, 11 MW in NO, and a 20 MW decrease in CE. The overall peak production of solar and wind decreased in winter, pushing the system to even more mismatching between demand and generation.

2040

2040 marks the arrival of geothermal energy as the leading source in terms of generation. Geothermal is a resource that is pushed to its maximum capacity by the energy planning and unit and power dispatch models due to its ability to produce at any given time.

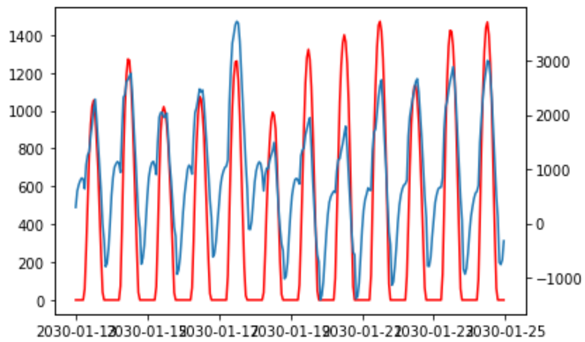

Figure 5.39: Capacity margin and solar power production for CN in 2030

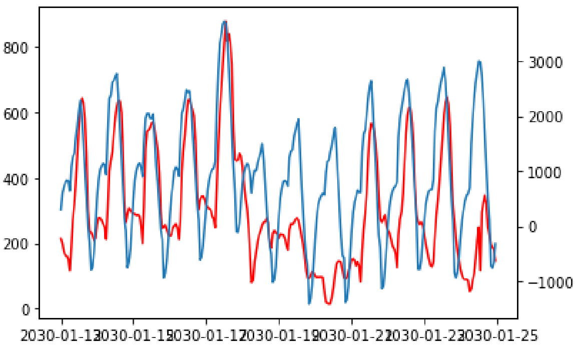

Figure 5.40: Capacity margin and wind power production for CN in 2030

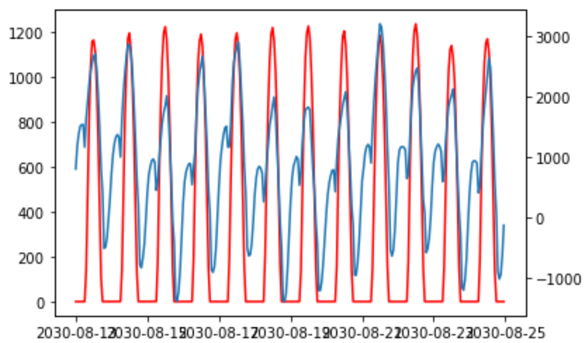

Figure 5.41: Capacity margin and solar power production in winter for CN in 2030

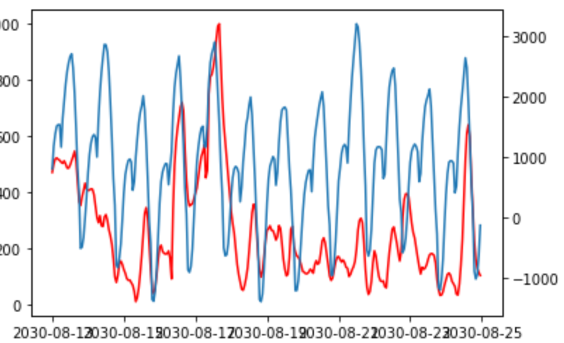

Figure 5.42: Capacity margin and wind power production in winter for CN in 2030

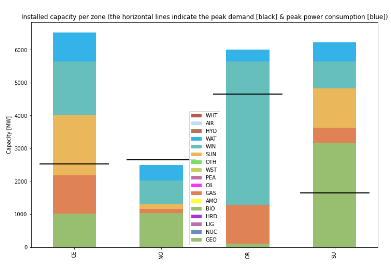

Figure 5.43: Capacity Installed for the CN in 2040

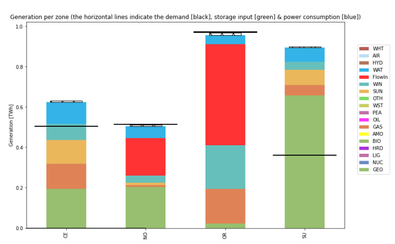

Figure 5.44: Generation per zone for the CN in 2040

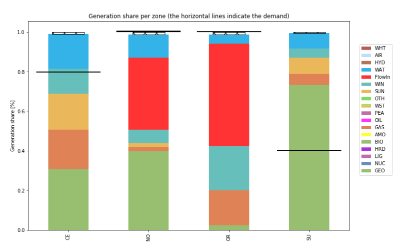

Figure 5.45: Generation share per zone for the CN in 2040

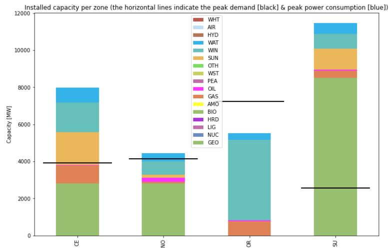

Figure 5.46: Capacity Installed for the CN in 2050

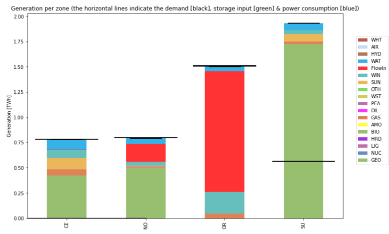

Figure 5.47: Generation per zone for the CN in 2050

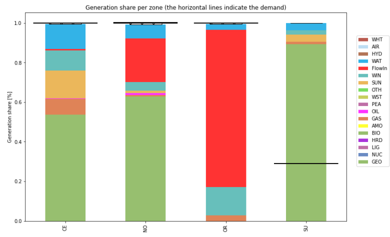

Figure 5.48: Generation share per zone for the CN in 2050

Unlike hydroelectric power plants, which have respect reservoir levels and are subject to weather and seasons, geothermal has no such limitation. In this case, the large amount of geothermal capacity that is given to the system implies that geothermal is the primary energy source.

However, even though the geothermal capacity, as the objective for this scenario in OSeMOSYS, was to nullify the GHG emissions, the hydroelectric power plants are less and less used, leading to, once again, infeasibility through negative overall capacity margins and congestioned NTC.

2050

By 2050, geothermal resources have reached their supposed full potential. Nevertheless, there are still hydroelectric and thermoelectric power plants in the mix, meaning that Dispa-SET cannot achieve net zero emissions. Although there is still infeasibility which was expected, when analyzed more in-depth, one can see that the natural gas power plants and hydroelectric power plants are used as ancillary services leading to GHG emissions.

5.2.3.1 CN conclusions

The evolution of the composition of the BES leading to the 2050 results shows that geothermal would be the go-to solution for the net zero GHG emissions in OSeMOSYS. In Dispa-SET, it is impossible to cover the demand with the capacity suggested by OSeMOSYS.

Moreover, as mentioned in the description of this scenario, the geothermal energy potential in Bolivia still has not currently shown its full potential, with only one of three zones that have seen capacity installed, but the two other zones are unlikely to be able to produce enough power even to consider this scenario realistic to an extent. The first geothermal powerplant installed in Bolivia provides 100MW, which leaves, following the results in figure 5.46, 13800 MW of capacity to be installed [63].

5.2.4 General observations

With all the run scenarios, the system can never fulfil its purpose for the years 2040 and 2050 in the BAU and from 2030 for the two others.

The results obtained for the BAU show that in 2040, the demand is not matched, and the system is infeasible even though this is the template model for which the demand increase is 3% yearly, with no taxes on any parameter. For the years 2040 and 2050, this scenario shows the issues that will be encountered in the two other scenarios—lack of capacity and NTC. Moreover, the penetration of VRES, albeit low for this scenario, shows the system's weakness is only increasing as it is now dependent on the weather.

For the Mixed Policies scenario, from 2030 on, the system displays a lack of capacity and net transfer capacities. As the demand grows, this mismatch between demand and generation only grows stronger. The penetration of the RES and VRES pushing the natural gas out of the merit order, however, shows that scenarios impact the transition. Natural gas power plants are relegated to ancillary services instead of providing most of the base load as it was in the BAU scenario. The VRES penetration also have the same impact on the BAU scenario but to a higher degree as it relies more on them than the BAU. For this scenario, the ENS in 2040 and 2050 is more than 8% of the load as shown in table 5.1. They are the years that have the highest VRES penetration compared to others. The OSeMOSYS model seems unable to capture the variable nature of power production of VRES.

As for the CN scenario, 2030 showed the same signs of seasonality dependence as ENS. However, in 2040 and 2050, the geothermal energy source made up the central part of the energy production leading to a transition from hydro/solar dominated composition to geothermal domination, reducing the dependence on the weather. However, by 2050,

	Emissions	RE share	CM min	ENS
BAU				
2030	5473.27	38.82	759.64	0.96
2040	10220.52	49.31	-657.72	5.60
2050	13273.51	29.82	-939.46	6.22
MP				
2030	11532.10	30.87	-708.17	2.27
2040	2675.02	82.66	-8192.33	8.80
2050	1428.66	91.13	-15193	9.47
CN				
2030	18115.14	61.84	-1518.48	5.49
2040	2810.92	88.2	-3777.91	5.84
2050	839.04	97.79	-3647.57	4.25

Table 5.1: Comparison of the scenarios' results

the emissions are not zero because the hydroelectric and thermoelectric power plants are used as ancillary services, producing GHG emissions.

The table 5.1 synthesizes the similarities and discrepancies between each scenario. In this table, Emissions are expressed in kton per year, the RE share in percentage, the capacity margin in MW, and ENS is the percentage of the load that was not served (Energy Not Served). Regarding the renewable energy share, compared to the share of the OSeMOSYS results, there is a consistent offset regarding those values. They are most likely due to the higher computation of Dispa-SET that can compute the RES penetration more precisely with the historical data it possesses.

The CN scenario in 2050 still produces 839.04 kton of $CO2_{eq}$, which does not match the IPCC goals. However, its ENS decreases with respect to 2040 and the lack of capacity. This is because geothermal energy represents a significant part of the generation. As it replaces a part of hydro and solar, the system becomes less prone to losing capacity with day and night cycles or seasons. This leads to a lesser lack of capacity and, therefore, reduced negative impact on the system.

The emissions are higher for the MP and CN scenarios by 2030 because they are pinched between demand increase and the RE penetration that takes time to fully be operating. Therefore, the natural gas thermoelectric plants cover the majority of the demand. This result was not seen in OSeMOSYS because OSeMOSYS also computes the emission of other transport, such as the transport sector. The electrification of the latter decreased the overall $CO2_{eq}$ emissions of Bolivia but increased the $CO2_{eq}$ emissions of the energy sector. Hence the increase in emissions between BAU and the two other scenarios.

It is also essential to know that ENS is common. However, in these cases, ENS represents several TWh and, frequently, several hundreds of MWh of loss of load. As mentioned before, loss of load occurs when there is a mismatch between generation and demand. ENS does happen, but the values reached, up to 9.47%, represent that too much energy is unserved, and the systems are infeasible.

5.2.5 Increased flexibility of the system

All the results tend to point to the fact that the limiting factors are installed and net transfer capacities. A couple of ways to possibly solve these issues, and consequently the infeasibility of the system, are implemented. Firstly, Dispa-SET offers a specificity that allows managing the demand-side of the system: flexible demand; the flexible demand allows to cut a pre-defined percentage of the peak demand and spread this percentage on other days. The number of days is defined as well. Secondly, scaling the NTC on the generation instead of the demand as mentioned in the subsection 2.3.2.

Simulations with these new parameters are run for the MP scenario. The flexible demand shifted 20% of the peak load over four days. The amount of shifted load and the number of days can be changed.

Flexible demand implementation

Implementing the flexible demand on the Mixed Policies scenario for the year 2030 increases the amount of ENS, but the load shedding went from 0.04 TWh to 0.22, and the load loss went from 16 311 MWh to 862.04 MWh. This means that the flexible demand shifts a certain amount of loss of load to shedded load. Having an important share of loss of load signifies recurring blackouts. In the current power systems, loss of load is avoided by various mechanisms, including load shedding, as load shedding reduces the load to avoid overloading the system. It is a last-resort solution for operators to avoid blackouts. It is not desired, but it lowers the loss of load. The implementation of the flexible demand is a tool to help the system be adequate to its demand.

However, for the MP year 2040, the flexible demand produces the opposite results. Although the load shedded increases, there is twice more loss of load than without the flexible demand implementation. This may be because the year 2040's issues are too significant for the flexible demand to produce favourable results. The lack of capacity and the initial ENS may impact the system so much that it cannot be recovered.

Generation-scaled NTC implementation

Regarding the generation-scaled NTC values, the results do not have any benefits regarding the load implementation. A simulation for these with very high NTC values, 10^9 GW, was realized.

The results showed that the transmission lines are still congestioned. This points to the transmission lines' congestion issue due to the lack of capacity. Even with no limit on the power flow capacity, the system still cannot match its generation with the demand. However, the lines helped cover the smaller gaps generation could not cover in certain regions by providing more exchange capacities between regions.

Flexible demand and high value NTC implementation

The implementation of both features at the same time revealed that systems profit off of the advantages of both sides. The combination of high NTC values and flexible demand helps shift the loss of load to load shedding. The inadequacy of the system is reduced.

5.3 Introduction of storage technology

Along with implementing the flexibility of the demand, another mechanism is realized to try to provide a solution. In the OSeMOSYS scenarios, storage technology is introduced.

The storage technology requires to be linked to a technology that can store energy such as hydro dams. A storage technology was implemented in OSeMOSYS to try to fix those issues. With that objective in mind, the Mixed Policies scenario is recreated with a new set of variables in OSeMOSYS with storage taken into account. However, as Bolivia possesses no storage facilities, it is impossible to use valid data for Bolivia. The storage is thus implemented to have a general idea of the impact of storage on the BES. Adapting the storage capacities to optimize the BES is out of the scope of this course.

The storage is considered to be generated from hydroelectric technologies.

5.3.1 Comparison in OSeMOSYS

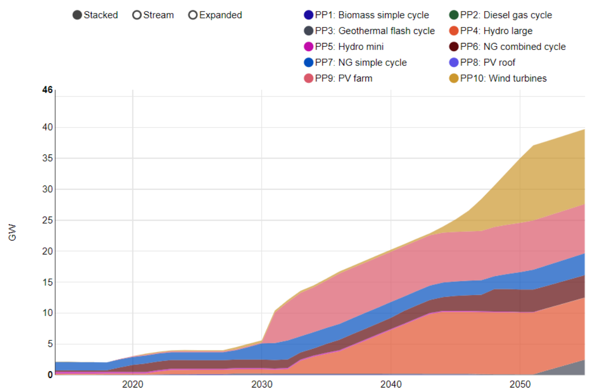

Figure 5.49: Total annual capacity for the MP scenario with storage in OSeMOSYS

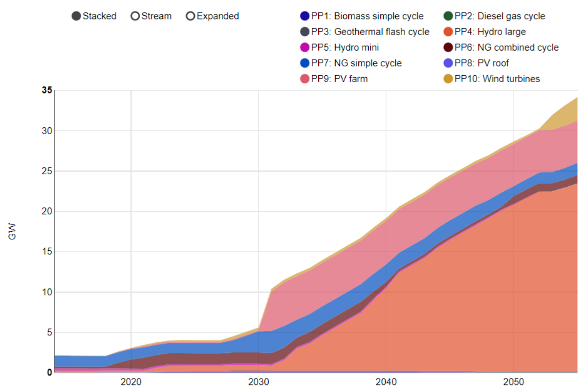

Figure 5.50: Total annual capacity for the MP scenario without storage in OSeMOSYS

There is a visible change in the installed capacity year per year from the figure 5.50 to the figure 5.49. More VRES penetration with the wind technologies being introduced much earlier in the mix. However, more natural gas is also being installed for the MP scenario without storage. 2.5 GW are installed without storage, whereas 7.1 GW are installed with storage.

