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University of Liège - Faculty of Applied Sciences

Evaluation of the climate uncertainties using the Dispa-SET model on the future power system of Bolivia

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Master's thesis carried out to obtain the Master's degree in Aerospace Engineering

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Abstract

This work represents a collaborative effort among the University of Liège, the Center of Investigations in Energy of the Mayor San Simon University in Bolivia, and the Bolivian electricity company ENDE Corporacion.

The primary tool used in this study is the Dispa-SET model, which is a short-term power dispatch and unit commitment model initially developed by the Joint Research Center of the EU Commission in 2009. The model has undergone significant improvements, including the development of an extension capable of accurately modeling cascades of hydroelectric power plants. Given that the Bolivian grid contains a large number of hydro units forming cascades, this new feature should offer enhanced precision in electricity dispatch simulations.

In collaboration with Matija Pavićević, this work focuses on the continued development and application of the new extension in the context of Bolivia. The results obtained from Dispa-SET 2.5 and the new version are compared using the same inputs to analyze the improvements achieved.

Bolivia aims to increase its share of renewable energy to 79% by 2030. Consequently, the second part of this study involves integrating a list of future projects into the electric grid, simulating their impact using the new formulation, and studying their influence on electricity dispatch.

As a significant portion of Bolivia's energy production comes from hydro power plants, the country's electricity generation is vulnerable to weather conditions. Hence, the final objective of this work is to utilize extreme scenarios from historical weather data to model and evaluate the impact of climate uncertainties on Bolivia's future power system.

The findings demonstrate that the new version of the model provides more accurate and realistic results, particularly concerning hydro power. The Bolivian electric system exhibits favorable conditions for the integration of renewables, offering the possibility to significantly reduce dependence on fossil fuels and achieve sustainability objectives. The study on climate uncertainties highlights the system's vulnerability, particularly during drier years, but suggests that new infrastructure can mitigate these issues.

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Nomenclature

CE	Central zone
CNDC	Comite Nacional de Despacho de Carga
GHG	Greenhouse Gases
HDAM	Conventional hydro dam
HDAMC	Cascade hydro dam
LL	Lost Load
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
MTS	Mid-Term Scheduling
NDC	Nationally Determined Contribution
NO	North zone
NTC	Net Transfer Capacities
OR	Oriental zone
PHOT	Solar photovoltaic
RES	Renewable Energy Source
RoW	Rest of the World
SDG	Sustainable Development Goal
SDP	Stochastic Dynamic Programming
SIN	National Interconnected System
SU	South zone
VRES	Variable Renewable Energy Source
WTON	Onshore wind turbine

Part I

Introduction

The urgent need to address climate change and its detrimental impact on the environment has become a global priority. In response, the Paris Agreement has set a target for countries to become climate-neutral by 2050, with the aim of limiting global warming to well below 2 degrees Celsius. Given that the energy sector is a major source of greenhouse gas emissions, it plays a crucial role in mitigating climate change. Consequently, an increasing number of countries are prioritizing decarbonization efforts. Bolivia is no exception to this trend and is actively working to enhance its renewable energy production.

Bolivia is the fifth largest country in South America but also one of the only landlocked countries of the continent. Its economy classified as lower-middle-income, has been greatly impacted by the gas industry. Following the discovery of large natural gas reservoirs, the government made significant investments in fossil-fuel energy power plants between 2006 and 2017, establishing Bolivia as an important gas exporter [1]. While significant progress has been made in improving access to electricity, with a 96% electrification rate achieved in 2020 [2], the majority of the energy sector still relies on gas, accounting for 60% of the energy mix in 2021. In line with Sustainable Development Goal (SDG) 7, Bolivia aims to achieve universal access to electricity by 2025. However, to address both SDG 7 and SDG 13, which focus on climate action, the Bolivian government is taking actions to implement more renewable in order to decrease their usage of fossil fuel.

Figure 1 depicts the division of Bolivia's energy sector into four zones, interconnected through the Central zone. The North zone contains the largest hydro capacity, while the Oriental zone relies predominantly on gas. The Southern zone has limited connectivity to the rest of the country. Bolivia's diverse topography results in a wide range of climates. The Altiplano, situated around 4,000 meters above sea level, experiences cold and semi-arid conditions with strong winds in the southwestern region. The central part enjoys a Mediterranean-like climate throughout the year. Towards the East lies the lowland plains of the Amazon Basin, characterized by a consistently wet and tropical climate.

In 2014, Bolivia has set a target of achieving 70% renewable energy production by 2025 [2]. The country possesses significant potential for solar and hydro power, with over 97% of its land suitable for solar generation [3]. In 2020, three solar plants with a total capacity of 115 MW were implemented in the Bolivian National Interconnected System (SIN). Hydroelectric power plays a significant role, accounting for over 30% of energy production in 2021. The installed capacity is planned to increase from 3495 MW to 4036 MW by 2025 [4]. Additionally, the expansion of the electrical transmission infrastructure between the zones is part of the plan. This thesis is based on the state of the SIN in 2026, incorporating these new infrastructures.

Figure 1: Map of Bolivia divided into 4 zones [4].

Aligned with their objective planned for 2025, Bolivia has decided to push even further in their energy transition. In fact, in their Nationally Determined Contribution (NDC) [5] they committed to the new goal of achieving 79% of renewable energy production and 50% of renewable capacity by 2030. To meet these goals, ENDE, the national electricity company, has planned a range of renewable projects, including solar panels and wind turbines, that will be integrated into the Bolivian grid. These projects introduce intermittency and variability into power generation, posing challenges in maintaining a consistent balance between energy supply and demand. Consequently, a significant focus of this thesis is devoted to testing the system's flexibility, considering the inclusion of these new projects.

The consequences of climate change, including extreme weather events and rising temperatures, pose significant challenges for Bolivia's energy sector. Bolivia relies heavily on hydroelectric power, and extreme weather conditions, such as droughts or heavy rainfall, can directly affect water availability and river flow. This thesis investigates the behavior and resilience of the Bolivian electricity system under extreme weather conditions, emphasizing the potential risks of water scarcity and excessive curtailment.

To simulate and analyze the different scenarios, this thesis used the Dispa-SET model, an open-source short-term unit-commitment and power dispatch model. This model is designed to optimize the operational cost of the power system under various conditions and constraints.

In addition, a module was has been developed in order to model hydroelectric cascade. A large part of the background work of this thesis was therefore to keep developing and adjust this new module to the Bolivian grid.

1 State of the art

Several dispatch models can be found in the literature. One model that shares similar characteristics to Dispa-SET is LUSYM (KULeuven Energy Institute) [6]. However, not all models have the same features as Dispa-SET. For instance, SimSEE [7], an open-source software developed by the Institute of Electrical Engineering of the University of the Oriental Republic of Uruguay, is a local model in South America that uses Stochastic Dynamic Programming (SDP) instead of Mixed-Integer Linear Programming (MILP). Another model frequently referenced in this work is SDDP, the model employed by the Bolivian national dispatch committee (CNDC). SDDP is a commercial stochastic dual dynamic programming model specifically designed for hydrothermal dispatch. While both SDDP and LUSYM can be employed for short and long-term studies, Dispa-SET is primarily used for short-term analysis.

The Dispa-SET model has been widely used in various studies to simulate future grids and evaluate the impact of renewable energy integration. However, many of these studies focus on regions other than Bolivia. For instance, Matija Pavičević modeled the power systems of seven countries in Southeast Europe [8]. The study simulated predicted scenarios for 2020 and 2030, aiming to assess the stability of the power system under high shares of renewable energy. In addition, Matija Pavičević also applied the Dispa-SET model to analyze African Power Pools [9]. Furthermore, Sylvain Quoilin conducted a comprehensive study on renewable energy integration in Europe using Dispa-SET 2.1 [10].

More recently Disap-SET have been applied on the Bolivian system. In his article [3], Marco Navia explores the potential of renewable energy in Bolivia. The study begins by examining the availability of renewable resources in the country, specifically wind, solar, and hydro. The Dispa-SET model is employed to simulate various scenarios with increasing levels of renewable penetration, allowing for an analysis of the system's behavior under these conditions. The findings indicate that Bolivia holds considerable potential for renewable energy, and that the integration of renewables in the overall generation mix can significantly reduce thermal generation and operational costs. However, it also highlights a notable challenge in the form of curtailment, where a significant amount of renewable energy goes unused. This underscores the importance of expanding the power capacity of transmission lines to accommodate the increased renewable generation and minimize curtailment.

Sulmayra Zarate conducted a comprehensive study on hydropower generation in the Bolivian electric system [11]. The study focuses on evaluating the influence of different rainfall years on hydropower generation and storage capacity. To analyze the impact, the study uses water input data obtained through the Soil Moisture method and the Water Evaluation and Planning software. The findings reveal that the system underutilizes water resources during the wet season. However, optimizing the utilization of available water resources could lead to significant reductions in operational costs and CO2 emissions. The study emphasizes that increasing the voltage in specific transmission lines would further improve system operation.

Part II

Methodology

1 The Dispa-SET model

The Dispa-SET model [1] is an open-source unit commitment and optimal dispatch model. The model focuses on minimizing the total power system costs to perform its optimization. However, it is not a capacity expansion model and does not make assumption about changing fuel prices, new policies or electricity demand projections.

The model was initially implemented for European grids [12], but it has since been adapted for other parts of the world, such as Africa or the Balkan countries [8]. As renewable energy plays a growing role in electric systems worldwide, the model has been reformulated to include more flexibility options [10] and was applied to the Bolivia system [3][11]. As part of this work, a new extension has been developed to handle additional constraints specific to hydro power cascade systems.

The optimization problem can be expressed as a MILP or relaxed into a Linear Program (LP). In the MILP formulation, integer variables represent the commitment and start-up/shut-down status of the units. The model is implemented in `Python` while the optimization problem with all its constraints is written and solved using `GAMS`[2]. Data conversion for inputs and results is handled by preprocessing and post-processing functions, which are executed automatically within the predefined workflow. All the necessary scripts to run the model can be found in the open-source `GitHub` repository [3].

The following sections provide an overview of the general parameters and features of the Dispa-SET 2.5 formulation. Additionally, a subsection is dedicated to outlining the new inputs and constraints that have been incorporated in the development of the new extension.

1.1 Inputs

Technologies
A list of various technologies are implemented in Dispa-SET. Each technology is categorized as either conventional or variable renewable which indicates whether the energy produced can be stored or not. Table 1 presents the technologies used within the scope of this work.

---

[1] Dispa-SET documentation: https://www.dispaset.eu/en/latest/

[2] GAMS website: https://www.gams.com

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

Technology	Description	VRES	Storage
GTUR	Gas turbine	N	N
HDAM	Conventional hydro dam	N	Y
HDAMC	Cascade hydro dame	N	Y
PHOT	Solar photovoltaic	Y	N
WTON	Onshore wind turbine	Y	N

Table 1: Technologies used

Fuels

Since certain technologies can be powered by multiple sources, it is necessary to specify the fuels used. For this purpose, Dispa-SET categorizes fuels into different groups, as listed below:

- BIO: Biomass
- GAS: Gas
- GEO: Geothermal heat
- SUN: Solar energy
- WAT: Water energy
- WIN: Wind energy

Demand

The electricity demand is provided for each zone as a time series, with hourly resolution. However, the time step can be adjusted to achieve a balance between accuracy and computational cost. This means that one can choose a shorter or longer time step depending on specific needs and computational resources. A shorter time step provides more detailed and accurate results but may require more computational resources, while a longer time step leads to less detailed results but may be computationally more efficient.

Zones

For this study, the country of Bolivia has been divided into four zones: Central (CE), North (NO), South (SU), and Oriental (OR). The distribution of these zones is illustrated in Figure 1.

Power Plants Data

The data related to the power plants are grouped together in a single file. The list of technical and operational parameters relevant to this work is presented in Table 2.

Description	**Field name**	**Units**
Unit name	Unit	-
Installed Power or Heat Capacity (for one unit)	PowerCapacity	MW
Number of thermal blocks belonging to one unit	Nunits	-
Technology	Technology	-
Primary fuel	Fuel	-
Zone (Power)	Zone	-
Efficiency	Efficiency	%
Efficiency at minimum load	MinEfficiency	%
CO2 intensity	CO2Intensity	t_{CO2eq}/MWh
Minimum load	PartLoadMin	%
Ramp up rate	RampUpRate	%/min
Ramp down rate	RampDownRate	%/min
Start-up time	StartUPTime	h
Minimum up time	MinUpTime	h

Table 2: Common parameters in the power plant database.

Storage and hydro data

Storage units, such as the HDAMs in this work, are an extension of regular units. They require four additional parameters, which are listed in Table 3.

Description	**Field name**	**Units**
Storage capacity	STOCapacity	MWh
Self-discharge rate	STOSelfDischarge	%/day
Maximum charging power	STOMaxChargingPower	MW
Charging efficiency	STOChargingEfficiency	%

Table 3: Parameters used in the power plant database for storage units

Inflows

The inflows are defined as the contribution of exogenous sources to the level or state of charge of the reservoir. To specify these inflows, a dedicated folder in the database should include the scaled inflows for each hydro unit. The scaled inflows are calculated by converting the inflows into a non-dimensional value using the following formula:

$$ScaledInflows = \frac{Inflows[m^3/s] \cdot EfficiencyFactor[MW/(m^3/s)]}{IntalledCapacity[MW]} \tag{1.1}$$

Storage Level

In the general objective function, emptying the storage level is assigned a zero marginal cost. Without any constraints, the optimization tends to deplete the storage completely by the end of the optimization horizon. To avoid this, a minimum storage level is enforced at the end of each horizon. In some cases, historical levels can be used for this purpose. However, this study employs a long-term hydro scheduling optimization approach known as Mid-term Scheduling (MTS). For more detailed information on MTS, please refer to Section 1.3.

Interconnections
The Dispa-SET model considers two types of interconnections: interconnections between the simulated zones and interconnections between the simulated zones and the rest of the world (RoW). In this work, these interconnections are represented by net transfer capacities (NTCs). However, the model simplifies the representation by not considering DC power flows.

The NTCs need to be provided as time series data in both directions, as they can vary over time and may not be symmetrical. This means that the NTCs can differ between the two directions of power flow. Specifically, for the case of Bolivia, the NTCs are defined for each pair of the four zones (NO, SU, OR, CE) in both directions. These values correspond to the constant and limit values of the high voltage transmission lines depicted in Figure 1.

Renewable Generation
Energy generated by Variable Renewable Energy Source (VRES) cannot be stored; it can either be fed directly into the grid or curtailed. Additionally, the availability of technologies such as wind turbines and photovoltaic panels varies over time. To account for this variability, an exogenous time series called the "availability factor" needs to be provided. The availability factor represents the proportion of the nominal power capacity that can be generated at each time step. For non-renewable technologies, the availability factor is automatically assigned a value of 1, indicating constant availability throughout the specified time period.

Fuel prices
Fuel prices can vary based on the zone and time, thus requiring them to be defined as time series for each zone. In cases where specific fuel prices are not available, a default value needs to be provided as a fallback option.

1.2 Model Description

Dispa-SET is a model used for representing the short-term operation of large-scale power systems. By utilizing the technical and economic data, the demands in each node and the transmission network, the model solves the unit commitment and economic dispatch problem to meet electricity demand while minimizing operating costs.

The problem consists of two parts: the unit commitment problem and the economic dispatch problem. The former problem involves making integer decisions to determine the start-up and shut-down schedule of all production units, considering constraints such as minimum up and down times. Binary variables representing the on-off status of each unit are assigned for each time interval. The economic dispatch problem determines the continuous power output of each committed unit for each hour of the time horizon, while considering transmission network constraints.

The problem is formulated as a MILP model, which is solved using a branch-and-bound algorithm implemented in GAMS. Additionally, the model can be relaxed to a Linear Program to reduce computational time. However, the LP formulation does not consider certain costs and constraints, such as start-up and shut-down costs and minimum up and down times.