As the storage is linked to hydroelectric power plants, it impacts the capacity of this technology, with twice less capacity with storage.

Overall, the storage also leads to an increase in the installed capacity. By 2040, the capacity increased by 5.6% and by 2050, 22.1%. This increase in capacity could lead to a better short-term assessment.

5.3.2 Comparison in Dispa-SET

By 2030, no changes are noticed as, in OSeMOSYS, the storage does not have an impact yet.

For MP 2040, the ENS drops from 8.8% to 6.4%. The lack of capacity now amounts to 6620.92 MW instead of 8192.33 MW, but the total emission amount is now 4632.49 ktonCO2. This means that the storage capacity brings more capacity that indeed helps reduce the infeasibility of the system. The lack of capacity reaches its maximum when there is the least amount of capacity available. For Bolivia, it means winter nights. If the lack of capacity decreases, the storage also mitigates the impact of seasonality on the system. However, the increase in natural gas power plants' capacity leads to this technology being used more often, leading to an increase in emissions.

As for 2050, the ENS decreases from 9.47% to 5.97%. The lack of capacity decreases by 4905 MW to reach 10288.11, but the emissions went from 1428.66 kton of CO2 to 4080.01 kton of CO2.

5.3.3 Observations

Although the introduction of the storage technology leads to an increase in installed capacity and thus a decreased lack of capacity and ENS, there is also an increase in GHG emissions. The introduction of the storage technology in the OSeMOSYS represents a path of a potential solution for solving the inadequacy of the data provided by OSeMOSYS; it is, however, necessary to combine it with other features to solve the resurgence of the thermoelectric gas power plants.

Chapter 6

Conclusion

The goal of this work was to assess the quality of the simulations produced by OSeMOSYS to apply those simulations as the framework for the energy transition in Bolivia.

In that regard, scenarios developed by Fernandez et al. [17] in an open-source energy planning optimization model are used as the baseline. The first scenario represents the evolution of the current Bolivian energy mix as it is, a second one is the improved version of the first scenario, with various energy policies put in place. The last scenario pushes the GHG emissions to zero to reach the IPCC goals leading to high RES penetration. Already in OSeMOSYS, some issues can be pointed out for the MP and CN scenarios, as the cost of energy transition suggested by the model represent up to 50 times the current Bolivian investment in the energy sector.

Afterwards, through a `Python` script, OSeMOSYS is soft-linked to Dispa-SET, a short-term open-source unit and power dispatch model. The soft-linking consists in a structural pre-processing of key data output from OSeMOSYS and to insert them as inputs in Dispa-SET. That allows the long-term results of OSeMOSYS to be dissected and analyzed at a short-term level to assess the feasibility of the solutions OSeMOSYS produced.

The results highlight an apparent lack of capacity compared to the demand for almost every scenario. In the Business-As-Usual scenario, the template scenario fails to match its demand in 2040 and 2050, even though it was the system with fewer constraints regarding the energy system composition.

For the Mixed Policies scenario from 2030, the demand increase only emphasizes the lack of capacity. The NTCs are also suspected to be too small to help balance out the system at this point. For the years 2040 and 2050, the scenario also showed that seasonality became a factor to consider with the penetration of renewable energy sources, variable or not, in the mix. However, the MP scenario also shows that the policies impacted the energy mix. Natural gas thermoelectric power plants were used as ancillary services instead of baseload providers.

In the end, the Carbon Neutral scenario shows the same issues as the other scenarios, with two additional problems. The first is linked to the limited resources for geothermal energy, with 13.9 GW of capacity to be installed for this scenario. The second issue is the unability to reach carbon neutrality because the natural gas power plants are used to try to fill in the mismatch between demand and generation but instead achieves a 95.3% of emission reduction. To use this scenario in future iterations, it is necessary to consider additional restrictions on the geothermal energy and its expectations.

Some assumptions can be made to discern the exact reason for the amount of ENS. The first assumption is that the demand can be shifted to decrease the peak load and therefore be covered by the capacity. The second assumption is that the NTC are not implemented the proper way. Simulations are run in Dispa-SET with the implementation of these assumptions, revealing that the lack of capacity is so significant that it was impossible to make the problem feasible at any point, thus confirming the inadequacy of the the system proposed by the OSeMOSYS model.

Following these observations, the Mixed Policies scenario from OSeMOSYS is modified by adding storage capacity in an attemps to make the scenarios more realistic. The results given by OSeMOSYS are then transferred to Dispa-SET to measure the impact on the system adequacy. It appears that, with this added capacity, the thermoelectric power plants increase their capacity factor and activity. The introduction of the storage is an excellent addition to the model, although it needs to be coupled with other mechanisms to avoid the activity resurgence of conventional power units.

Overall, the above results indicate that OSeMOSYS optimizes too optimistically the energy balance. Not considering key system constraints leads to underestimating the necessary capacity for each technology. It eventually leads to infeasible systems when small time steps are used.

As a result, the scenarios generated by OSeMOSYS should be considered with great care when it comes to planning the energy transition in Bolivia.

There is currently a lack of energy planning capacity and models in Bolivia. The present work should only be considered as a first attempt to bridge this gap and provide solid simulation tools. It is however subject to multiple hypotheses and limitations which can be questioned. They are listed hereunder together with suggestions for future works.

The lack of data for the load may have led to errors. It is impossible to know the standard energy consumption curve for Bolivia without more historical time series for the load. The Remote-Areas Multi-energy systems load Profiles (RAMP) model may be used to solve the lack of precision in the data. RAMP is a bottom-up stochastic model used to generate load profiles with high precision. It was designed to build load profiles with a rough approximation of the nature of energy consumption. Its scale can range from villages to countries [65]. This model can be used with various databases containing the energy consumption of Bolivian cities with a rough knowledge of the nature of the demand.

The OSeMOSYS scenarios can be questioned as well. The hypotheses relative to future electrification rates are highly uncertain and can lead to under/overestimated demand levels.

Data relative to the energy system is rarely openly available in Bolivia. Whereas in Europe, transparency platforms provide extensive techno-economic, market, or time series data, this was not the case for the present work. Efforts should be made to provide more information on the system and the planned short-term investments.

From a methodological viewpoint, the soft-linking between OSeMOSYS and Dispa-SET offers a new view on the Bolivian energy system as it clarified how the demand is dispatched throughout the renewable energy sources and how their availability varied. Although the systems are not feasible, Dispa-SET, thanks to its simulation step, provided insight into the repartition of the RE production. It is possible to pinpoint the problems encountered by the system. Moreover, the dispatch displays the impact of the different scenario parameters.

As a continuation of this work, a bi-directional automated soft-linking could be implemented, utilizing the feedback loop initiated in section 5.3, to decrease the impact of the optimistic approach of OSeMOSYS. This next step could bring the corrections and the precision needed for a feasible energy system by 2050.

The combination of the different tools in energy modelling has always proven to be the best solution, and OSeMOSYS is no exception to this rule. The uni-directional soft-link realized in the scope of this work and future works regarding this topic shows a clear potential to support the upcoming Bolivian energy transition.

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Appendix A

OSeMOSYS data

OSeMOSYS scenario variables:

- AccumulatedAnnualDemand: Accumulated Demand for a certain commodity in one specific year.
- AnnualEmissionLimit: Annual upper limit for a specific emission generated in the whole modelled region.
- AnnualExogenousEmission: It allows the user to account for additional annual emissions, on top of those computed endogenously by the model
- AvailabilityFactor: Capacity available each TimeSlice expressed as a fraction of the total installed capacity, with values ranging from 0 to 1. It gives the possibility to account for forced outages.
- CapacityFactor: Capacity Factor is used to convert annual capacity to the capacity available for each timeslice.
- CapacityOfOneTechnologyUnit: Capacity of one new unit of a technology. In case the user sets this parameter, the related technology will be installed only in batches of the specified capacity and the problem will turn into a Mixed Integer Linear Problem.
- CapacityToActivityUnit: Conversion factor relating the energy that would be pro-

duced when one unit of capacity is fully used in one year.

- CapitalCost: Capital investment cost of a technology, per unit of capacity.
- CapitalCostStorage: Binary parameter linking a technology to the storage facility it charges. It has value 0 if the technology and the storage facility are not linked, 1 if they are.
- Conversionld: Binary parameter linking one TimeSlice to a certain DayType. It has value 0 if the TimeSlice does not pertain to the specific DayType, 1 if it does.
- Conversionlh: Binary parameter linking one TimeSlice to a certain DaylyTimeBracket. It has value 0 if the TimeSlice does not pertain to the specific DaylyTimeBracket, 1 if it does.
- Conversionls: Binary parameter linking one TimeSlice to a certain Season. It has value 0 if the TimeSlice does not pertain to the specific season, 1 if it does.
- DaysInDayType: Number of days for each day type, within one week (natural number, ranging from 1 to 7)
- DaySplit: Length of one DailyTimeBracket in one specific day as a fraction of the year (e.g., when distinguishing between days and night: 12h/(24h*365d)).
- DepreciationMethod: Binary parameter defining the type of depreciation to be applied. It has value 1 for sinking fund depreciation, value 2 for straight-line depreciation.
- DiscountRate: Region-specific value for the discount rate, expressed in decimals (e.g. 0.05)
- EmissionActivityRatio: Emission factor of a technology per unit of activity, per mode of operation.
- EmissionsPenalty: Penalty per unit of emission.
- FixedCost: Fixed operational and maintenance cost of a technology, per unit of capacity.

- InputActivityRatio: Rate of input (use) of a fuel (commodity) by a technology, as a ratio of the rate of activity.
- MinStorageCharge: It sets a lower bound to the amount of energy stored, as a fraction of the maximum, with a number ranging between 0 and 1. The storage facility cannot be emptied below this level.
- ModelPeriodEmissionLimit: Annual upper limit for a specific emission generated in the whole modelled region, over the entire modelled period.
- ModelPeriodExogenousEmission: It allows the user to account for additional emissions over the entire modelled period, on top of those computed endogenously by the model (e.g. generated outside the region).
- OperationalLife: Useful lifetime of a technology, expressed in years.
- OperationalLifeStorage: The useful lifetime of the storage facility.
- OutputActivityRatio: The rate of output of fuel (commodity) as a ratio to the rate of activity in which a technology is operating.
- REMinProductionTarget: Minimum ratio of all renewable commodities tagged in the RETagCommodity parameter, to be produced by the technologies tagged with the RETechnology parameter.
- ReserveMargin: Minimum level of the reserve margin required to be provided for all the tagged commodities, by the tagged technologies. If no reserve margin is required, the parameter will have value 1; if, for instance, 20% reserve margin is required, the parameter will have value 1.2.
- ReserveMarginTagFuel: Binary parameter tagging the fuels to which the reserve margin applies. It has value 1 if the reserve margin applies to the fuel, 0 otherwise.
- ReserveMarginTagTechnology: Binary parameter tagging the technologies that are allowed to contribute to the reserve margin. It has value 1 for the technologies allowed, 0 otherwise.
- ResidualCapacity: Is the capacity left over from a period prior to the modelling

period.

- ResidualStorageCapacity: Binary parameter linking a storage facility to the technology it feeds. It has value 0 if the technology and the storage facility are not linked, 1 if they are.

- RETagFuel: Binary parameter tagging the fuels to which the renewable target applies to. It has value 1 if the target applies, 0 otherwise.

- RETagTechnology: Binary parameter tagging the renewable technologies that must contribute to reaching the indicated minimum renewable production target. It has value 1 for the technologies contributing, 0 otherwise.

- SpecifiedAnnualDemand: Total specified demand for the year, linked to a specific 'time of use' during the year.

- SpecifiedDemandProfile: Annual fraction of energy-service or commodity demand that is required in each time slice. For each year, all the defined SpecifiedDemandProfile input values should sum up to 1.

- StorageLevelStart: Level of storage at the beginning of first modelled year, in units of activity.

- StorageMaxChargeRate: Maximum charging rate for the storage, in units of activity per year.

- StorageMaxDischargeRate: Maximum discharging rate for the storage, in units of activity per year.

- TechnologyFromStorage: Binary parameter linking a storage facility to the technology it feeds. It has value 1 if the technology and the storage facility are linked, 0 otherwise.

- TechnologyToStorage: Binary parameter linking a technology to the storage facility it charges. It has value 1 if the technology and the storage facility are linked, 0 otherwise.

- TotalAnnualMaxCapacity: Total maximum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.

- TotalAnnualMaxCapacityInvestment: Maximum capacity of a technology expressed in power units.
- TotalAnnualMinCapacity: Total minimum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.
- TotalAnnualMinCapacityInvestment: Minimum capacity of a technology expressed in power units.
- TotalTechnologyAnnualActivityLowerLimit: Total minimum level of activity allowed for a technology in one year.
- TotalTechnologyAnnualActivityUpperLimit: Total maximum level of activity allowed for a technology in one year.
- TotalTechnologyModelPeriodActivityLowerLimit: Total minimum level of activity allowed for a technology in the entire modelled period.
- TotalTechnologyModelPeriodActivityUpperLimit: Total maximum level of activity allowed for a technology in the entire modelled period.
- TradeRoute: Binary parameter defining the links between region r and region rr, to enable or disable trading of a specific commodity. It has value 1 when two regions are linked, 0 otherwise
- VariableCost: Cost of a technology for a given mode of operation (Variable OM cost), per unit of activity.
- YearSplit: Duration of a modelled time slice expressed as a fraction of the year. The sum of each entry over one modelled year should equal 1.