Dispa-SET is designed to model large interconnected power systems, requiring a compact and tight formulation. Tightness refers to the proximity between the relaxed and integer solutions of the MILP and the space explored by the solver. Compactness relates to the amount of data processed by the solver, affecting the computation speed. Adding constraints increases tightness but reduces compactness by increasing problem size, and vice versa. Therefore, striking the right balance between the two is crucial.

Objective function
The primary objective of the model is to minimize the total power system cost. This total cost is the sum of different contributions that can be listed as:

- 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 of 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.

Therefore, for this model, this objective function is used:

$$
\begin{aligned}
min\Bigg[&\sum_{u,i} CostFixed_u \cdot Committed_{u,i} \cdot TimeStep \\
&+\sum_{u,i}(CostStartUpH_{u,i} + CostShutDownH_{u,i}) \\
&+\sum_{u,i}(CostRampUpH_{u,i} + CostRampDownH_{u,i}) \\
&+\sum_{u,i} CostVariable_{u,i} \cdot Power_{u,i} \cdot TimeStep \\
&+\sum_{l,i} PriceTransmission_{l,i} \cdot Flow_{l,i} \cdot TimeStep \\
&+\sum_{n,i} CostLoadShedding_{n,i} \cdot ShedLoad_{n,i} \cdot TimeStep \\
&+\sum_{i,n} VOLL_{Power} \cdot (LL_{MaxPower,i,n} + LL_{MinPower,i,n}) \cdot TimeStep \\
&+\sum_{u,i} 0.7 \cdot VOLL_{Ramp} \cdot (LL_{RampUp,u,i} + LL_{RampDown,u,i}) \cdot TimeStep \\
&+\sum_{s,i} CostOfSpillage \cdot Spillage_{s,i} \cdot TimeStep \\
&+\sum_{s} WaterValue \cdot WaterSlack_s\Bigg]
\end{aligned} \tag{1.2}
$$

where the sets u, i, l and n respectively represents the power generation units, the simulated hours, the interconnection lines between zones. s represents the storage technologies (without heat units).
As seen in the equation, the model gives the possibility of voluntary load shedding some units in case of a contractual arrangement between generator and consumers.

Day-ahead energy balance

In addition to minimizing costs, the model must satisfy the supply-demand balance for each period and each node in the day-ahead market equation. This constraint ensures that the total power in one node in equal to the demand of that node.

$$
\begin{aligned}
&\sum_{u}(Power_{u,i} \cdot Location_{u,n}) + \sum_{l}(Flow_{l,i} \cdot LineNode_{l,n}) = \\
&\qquad Demand_{DA,n,h} + \sum_{s}(StorageInput_{s,h} \cdot Location_{s,n}) - ShedLoad_{n,i} + \\
&\qquad \sum_{p2h} PowerConsumption_{p2h,i} \cdot Location_{p2h,n} - LL_{MaxPower_{n,i}} + LL_{MaxPower_{n,i}}
\end{aligned} \tag{1.3}
$$

If the supply-demand balance cannot be met, lost loads (LL) can be introduced to fill the gap. Lost loads are assigned a very high price, indicating that they should only be used as a last resort. This approach allows the simulation to provide results even in the presence of system unfeasibilities and aids in identifying the underlying issues.

Storage-related constraints

Units with energy storage, such as hydro reservoirs, batteries, or hydrogen storages, are subject to additional constraints beyond those of non-storage power plants. These constraints include storage capacity, inflows and outflows, charging capacity, charge and discharge efficiency, etc., ensuring reserve balance as illustrated in Fig. 2. Because in this work the storage units in the system are all water reservoirs, only the constraints relative to that type of storage is detailed hereunder.

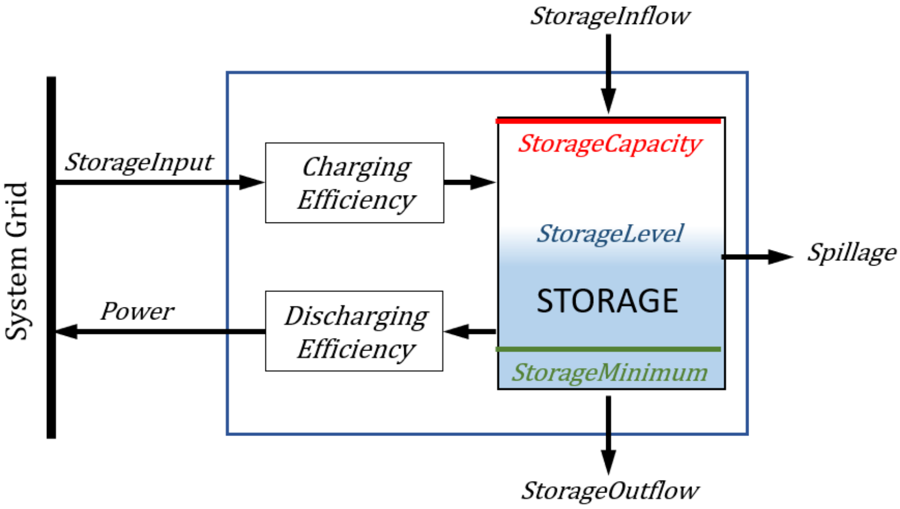


Figure 2: Energy balance within a storage.

The energy storage are obviously limited by an upper bound and in some cases by a lower bound as well. Those two constraints are respectively expressed as:

$$StorageLevel_{s,i} \leq StorageCapacity_s \cdot AvailabilityFactor_{s,i} \cdot Nunits_s \tag{1.4}$$

$$StorageMinimum_s \leq StorageLevel_{s,i} \cdot Nunits_s \tag{1.5}$$

Since all the storage is not always available at anytime, the $AvailibilityFactor_{s,i}$ can be used as a time series to restrict storage capacity at different times.

The energy added to the storage during a time step is limited by the charging capacity. Charging is allowed only if the storage is not producing power simultaneously. In other words, if the committed integer variable is equal to 0.

$$StorageInput_{s,i} \leq StorageChargingCapacity_s \cdot (Nunits_s - Committed_{s,i}) \tag{1.6}$$

Discharge, which corresponds to power production, is limited by the level of charge of the storage unit. Parameters such as storage outflow, inflow, and spillage must also be taken into account.

$$\begin{gathered}\frac{Power_{i,s} \cdot TimeStep}{StorageDischargeEfficiency_s} - StorageInflow_{s,i} \cdot Nunits_s \cdot TimeStep \\ + Spillagewat, i + StorageOutflow_{s,i} \cdot Nunits_s \cdot TimeStep - Spillage_{wat,i} \\ \leq StorageLevel_{s,i-1}\end{gathered} \tag{1.7}$$

It is important to note that inflow and outflow parameters for energy storage units need to be multiplied by the number of units since they are defined per storage plant. However, this multiplication is not necessary for other parameters like storage level, spillage, and power because they are defined for all units in the same plant.

The charge of the storage is constrained by the inflows, outflows, maximum storage capacity, and the level of charge at the previous time step. This constraint ensures that the charge does not exceed the available storage capacity.

$$\begin{split} &StorageInputs_{s,i} \cdot StorageChargingEfficiency_s \cdot TimeStep \\ &\quad - StorageOutflow_{s,i} \cdot Nunits_s \cdot TimeStep - Spillage_{wat,i} \\ &\quad + StorageInflow_{s,i} \cdot Nunits_s \cdot TimeStep \\ &\quad \leq StorageCapacity_s \cdot AvailabilityFactor_{s,i} \cdot Nunits_s - StorageLevel_{s,i-1} \end{split} \tag{1.8}$$

The energy balance constraint ensures that the energy stored in the storage unit remains balanced at each time step. It is defined as follows:

$$\begin{split} &StorageLevel_{s,i-1} + StorageInflow_{s,i} \cdot Nunits_s \cdot TimeStep \\ &\quad + StorageInputs_{s,i} \cdot StorageChargingEfficiency_s \cdot TimeStep \\ &\quad = StorageLevel_{s,1} + StorageOutflow_{s,i} \cdot Nunits_s \cdot TimeStep \\ &\quad + Spillage_{wat,i} + \frac{Power_{i,s} \cdot TimeStep}{StorageDischargeEfficiency_s} \end{split} \tag{1.9}$$

By satisfying this constraint at each time step, the energy stored in the unit remains balanced, accounting for inflows, outflows, spillage, charging efficiency, and discharging efficiency.

In some cases, certain storage units have large reservoirs with a capacity that exceeds the duration of the optimization horizon. Without a minimum level constraint, the optimization process would tend to deplete the reservoir as much as possible in the last hour. To prevent this, a minimum level constraint is imposed for the final hour of the optimization. This constraint is defined as follows:

$$StorageLevel_{s,N} \geq StorageFinalMin_s + WaterSlack_{wat} \tag{1.10}$$

1.3 Mid-Term Scheduling

As mentioned earlier, the accurate definition of exogenous level profiles is crucial for the simulation to produce accurate, feasible, and coherent results. While historical data can be one source for obtaining storage level profiles, finding precise hourly time series data for storage levels may be unrealistic. The absence of such data could negatively impact the accuracy of the simulation results, especially in the case of Bolivia where hydroelectric power plays a significant role.

Instead, Dispa-SET used its MTS module, which can be activated or not. It utilizes simplified equations, linear optimization, and a longer time step to pre-define storage levels for the entire year. In this configuration, the binary variables, such as $Committed$, $StartUp$, and $ShutDown$, are treated as linear variables, and certain constraints are ignored, including:

- The commitment equations
- The minimum Up and Down times equations
- The ramp up and Ramp down limitation equations

By running the MTS module as a preprocessing step before the actual simulation, a parameter called $StorageProfiles$ is derived. This parameter serves as a guidance curve for the minimum level constraints at the end of each optimization horizon in the main simulation. This approach enables accurate foresight and allocation of storage resources throughout the entire optimization period, eliminating the reliance on historical data for storage level profiles.

Storage Cyclic Condition

In the scope of this work, an additional constraint has been added to the MTS module, expressed as:

$$StorageFinalMin_s = torageInitial_s \tag{1.11}$$

Given the seasonal variation of storage levels, this constraint enforces the cyclic behavior of storage levels by requiring the initial and final storage levels to be the same. It ensures that storage units are properly prepared for the following year, maintaining continuity and consistency in the system.

1.4 Rolling Horizon

The optimization problem described can be solved for the entire year with hourly time steps. However, running the simulation in this manner would impose an extremely high computational cost. To overcome this challenge, the problem can be divided into smaller optimization problems and solved recursively over the course of the year.

To facilitate this approach, two parameters are introduced: the optimization horizon and the look-ahead (or overlap) period. In the example presented in Figure 3, these parameters are set to 2 days and 1 day, respectively. It is demonstrated that when optimizing day j, the initial values for the optimization are the final values obtained from the optimization of the previous day.

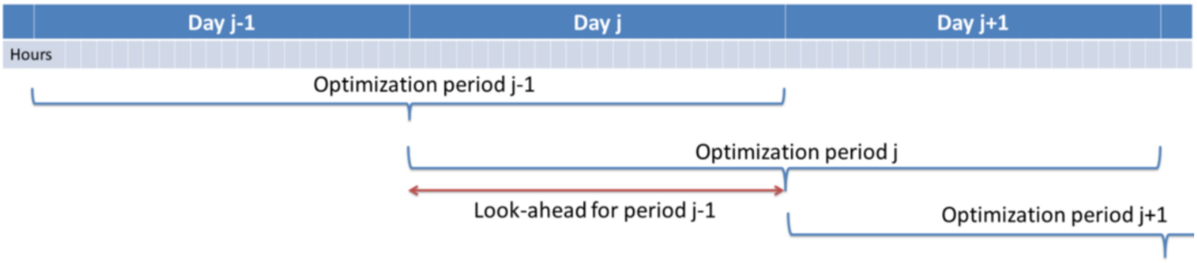


Figure 3: Illustration of the optimization horizon [13].

The look-ahead period serves the purpose of mitigating potential issues that may arise at the end of the horizon period, such as the depletion of hydro reservoirs. By considering the subsequent day(s) during the optimization process, the model can make informed decisions to avoid undesirable outcomes and ensure the feasibility of the solution.

2 Boundary sectors formulation

The boundary sector formulation is an extension of the Dispa-SET 2.5 model designed to accurately model hydro cascade systems. This formulation was developed in collaboration with Matija Pavičevi'c to address the limitations of the previous model in representing water transfers between different reservoirs within a cascade.

This was not possible in the previous formulation because the storage constraints discussed in Section 1.2 were applied separately to each storage unit and did not account for water transfer between different reservoirs within a cascade. Therefore, new variables, equations, and concepts have been introduced to replace the previous ones. Figure 4 provides a visual representation of these variables.

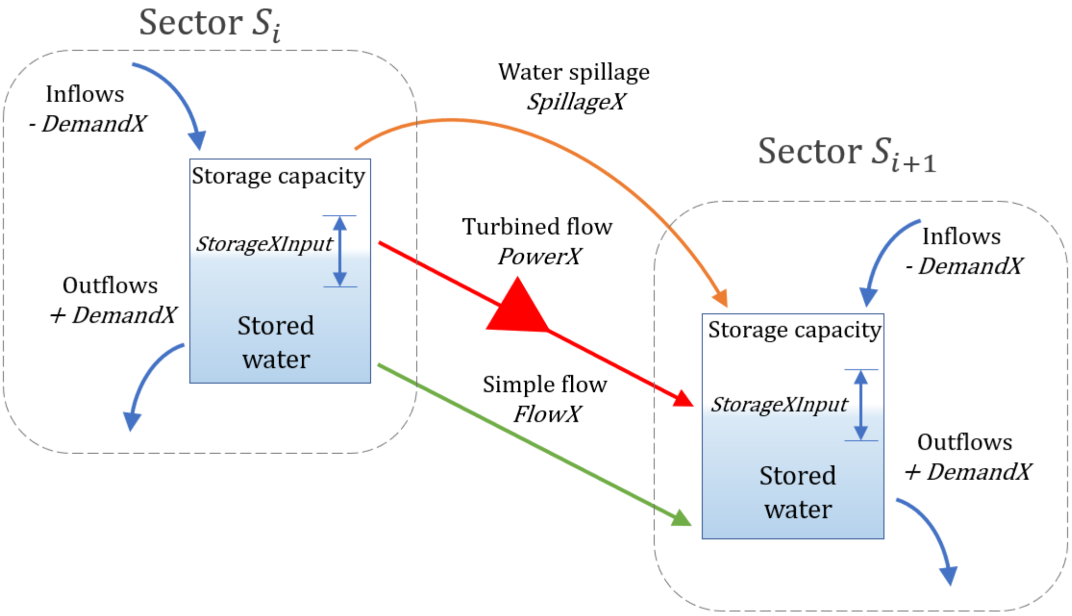


Figure 4: Links and exchanges between two sectors.

As illustrated, the river cascades in the model are divided into multiple sectors, each representing a water storage. The difference here is that water transfers represented by $SpillageX$, $PowerX$ and $FlowX$ are variables and part of the water flow balance equations of both sectors defined in Section 2.2.

2.1 Configuration

To configure the model for a specific cascade, it is necessary to specify the upstream and downstream sectors for each hydro power plant within the cascade. This information is added to the power plant database, which was discussed in Section 1.1. These additional fields, including the conversion efficiency that represents the turbine efficiency of the hydro station, are detailed in Table 5.

Description	Field name	Units
Upstream Sector	Sector1	-
Conversion Efficiency Sector 1	EfficiencySector1	MW/(m^3/s)
Downstream Sector	Sector1	-
Conversion Efficiency Sector 2	EfficiencySector2	MW/(m^3/s)

Table 4: Parameters used in the power plant database for storage units inside a cascade.