OSeMOSYS constraints:

- s.t. Acc1FuelProductionByTechnologyr in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR: RateOfProductionByTechnology [r, l, t, f, y] * YearSplit [l, y] = ProductionByTechnology [r, l, t, f, y]; .t. Acc2FuelUseByTechnologyr in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR: RateOfUseByTechnology [r, l, t, f, y] * YearSplit [l, y] = UseByTechnology [r, l, t, f, y]; .t. Acc3AverageAnnualRateOfActivityr in REGION, t in TECHNOLOGY, m in MODEOFOPERATION, y in YEAR: suml in TIMESLICE RateOfActivity [r, l, t, m, y] * YearSplit [l, y] = TotalAnnualTechnologyActivityByMode [r, t, m, y];

- s.t. CAa1TotalNewCapacityr in REGION, t in TECHNOLOGY, y in YEAR: AccumulatedNewCapacity [r, t, y] = sumyy in YEAR: y - yy ¡ OperationalLife [r, t] y - yy ¿= 0 NewCapacity [r, t, yy];
- s.t. CAa2TotalAnnualCapacityr in REGION, t in TECHNOLOGY, y in YEAR: AccumulatedNewCapacity [r, t, y] + ResidualCapacity [r, t, y] = TotalCapacityAnnual [r, t, y];
- s.t. CAa5TotalNewCapacityr in REGION, t in TECHNOLOGY, y in YEAR: CapacityOfOneTechnologyUnit [r, t, y] ¡¿ 0: CapacityOfOneTechnologyUnit [r, t, y] * NumberOfNewTechnologyUnits [r, t, y] = NewCapacity [r, t, y];
- s.t. CC1UndiscountedCapitalInvestmentr in REGION, t in TECHNOLOGY, y in YEAR: CapitalCost [r, t, y] * NewCapacity [r, t, y] = CapitalInvestment [r, t, y];
- s.t. E2AnnualEmissionProductionr in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR: summ in MODEOFOPERATION AnnualTechnologyEmissionByMode [r, t, e, m, y] = AnnualTechnologyEmission [r, t, e, y];
- s.t. EBa10EnergyBalanceEachTS4r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR: Trade [r, rr, l, f, y] = -1 * Trade [r, rr, l, f, y];
- s.t. EBa1RateOfFuelProduction1r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODEOFOPERATION, y in YEAR, f in FUEL: OutputActivityRatio [r, t, f, m, y] ¡¿ 0: RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m, y] = RateOfProductionByTechnologyByMode [r, l, t, m, f, y];
- s.t. EBa2RateOfFuelProduction2r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR, l in TIMESLICE: summ in MODEOFOPERATION: OutputActivityRatio [r, t, f, m, y] ¡¿ 0 RateOfProductionByTechnologyByMode [r, l, t, m, f, y] = RateOfProductionByTechnology [r, l, t, f, y];

- s.t. EBa4RateOfFuelUse1r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODEOFOPERATION, y in YEAR, f in FUEL: InputActivityRatio [r, t, f, m, y] ¡¿ 0: RateOfActivity [r, l, t, m, y] * InputActivityRatio [r, t, f, m, y] = RateOfUseByTechnologyByMode [r, l, t, m, f, y];
- s.t. EBa5RateOfFuelUse2r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR, l in TIMESLICE: summ in MODEOFOPERATION: InputActivityRatio [r, t, f, m, y] ¡¿ 0 RateOfUseByTechnologyByMode [r, l, t, m, f, y] = RateOfUseByTechnology [r, l, t, f, y];
- s.t. NCC1TotalAnnualMaxNewCapacityConstraintr in REGION, t in TECHNOLOGY, y in YEAR: NewCapacity [r, t, y] ¡= TotalAnnualMaxCapacityInvestment [r, t, y];
- s.t. NCC2TotalAnnualMinNewCapacityConstraintr in REGION, t in TECHNOLOGY, y in YEAR: TotalAnnualMinCapacityInvestment [r, t, y] ¿ 0: NewCapacity [r, t, y] ¿= TotalAnnualMinCapacityInvestment [r, t, y];
- s.t. OC1OperatingCostsVariabler in REGION, t in TECHNOLOGY, y in YEAR: summ in MODEOFOPERATION TotalAnnualTechnologyActivityByMode [r, t, m, y] * VariableCost [r, t, m, y] = AnnualVariableOperatingCost [r, t, y];
- s.t. OC2OperatingCostsFixedAnnualr in REGION, t in TECHNOLOGY, y in YEAR: TotalCapacityAnnual [r, t, y] * FixedCost [r, t, y] = AnnualFixedOperatingCost [r, t, y];
- s.t. SI6SalvageValueStorageAtEndOfPeriod1r in REGION, s in STORAGE, y in YEAR: (y + OperationalLifeStorage [r, s] - 1) ¡= (maxyy in YEAR max(yy)): 0 = SalvageValueStorage [r, s, y];
- s.t. SV3SalvageValueAtEndOfPeriod3r in REGION, t in TECHNOLOGY, y in YEAR: (y + OperationalLife [r, t] - 1) ¡= (maxyy in YEAR max(yy)): SalvageValue [r, t, y] = 0;
- s.t. SV4SalvageValueDiscountedToStartYearr in REGION, t in TECHNOLOGY, y in YEAR: DiscountedSalvageValue [r, t, y] = SalvageValue [r, t, y] / ((1 + Dis-

countRate [r])$^(1 + maxyyinYEARmax(yy) - minyyinYEARmin(yy)))$;

- s.t. TAC1TotalModelHorizonTechnologyActivityr in REGION, t in TECHNOLOGY: sumy in YEAR TotalTechnologyAnnualActivity [r, t, y] = TotalTechnologyModelPeriodActivity [r, t];

- s.t. AAC1TotalAnnualTechnologyActivityr in REGION, t in TECHNOLOGY, y in YEAR: suml in TIMESLICE RateOfTotalActivity [r, t, l, y] * YearSplit [l, y] = TotalTechnologyAnnualActivity [r, t, y]; .t. AAC2TotalAnnualTechnologyActivityUpperLimitr in REGION, t in TECHNOLOGY, y in YEAR: TotalTechnologyAnnualActivity [r, t, y] ¡= TotalTechnologyAnnualActivityUpperLimit [r, t, y];

- s.t. AAC3TotalAnnualTechnologyActivityLowerLimitr in REGION, t in TECHNOLOGY, y in YEAR: TotalTechnologyAnnualActivityLowerLimit [r, t, y] ¿ 0: TotalTechnologyAnnualActivity [r, t, y] ¿= TotalTechnologyAnnualActivityLowerLimit [r, t, y];

- s.t. Acc4ModelPeriodCostByRegionr in REGION: sumy in YEAR TotalDiscountedCost [r, y] = ModelPeriodCostByRegion [r];

- s.t. CAa3TotalActivityOfEachTechnologyr in REGION, l in TIMESLICE, t in TECHNOLOGY, y in YEAR: summ in MODEOFOPERATION RateOfActivity [r, l, t, m, y] = RateOfTotalActivity [r, t, l, y];

- s.t. CAa4ConstraintCapacityr in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR: RateOfTotalActivity [r, t, l, y] ¡= TotalCapacityAnnual [r, t, y] * CapacityFactor [r, t, l, y] * CapacityToActivityUnit [r, t];

- s.t. CAb1PlannedMaintenancer in REGION, t in TECHNOLOGY, y in YEAR: suml in TIMESLICE RateOfTotalActivity [r, t, l, y] * YearSplit [l, y] ¡= suml in TIMESLICE (TotalCapacityAnnual [r, t, y] * CapacityFactor [r, t, l, y] * YearSplit [l, y]) * AvailabilityFactor [r, t, y] * CapacityToActivityUnit [r, t];

- s.t. CC2DiscountingCapitalInvestmentr in REGION, t in TECHNOLOGY, y in YEAR: CapitalInvestment [r, t, y] / ((1 + DiscountRate [r]) $^(y - minyyinYEARmin(yy)))$ = DiscountedCapitalInvestment [r, t, y];

- s.t. E1AnnualEmissionProductionByModer in REGION, t in TECHNOLOGY, e in EMISSION, m in MODEOFOPERATION, y in YEAR: EmissionActivityRatio [r, t, e, m, y] * TotalAnnualTechnologyActivityByMode [r, t, m, y] = AnnualTechnologyEmissionByMode [r, t, e, m, y];

- s.t. E3EmissionsPenaltyByTechAndEmissionr in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR: AnnualTechnologyEmission [r, t, e, y] * EmissionsPenalty [r, e, y] = AnnualTechnologyEmissionPenaltyByEmission [r, t, e, y];

- s.t. E4EmissionsPenaltyByTechnologyr in REGION, t in TECHNOLOGY, y in YEAR: sume in EMISSION AnnualTechnologyEmissionPenaltyByEmission [r, t, e, y] = AnnualTechnologyEmissionsPenalty [r, t, y];

- s.t. E5DiscountedEmissionsPenaltyByTechnologyr in REGION, t in TECHNOLOGY, y in YEAR: AnnualTechnologyEmissionsPenalty [r, t, y] / ((1 + DiscountRate [r]) $^{(}y - minyyinYEARmin(yy) + 0.5)$) = DiscountedTechnologyEmissionsPenalty [r, t, y];

- s.t. E6EmissionsAccounting1r in REGION, e in EMISSION, y in YEAR: sumt in TECHNOLOGY AnnualTechnologyEmission [r, t, e, y] = AnnualEmissions [r, e, y];

- s.t. E7EmissionsAccounting2r in REGION, e in EMISSION: sumy in YEAR AnnualEmissions [r, e, y] = ModelPeriodEmissions [r, e] - ModelPeriodExogenousEmission [r, e];

- s.t. E8AnnualEmissionsLimitr in REGION, e in EMISSION, y in YEAR: AnnualEmissions [r, e, y] + AnnualExogenousEmission [r, e, y] ¡= AnnualEmissionLimit [r, e, y];

- s.t. E9ModelPeriodEmissionsLimitr in REGION, e in EMISSION: ModelPeriodEmissions [r, e] ¡= ModelPeriodEmissionLimit [r, e];

- s.t. EBa11EnergyBalanceEachTS5r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: Production [r, l, f, y] ¿= Demand [r, l, f, y] + Use [r, l, f, y] + sumrr in REGION Trade [r, rr, l, f, y] * TradeRoute [r, rr, f, y];

- s.t. EBa3RateOfFuelProduction3r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: sumt in TECHNOLOGY RateOfProductionByTechnology [r, l, t, f, y] = RateOfProduction [r, l, f, y];
- s.t. EBa6RateOfFuelUse3r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: sumt in TECHNOLOGY RateOfUseByTechnology [r, l, t, f, y] = RateOfUse [r, l, f, y];
- s.t. EBa7EnergyBalanceEachTS1r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: RateOfProduction [r, l, f, y] * YearSplit [l, y] = Production [r, l, f, y];
- s.t. EBa8EnergyBalanceEachTS2r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: RateOfUse [r, l, f, y] * YearSplit [l, y] = Use [r, l, f, y];
- s.t. EBa9EnergyBalanceEachTS3r in REGION, l in TIMESLICE, f in FUEL, y in YEAR: RateOfDemand [r, l, f, y] * YearSplit [l, y] = Demand [r, l, f, y];
- s.t. EBb1EnergyBalanceEachYear1r in REGION, f in FUEL, y in YEAR: suml in TIMESLICE Production [r, l, f, y] = ProductionAnnual [r, f, y];
- s.t. EBb2EnergyBalanceEachYear2r in REGION, f in FUEL, y in YEAR: suml in TIMESLICE Use [r, l, f, y] = UseAnnual [r, f, y];
- s.t. EBb3EnergyBalanceEachYear3r in REGION, rr in REGION, f in FUEL, y in YEAR: suml in TIMESLICE Trade [r, rr, l, f, y] = TradeAnnual [r, rr, f, y];
- s.t. EBb4EnergyBalanceEachYear4r in REGION, f in FUEL, y in YEAR: ProductionAnnual [r, f, y] ¿= UseAnnual [r, f, y] + sumrr in REGION TradeAnnual [r, rr, f, y] * TradeRoute [r, rr, f, y] + AccumulatedAnnualDemand [r, f, y];
- s.t. EQSpecifiedDemandr in REGION, f in FUEL, y in YEAR, l in TIMESLICE: SpecifiedAnnualDemand [r, f, y] * SpecifiedDemandProfile [r, f, l, y] / YearSplit [l, y] = RateOfDemand [r, l, f, y];
- s.t. OC3OperatingCostsTotalAnnualr in REGION, t in TECHNOLOGY, y in YEAR: AnnualFixedOperatingCost [r, t, y] + AnnualVariableOperatingCost [r, t, y] = OperatingCost [r, t, y];

- s.t. OC4DiscountedOperatingCostsTotalAnnualr in REGION, t in TECHNOLOGY, y in YEAR: OperatingCost [r, t, y] / ((1 + DiscountRate [r]) $^{(y-minyyinYEARmin(yy)+}$ 0.5)) = DiscountedOperatingCost [r, t, y];
- s.t. RE1FuelProductionByTechnologyAnnualr in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR: suml in TIMESLICE ProductionByTechnology [r, l, t, f, y] = ProductionByTechnologyAnnual [r, t, f, y];
- s.t. RE2TechIncludedr in REGION, y in YEAR: sumt in TECHNOLOGY, f in FUEL ProductionByTechnologyAnnual [r, t, f, y] * RETagTechnology [r, t, y] = TotalREProductionAnnual [r, y];
- s.t. RE3FuelIncludedr in REGION, y in YEAR: suml in TIMESLICE, f in FUEL RateOfProduction [r, l, f, y] * RETagFuel [r, f, y] * YearSplit [l, y] = RETotalProductionOfTargetFuelAnnual [r, y];
- s.t. RE4EnergyConstraintr in REGION, y in YEAR: REMinProductionTarget [r, y] * RETotalProductionOfTargetFuelAnnual [r, y] ¡= TotalREProductionAnnual [r, y];
- s.t. RE5FuelUseByTechnologyAnnualr in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR: suml in TIMESLICE RateOfUseByTechnology [r, l, t, f, y] * YearSplit [l, y] = UseByTechnologyAnnual [r, t, f, y];
- s.t. RM1ReserveMarginTechnologiesIncludedInActivityUnitsr in REGION, y in YEAR: sumt in TECHNOLOGY TotalCapacityAnnual [r, t, y] * ReserveMarginTagTechnology [r, t, y] * CapacityToActivityUnit [r, t] = TotalCapacityInReserveMargin [r, y];
- s.t. RM2ReserveMarginFuelsIncludedr in REGION, l in TIMESLICE, y in YEAR: sumf in FUEL RateOfProduction [r, l, f, y] * ReserveMarginTagFuel [r, f, y] = DemandNeedingReserveMargin [r, l, y];
- s.t. RM3ReserveMarginConstraintr in REGION, l in TIMESLICE, y in YEAR: DemandNeedingReserveMargin [r, l, y] * ReserveMargin [r, y] ¡= TotalCapacityInReserveMargin [r, y];