Moreover, separate CSV files are required to provide inputs for the boundary sector formulation. The paths to these files are specified in the configuration file as:

Field name	Description
Boundary Sector Demand	Path to the file with the inflows/outflows of the cascades
Boundary Sector Inputs	Path to the file with the storage capacities of the sectors
Boundary Sector NTC	Path to the file with the simple flow links
Boundary Sector Max Spillage	Path to the file with the spillage flow links

Table 5: Additional fields required in the Configuration file for the BS formulation.

2.2 Water flow balance

The sectors are interconnected either through hydro plants or flow lines. Each sector is subject to an energy balance constraint, which is expressed as:

$$DemandX_{nx,i} + StorageXInput_{nx,i} + LostLoadX_{nx,i} = \sum_{p2x} PowerX_{nx,p2x,i} + \sum_{xu} PowerX_{nx,xu,i} + EnergyNotServedX_{nx,i} + \sum_{lx} (FlowX_{lx,i} \cdot LineXNode_{lx,nx}) + \sum_{slx} (SpillageX_{slx,i} \cdot SpillageXNode_{slx,nx}) \quad (2.1)$$

In this equation, $DemandX_{nx,i}$ represents the exchange of water between the river and the system. I can be inflows entering the cascades (- sign) at a confluence or outflows (+ sign) for agricultural and daily purposes. $StorageXInput_{nx,i}$ accounts for the charging and discharging of the water storage.

The sectors are linked together by unidirectional flows in the downstream direction of the rivers. These links representing the water exchanges between two sectors, are categorized into 3 types:

- $PowerX_{nx,xu,i}$: the water flow that produces energy as it passes through the hydrostation turbine
- $FlowX_{lx,i}$: the water flow between two sectors without a power plant modeled using a simple NTC approach
- $SpillageX_{slx,nx}$: the lost water passing over the dams when it reaches its maximum storage capacity or when it cannot pass through the turbine due to flow constraints

A maximum flow requirement limits the flow at the maximum input of the downstream turbine:

$$FlowX_{lx,i} < FlowXMaximum_{lx,i} \tag{2.2}$$

To prevent infeasibility, if the water flow balance equation cannot be satisfied, the variable $LostLoadX_{nx,i}$ is introduced with a high cost. This approach is similar to the concept of the lost load variable mentioned in Equation 1.3.

2.3 Storage balance

The storage balance ensures the continuity of water flow in and out of the dams between each time step. It can be expressed as follows:

$$\begin{aligned} &SectorXStorageLevel_{sx,i-1} + SectorXStorageInputs_{sx,i} \cdot TimeStep \\ &= SectorXStorageLevel_{sx,i} + SectorXSelfDischarging_{nx} \cdot SectorXStorageLevel_{sx,i} \end{aligned} \tag{2.3}$$

In this constraint, the self-discharge factor is taken into account, representing the percentage of water lost due to evaporation.

2.4 Power balance

In the hydro cascade system, the power balance involves converting water flow into electric power using a hydro plant's turbine. The relationship between the sector and the electric grid is depicted in Figure 5. The amount of power generated depends on the turbine's efficiency as expressed in the following equation:

$$PowerX_{nx,p2x,i} = \frac{Power_{p2x,i}}{(EfficiencyX_{nx,p2x,i} + \varepsilon) \cdot LocationX_{p2x,nx}} \tag{2.4}$$

Here, the conversion efficiency of the turbine is denoted as $EfficiencyX_{nx,p2x,i}$, expressed in units of $MW/(m^3/s)$. The parameter ε represents a small positive constant, which prevents division by zero.

The power generated is then transmitted to the grid, where it contributes to the overall supply-demand balance of the national electric grid.

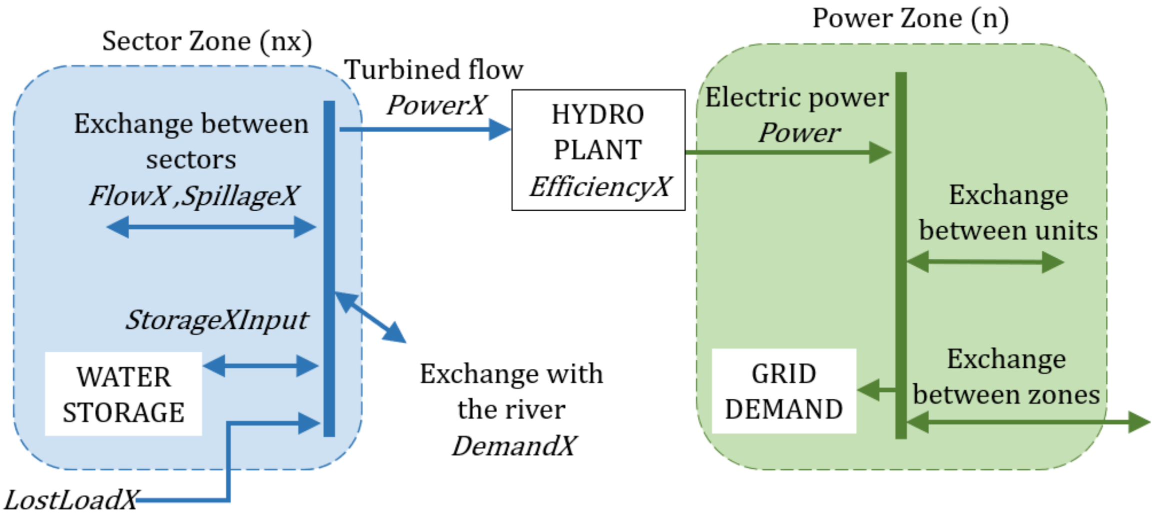


Figure 5: Links and exchanges between grid and sector.

3 Projects implementation matrix

As mentioned in the introduction,the Bolivian electricity company ENDE plans to integrate six renewable projects into the grid. One objective of this study is to access the flexibility of the grid after the implementation of the projects. To accomplish this, the input database for the Dispa-SET simulation needs to be adjusted. The original intention was not only to test the six projects together but also to explore all possible combinations. Consequently, a small program has been developed to facilitate the merging of databases. This tool is designed in a generic manner to enable easy adaptation of inputs by other users seeking to incorporate new units into their own Dispa-SET cases, even with limited programming knowledge. However, it should be noted that, currently, these functions only work for the WTON (wind turbines) and PHOT (photovoltaic panels) technologies but the implementation of the other technologies will be part of future work. Figure 6 illustrates, the workflow of the small program.

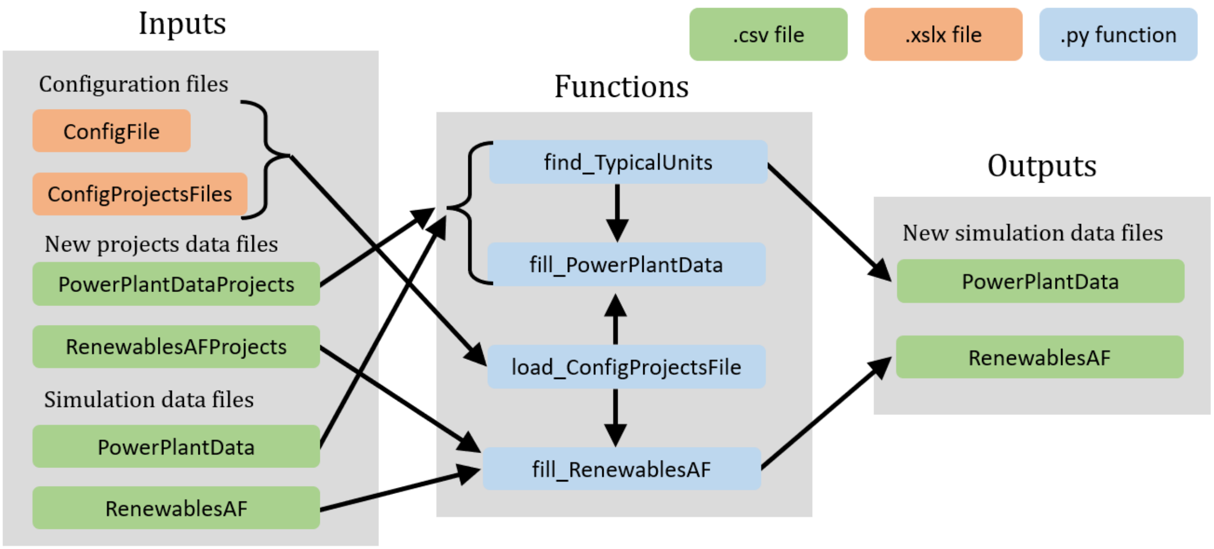


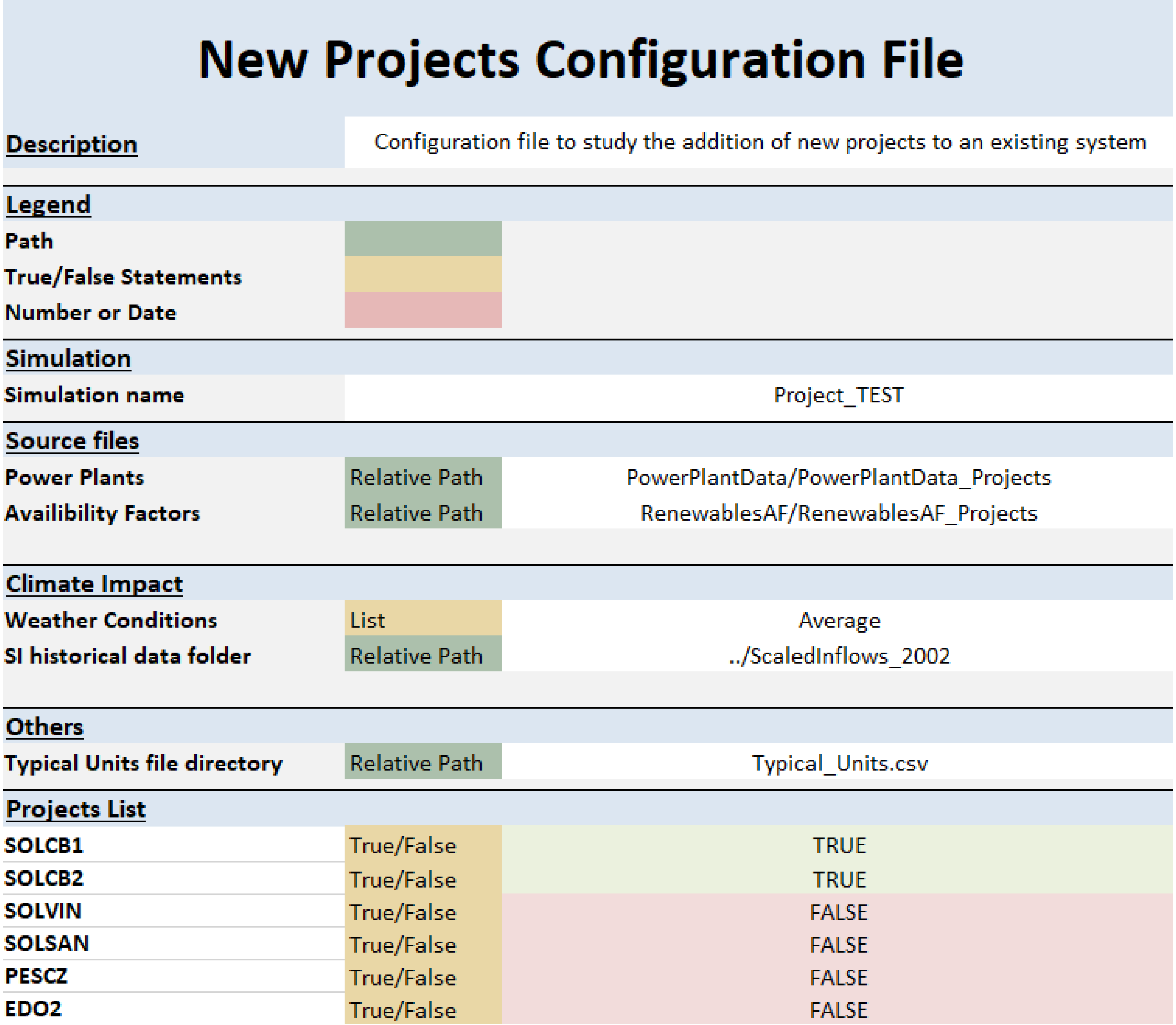
Figure 6: Project implementation Workflow.

The main concept is to use the baseline simulation database and the input data for the new projects as inputs to the program. Subsequently, a series of functions are applied to these inputs, resulting in the generation of new files within the baseline database containing the merged data.

The script and excel files have to be grouped in a folder called 'NewProjects" inside the baseline simulation folder.

3.1 Configuration files

As depicted in Figure 6, two of the inputs required for the simulation are configuration files. The first one, labeled "ConfigFile," is the one used for the general Dispa-SET simulation. The second file, specifically created for this section of the work, aims to make the introduction of new projects in a more generic manner and to centralize various parameters described hereunder. The new projects configuration file used in this study is illustrated in Figure 7.



New Projects Configuration File

Description	Configuration file to study the addition of new projects to an existing system	
Legend		
Path	🟩	
True/False Statements	🟨	
Number or Date	🟥	
Simulation		
Simulation name		Project_TEST
Source files		
Power Plants	Relative Path	PowerPlantData/PowerPlantData_Projects
Availibility Factors	Relative Path	RenewablesAF/RenewablesAF_Projects
Climate Impact		
Weather Conditions	List	Average
SI historical data folder	Relative Path	../ScaledInflows_2002
Others		
Typical Units file directory	Relative Path	Typical_Units.csv
Projects List		
SOLCB1	True/False	TRUE
SOLCB2	True/False	TRUE
SOLVIN	True/False	FALSE
SOLSAN	True/False	FALSE
PESCZ	True/False	FALSE
EDO2	True/False	FALSE

Figure 7: Configuration file used in the new projects program.

Simulation name: This parameter is used to rename the output files so that they can be distinguished from the baseline inputs and to prevent overwriting the original files.

Source files: The source files are the data files that contain information for the new projects. These files should follow the same structure as the baseline data files.

Typical units: The typical units file includes an inventory of typical power plants along with their technical and operational parameters.

Projects list: The projects list is a compilation of all the new projects that need to be considered in the simulation. For each project, a boolean variable (True/False) is assigned to indicate whether it should be included in the simulation or not.

3.2 Functions

`load_ConfigProjectsFile`: This function takes the two configuration files as inputs. It is mandatory that these files follow the specific structure for the function to work correctly. The purpose of this function is to read the configuration files, extract the relevant information, and convert it into variables that are inputs of the other functions.

`fill_PowerPlantData`: As shown in Figure 6, this functions takes the original power plant data file and the future projects power plant data file. Once again, it assumes that both files follow the required structure. Within the function, the files are read and combined through concatenation. The resulting output is a new power plant data file that contains the merged data and is named based to the simulation name provided in the configuration file.

`find_TypicalUnits` This function uses the "Typical_Units" file as its input. It is used only when operational parameters for the new projects are missing in the power plant data file. In such cases, this function calculates and returns an average value for the missing parameter using the units from the inventory with the same technology-fuel pair.

`fill_RenewablesAFFile`: This function operates in a similar manner to the `fill_PowerPlantData` function. It takes two files that contain the availability factors of the renewable units. These files are merged together to generate a single file that includes all the availability factors.

4 Evaluation of extreme weather conditions

In countries like Bolivia, where share of hydro generation amounts to 33.24% of the overall generation [14], the reliability of the grid is greatly influenced by weather conditions. Therefore, it is crucial to assess how the system performs under extreme weather conditions.

To begin this analysis, it is necessary to identify the years with the most extreme weather conditions in terms of precipitation. A `Python` function is employed to compute them, taking into account historical inflows from 1980 to 2019 provided by ENDE. The function calculates the available capacity for each year using the following formula:

$$TotalHydroCapacity = PowerCapacity_{HYDRO} \cdot \sum_i ScaledInflows_i \tag{4.1}$$

The year with the lowest renewable capacity available is considered the most severe in terms of weather conditions, while the year with the highest capacity is regarded as the most favorable. Additionally, the median year is also computed, as it serves as a representative year for most of the simulations conducted in this study.

Part III

Case study description

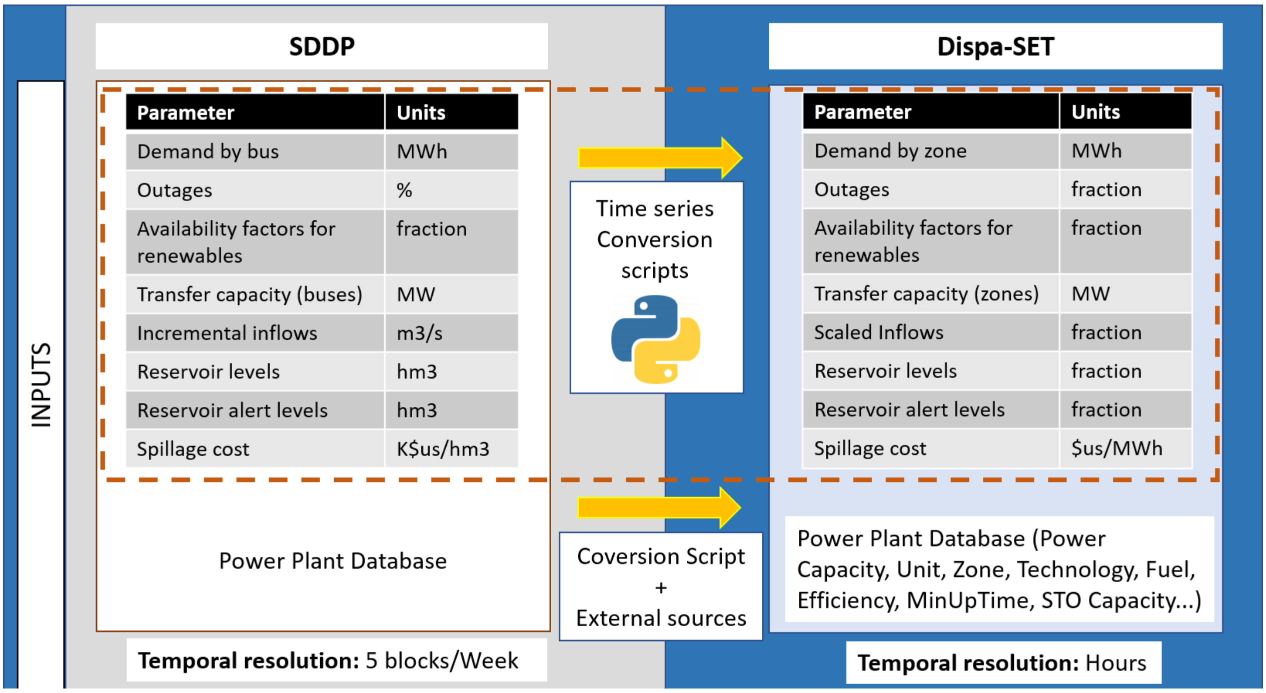
The case study presented in this work consists of six scenarios divided into three sections, each analyzing different aspects of the scenarios. This section describes the construction of the input database and provides details about the inputs and objectives of each scenario.

1 Database creation

The input database used in this study corresponds to the predicted state of the Bolivian electric system for 2026. Assembling this comprehensive database was a crucial task and formed the initial phase of this research. The original database provided in [3] served as the foundation and was further enhanced in collaboration with A. Huallpara [4]. This section outlines the process employed to construct the final database utilized in this study.

1.1 SDDP to Dispa-SET mapping

The input data for Dispa-SET was derived from the inputs of a software called SDDP, originally used by Comite Nacional de Despacho de Carga (CNDC) and ENDE Corporation to model the electricity dispatch of the Bolivian electric system. However, the organization and structure of the input data in Dispa-SET differ from SDDP, as depicted in Figure 8. Consequently, a mapping between the two models was essential. To facilitate this mapping process, a collection of Python conversion scripts was developed to enable automatic conversion of the input data.



Parameter	**Units**
Demand by bus	MWh
Outages	%
Availability factors for renewables	fraction
Transfer capacity (buses)	MW
Incremental inflows	m3/s
Reservoir levels	hm3
Reservoir alert levels	hm3
Spillage cost	K$us/hm3

Parameter	**Units**
Demand by zone	MWh
Outages	fraction
Availability factors for renewables	fraction
Transfer capacity (zones)	MW
Scaled Inflows	fraction
Reservoir levels	fraction
Reservoir alert levels	fraction
Spillage cost	$us/MWh

Figure 8: Input data mapping of SDDP to Dispa-SET [4].

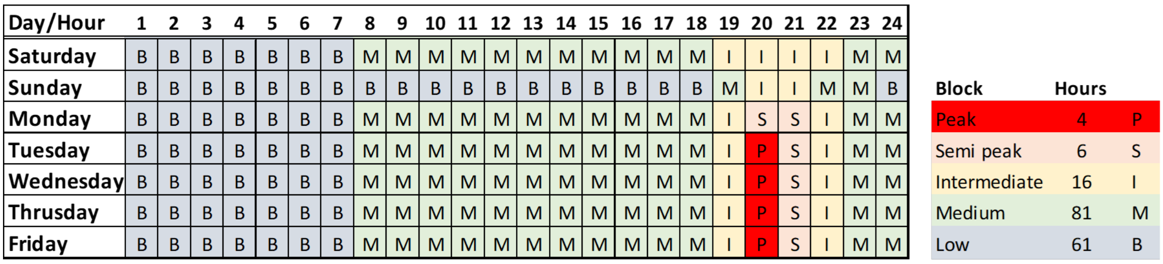
The data mapping involved three types of mapping.

1-1 Mapping

Simple direct mapping is used for parameters that are defined in the same way in both models, such as power plant data.

1-N Mapping

Some inputs, such as demand and availability factors, required 1-N mapping to convert them into the appropriate form used in Dispa-SET. In SDDP, certain inputs are organized into 5 blocks, and each hour of the week is assigned to one of the blocks, as illustrated in Figure 9.



Day/Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Saturday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	I	I	I	M	M
Sunday	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	M	I	I	M	M	B
Monday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	S	S	I	M	M
Tuesday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	P	S	I	M	M
Wednesday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	P	S	I	M	M
Thrusday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	P	S	I	M	M
Friday	B	B	B	B	B	B	B	M	M	M	M	M	M	M	M	M	M	M	I	P	S	I	M	M

Block	**Hours**	
Peak	4	P
Semi peak	6	S
Intermediate	16	I
Medium	81	M
Low	61	B

Figure 9: Distribution of the demand block over a week [4].

Furthermore, the input data for inflows and outages in SDDP is provided on a weekly basis as averaged values. Therefore, interpolation was used to map from a single weekly value to an hourly resolution. On the other hand, the value of the Net Transfer Capacity (NTC), initially provided as constant values, was also converted into hourly time series data.

N-1 Mapping

In addition, the demand is expressed by buses in SDDP and by zones in Dispa-SET, so it has to undergo an additional N-1 mapping.

1.2 Input Data

Power Plant Data

This work is based on the SIN planned for 2026; therefore, the power plant database is composed of the stations currently working and those projected for 2025.

Area	**Power Plant**	**Technology**	**Total Capacity [MW]**
Central	Miguillas System	HDAM WAT	21.11
	Corani System		156.36
	Misicuni System		118.68
	Juntas System		284.36
	San Jose I & II	HROR	122.89
	Kanata		7.54
	Quehata		1.89
	Valle Hermoso	GTUR GAS	115.41
	Carrasco		129.48
	Bulo Bulo		133.4
	Entre Rios		113.76
	Entre Rios	COMC GAS	787.36
	Oruro I & II	PHOT SUN	98.62
	Qollpana I & II	WTON WIN	26.54
North	Taquesi System	HDAM WAT	89.19
	Zongo System		188.04
	Umapalca		83.91
	Palillada		116.87
	El Alto	GTUR GAS	49.25
	Rurrenabaque	GTUR OIL	1.76
	Yucumo		0.35
	San Borja		1.76
	Say		1.6
	San Ignacio de Moxos		0.73
	Moxos		5.54
	San Buenaventura	GTUR BIO	4.94
Oriental	Guaracachi	COMC GAS	194.68
	Warnes		1008.32
	Guaracachi	GTUR GAS	133.42
	Santa Cruz		41.02
	Warnes		214.89
	Unagro	GTUR BIO	34.75
	Guabira		20.64
	IAG		16.9
	San Julian	WTON WIN	39.4
	Warnes I & II		34.66
	El Dorado		49.39

Table 6: Power plants by 2026.

Area	Power Plant	Technology	Total Capacity [MW]
South	Yura System	HROR WAT	20.47
	San Jacinto	HDAM WAT	7.46
	Aranjuez	GTUR GAS	34.5
	Del Sur		165.97
	Del Sur	COMC GAS	956.97
	Uyuni	PHOT SUN	59.7
	Yunchara		4.53
	La Ventolera	WTON WIN	23.59
SIN	**All Units**		**5722.58**

Table 7: Cont.: Power plants by 2026.

Demand

The demand used in this study is the demand forecasted for 2026, originally obtained from the `ENDE` data in the `SDDP` software. In Dispa-SET, the demand is defined on an hourly basis and divided into zones. Therefore, it had to be converted using the 1-N and N-1 mapping techniques mentioned above. The national demand used as input is shown in Figure 10.

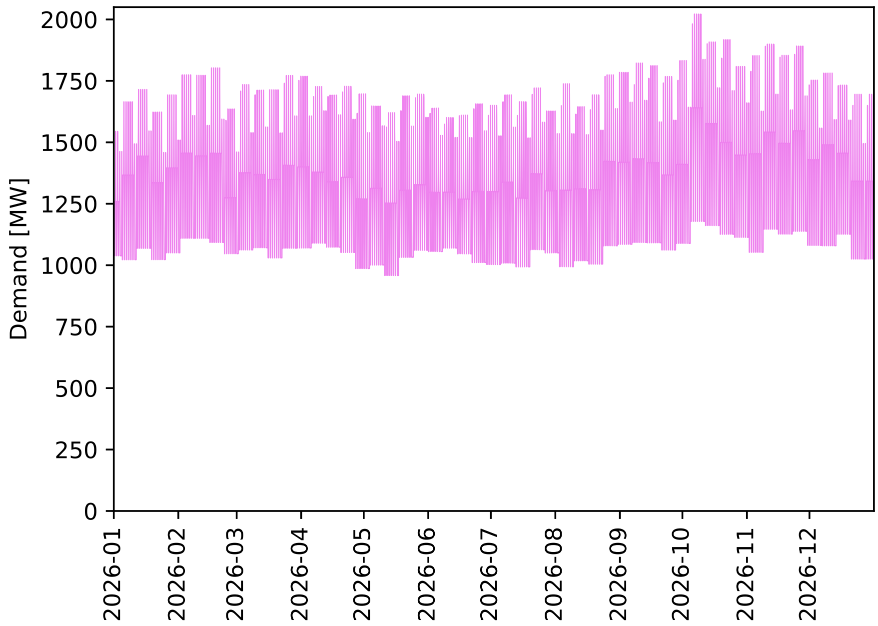


Figure 10: National demand predicted for 2026.

The demand exhibits a relatively constant pattern throughout the year, with a slight increase towards the end of the year and a peak of 2022 MW in October. The distribution of the total demand and the peak demand of each zone is illustrated in Figure 11.

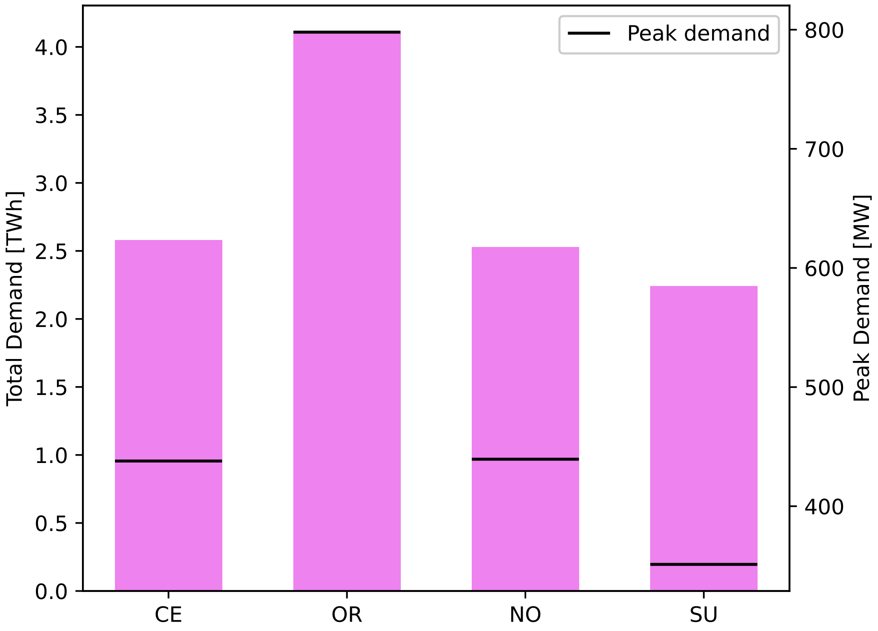


Figure 11: Total demand predicted for 2026 by zone.

Transmission network

The transmission lines of the system are depicted on the map of Bolivia shown in Figure 1. However, in the Dispa-SET model, only the high-voltage lines that interconnect the zones are modeled. The maximum capacity of these lines is listed in Table 12.

Transmissions line	Net transfer capacity [MW]
SU <-> CE	444.5
CE <-> OR	1023
OR <-> NO	140.04
CE <-> NO	441.7

Table 8: Transmission lines maximum net transfer capacity.

Inflows

Regarding the inflows, the data from SDDP consists of weekly mean incremental inflow values. In the context of cascaded hydro power units, each unit's inflows represent the external inflows entering the cascade before that unit. This is illustrated in Figure 12, where units 1 and 2 are two power units in cascade, and the inflow input provided is represented by the red arrow.

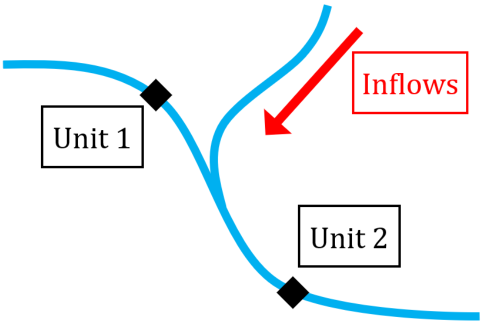


Figure 12: Two hydro power units in a cascade.

The inflows are defined for each hydro station. The handling of inflows depends on the version of the model used and is explained in the following sections.

Unless specified otherwise, the simulations use the input inflows from the year 2019. This particular year was selected as the median year through the calculation performed using the Python function described in Section 4.

Availability factors
Availability factors are necessary for VRES power plants such as solar panels or wind turbines. They are provided on a weekly basis and in the 5-block configuration mentioned earlier. These factors were converted into hourly time series using a 1-N mapping to align them with the hourly resolution of the Dispa-SET model.

Outages
An outage factor is assigned to each unit in the power plant database. To achieve an hourly resolution, these factors need to be transformed using a 1-N mapping. This transformation is necessary to make them suitable inputs for the Dispa-SET model.

2 Baseline scenario

In the baseline scenario, the study focuses on the projected state of the National Interconnected System (SIN) for 2026. Bolivia plans to enhance its electrical grid by adding new transmission lines and hydro projects that will significantly increase the share of hydroelectric power in the total installed capacity. Figure 13 representing the capacity distribution for each type technology.