- s.t. S11andS12StorageLevelDayTypeStartld in DAYTYPE, r in REGION, s in STORAGE, ls in SEASON, y in YEAR: if ld = minldld in DAYTYPE min(ldld) then StorageLevelSeasonStart [r, s, ls, y] else StorageLevelDayTypeStart [r, s, ls, ld-1, y] + sumlh in DAILYTIMEBRACKET NetChargeWithinDay [r, s, ls, ld-1, lh, y] * DaysInDayType [ls, ld-1, y] = StorageLevelDayTypeStart [r, s, ls, ld, y];
- s.t. S13andS14andS15StorageLevelDayTypeFinishls in SEASON, ld in DAYTYPE, r in REGION, s in STORAGE, y in YEAR: if ls = maxlsls in SEASON max(lsls) ld = maxldld in DAYTYPE max(ldld) then StorageLevelYearFinish [r, s, y] else if ld = maxldld in DAYTYPE max(ldld) then StorageLevelSeasonStart [r, s, ls+1, y] else StorageLevelDayTypeFinish [r, s, ls, ld+1, y] - sumlh in DAILYTIMEBRACKET NetChargeWithinDay [r, s, ls, ld+1, lh, y] * DaysInDayType [ls, ld+1, y] = StorageLevelDayTypeFinish [r, s, ls, ld, y];
- s.t. S1RateOfStorageCharger in REGION, s in STORAGE, y in YEAR, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET: suml in TIMESLICE, t in TECHNOLOGY, m in MODEOFOPERATION: TechnologyToStorage [r, t, s, m] ¿ 0 RateOfActivity [r, l, t, m, y] * TechnologyToStorage [r, t, s, m] * Conversionls [l, ls] * Conversionld [l, ld] * Conversionlh [l, lh] = RateOfStorageCharge [r, s, ls, ld, lh, y];
-
- s.t. S2RateOfStorageDischarger in REGION, s in STORAGE, y in YEAR, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET: suml in TIMESLICE, t in TECHNOLOGY, m in MODEOFOPERATION: TechnologyFromStorage [r, t, s, m] ¿ 0 RateOfActivity [r, l, t, m, y] * TechnologyFromStorage [r, t, s, m] * Conversionls [l, ls] * Conversionld [l, ld] * Conversionlh [l, lh] = RateOfStorageDischarge [r, s, ls, ld, lh, y];
- s.t. S3NetChargeWithinYearls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, r in REGION, s in STORAGE, y in YEAR: suml in TIMESLICE: Conversionls [l, ls] ¿ 0 Conversionld [l, ld] ¿ 0 Conversionlh [l, lh] ¿ 0 (RateOfStorageCharge [r, s, ls, ld, lh, y] - RateOfStorageDischarge [r, s, ls, ld, lh, y]) *

YearSplit [l, y] * Conversionls [l, ls] * Conversionld [l, ld] * Conversionlh [l, lh] = NetChargeWithinYear [r, s, ls, ld, lh, y];

- s.t. S4NetChargeWithinDayr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR: (RateOfStorageCharge [r, s, ls, ld, lh, y] - RateOfStorageDischarge [r, s, ls, ld, lh, y]) * DaySplit [lh, y] = NetChargeWithinDay [r, s, ls, ld, lh, y];

- s.t. S5andS6StorageLevelYearStarty in YEAR, r in REGION, s in STORAGE: if y = minyy in YEAR min(yy) then StorageLevelStart [r, s] else StorageLevelYearStart [r, s, y-1] + sumls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET NetChargeWithinYear [r, s, ls, ld, lh, y-1] = StorageLevelYearStart [r, s, y];

- s.t. S7andS8StorageLevelYearFinishy in YEAR, r in REGION, s in STORAGE: if y ¡ maxyy in YEAR max(yy) then StorageLevelYearStart [r, s, y+1] else StorageLevelYearStart [r, s, y] + sumls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET NetChargeWithinYear [r, s, ls, ld, lh, y] = StorageLevelYearFinish [r, s, y]; .t. S9andS10StorageLevelSeasonStartls in SEASON, r in REGION, s in STORAGE, y in YEAR: if ls = minlsls in SEASON min(lsls) then StorageLevelYearStart [r, s, y] else StorageLevelSeasonStart [r, s, ls-1, y] + sumld in DAYTYPE, lh in DAILYTIMEBRACKET NetChargeWithinYear [r, s, ls-1, ld, lh, y] = StorageLevelSeasonStart [r, s, ls, y];

- s.t. SC1LowerLimitBeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInFirstWeekConstr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR, lh in DAILYTIMEBRACKET: 0 ¡= (StorageLevelDayTypeStart [r, s, ls, ld, y] + sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¿ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageLowerLimit [r, s, y]; .t. SC1UpperLimitBeginningOfDailyTimeBracketOfFirstInstanceOfD in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR, lh in DAILYTIMEBRACKET: (StorageLevelDayTypeStart [r, s, ls, ld, y] + sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¿ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageUpperLimit [r, s, y] ¡= 0;

- s.t. SC2LowerLimitEndOfDailyTimeBracketOfLastInstanceOfDayTypeInFirstWeekConstraintld in DAYTYPE, r in REGION, s in STORAGE, ls in SEASON, y in YEAR, lh in DAILYTIMEBRACKET: 0 ¡= if ld ¿ minldld in DAYTYPE min(ldld) then (StorageLevelDayTypeStart [r, s, ls, ld, y] - sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¡ 0 NetChargeWithinDay [r, s, ls, ld-1, lhlh, y]) - StorageLowerLimit [r, s, y];

- s.t. SC2UpperLimitEndOfDailyTimeBracketOfLastInstanceOfDayTypeInFirstWeekConstraintld in DAYTYPE, r in REGION, s in STORAGE, ls in SEASON, y in YEAR, lh in DAILYTIMEBRACKET: if ld ¿ minldld in DAYTYPE min(ldld) then (StorageLevelDayTypeStart [r, s, ls, ld, y] - sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¡ 0 NetChargeWithinDay [r, s, ls, ld-1, lhlh, y]) - StorageUpperLimit [r, s, y] ¡= 0;
- s.t. SC3LowerLimitEndOfDailyTimeBracketOfLastInstanceOfDayTypeInLastWeekConstraintr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR, lh in DAILYTIMEBRACKET: 0 ¡= (StorageLevelDayTypeFinish [r, s, ls, ld, y] - sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¡ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageLowerLimit [r, s, y];
- s.t. SC3UpperLimitEndOfDailyTimeBracketOfLastInstanceOfDayTypeInLastWeekConstraintr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR, lh in DAILYTIMEBRACKET: (StorageLevelDayTypeFinish [r, s, ls, ld, y] - sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¡ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageUpperLimit [r, s, y] ¡= 0;
- s.t. SC4LowerLimitBeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInLastWeekConstra in DAYTYPE, r in REGION, s in STORAGE, ls in SEASON, y in YEAR, lh in DAILYTIMEBRACKET: 0 ¡= if ld ¿ minldld in DAYTYPE min(ldld) then (StorageLevelDayTypeFinish [r, s, ls, ld-1, y] + sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¿ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageLowerLimit [r, s, y];
- s.t. SC4UpperLimitBeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInLastWeekConstra in DAYTYPE, r in REGION, s in STORAGE, ls in SEASON, y in YEAR, lh in DAILYTIMEBRACKET: if ld ¿ minldld in DAYTYPE min(ldld) then (StorageLevelDayTypeFinish [r, s, ls, ld-1, y] + sumlhlh in DAILYTIMEBRACKET: lh - lhlh ¿ 0 NetChargeWithinDay [r, s, ls, ld, lhlh, y]) - StorageUpperLimit [r, s, y] ¡= 0;

- s.t. SC5MaxChargeConstraintr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR: RateOfStorageCharge [r, s, ls, ld, lh, y] ¡= StorageMaxChargeRate [r, s];
- s.t. SC6MaxDischargeConstraintr in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR: RateOfStorageDischarge [r, s, ls, ld, lh, y] ¡= StorageMaxDischargeRate [r, s];
- s.t. SI10TotalDiscountedCostByStorager in REGION, s in STORAGE, y in YEAR: DiscountedCapitalInvestmentStorage [r, s, y] - DiscountedSalvageValueStorage [r, s, y] = TotalDiscountedStorageCost [r, s, y];
- s.t. SI1StorageUpperLimitr in REGION, s in STORAGE, y in YEAR: AccumulatedNewStorageCapacity [r, s, y] + ResidualStorageCapacity [r, s, y] = StorageUpperLimit [r, s, y];
- s.t. SI2StorageLowerLimitr in REGION, s in STORAGE, y in YEAR: MinStorageCharge [r, s, y] * StorageUpperLimit [r, s, y] = StorageLowerLimit [r, s, y];
- s.t. SI3TotalNewStoragey in YEAR, r in REGION, s in STORAGE: sumyy in YEAR: y - yy ¡ OperationalLifeStorage [r, s] y - yy ¿ 0 NewStorageCapacity [r, s, yy] = AccumulatedNewStorageCapacity [r, s, y];
- s.t. SI4UndiscountedCapitalInvestmentStorager in REGION, s in STORAGE, y in YEAR: CapitalCostStorage [r, s, y] * NewStorageCapacity [r, s, y] = CapitalInvestmentStorage [r, s, y];
- s.t. SI5DiscountingCapitalInvestmentStorager in REGION, s in STORAGE, y in YEAR: CapitalInvestmentStorage [r, s, y] / ((1 + DiscountRate [r]) $^{(y-minyyinYEARmin(yy)))}$ = DiscountedCapitalInvestmentStorage [r, s, y];
- s.t. SI7SalvageValueStorageAtEndOfPeriod2r in REGION, s in STORAGE, y in YEAR: (DepreciationMethod [r] = 1 y + OperationalLifeStorage [r, s] - 1 ¿ maxyy in YEAR max(yy) DiscountRate [r] = 0) —— (DepreciationMethod [r] = 2 (y + OperationalLifeStorage [r, s] - 1) ¿ (maxyy in YEAR max(yy))): CapitalInvestmentStorage [r, s, y] * (1 - (maxyy in YEAR max(yy) - y+1) / OperationalLifeStor-

age [r, s]) = SalvageValueStorage [r, s, y];

- s.t. SI8SalvageValueStorageAtEndOfPeriod3r in REGION, s in STORAGE, y in YEAR: DepreciationMethod [r] = 1 (y + OperationalLifeStorage [r, s] - 1) ¿ (maxyy in YEAR max(yy)) DiscountRate [r] ¿ 0: CapitalInvestmentStorage [r, s, y] * (1 - ((((1 + DiscountRate [r]) $^(maxyyinYEARmax(yy) - y + 1)$) - 1) / ((1 + DiscountRate [r]) $^Operational Life Storage[r, s]$ - 1))) = SalvageValueStorage [r, s, y];

- s.t. SI9SalvageValueStorageDiscountedToStartYearr in REGION, s in STORAGE, y in YEAR: SalvageValueStorage [r, s, y] / ((1 + DiscountRate [r]) $^(maxyyinYEARmax(yy) - minyyinYEARmin(yy) + 1)$) = DiscountedSalvageValueStorage [r, s, y];

- s.t. SV1SalvageValueAtEndOfPeriod1r in REGION, t in TECHNOLOGY, y in YEAR: DepreciationMethod [r] = 1 (y + OperationalLife [r, t] - 1) ¿ (maxyy in YEAR max(yy)) DiscountRate [r] ¿ 0: SalvageValue [r, t, y] = CapitalCost [r, t, y] * NewCapacity [r, t, y] * (1 - (((1 + DiscountRate [r]) $^(maxyyinYEARmax(yy) - y + 1)$ - 1) / ((1 + DiscountRate [r]) $^OperationalLife[r, t]$ - 1)));

- s.t. SV2SalvageValueAtEndOfPeriod2r in REGION, t in TECHNOLOGY, y in YEAR: (DepreciationMethod [r] = 1 (y + OperationalLife [r, t] - 1) ¿ (maxyy in YEAR max(yy)) DiscountRate [r] = 0) —— (DepreciationMethod [r] = 2 (y + OperationalLife [r, t] - 1) ¿ (maxyy in YEAR max(yy))): SalvageValue [r, t, y] = CapitalCost [r, t, y] * NewCapacity [r, t, y] * (1 - (maxyy in YEAR max(yy) - y+1) / OperationalLife [r, t]);

- s.t. TAC2TotalModelHorizonTechnologyActivityUpperLimitr in REGION, t in TECHNOLOGY: TotalTechnologyModelPeriodActivityUpperLimit [r, t] ¿ 0: TotalTechnologyModelPeriodActivity [r, t] ¡= TotalTechnologyModelPeriodActivityUpperLimit [r, t];

- s.t. TAC3TotalModelHorizenTechnologyActivityLowerLimitr in REGION, t in TECHNOLOGY: TotalTechnologyModelPeriodActivityLowerLimit [r, t] ¿ 0: TotalTechnologyModelPeriodActivity [r, t] ¿= TotalTechnologyModelPeriodActivityLowerLimit [r, t];

- s.t. TCC1TotalAnnualMaxCapacityConstraintr in REGION, t in TECHNOLOGY, y in YEAR: TotalCapacityAnnual [r, t, y] ¡= TotalAnnualMaxCapacity [r, t, y];
- s.t. TCC2TotalAnnualMinCapacityConstraintr in REGION, t in TECHNOLOGY, y in YEAR: TotalAnnualMinCapacity [r, t, y] ¿ 0: TotalCapacityAnnual [r, t, y] ¿= TotalAnnualMinCapacity [r, t, y];
- s.t. TDC1TotalDiscountedCostByTechnologyr in REGION, t in TECHNOLOGY, y in YEAR: DiscountedOperatingCost [r, t, y] + DiscountedCapitalInvestment [r, t, y] + DiscountedTechnologyEmissionsPenalty [r, t, y] - DiscountedSalvageValue [r, t, y] = TotalDiscountedCostByTechnology [r, t, y];
- s.t. TDC2TotalDiscountedCostr in REGION, y in YEAR: sumt in TECHNOLOGY TotalDiscountedCostByTechnology [r, t, y] + sums in STORAGE TotalDiscountedStorageCost [r, s, y] = TotalDiscountedCost [r, y];

Appendix B

Carbon taxing scenario in-depth

Regarding the implementation, this scenario was declined in multiple versions; the difference was the value of the tax imposed. It was decided that the taxes would be imposed from 2025 onwards. Indeed, the Bolivian government approved the plan to initiate the energy transition in the Bolivian energy mix by 2026 [46]. The taxes are not fixed throughout the studied timeframe; the idea was to perform an evolution so that the taxes would see their value steadily increase from 2026 to 2050. Essentially, there are two different ways with which values would vary for this sensitivity analysis. For the first case, the initial values in 2026 are \$10/t with a yearly increase value from \$2/y to \$40/y. There is also a "Swedish" version which is an adaptation of the Swedish tax carbon plan, \$5.5/y increase with a value of \$126/t in 2020, \$137/t in 2022 and of \$159/t in 2026 with the same yearly increase, resulting in a \$318/t carbon tax by 2055 [47] which was considered as the maximum version for this scenario. These first values were labelled as "realistic". Bolivia is one of the poorest countries in South America [37] [38], consequently, it is only normal to take this factor into account and to avoid having high value taxes. The natural gas subsidy allows the electricity and the energy to be cheap [39], which compensates the low average income of Bolivia. Keeping in mind these new parameters, here are the combinations of base yearly increase used for the realistic case:

- \$10/t in 2026 \$2/y
- \$10/t in 2026 \$10/y

- \$10/t in 2026 \$15/y
- \$10/t in 2026 \$20/y
- \$10/t in 2026 \$30/y
- \$10/t in 2026 \$40/y
- "Swedish version"

The objective of these first scenarios is the establish a general behavior for the carbon taxing impact and afterwards, optimize the carbon tax value so that the energy mix is or tends to be in line with the objective of the Carbon Taxing Scenario. A sensitivity analysis will be conducted in order to point out the value that offers the best mix possible. If the realistic case ends up providing unsatisfying results, then, an "unrealistic" case will be studied with various scenarios as well to find out what the optimal carbon taxing version is. Note that 6 versions can seem as a low amount to study this case. However, various other cases were simulated, with \$5 and \$15 per ton in 2026 and up to \$100/y increase. The \$5/t and \$15/t versions were deemed redundant with respect to the \$10/t version, therefore, as a first study of this scenario, they were not considered. Nonetheless, if the \$10/t proves to be inadequate, the \$5/t and \$15/t will be used as a secondary sensitivity analysis in the realistic case to try to point out the optimal carbon taxing scenario.