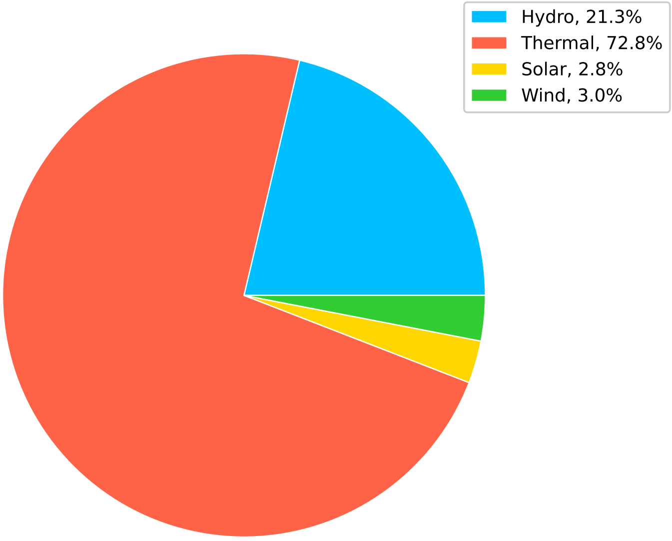


Figure 13: Distribution of the total installed capacity for the baseline scenario.

Having a substantial portion of hydro energy generation is advantageous for the Bolivian system. The ability to store water for energy production adds flexibility to the grid. However, most hydroelectric plants in the 2026 SIN are part of a cascade system, where downstream water availability depends on the usage of upstream units. Modeling the water flow through the cascade presents challenges, and the handling of inflows can significantly impact the results.

The purpose of this case study is therefore, to analyze and compare the results of two versions of the Dispa-SET model: the standard version 2.5 and the newly developed version with the boundary sector feature. These two different formulations manage inflows differently, and the study aims to evaluate their accuracy and identify any differences between them.

The input data for this scenario originates from the SDDP software and was converted as explained in the previous section 1. The only point that differentiate the two formulation regarding the input data, is the inflows. In fact, the construction of the inflow input data is different for the two formulations, as explained below.

2.1 Standard formulation

In the standard formulation, the exchanges between reserves within the cascade are managed using scaled inflows provided in the input data. However, these scaled inflows need to be calculated in advance, which involves a complex computation to predict the behavior of the reserves. It requires an approximation based on three hypotheses:

- The inflow entering one unit is the sum of the inflows of the units upstream and its external inflows entering the cascade before this one unit.
- For the units that do not have generation capacity but gather or provide flows, an ap-

proximation function is used to obtain their outflow and spillage.

- For the largest hydro dam, Corani, with 2958 storage hours, the outflows are considered as the average of the total yearly inflows, assuming that Corani has nearly constant generation throughout the year.

However, a limitation of this formulation is that the inflows are defined as fixed parameters in the input data. As a result, the water flows passing through the reserves of a cascade cannot be adjusted based on the demand.

2.2 Boundary sector formulation

In this formulation, an equation has been added to consider the water flow within the cascade, as discussed in Section 2.2. The input data regarding inflows only include external inflows entering the cascade. Consequently, the transfer of water between consecutive reservoirs within the cascade is determined endogenously by the model through a cost optimization process throughout the year.

The links between the sectors are defined in the inputs and based on the cascade system implemented in SDDP.

3 Renewable energy scenarios

The Bolivian governments published in 2014 an electric plan [2] where they mentioned the objective to reach 70% of renewable generation by 2025. More recently, in Bolivia's Nationally Determined Contribution HDAM(NDC) [5], an ambitious target of achieving 79% of renewable energy production and 50% of renewable capacity by 2030 has been set.

This case study aims to compare and analyze the two scenarios, along with the baseline scenario, to understand the impact of renewable energy integration on the overall system. These two scenario consist of the baseline scenario with additional renewable projects at different intensities. This analysis focuses on assessing the feasibility and flexibility aspects resulting from the increased penetration of renewable energy sources.

To simulate these new projects, availability factors for each renewable unit are required. These factors were obtained from the Renewables.ninja dataset[4]. The dataset provides availability factors based on the approximate geographic locations and technical characteristics of the wind turbines and photovoltaic panels.

3.1 RES scenario

The RES scenario incorporates six new renewable projects into the 2026 grid, which have been planned by the Bolivian electricity company, ENDE. These projects consist of wind turbines

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[4] Renewables.ninja website

and photovoltaic panels, with their respective power capacities and technologies specified in Table 9.

Unit Name	**Capacity [MW]**	**Technology**	**Zone**
SOLCB1	81	PHOT	NO
SOLCB2	40	PHOT	NO
SOLVIN	126	PHOT	CE
SOLSAN	63	PHOT	CE
PESCZ	160	WTON	OR
EDO2	54	WTON	OR
Total	**524**		

Table 9: New renewable projects integrated to the SIN.

The distribution of the total installed capacity in the 2016 SIN, including these six projects, is illustrated in Figure 14.

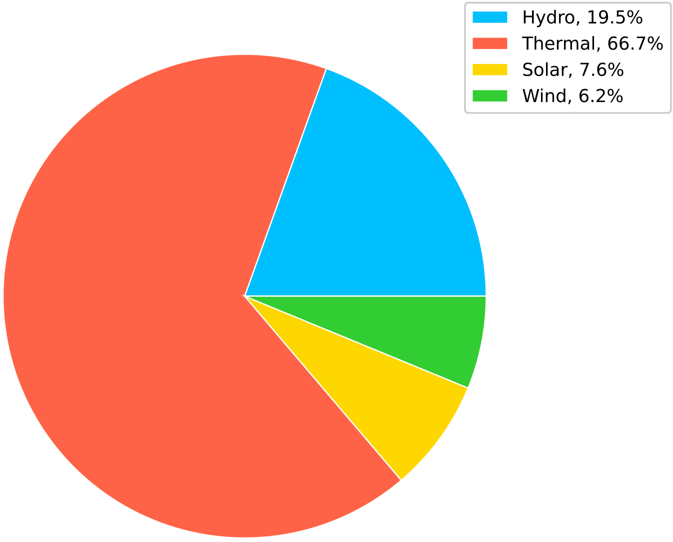

Figure 14: Distribution of the total installed capacity for the renewable energy scenario.

As expected, there is a significant increase in solar and wind power compared to the baseline scenario (Fig. 13). Yet, the contribution of renewable energy sources accounts for only 32.2% of the total installed capacity, falling short of the 50% target for renewable capacity.

3.2 High RES scenario

In order to achieve the target of 50% renewable capacity by 2030, a second scenario is analyzed, where the capacities of the new projects are multiplied by 5. The new capacity values and the distribution for this scenario are presented in Table 10 and Figure 15.

Unit Name	**Capacity [MW]**	**Technology**	**Zone**
SOLCB1	405	PHOT	NO
SOLCB2	200	PHOT	NO
SOLVIN	630	PHOT	CE
SOLSAN	315	PHOT	CE
PESCZ	800	WTON	OR
EDO2	270	WTON	OR
Total	**2620**		

Table 10: New renewable projects integrated to the SIN.

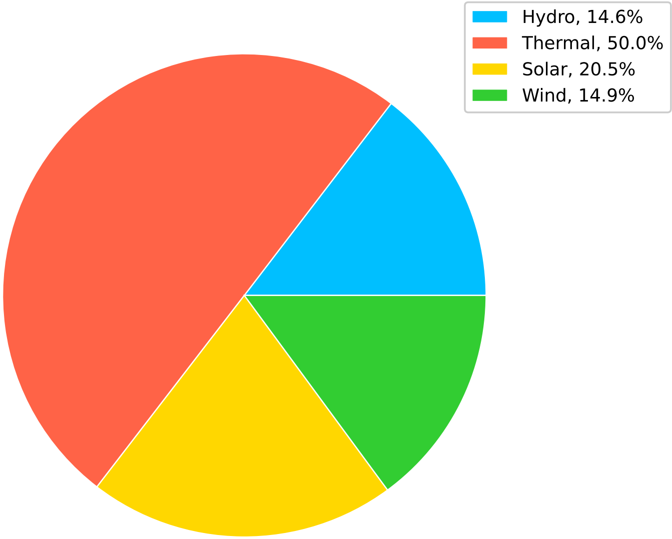

Figure 15: Distribution of the total installed capacity for the second renewable energy scenario.

Figure 15 displays the distribution of the total installed capacity for this high renewable energy scenario. This scenario represents an even more ambitious approach towards achieving the renewable capacity target.

4 Extreme scenarios

Extreme weather events are becoming more frequent and severe due to global warming. Bolivia, like many other regions, is particularly vulnerable to these extreme weather conditions, which can significantly impact the country's electricity production. Since a large portion of Bolivia's electricity comes from hydroelectric power stations, the availability of water resources, especially rainfalls, directly affects the inflows into the hydro cascade systems.

The objective of this scenario is to assess the behavior of the 2026 National Interconnected System (SIN) under extreme weather conditions and predict potential challenges that may arise, such as water shortages or excessive curtailment. By comparing different scenarios, the study aims to understand the impact of weather variability on system flexibility.

To simulate extreme weather conditions, historical hydrological data from 1980 to 2021 were analyzed to identify the wettest, median, and driest years in terms of water availability. These years were selected using a function described in Section 4. The identified years are as follows:

Wettest	**Median**	**Driest**
2001	2019	2016

The input data that differ between the two extreme scenarios are the inflows. To highlight the disparity between these scenarios, the inflows for the median year and the extreme weather years are plotted in Figure 16.

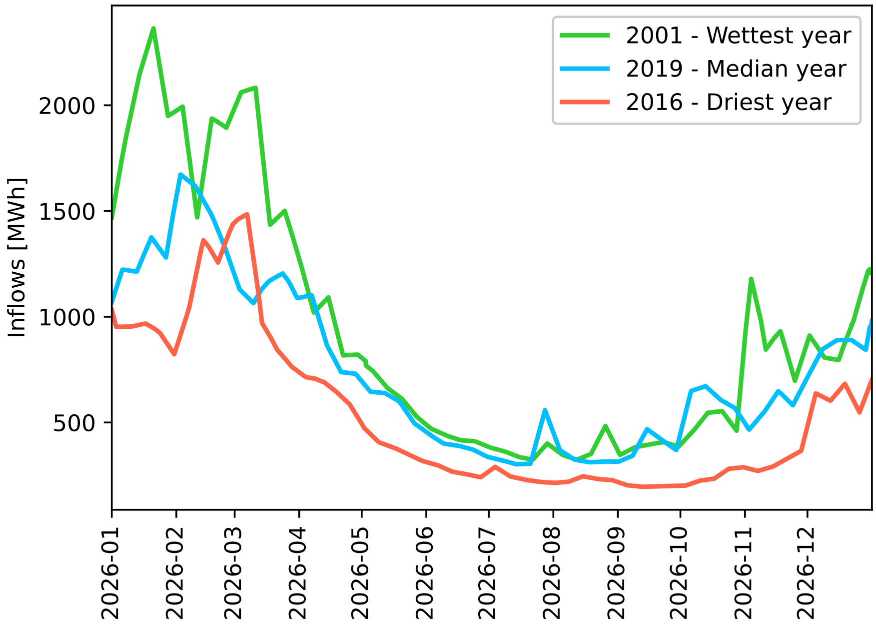

Figure 16: Inflows throughout the year of the median and extreme weather years.

The plot clearly illustrates a significant gap between the inflow patterns of the two extreme weather scenarios.

5 Summary

Table 11 summarizes the installed capacities, the formulation and the inflows year used for each scenario.

Scenarios	Hydro + Thermal [MW]	VRES [MW]	Total [MW]	Form.	Year
ST Form.	1218.77 + 4167.38	336.43	5722.58	ST	2019
BS Form.				BS	
RES		860.43	6246.58		
High RES		2956.43	8342.58		
Wettest year		336.43	5722.58		2001
Driest year					2016

Table 11: Summary of the scenarios with their main parameters

Part IV

Results and analysis

The results from the different scenarios defined in the previous section (Section III) are presented and analyzed below.

1 Comparison of the Two Dispa-SET Formulations

In the scope of this work, a newer version of the Dispa-Set model has been developed, with the main difference being how the water cascades are modeled. This section analyzes and compares various variables, such as generation, storage level and spillage between the two formulations.

1.1 Generation

In Figure 17, the distribution of power generation by technology type is depicted. The figure highlights that the BS formulation results in a 4% higher hydro generation compared to the ST formulation. This difference can be attributed to the fact that in the BS formulation, the reserves within the same cascade are interconnected, allowing for water flow exchanges and better optimization. On the other hand, the ST formulation relies on pre-determined fixed inflows for water flows in the cascades, limiting the ability to adjust them based on the system's needs.

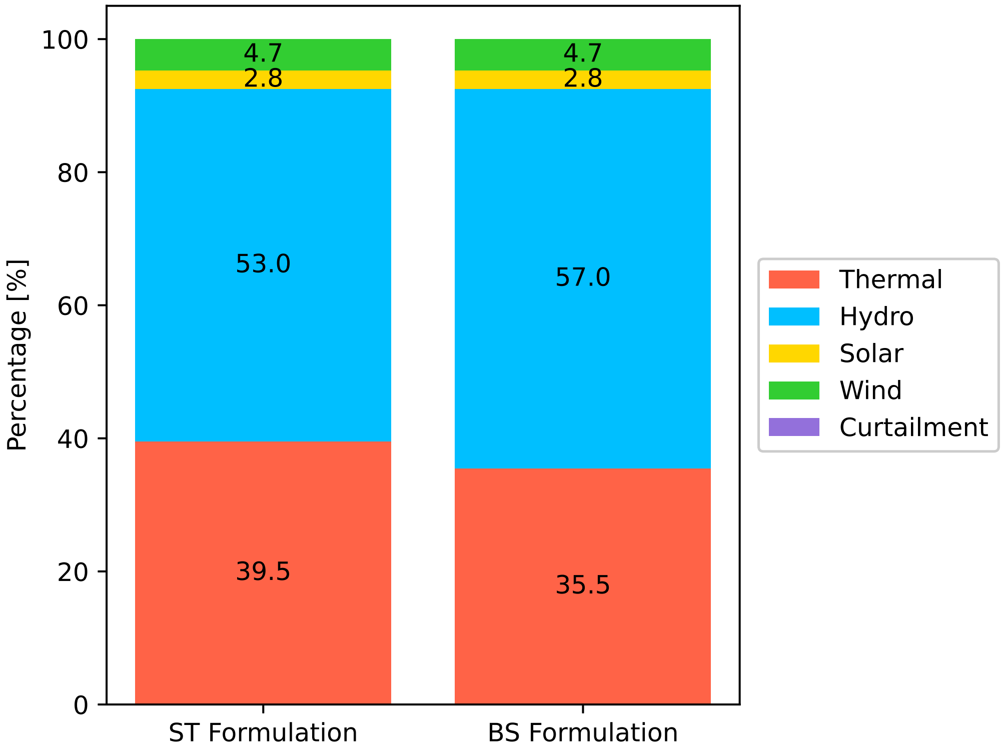

Figure 17: Distribution of the power generation for the ST formulation and the BS formulation.

The generation dispatch by technology for the ST formulation and the BS formulation is depicted in Figures 18 and 19. In the case of the ST formulation the hydro energy production is mainly concentrated from January to April which correspond to the wet season while for the BS formulation the water generation is more evenly spread throughout the year, which is a sign of improvement in the management of storage.