The results of these different versions are presented in the following table containing the figures:

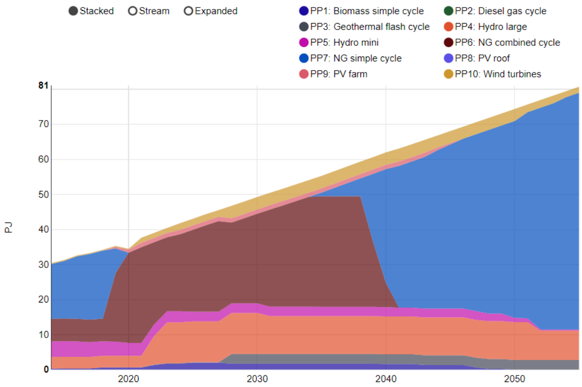

Figure B.1: Energy mix \$10/t +\$2/y

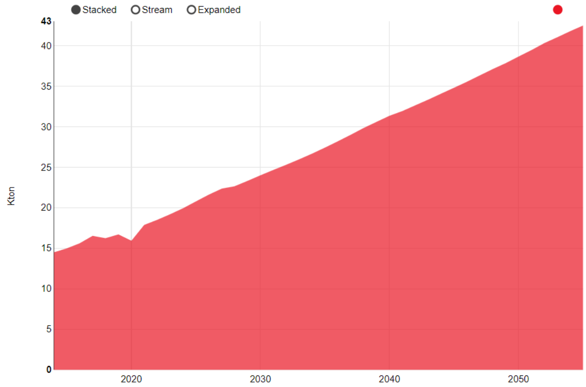

Figure B.2: $CO2_{eq}$ emission for \$10/t +\$2/y
The value reached in 2055 is 42.51 kton of CO2 emitted.

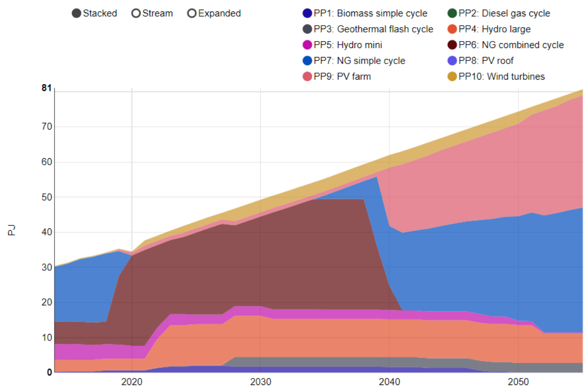

Figure B.3: Energy mix \$10/t +\$10/y

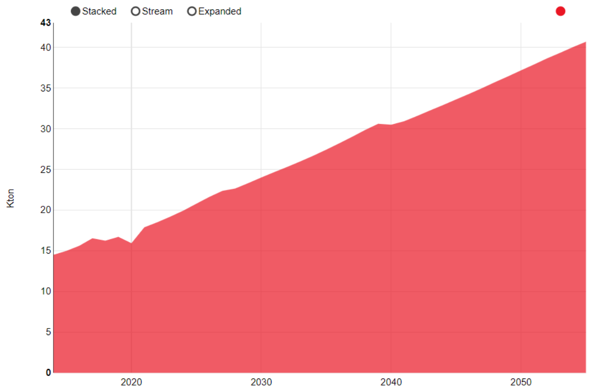

Figure B.4: $CO2_{eq}$ emission for \$10/ +\$10/y
The value reached in 2055 is 42.51 kton of CO2 emitted.

Multiple points can be drawn from these results. The first one is that, for low values, with \$10/t in 2026 and yearly increase ranging from \$0 to \$10, there is no major change before 2040 in the energy mix. Moreover, by 2055, natural gas still represents most of the energy sources' share. By 2040, the first major apparition of VRES technology (wind and solar energy sources) occurs, with PV spawning in the mix. These results show that low values have an inconclusive impact on the energy mix. Bolivia is a country with plenty of renewable energy resources. As demonstrated by Navia et al. [13], Bolivia has its fair share of wind resource, although scarcer than solar resource. Realizing that solar resource was the one put in emphasis by OSeMOSYS-MoManI, it was decided to try to

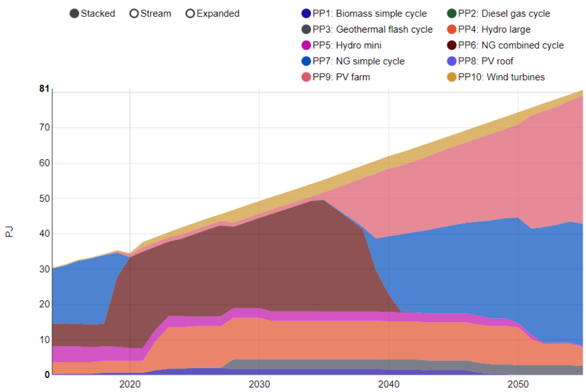

Figure B.5: Energy mix \$10/t +\$15/y

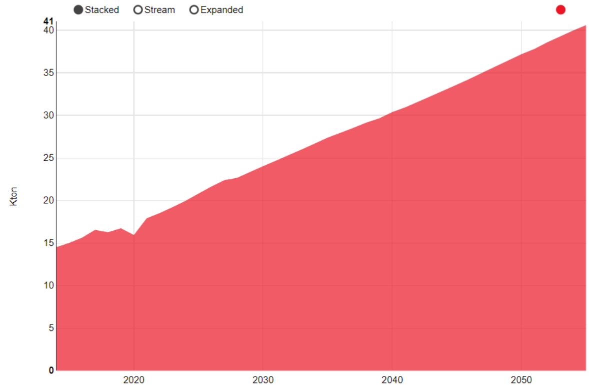

Figure B.6: $CO2_{eq}$ emission for \$10/ +\$15/y

The value reached in 2055 is 42.51 kton of CO2 emitted.

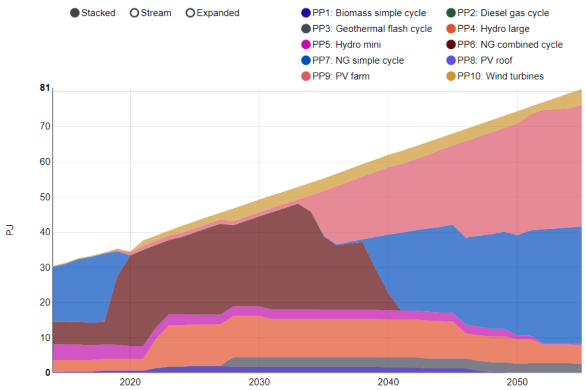

Figure B.7: Energy mix \$10/t +\$20/y

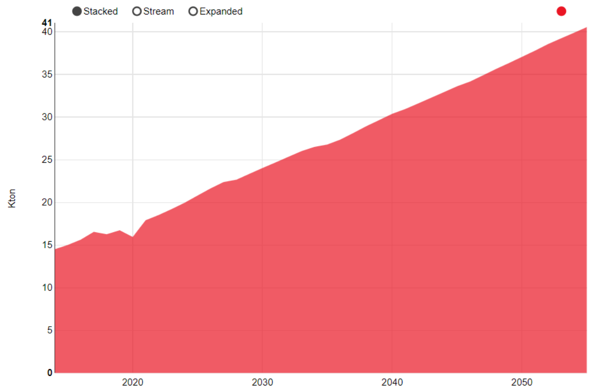

Figure B.8: $CO2_{eq}$ emission for \$10/ +\$20/y

The value reached in 2055 is 42.51 kton of CO2 emitted.

have an energy mix built with a relatively present wind energy generation. Additionally, PV technology has a gCO2eq/kWh emission slightly higher than on-shore wind turbines [66] [67]. In order to minimize the CO2eq emission, having wind as a big player in the Bolivian energy mix was considered necessary. Nevertheless, having wind and, as a matter of fact, solar electricity production making up for most of the electricity production is not healthy for the grid. Indeed, wind and solar electricity production are considered VRES, Variable Renewable Energy Sources. In comparison to other RES, hydropower, geothermal, biomass that generate a steady and controllable amount of energy on the grid,

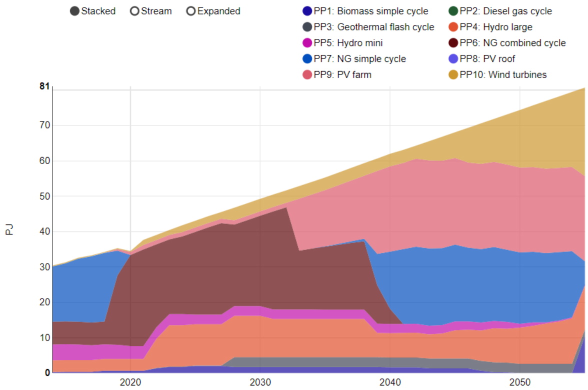

Figure B.9: Energy mix \$10/t +\$30/y

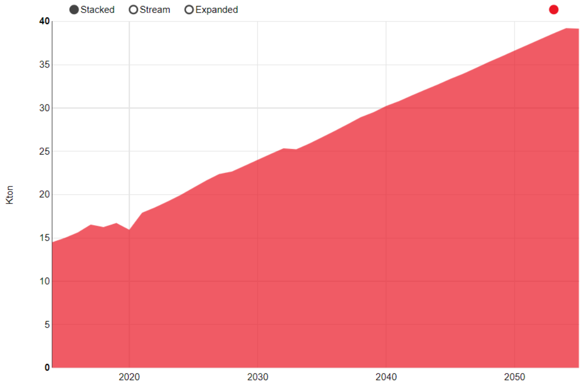

Figure B.10: $CO2_{eq}$ emission for \$10/ +\$30/y

The value reached in 2055 is 42.51 kton of CO2 emitted.

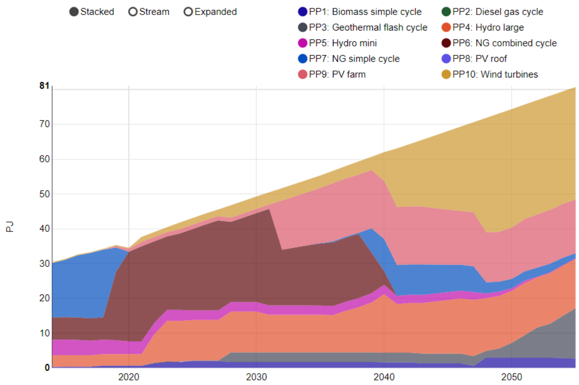

Figure B.11: Energy mix \$10/t +\$40/y

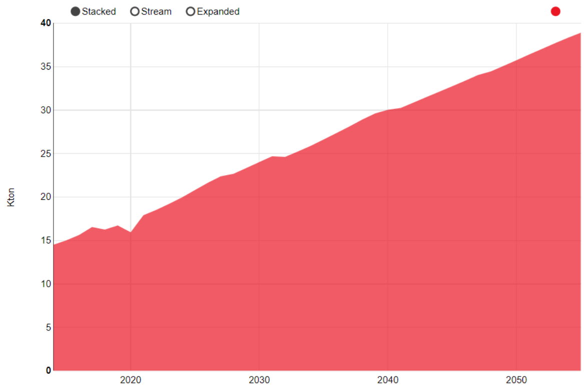

Figure B.12: $CO2_{eq}$ emission for \$10/ +\$40/y

The value reached in 2055 is 42.51 kton of CO2 emitted.

the VRES have a highly variable, highly uncertain energy production that generates a lot of perturbation on the system [68] and the apparition of "duck curves". As stated by Louis Wehenkel in scope of the course "Analysis of electric power and energy systems": "Duck curves lead to higher variability of flows and more changes in flow directions, making voltage control more complex/difficult" [69].

Moreover, B. Kroposki states in his paper "Integrating high levels of variable energy into power systems" [70] that no grids rely on more than 50% of VRES although high percentages of VRES penetration are feasible instantaneously but they average 35% on

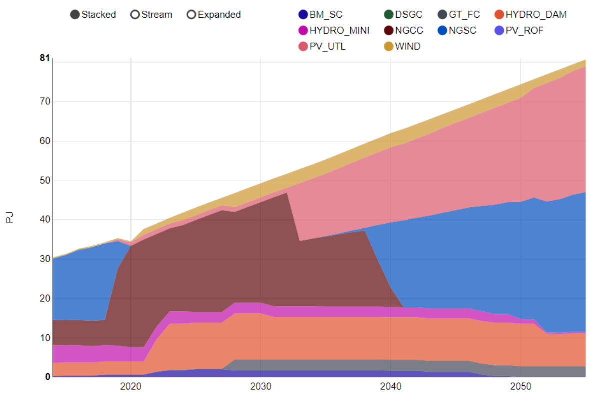

Figure B.13: Energy mix for swedish version

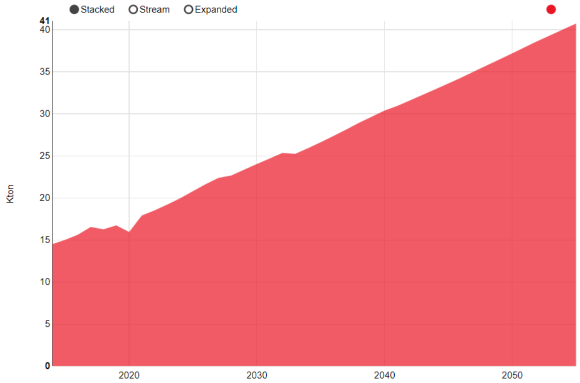

Figure B.14: $CO2_{eq}$ emission for swedish version

The value reached in 2055 is 42.51 kton of CO2 emitted.

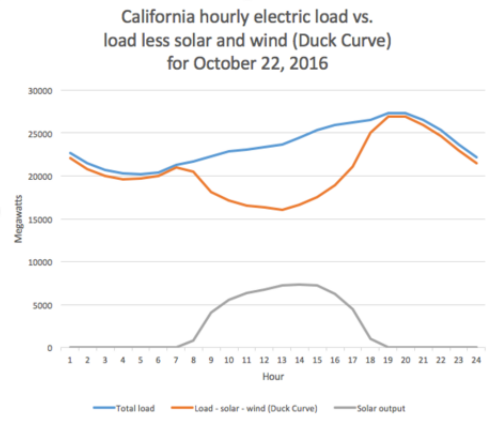

Figure B.15: Duck curves (SOURCE WIKIPEDIA)

yearly basis. And this dependance is exactly what can be observed, for the version $10/t base with a yearly increase of $40, the effects are perceived earlier in the mix, with respect to low tax values, but there is also the almost disappearance of natural gas and the dependance on wind and solar technologies. Going from one dependance to another is not a satisfying result. Recalling the previous paragraph, this is not a healthy, and consequently, satisfying result. Although it is clear that the high value taxes are not satisfying due to their dependance on VRES, almost 60% for the $40/y version. Another problem that starts to show up is the geothermal energy being heavily included in the mix. In the year 2000, it was stated that Bolivia had a geothermal potential of the most potent source was between 283 and 374 MW for an exploitation of 20 years [71]. It is also stated that, in 2019, the same geothermal could produce 100 MWe [72]. Counting on geothermal energy to fill up a large part of the Bolivian energy mix appears to be somewhat unrealistic. The "Swedish" version was found to be a mix of the +$15/y and +$20/y versions. Both versions emphasizing only PV technology, the "Swedish" version revealed to be unsatisfying as well. As stated earlier, Sweden has the world's highest carbon tax, it was only legitimate to wonder why this version didn't work for Bolivia. Sweden has been investing in RES since the 1990's - early 2000's, their energy mix is also different from the Bolivian [48] [9] and low carbon energy sources (hydro, biowaste,

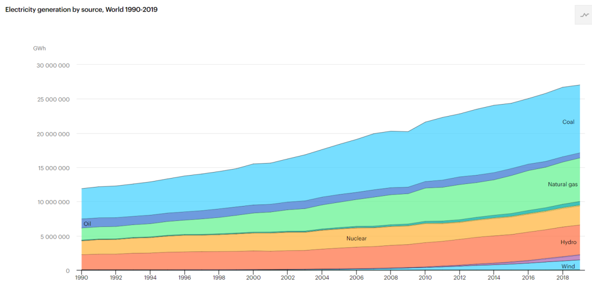

Figure B.16: Swedish energy mix

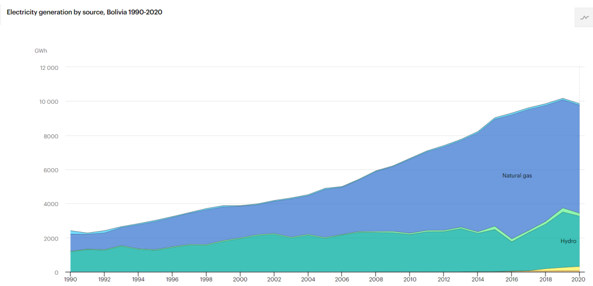

Figure B.17: Bolivian energy mix

nuclear, wind, solar) make up for 72.9% of the total energy supply. Therefore, their evolution towards carbon neutral is in a more advanced state with respect to Bolivia. To reach this same objective, Bolivia needs a harsher carbon taxing scenario, as it will be starting close to 20 years later, to catch up on Sweden, for instance. This leads to another point, the feasibility of a particular solution, what resources does Bolivia have in order to match the perfect scenario, if there ever is one. With what could be observed, the only versions that gives a somewhat satisfying result is the +30/y version. Henceforth, a sensitivity analysis was performed with the objective to find the "tipping point", the tipping point was defined as the point where the electricity generation in the Bolivian mix was not dominated by one or two technologies that could bring instabilities on the grid, such as wind or PV. It was clear that taxes with high values ($40/y or above) were not going to include the tipping As for the lower tax values, from $0/y to $10/y, the change they present is too low to be relevant. Therefore, the chosen values for the sensitivity analysis are the values around $10/t+$30/y. Going from $25/y to $35/y to measure the feasibility and balanced shares among energy sources. The following figures show the results of this sensitivity analysis: These results show a clear shift in the energy mix

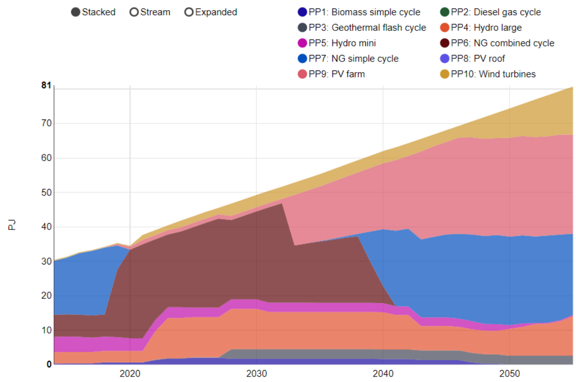

Figure B.18: Sensitivity analysis for +$25/y

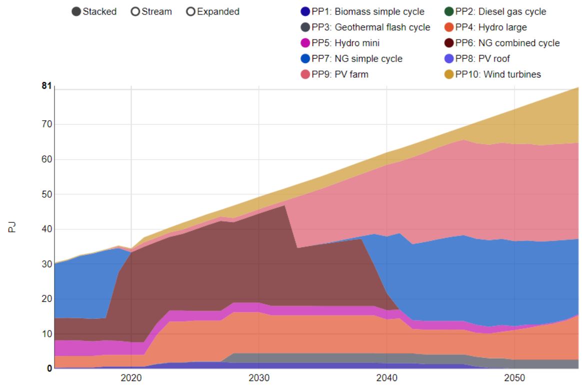

Figure B.19: Sensitivity analysis for +$26/y

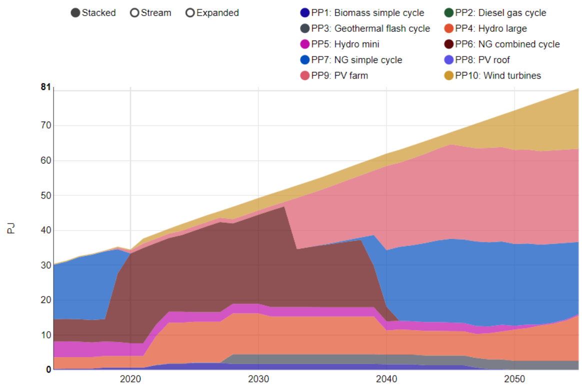

Figure B.20: Sensitivity analysis for +$27/y

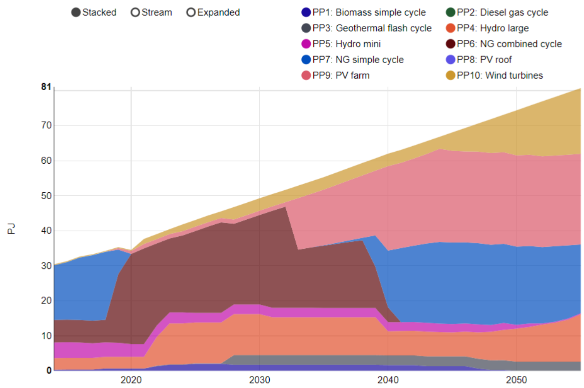

Figure B.21: Sensitivity analysis for +$28/y

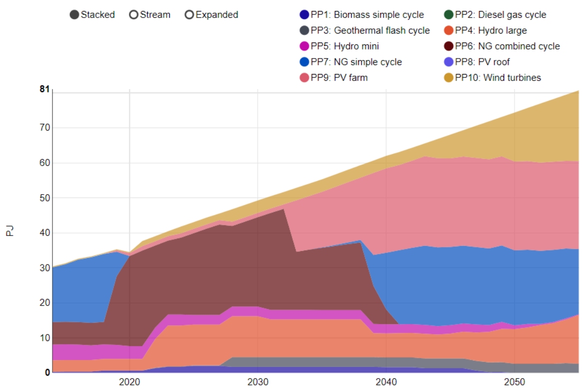

Figure B.22: Sensitivity analysis for +$29y

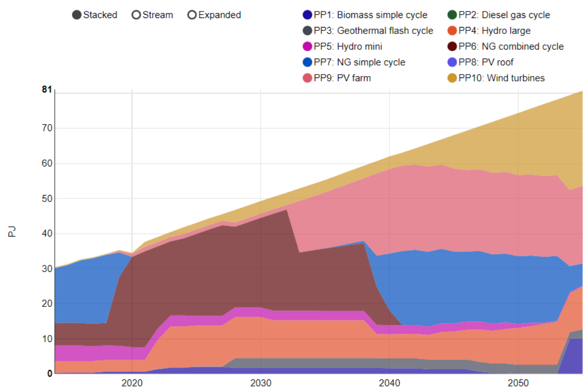

Figure B.23: Sensitivity analysis for +$31/y

when going from $29/y to $31/y, recalling the $30/y version, the tipping point seems to be located around $29/y with $10/t base in 2026. However, the VRES energy share is at 56%, and here comes the problem for balancing out energy mix with VRES and natural gas, the simulation offers a 40-50% VRES but high natural gas. For instance,

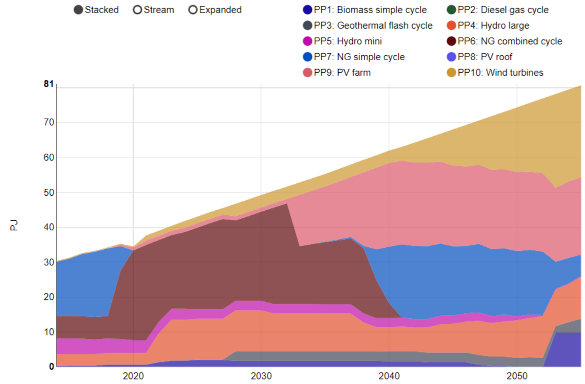

Figure B.24: Sensitivity analysis for +$32y

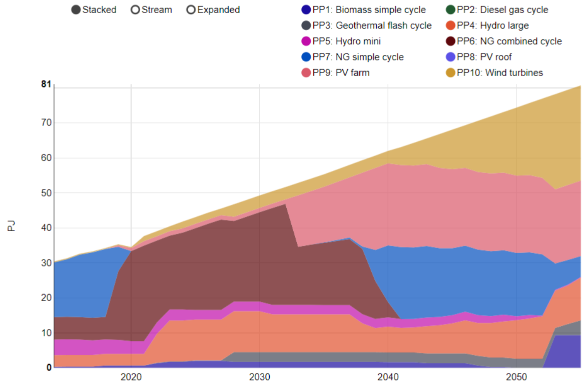

Figure B.25: Sensitivity analysis for +$33/y

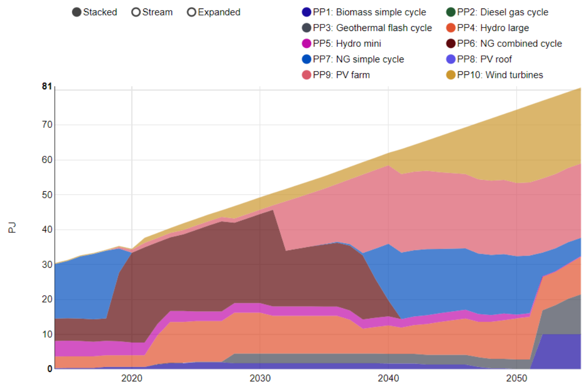

Figure B.26: Sensitivity analysis for +$34y

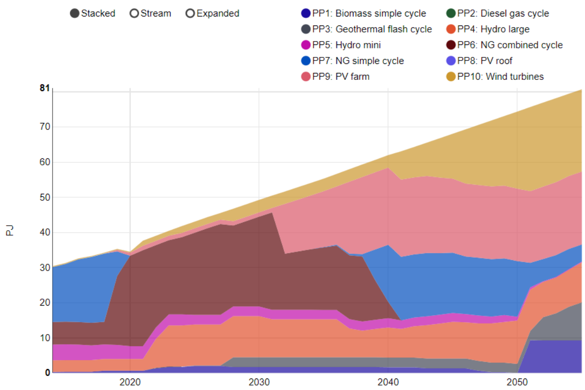

Figure B.27: Sensitivity analysis for +$35/y

$20/y offers 48% VRES share with 41% natural gas share, it's better than the current shares but nevertheless, unsatisfying or 10-15% of natural gas share but 60¡% of VRES share. If the goal was to reduce the natural gas share, then the highest tax value would be chosen but it gives instability on the grid with important presence of VRES. If the goal was to have balanced shares, $20/y would do the trick. However, the goal in this case is both which results in a barely achievable solution. It is possible, nonetheless, to rely on the complementarity between wind and solar energy sources that smoothens their intermittent nature [73]. This phenomenon makes it acceptable to exceed the 50% limit which is why a maximum of 55% will be accepted for the share of VRES. Taking this last factor into account, it is the $27/y version that fits best with 54.5% of VRES share in the energy mix. Regarding this version, one can see that, relatively early in the timeframe, the effect of the taxes is perceived in the mix and, as the resolution goes further in the years, the energy mix becomes almost equally split between PV, Wind, Natural gas and hydro technologies, with a few percentages of geothermal energy.