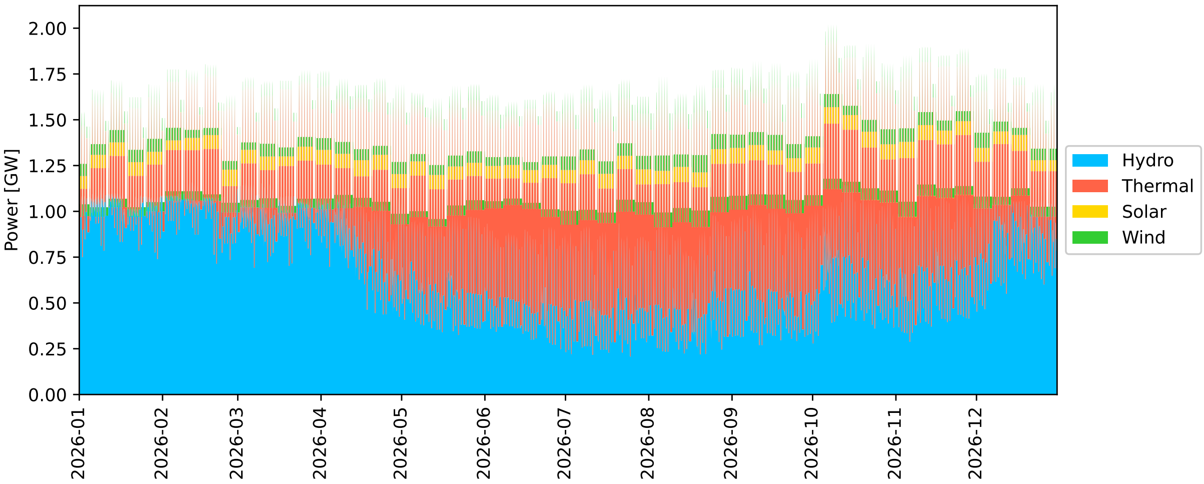

Figure 18: Generation dispatch by technology for the ST formulation.

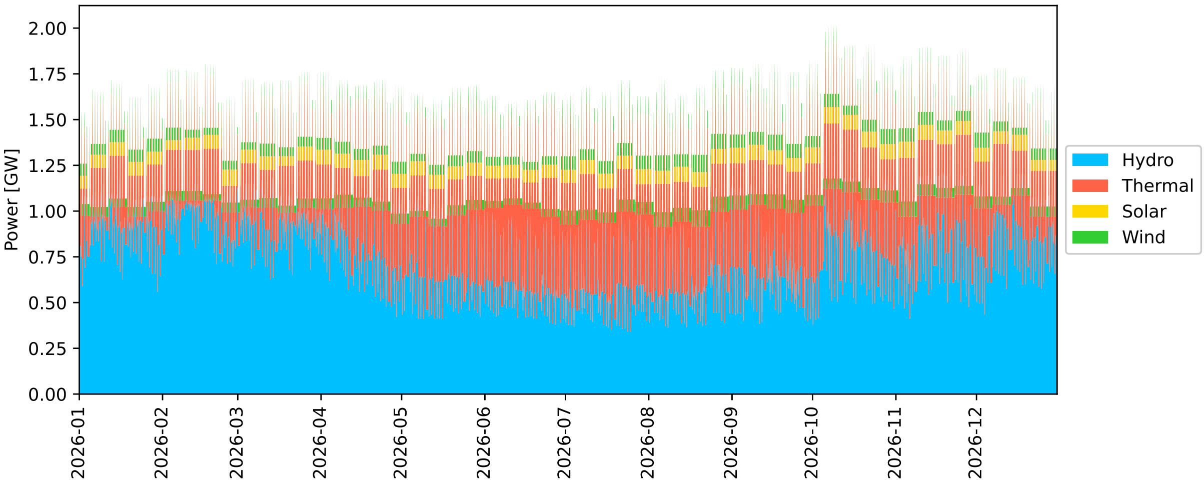

Figure 19: Generation dispatch by technology for the BS formulation.

1.2 Storage level

Figure 20 illustrates the storage level curves for the two formulations. For the ST formulation it exhibits a steeper increase and decrease. These curves also demonstrate the cyclic condition in the MTS imposed on the reserves to start and finish the year at the same level and follow the seasonal pattern.

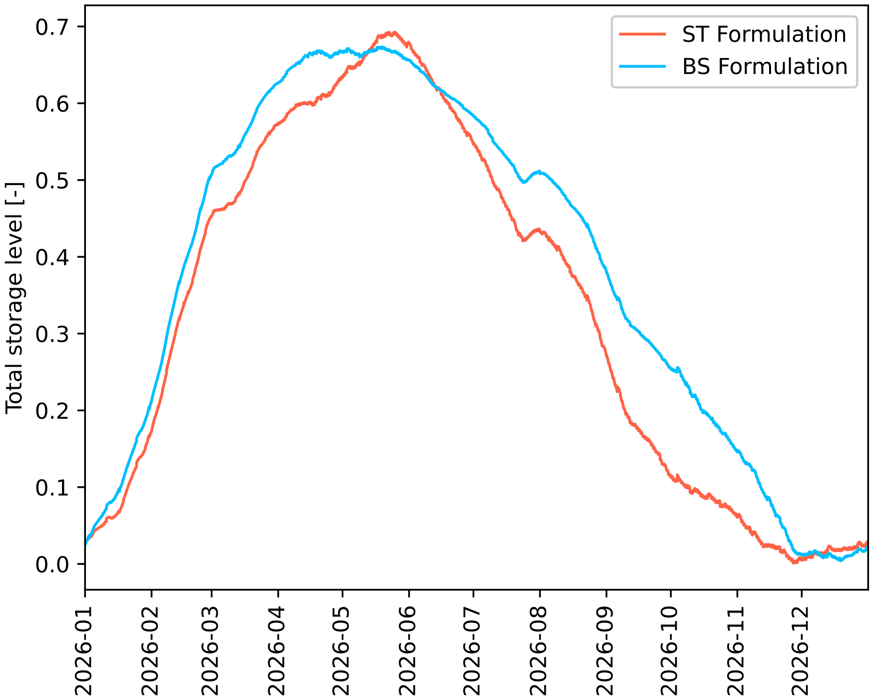

Figure 20: Storage level curves for the ST formulation and the BS formulation.

While the overall shape of the storage level curves is similar between the two formulations, there are noticeable differences when analyzing specific reserves placed consecutively in the cascades. Figure 21 shows the storage level curves for two consecutive units in a cascade which are:

	Storage capacity [MWh]
Umapalca	162.3
Palillada	144.3

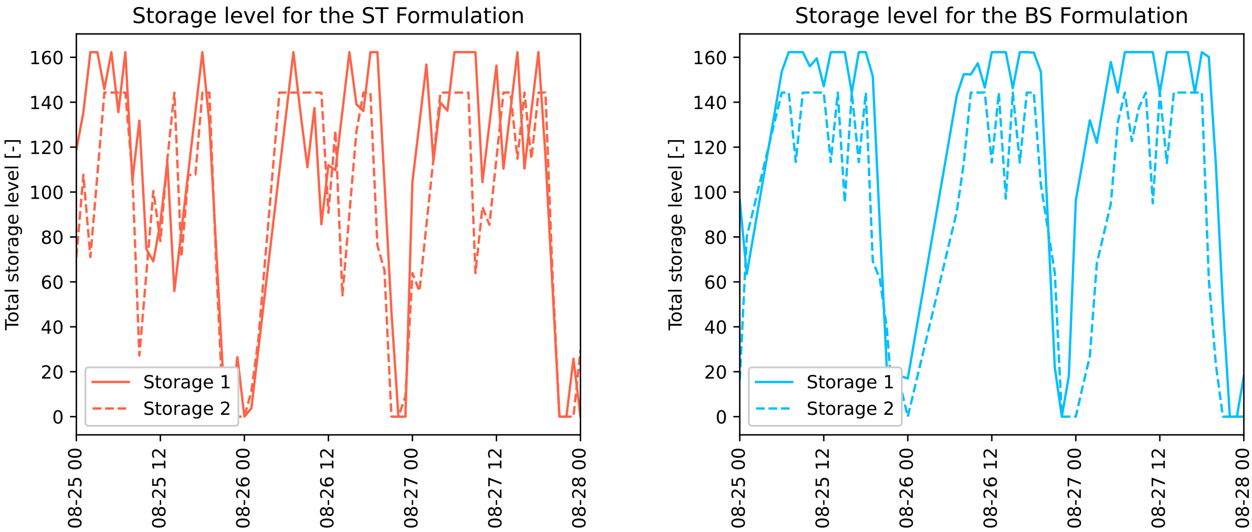

Figure 21: Storage level of two consecutive units in a cascade model with the ST and BS formulations.

For the BS curves it can be observed that the behaviors of the two storage units are related. When the upstream reserve releases water, decreasing its storage level, the downstream storage is being filled as it retains the released water. However, this linked behavior is not present in the ST formulation, where the storage levels appear more chaotic. This difference highlights the improvement of the newer version of Dispa-SET, where units and reserves of a cascade can communicate with each other within the simulation.

1.3 Spillage

The implementation of inflows in the two formulations significantly impacts the spillage results. Figure 22 illustrates the spillage time series for both simulations. In the newer version of the model, the spillage is bounded and relatively constant, with a decrease during the dry season. On the other hand, the spillage in the standard version is more unstable, characterized by high spillage during the wet season and no spillage for the rest of the year. Comparing the two formulations, it is evident that the BS formulation captures more realistic spillage patterns.

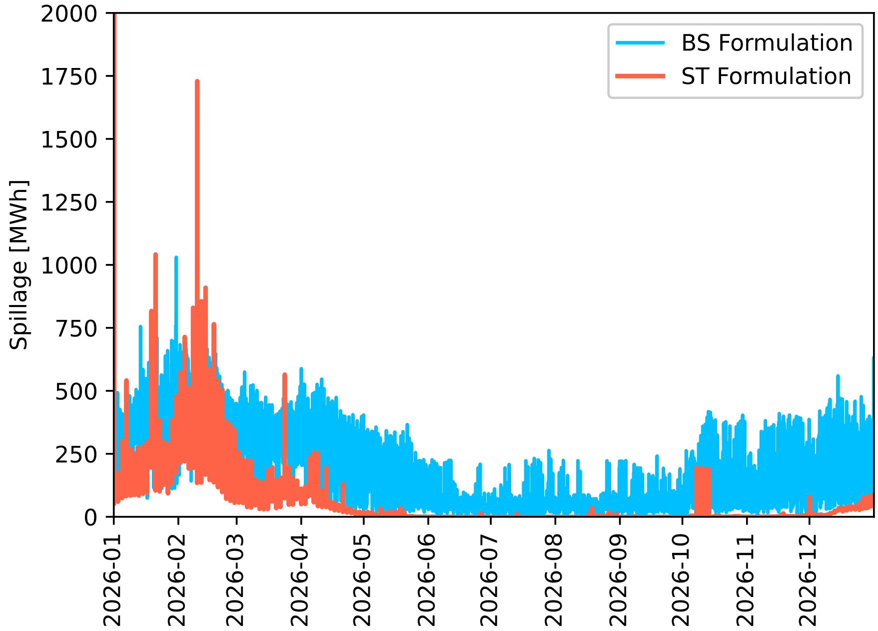

Figure 22: Spillage curves for the ST formulation and the BS formulation.

The total spillage, as shown in Figure 23, is approximately three times less in the ST simulation. However, Figure 17 demonstrates that hydro generation is higher in the BS formulation, suggesting that it should have lower spillage. This difference can be attributed to the inflow implementations. In the ST formulation, the computation of input inflows was based on a set of assumptions and approximations. This discrepancy shows that the approximation leads to a "loss of water" during the calculation of the inflows.

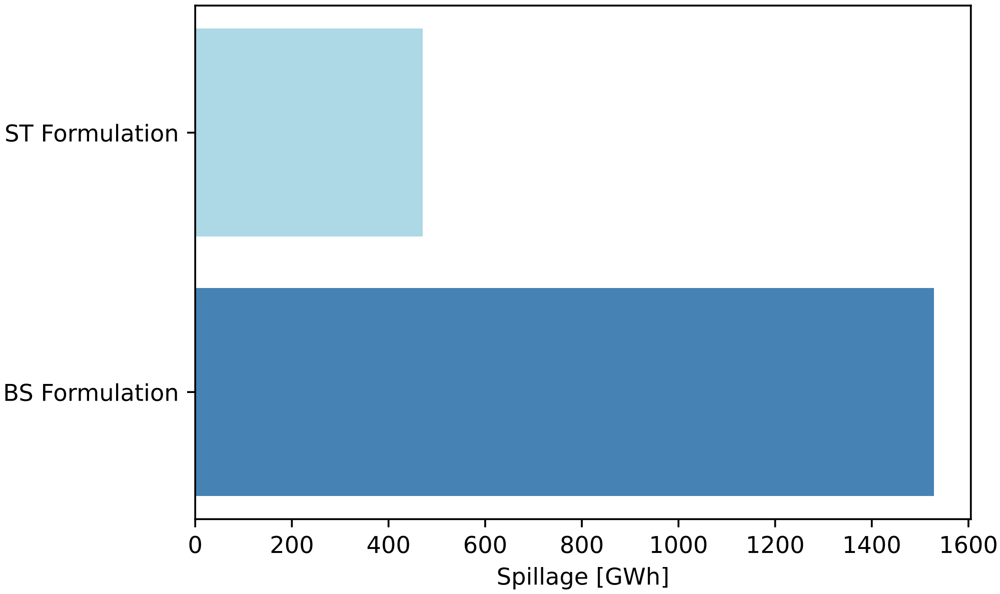

Figure 23: Total spillage for the ST formulation and the BS formulation.

These results highlight the inaccuracy of computing inflows in advance and outside of the model, as done in the standard version. Consequently, the newer version of Dispa-SET, which provides more realistic results, is used in all subsequent analysis.

2 Comparison of with renewable projects

In this section, three scenarios with varying levels of renewable penetration are compared. The first scenario, called the "Baseline" scenario, represents the projected state of the SIN for 2026. The second scenario is the "RES" scenario, which includes the 2026 SIN with the addition of six new renewable projects. The third scenario, called the "High RES" scenario, further multiplies the installed capacity of these projects by a factor of 5. The total installed capacity for each scenario is presented in the following table:

	Baseline	**RES**	**High RES**
Total capacity [MW]	5722.28	6246.58	8342.58

2.1 Generation

Figure 24 shows the distribution of power generation by technology for the three scenarios. In the RES scenario, there is a notable 11% decrease in thermal production compared to the Baseline scenario, which aligns with Bolivia's goal of reaching 70% renewable generation by 2025. This reduction is achieved without curtailing any power, demonstrating the flexibility of the Bolivian grid thanks to its large hydro storage capacity.

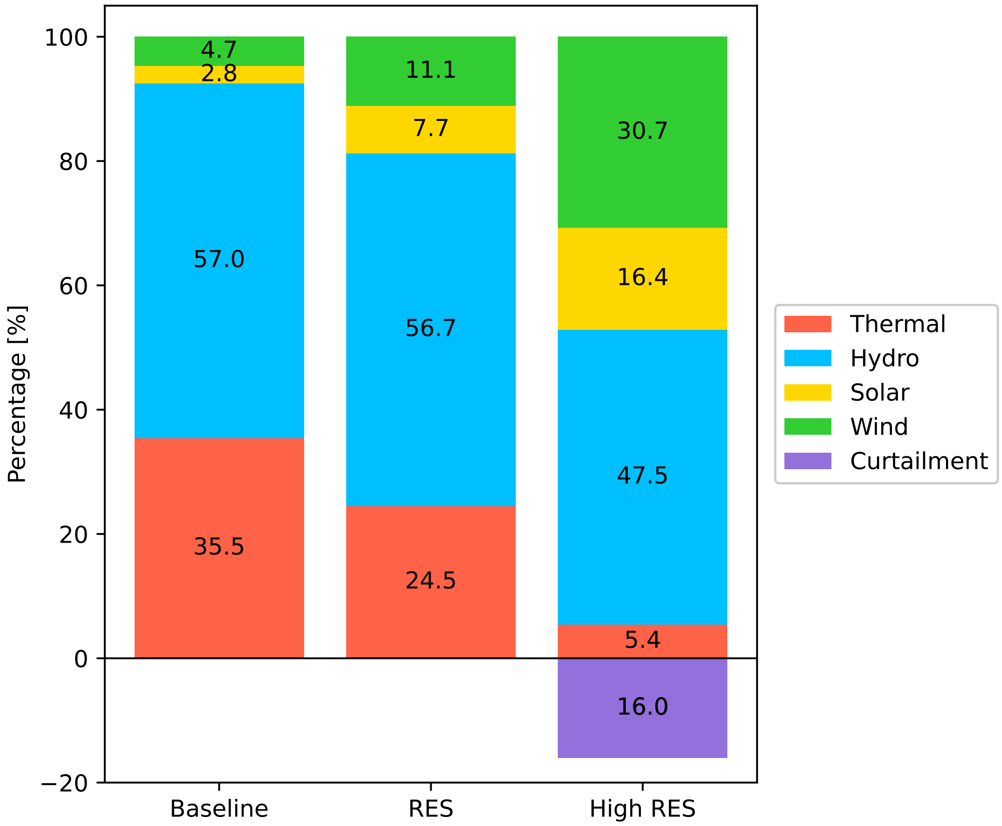

Figure 24: Distribution of the power generation for the baseline scenario and the renewable scenarios.

The High RES scenario significantly boosts the proportion of renewable generation, reaching a remarkable 94.6% of total power production. This achievement surpasses the 2030 target of 79% renewable generation. However, the substantial increase in VRES results in a curtailment of 16% of the total generation due to their intermittent nature. This curtailment arises from the challenges posed by the variability and unpredictability of VRES.

2.2 Curtailment

Curtailment represents intentionally wasted energy that exceeds the demand and should be minimized if possible. Figure 25 shows the generation dispatch for each zone in the High RES scenario. It is observed that curtailment mainly occurs between 2 pm and 6 pm, when solar energy production is at its maximum. One possible solution to address this issue is to incorporate more energy storage, allowing excess energy generated during the day to be stored and used during periods of low energy availability.

Figure 26 presents the total amount of curtailment for each zone and their peak values. The central zone exhibits the highest amount of curtailed power, which is expected considering its higher renewable capacity. Since this zone is also producing hydro power, one possible strategy to mitigate curtailment is to add more water storage in the central zone, allowing water to be stored while solar panels are producing energy.

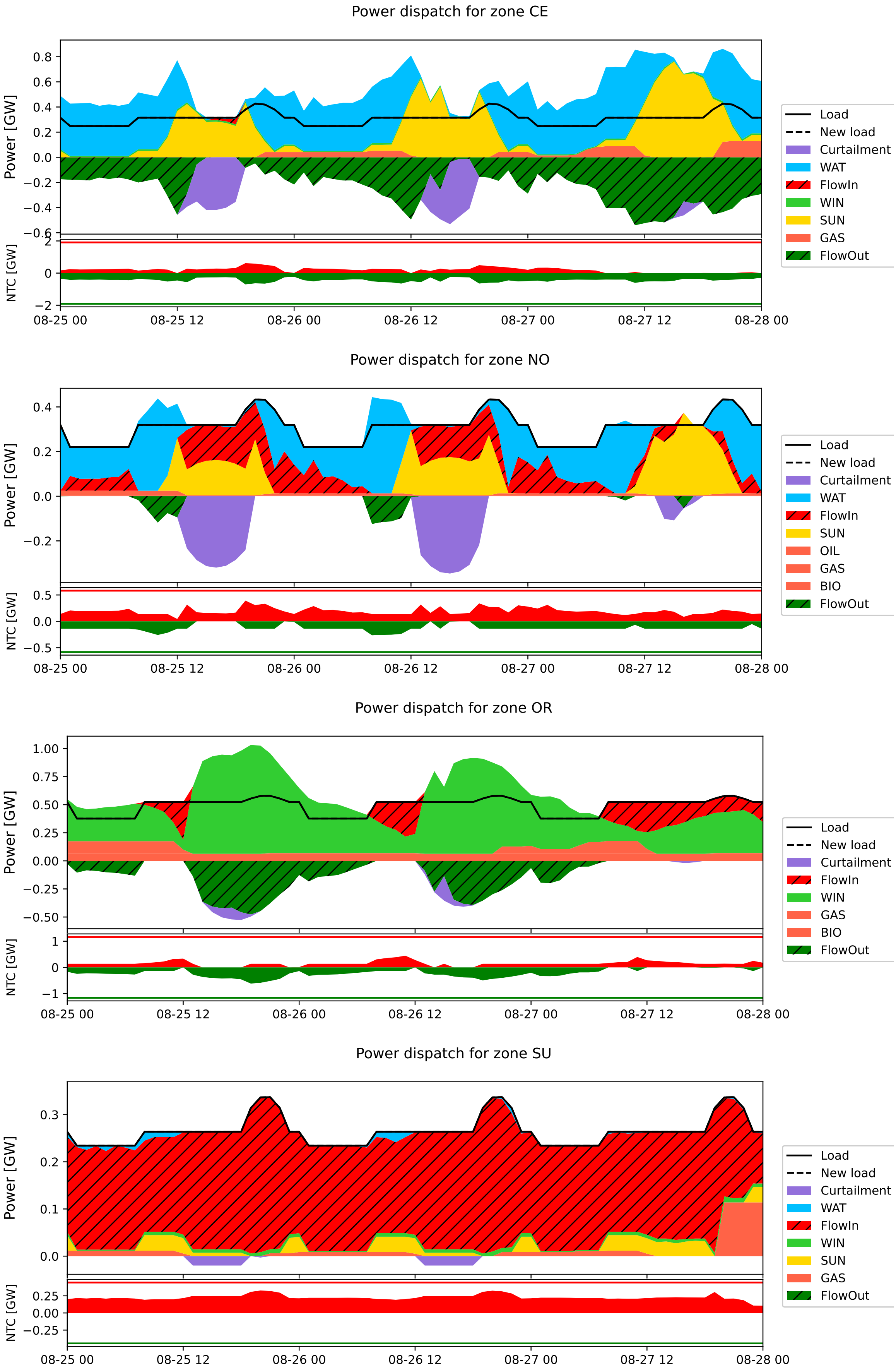

Figure 25: Generation dispatch for each zone of the high RES scenario.

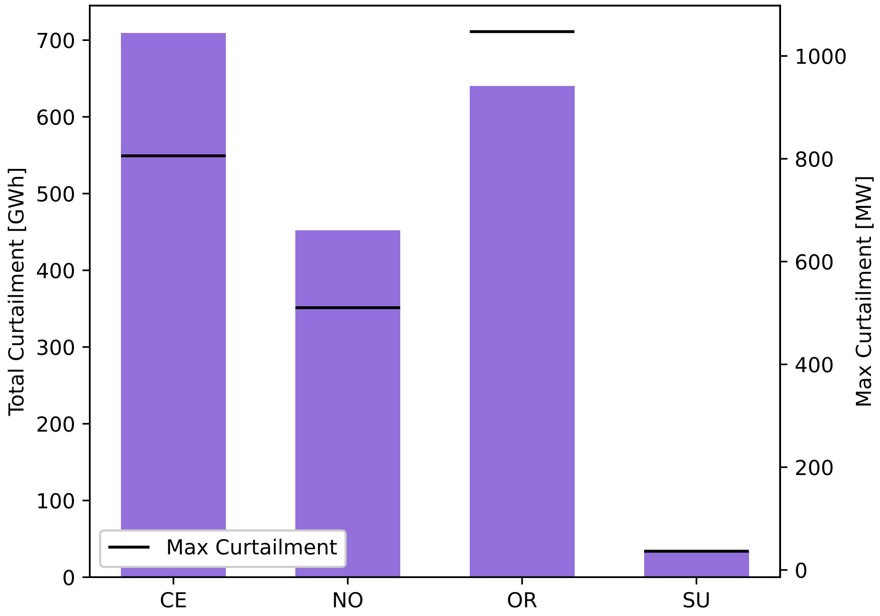

Figure 26: Curtailment by zone for the High RES scenario.

2.3 Congestion

Furthermore, the dispatch graphs in Figure 25 reveal a small amount of energy being thermally produced in the Oriental zone, coinciding with the curtailment of energy in other zones. This occurrence contradicts the intended priority use of RES. It indicates either a lack of system flexibility or limitations in transmission capacity between zones. Congestion issues can be observed through the number of hours of congestion for each transmission line shown in the following table:

Transmissions line	**Number of hours [h]**
CE -> NO	65
NO -> OR	8409
OR -> NO	695

Table 12: Number of congested hours in the transmission lines

The congestion in the NO -> OR transmission line explains the utilization of thermal energy in the Oriental zone while the North zone curtails power. Increasing the transfer capacity of the transmission between these zones could reduce the reliance on gas and the curtailment.

2.4 CO2 Emissions

Finally, the comparison includes the assessment of CO2 emissions. The integration of renewable projects aims to decrease Bolivia's greenhouse gas (GHG) emissions. Figure 27 illustrates the total CO2 equivalent emissions for each scenario.

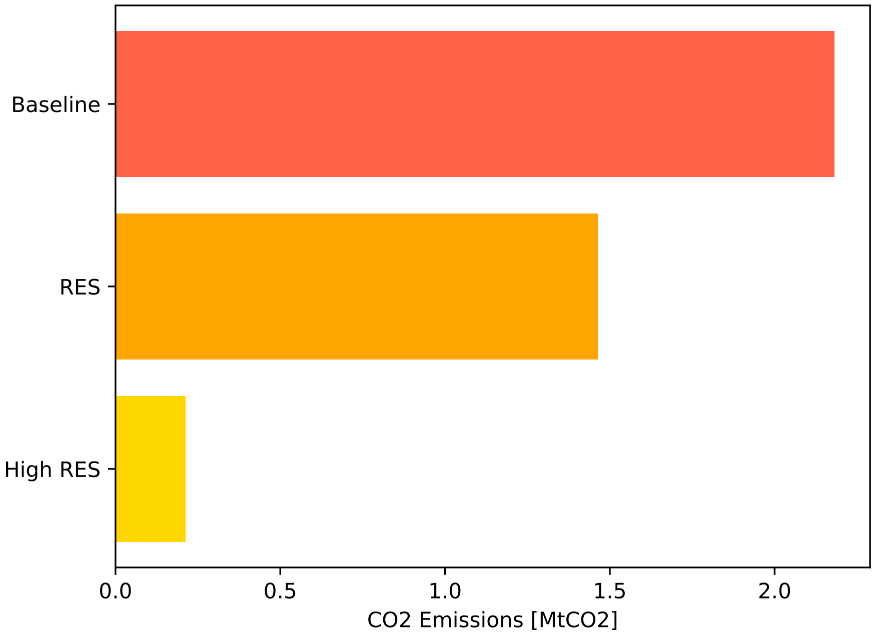

Figure 27: CO2 emissions for the baseline scenario and the renewable scenarios.

The RES scenario leads to a significant reduction in emissions, achieving up to a 30% decrease compared to the Baseline scenario. The High RES scenario shows even more promising results, with a potential emissions decrease of 90%, reducing emissions from 2.18 MtCO2 to 0.21 MtCO2. Taking into account Bolivia's total CO2 emissions in 2021, estimated at 22.4 MtCO2 [15], this reduction represents nearly 9% of the total emissions, signifying a substantial improvement. These results clearly demonstrate the positive impact of renewable integration in reducing Bolivia's CO2 emissions.

3 Comparison of extreme conditions

This section compares three scenarios using different inflow years computed with the function detailed in Section 4. Three specific years are studied: the "driest year" in terms of total inflows, which is 2016; the "wettest year" with the highest inflows, which is 2001; and the "median year," 2019, which represents the midpoint between these two extremes.

3.1 Generation

Hydro generation plays a significant role in the Bolivian system, and it is expected that the intensity of rainfall would have a substantial impact on the overall generation. To analyze this parameter, we examine the distribution of power generation by type of production for each scenario, as shown in Figure 28.

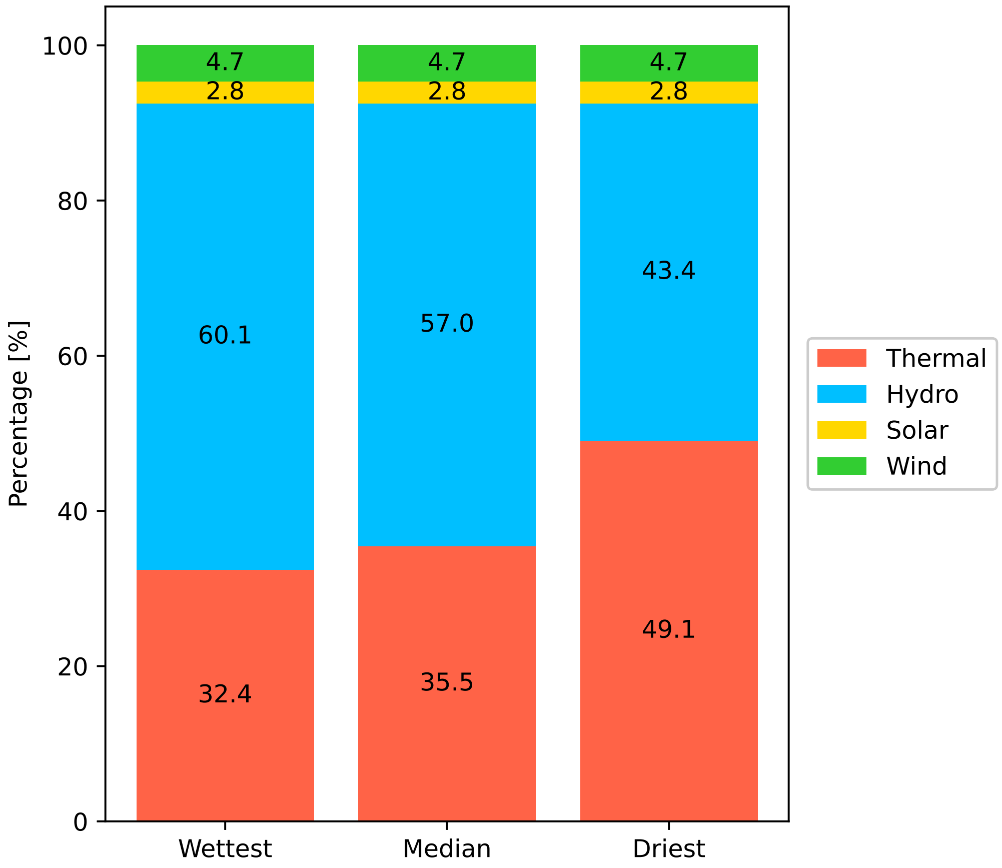

Figure 28: Distribution of the power generation by technology for the median, wettest and driest year.

Comparing the hydro generation between the rainiest year and the median year, we observe no significant difference. However, the driest year exhibits more than a 13% reduction in hydro generation. This disparity highlights the vulnerability of the Bolivian system to weather conditions. Nonetheless, no energy is curtailed in any of the scenarios, indicating the flexibility of the Bolivian SIN.

Furthermore, due to its proximity to the equator, Bolivia experiences a two-season cycle. The wet season, from November to March, is characterized by significant precipitation, while the dry season, from May to September, sees minimal rainfall and lower humidity. To observe this phenomenon, the generation as a time series for 2001 is presented in Figure 29, and for 2016 in Figure 30. Zoomed-in views of two weeks in January and August are included to illustrate the effects of the wet and dry seasons, respectively.