Obviously, the first analysis of the realistic case doesn't cover every aspect that needed to be covered. The versions left aside, $15 and $5 per ton in 2026 will be put in use now as it was observable, with the sensitivity analysis, that a slight change in the tax values can make a relevant difference. Here are the versions used: Some of these results give

$5/t in 2026 & $20/y	$15/t in 2026 & $15/y
$5/t in 2026 & $25/y	$15/t in 2026 & $20/y
$5/t in 2026 & $30/y	$15/t in 2026 & $25/y
$5/t in 2026 & $40/y	$15/t in 2026 & $30/y
$5/t in 2026 & $50/y	$15/t in 2026 & $40/y

Table B.1: Versions used

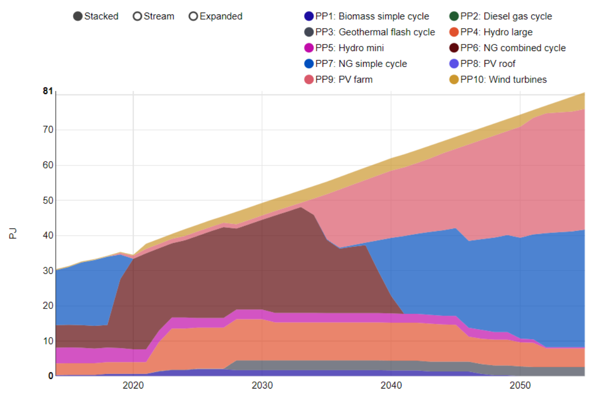

Figure B.28: $5/t + $20/y

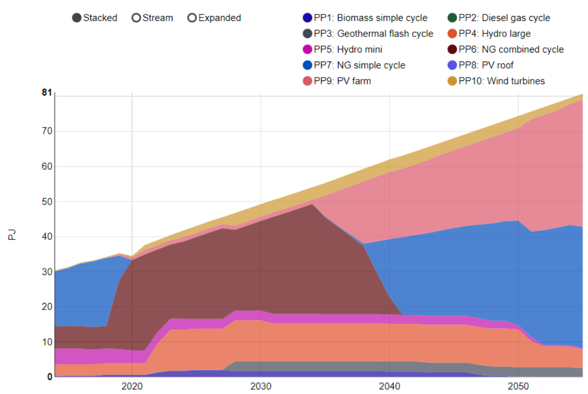

Figure B.29: $15/t + $15/y

a very satisfying, however, as stated earlier, with high values taxes, geothermal resources grow more and more important, but they tend to be uncertain, basing a planification off of geothermal resources is not safe. Therefore, the results presenting an important share of geothermal will be neglected. The most satisfying result is found for the version $15/t $25/y version. It has a VRES energy share of 53% and 29% for natural gas. With more precision, the best version is the version $15/t $27/y as the share of natural gas drops to about 25% and there is 54.7% of VRES share which remains under the 5% excess allowed. It is also the version that provides the most hydropower from all of them with a share of 16.48%. As the results from this last version is satisfying enough, the unrealistic

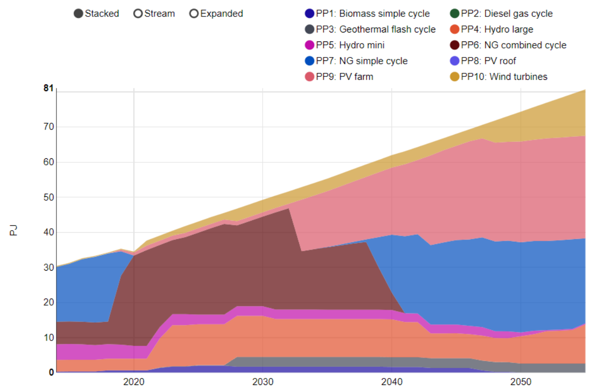

Figure B.30: \$5/t + \$25/y

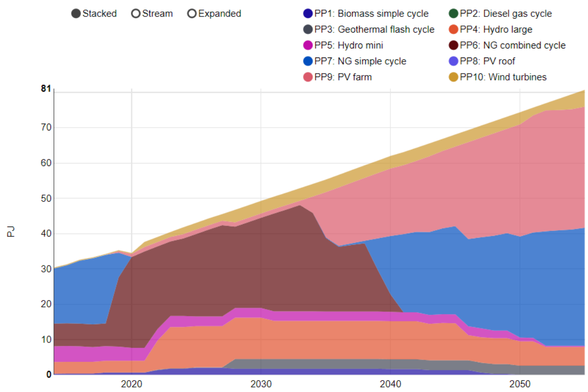

Figure B.31: \$15/t + \$20/y

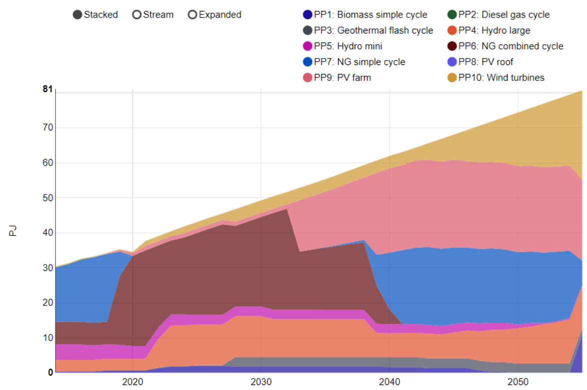

Figure B.32: \$5/t + \$30/y

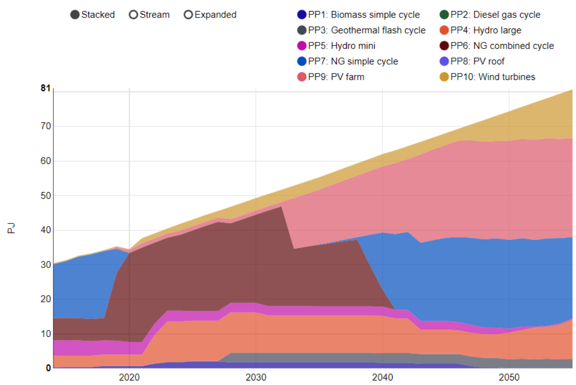

Figure B.33: \$15/t + \$15/y

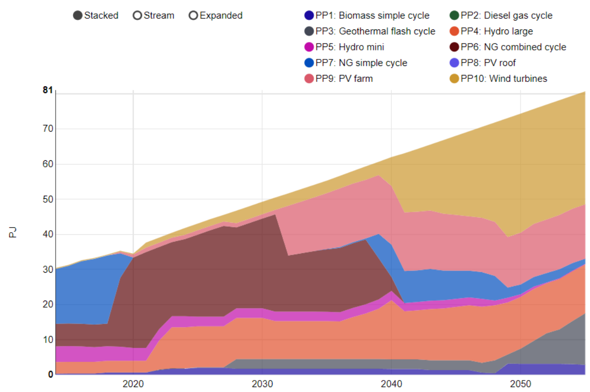

Figure B.34: \$5/t + \$40/y

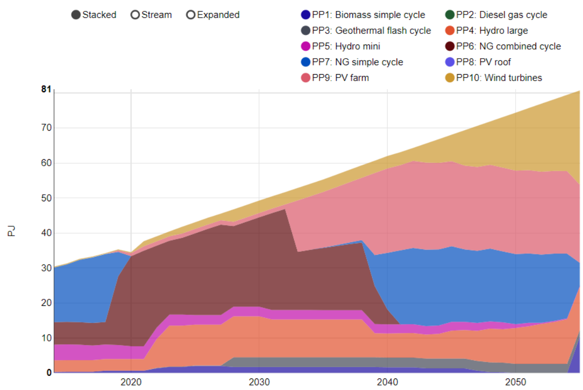

Figure B.35: \$15/t + \$30/y

scenarios would not bring anything better to the table. It was realized that the value this fits the most for this scenario is around \$875/t in 2055. Instead of running unrealistic scenarios, the behavior of the taxes was studied, linear, quadratic, exponential. Although the quadratic version gives a 57.4% share of VRES, the exponential gives very satisfying

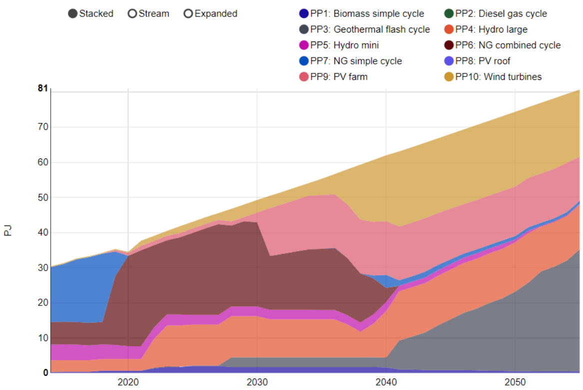

Figure B.36: \$5/t + \$50/y

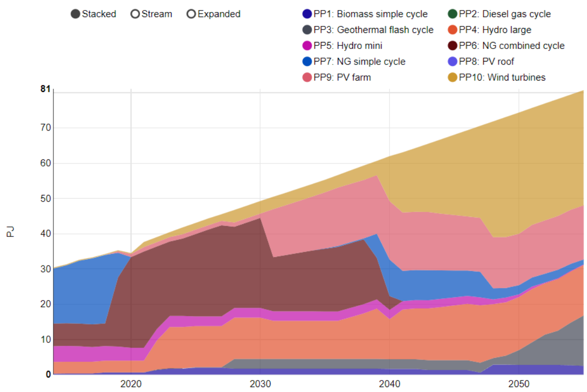

Figure B.37: \$15/t + \$40/y

results. With a VRES share of 54% and a natural gas share of 10%. It is promising. However, it also requires a high investment in biomass. As pointed out by Lopez et al [74], the Ministerio de Hidrocarburos y Energia states that biomass should make up for 8% of the total energy demand in 2027. For the exponential version, 2.2% of electricity demand is covered by biomass, therefore, it is possible to consider that this version is also a relevant solution. Therefore, the two satisfying versions, \$15/t + \$27/y and exponential, will be kept for further study.

However, a fair question comes out of this scenario: “Is the carbon taxing enough on its own?” and the answer would be obvious, the version of the CTI scenario that was chosen only has a CO2eq emission lower from the BAU’s emission by 2.55 kton. This lies in the fact the most of Bolivia’s emission is in sectors others than electricity production.

B.1 Carbon Taxing Scenario

Regarding the implementation, this scenario was declined in multiple versions; the difference was the value of the tax imposed. It was decided that the taxes would be imposed from 2025 onwards. Indeed, the Bolivian government approved the plan to initiate the energy transition in the Bolivian energy mix by 2026 [46]. The taxes are not fixed throughout the studied timeframe; the idea was to perform an evolution so that the taxes would see their value steadily increase from 2026 to 2050. Essentially, there are two different ways with which values would vary for this sensitivity analysis. For the first case, the initial values in 2026 are \$10/t with a yearly increase value from \$2/y to \$40/y. There is also a “Swedish” version which is an adaptation of the Swedish tax carbon plan, \$5.5/y increase with a value of \$126/t in 2020, \$137/t in 2022 and of \$159/t in 2026 with the same yearly increase, resulting in a \$318/t carbon tax by 2055 [47] which was considered as the maximum version for this scenario. These first values were labelled as “realistic”.

B.1.1 Initial carbon tax values

Bolivia is one of the poorest countries in South America [37] [38], consequently, it is only normal to take this factor into account and to avoid having high value taxes. The natural gas subsidy allows the electricity and the energy to be cheap [39], which compensates the low average income of Bolivia. Keeping in mind these new parameters, here are the combinations of base yearly increase used for the realistic case:

- \$10/t in 2026 \$2/y
- \$10/t in 2026 \$10/y
- \$10/t in 2026 \$15/y
- \$10/t in 2026 \$20/y
- \$10/t in 2026 \$30/y
- \$10/t in 2026 \$40/y
- ”Swedish version”

The objective of these first scenarios is the establish a general behavior for the carbon taxing impact and afterwards, optimize the carbon tax value so that the energy mix is or tends to be in line with the objective of the Carbon Taxing Scenario. A sensitivity analysis will be conducted in order to point out the value that offers the best mix possible. If the realistic case ends up providing unsatisfying results, then, an “unrealistic” case will be studied with various scenarios as well to find out what the optimal carbon taxing version is. Note that 6 versions can seem as a low amount to study this case. However, various other cases were simulated, with \$5 and \$15 per ton in 2026 and up to \$100/y increase. The \$5/t and \$15/t versions were deemed redundant with respect to the \$10/t version, therefore, as a first study of this scenario, they were not considered. Nonetheless, if the

$10/t proves to be inadequate, the $5/t and $15/t will be used as a secondary sensitivity analysis in the realistic case to try to point out the optimal carbon taxing scenario.

The results of these different versions are presented in the following table containing the figures:

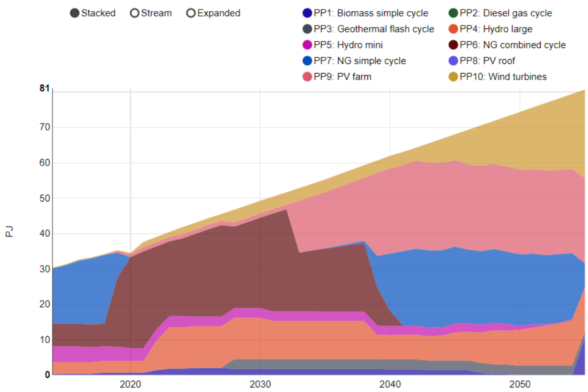

Figure B.38: Energy mix $10/t +$2/y

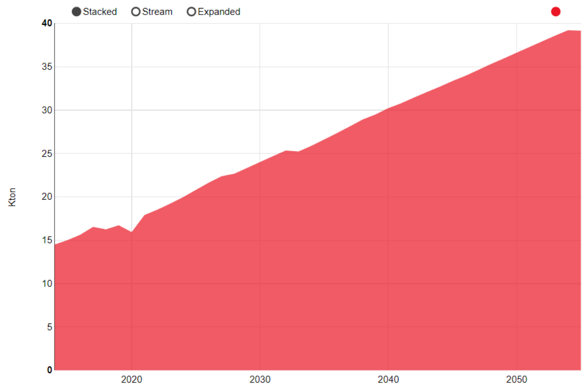

Figure B.39: $CO2_{eq}$ emission for $10/t +$2/y

With what could be observed, the only versions that gives a somewhat satisfying result is the +30/y version. For multiple reasons. The first one is that, for low values, with $10/t in 2026 and yearly increase ranging from $0 to $10, there is no major change before 2040 in the energy mix. Moreover, by 2055, natural gas still represents most of the energy sources' share. By 2040, the first major apparition of VRES technology (wind and solar energy sources) occurs, with PV spawning in the mix. These results show that low values have an inconclusive impact on the energy mix. Bolivia is a country with plenty of renewable energy resources.

As demonstrated by Navia et al. [13], Bolivia has its fair share of wind resource, although scarcer than solar resource. Realizing that solar resource was the one put in emphasis by OSeMOSYS-MoManI, it was decided to try to have an energy mix built with a relatively present wind energy generation. Additionally, PV technology has a gCO2eq/kWh emission slightly higher than on-shore wind turbines [66] [67]. In order to minimize the CO2eq emission, having wind as a big player in the Bolivian energy mix was considered necessary. Nevertheless, having wind and, as a matter of fact, solar electricity production making

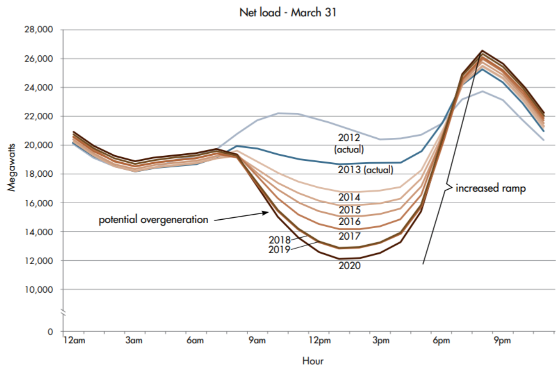

Figure B.40: Californian duck curve, from 2012 to 2020 [75]

up for most of the electricity production is not healthy for the grid. Indeed, wind and solar electricity production are considered VRES, Variable Renewable Energy Sources. In comparison to other RES, hydropower, geothermal, biomass that generate a steady and controllable amount of energy on the grid, the VRES have a highly variable, highly uncertain energy production that generates a lot of perturbation on the system [68] and the apparition of "duck curves". As stated by Louis Wehenkel in scope of the course "Analysis of electric power and energy systems": "Duck curves lead to higher variability of flows and more changes in flow directions, making voltage control more complex/difficult" [69].

Moreover, B. Kroposki states in his paper "Integrating high levels of variable energy into power systems" [70] that no grids rely on more than 50% of VRES although high percentages of VRES penetration are feasible instantaneously but they average 35% on yearly basis. And this dependance is exactly what can be observed, for the version \$10/t base with a yearly increase of \$40, the effects are perceived earlier in the mix, with respect to low tax values, but there is also the almost disappearance of natural gas and the dependance on wind and solar technologies. Going from one dependance to another is not a satisfying result. Recalling the previous paragraph, this is not a healthy, and consequently, satisfying result. Although it is clear that the high value taxes are not satisfying due to their dependance on VRES, almost 60% for the \$40/y version. Another problem that starts to show up is the geothermal energy being heavily included in the mix. In the year 2000, it was stated that Bolivia had a geothermal potential of the most potent source was between 283 and 374 MW for an exploitation of 20 years [71]. It is also stated that, in 2019, the same geothermal could produce 100 MWe [72]. Counting on geothermal energy to fill up a large part of the Bolivian energy mix appears to be somewhat unrealistic. The "Swedish" version was found to be a mix of the +$15/y and +$20/y versions. Both versions emphasizing only PV technology, the "Swedish" version revealed to be unsatisfying as well. As stated earlier, Sweden has the world's highest carbon tax, it was only legitimate to wonder why this version didn't work for Bolivia. Sweden has been investing in RES since the 1990's - early 2000's, their energy mix is also different from the Bolivian [48] [9] and low carbon energy sources (hydro, biowaste, nuclear, wind,

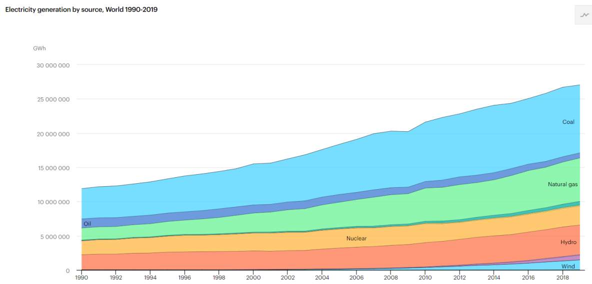

Figure B.41: Swedish energy mix

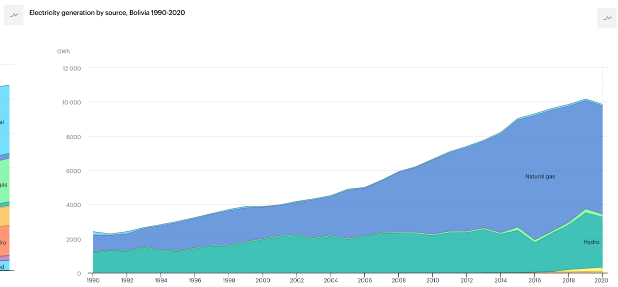

Figure B.42: Bolivian energy mix

solar) make up for 72.9% of the total energy supply. Therefore, their evolution towards carbon neutral is in a more advanced state with respect to Bolivia. To reach this same objective, Bolivia needs a harsher carbon taxing scenario, as it will be starting close to 20 years later, to catch up on Sweden, for instance.

B.1.2 Sensitivity Analysis

This leads to another point, the feasibility of a particular solution, what resources does Bolivia have in order to match the perfect scenario, if there ever is one. From the fact that the +30/y version is the most satisfying version, a sensitivity analysis was performed with the objective to find the "tipping point", the tipping point was defined as the point where the electricity generation in the Bolivian mix was not dominated by one or two technologies that could bring instabilities on the grid, such as wind or PV. It was clear that taxes with high values ($40/y or above) were not going to include the tipping As for the lower tax values, from $0/y to $10/y, the change they present is too low to be relevant. Therefore, the chosen values for the sensitivity analysis are the values around $10/t+$30/y. Going from $25/y to $35/y to measure the feasibility and balanced shares among energy sources. The following figures show the values for which a important change in the energy mix is noticed

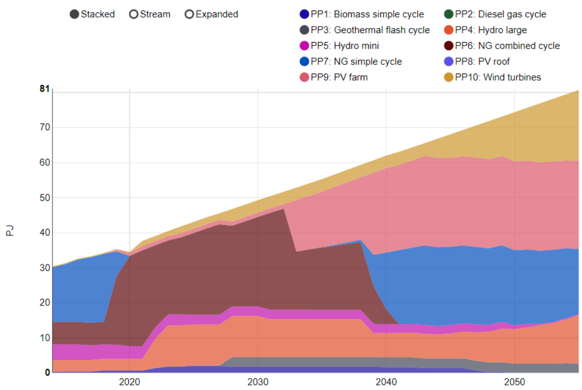

Figure B.43: Sensitivity analysis for +$29y

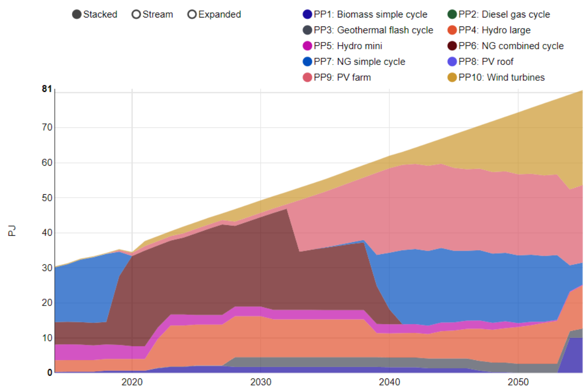

Figure B.44: Sensitivity analysis for +$31/y

These results show a clear shift in the energy mix when going from $29/y to $31/y, recalling the $30/y version, the tipping point seems to be located around $29/y with $10/t base in 2026. However, the VRES energy share is at 56%, and here comes the problem for balancing out energy mix with VRES and natural gas, the simulation offers a 40-50% VRES but high natural gas. For instance, $20/y offers 48% VRES share with 41% natural gas share, it's better than the current shares but nevertheless, unsatisfying or 10-15% of natural gas share but 60¡% of VRES share. If the goal was to reduce the natural gas share, then the highest tax value would be chosen but it gives instability on the grid with important presence of VRES. If the goal was to have balanced shares, $20/y would do the trick. However, the goal in this case is both which results in a barely achievable solution. It is possible, nonetheless, to rely on the complementarity between wind and solar energy sources that smoothens their intermittent nature [73]. This phenomenon makes it acceptable to exceed the 50% limit which is why a maximum of 55% will be accepted for the share of VRES. Taking this last factor into account, it is the $27/y version that fits best with 54.5% of VRES share in the energy mix. Regarding this version, one can see that, relatively early in the timeframe, the effect of the taxes is perceived in the mix and, as the resolution goes further in the years, the energy mix becomes almost equally split between PV, Wind, Natural gas and hydro technologies, with a few percentages of geothermal energy.

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\$5/t in 2026 & \$20/y	\$15/t in 2026 & \$15/y
\$5/t in 2026 & \$25/y	\$15/t in 2026 & \$20/y
\$5/t in 2026 & \$30/y	\$15/t in 2026 & \$25/y
\$5/t in 2026 & \$40/y	\$15/t in 2026 & \$30/y
\$5/t in 2026 & \$50/y	\$15/t in 2026 & \$40/y

Table B.2: Versions used

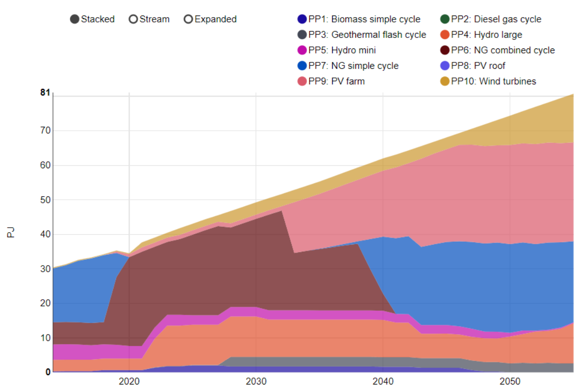

Figure B.45: \$15/t + \$25/y

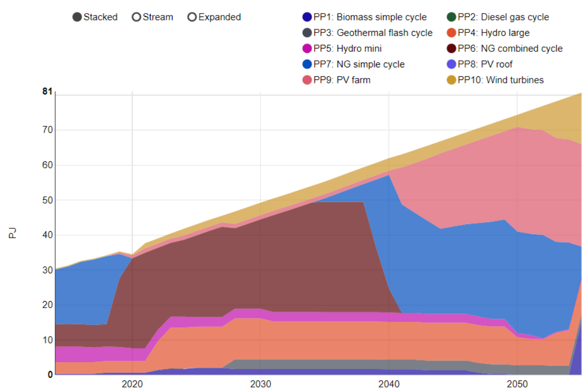

Figure B.46: Exponential evolution

a very satisfying, however, as stated earlier, with high values taxes, geothermal resources grow more and more important, but they tend to be uncertain, basing a planification off of geothermal resources is not safe. Therefore, the results presenting an important share of geothermal will be neglected. The most satisfying result is found for the version \$15/t \$25/y version. It has a VRES energy share of 53% and 29% for natural gas. By performing a sensitivity analysis, the best version is the version \$15/t \$27/y as the share of natural gas drops to about 25% and there is 54.7% of VRES share which remains under the 5% excess allowed. It is also the version that provides the most hydropower from all of them with a share of 16.48%. As the results from this last version is satisfying enough, the unrealistic scenarios would not bring anything better to the table. It was realized that the value this fits the most for this scenario is around $875/t in 2055. Instead of running unrealistic scenarios, the behavior of the taxes was studied, linear, quadratic, exponential. Although the quadratic version gives a 57.4% share of VRES, the exponential gives very satisfying results. With a VRES share of 54% and a natural gas share of 10%. It is promising. However, it also requires a high investment in biomass. As pointed out by Lopez et al [74], the Ministerio de Hidrocarburos y Energia states that biomass should make up for 8% of the total energy demand in 2027. For the exponential version, 2.2% of electricity demand is covered by biomass, therefore, it is possible to consider that this version is also a relevant solution. Therefore, the two satisfying versions, $15/t + $27/y and exponential, will be kept for further study.

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Appendix C

Dispa-SET detailed description

All types of technologies in Dispa-SET

Technology	Description	VRES	Storage
COMC	Combined cycle	N	N
GTUR	Gas turbine	N	N
HDAM	Conventional hydro dam	N	Y
HROR	Hydro run-of-river	Y	N
HPHS	Pumped hydro storage	N	Y
ICEN	Internal combustion engine	N	N
PHOT	Solar photovoltaic	Y	N
STUR	Steam turbine	N	N
WTOF	Offshore wind turbine	Y	N
WTON	Onshore wind turbine	Y	N
CAES	Compressed air energy storage	N	Y
BATS	Stationary batteries	N	Y
BEVS	Battery-powered electric vehicles	N	Y
THMS	Thermal storage	N	Y
P2GS	Power-to-gas storage	N	Y
P2HT	Power-to-heat	N	Y
SCSP	Concentrated solar power	Y	Y

Reserve constraints

Besides the production/demand balance, the reserve requirements (upwards and downwards) in each node must be met as well. In Dispa-SET, three types of reserve requirements are taken into account:

- Upward secondary reserve (2U): reserve that can only be covered by spinning units
- Downward secondary reserve (2D): reserve that can only be covered by spinning units
- Upward tertiary reserve (3U): reserve that can be covered either by spinning units or by quick-start offine units

The secondary reserve capability of committed units is limited by the capacity margin between current and maximum power output:

$$Reserve2U_{u,i} \leq PowerCapacity_u AvailabilityFactor_{u,i} \times (1 OutageFactor_{u,i}) \times Committed_{u,i} Poweru, i$$

The same applies to the downwards secondary reserve capability, with an additional term to take into account the downward reserve capability of storage units:

$$Reserve2D_{u,i} \leq Power_{u,i} PowerMustRun_{u,i} \times Committed_{u,i} + (StorageChargingCapacityu \times Nunits_u S$$

The quick start (non-spining) reserve capability is given by:

$$Reserve3U_{u,i} \leq (Nunits_u Committed_{u,i}) QuickStartPower_{u,i} \times TimeStep$$

The secondary reserve demand should be fulfilled at all times by all the plants allowed to participate in the reserve market:

$$Demand2U_{n,h} \leq \sum_{u,t} (Reserve2U_{u,i} \times Technology_{u,t} \times Reserve_t \times Location_{u,n} + LL2U_{n,i}$$

The same equation applies to downward reserve requirements (2D). The tertiary reserve can also be provided by non-spinning units. The inequality is thus transformed into:

$$Demand_{3U,n,h} \leq \sum_{u,t} [(Reserve_{2U,u,i} + Reserve_{3U,u,i}) \times Technology_{u,t} \times Reserve_t \times Location_{u,n}] + LL_{3U,n,i}$$

The reserve requirements are defined by the users. In case no input is provided a default formula is used to evaluate the needs for secondary reserves as a function of the maximum expected load for each day. The default formula is described by:

$$Demand_{2U,n,i} = \sqrt{10 \times max_h(DemandDA, n, h) + 150^2} - 150$$

Ramping constraints

Each unit is characterized by a maximum ramp-up and ramp-down capability. This is translated into the following inequality for the case of ramping up:

$$Power_{u,i}Power_{u,i1} \leq (Committed_{u,i}StartUp_{u,i}) \times RampUpMaximum_u \times TimeStep + StartUp_{u,i} \times Ramp$$

and for the case of ramping down:

$$Power_{u,i1}Power_{u,i} \leq (Committed_{u,i}ShutDown_{u,i}) \times RampDownMaximum_u \times TimeStep + ShutDown_{u,}$$

Note that this formulation is valid for both the clustered formulation and the binary formulation. In the latter case (there is only one unit u), if the unit remains committed, the inequality simplifies into:

$$Power_{u,i}Power_{u,i1} \leq RampUpMaximum_u TimeStep + LLRampUp_{u,i}$$

If the unit has just been committed, the inequality becomes:

$$Power_{u,i}Power_{u,i1} RampStartUpMaximum_u TimeStep + LLRampUp_{u,i}$$

And if the unit has just been stopped:

$$Power_{u,i}Power_{u,i1} \leq PowerMustRun_{u,i} + LLRampUp_{u,i}$$

Network-relate constraints The flow of power between nodes is limited by the capacities of the transmission lines:

$$Flow_{l,i} \geq FlowMinimum_{l,i}$$

$$Flow_{l,i} \leq FlowMaximum_{l,i}$$

In this model a simple Net Transfer Capacity (NTC) between countries approach is followed. No DC power flow or Locational Marginal Pricing (LMP) model is implemented.