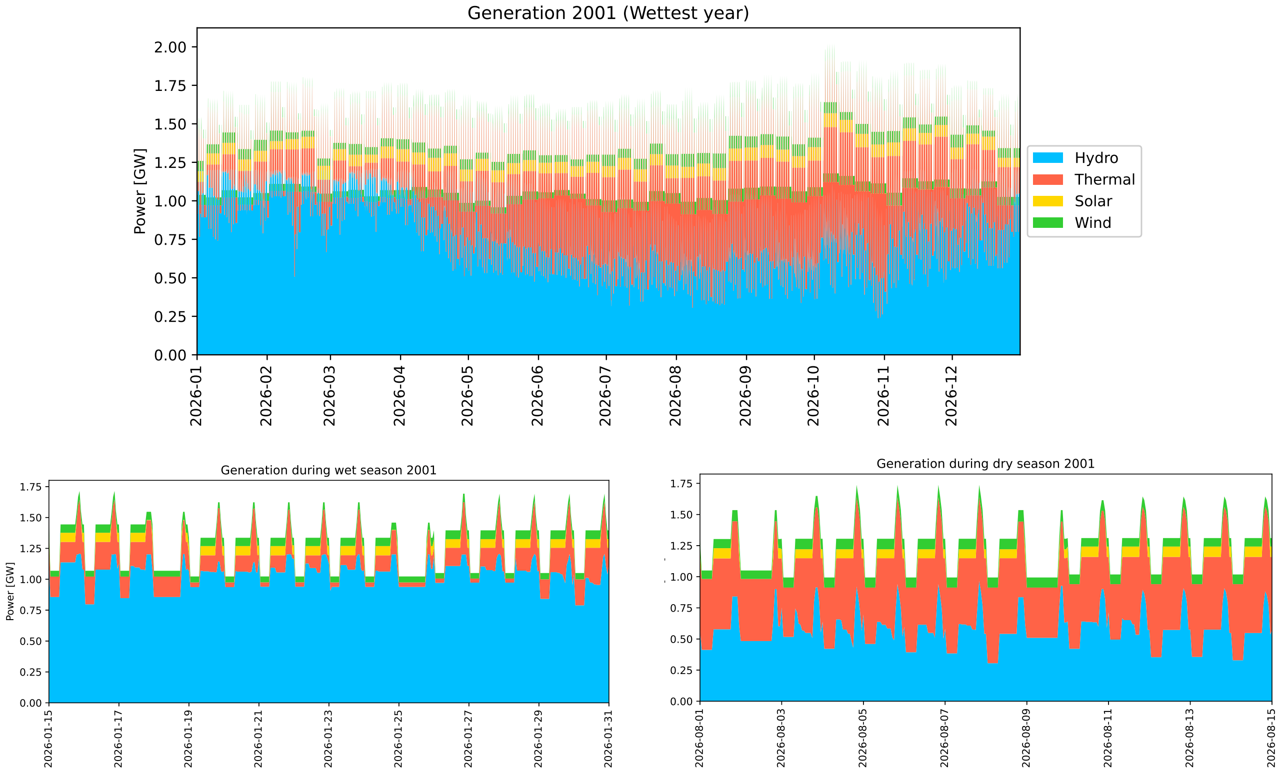

Figure 29: Generation during the rainiest year 2001.

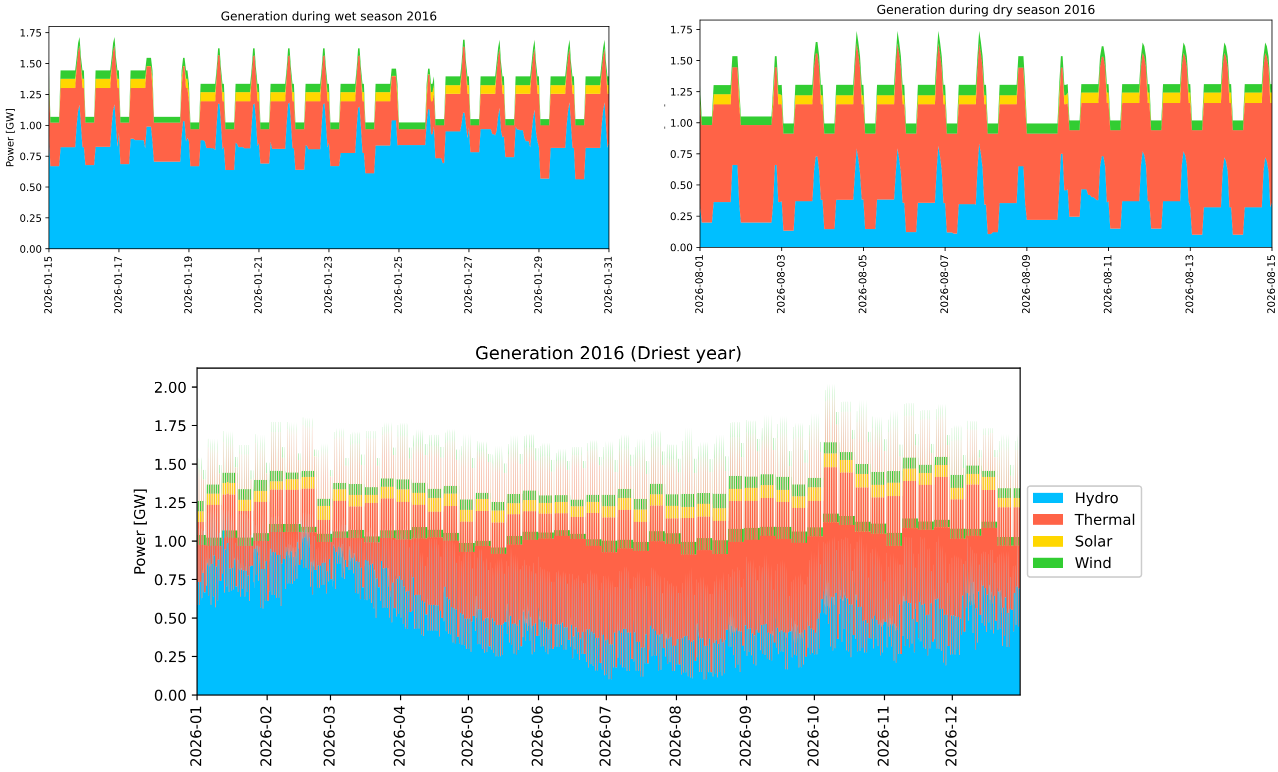

Figure 30: Generation during the driest year 2016.

The hydro generation of each year's time series clearly reflects the two-season pattern. When examining the two-week time series, it becomes evident that during the wet month of 2001, the majority of energy is produced by water. In fact during these two weeks, 80% of the power is produced by hydro generation. Conversely, during the depicted two weeks in August 2016, thermal production contributes to 63.2% of the electricity generated, indicating a shift away from hydro generation during that period.

Given that extreme events like these are likely to become more frequent in the future due to climate change, it is crucial for Bolivia to be aware of the consequences and optimize its water resources as much as possible. This optimization begins with limiting spillage.

3.2 Spillage

Spillage, similar to curtailment, refers to the loss of water and thus energy. To understand the reasons behind spillage, Figure 31 quantifies the total amount of water spilled during each of the three studied years.

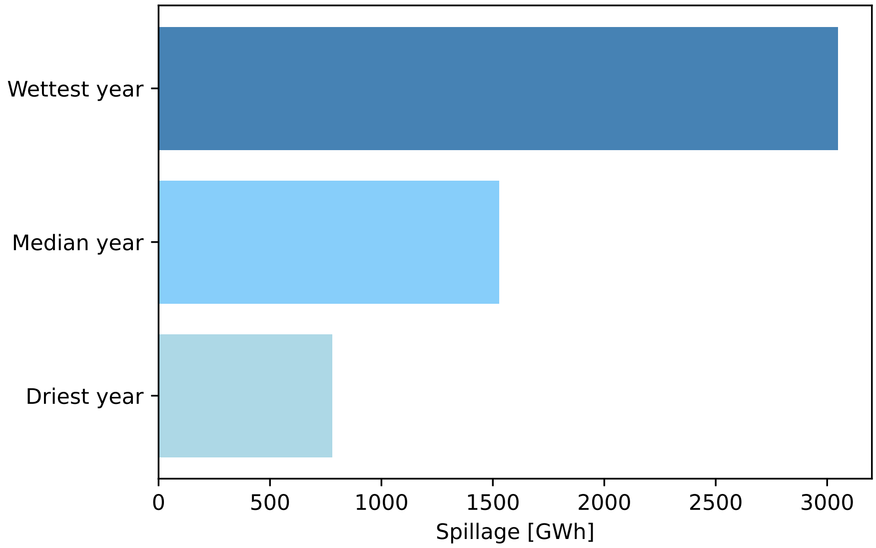

Figure 31: Spillage for the median, wettest and driest year.

As expected, the year with the highest spillage is the wettest year. The significant increase in spillage compared to the other two scenarios accounts for the mere 3% additional hydro energy produced during that year observed in Figure 28. It demonstrates that even with a large quantity of water available, the electric system is unable to generate more due to the limitation of water flow passing through the turbines in the hydro plants. Therefore, one way to optimize water usage would be to increase the capacity of these plants.

3.3 Storage Level

However, the maximum turbining outflow is not the sole factor that impacts water optimization. Reserves also play an important role in water management. The storage levels of all the reserves combined throughout the years are plotted in Figure 32.

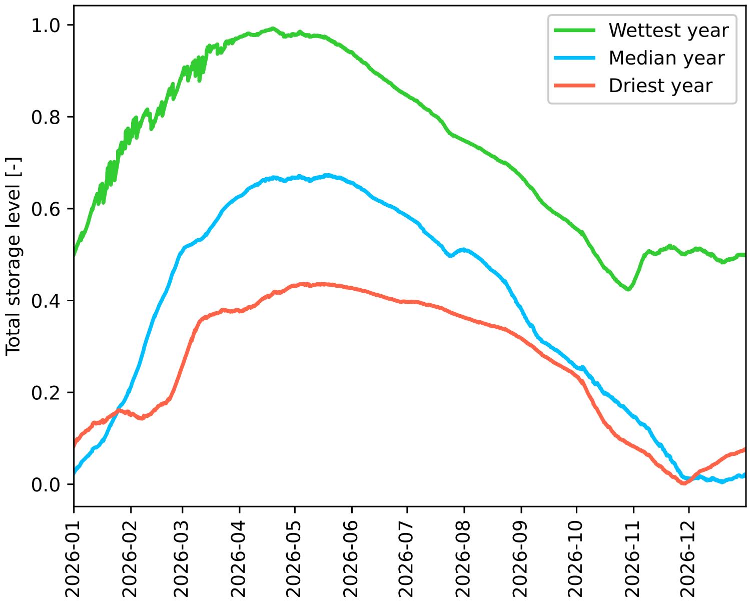

Figure 32: Storage levels of the median, wettest and driest year.

As expected, the overall reserves level is highest during the year with the most rainfall and lowest during the driest year only reaching at its maximum 40% of the total capacity. Furthermore, when examining the former year specifically, it is evident that the storage reaches full capacity at the end of the wet season. This means that during that time, all the water entering the reserves is directly spilled, which could explain the high spillage observed in Figure 31. Therefore, another way to prevent excessive spillage is to increase the storage capacity.

By comparing the storage levels and the power generation time series, an interesting pattern emerges. During the wet season when more water is available, all of it is used to fill the reservoirs until their yearly maximum and to generate energy. However, once the reservoirs are full, hydro generation decreases to conserve stored water for the drier period of the year.

Part V

Conclusion

This study aimed to accurately model the future Bolivian electricity system for 2026 and anticipate challenges arising from the climate emergency. Three main objectives were pursued: enhancing the Dispa-SET model to include hydro power cascade systems, modeling high renewable energy penetration scenarios, and analyzing the system's performance under extreme weather conditions.

This study introduced a significant improvement to the Dispa-SET model, enhancing its capability to accurately model hydro power cascade systems. By treating the cascade as a group of sectors and incorporating new constraints into the model to regulate the storage levels and inter-sector water flows, the model enables better optimization of operational costs and hydro power generation. This new feature is particularly important for the Bolivian case, where a significant portion of electricity is generated by hydro cascades. To assess the accuracy and effectiveness of the new version, a comparison between the two versions was conducted and analyzed.

The global shift to net-zero emissions requires countries to transition their energy sectors by reducing reliance on fossil fuels and increasing their share of renewable technologies. Two scenarios were examined, based on a list of six renewable projects provided by ENDE. The first scenario integrates these projects as initially proposed. In the second scenario, the same projects were integrated with their installed capacity multiplied to meet the national objective of reaching 50% of the total installed capacity by 2030. Both scenarios were simulated using the enhanced version of the Dispa-SET model.

Given the increasing occurrence of extreme weather events associated with climate change, it is crucial for hydro-dependent countries such as Bolivia to be prepared for the potential impact of these events on their electrical systems. To assess the vulnerability and behavior of the grid, two scenarios were created using historical inflow data from the past 40 years. The years with the highest and lowest rainfall were identified and used as inputs. By comparing the results of the two scenarios, the grid's response and vulnerability to extreme weather events were evaluated.

The comparison of the two model formulations reveals that the new version offers improved management of inflows and storage levels, resulting in better optimization of hydro generation and more realistic outcomes. Consequently, this version is employed for the remaining simulations, ensuring greater accuracy and reliability in the analysis.

The analysis of the two RES scenarios demonstrates that increasing the proportion of renewable energy can effectively reduce reliance on fossil fuels and achieve the national objective of a 79% renewable energy share in the overall energy production. In particular, the High RES scenario achieves a remarkably low thermal production of only 5.4%. Although there is a 16% curtailment of energy due to the intermittent nature of VRES like solar, this level remains acceptable considering the overall energy generation. These findings suggest that the Bolivian SIN is well-suited for the integration of a high share of renewable energy sources.

The last analysis compares the two extreme scenarios with the baseline scenario. Firstly, the results show that Bolivia's two-season cycle exacerbates the impact of extreme conditions during wet and dry seasons. In the year with the most rainfall, the energy generated by hydro is only 3% higher than the baseline scenario due to turbined flow restrictions, resulting in excessive water spillage. Conversely, the driest year demonstrates a significant decrease in water-based energy production, highlighting the grid's vulnerability to such conditions. Although no shortage or load shedding occurred in the simulations, adding additional water storage could mitigate complications during even more extreme events. This approach ensures excess water during the rainiest months is preserved for the drier periods when it is most needed.

In conclusion, this study successfully achieved its objectives of accurately modeling the future Bolivian electrical system, analyzing renewable energy scenarios, and assessing the system's performance under extreme weather conditions. The findings show that the Bolivia system is quite suitable for a transition to renewable energy sources especially if new infrastructures are integrated enhancing the flexibility and resilience of the grid.

Future work involves enhancing the Dispa-SET model for improved accuracy. Additionally, a detailed analysis on the location and parameters of potential new infrastructures is needed to maximize their utilization. This will facilitate the expansion of renewable energy and increase its share in the installed capacity with more concrete projects. By focusing on these areas, future efforts can contribute to the ongoing advancement of the Bolivian energy sector towards a sustainable and resilient future.

Part VI

Appendices

A Python functions

```python
# -*- coding: utf-8 -*-
"""
@author: Isaline Gomand
"""

import os
import sys
sys.path.append(os.path.abspath('..'))

import pandas as pd

def load_ConfigProjectsFile(ConfigProjectFile):
    """
    Load the new projects excel configuration file and returns a dictionary
    with the values

    :param ConfigProjectFile: String with (relative) path to the new projects excel configuration file
    """
    import xlrd
    wb = xlrd.open_workbook(filename=ConfigProjectFile)  # Option for csv to be added later
    sheet = wb.sheet_by_name('main')
    config = {'SimName': sheet.cell_value(9, 2), 'PP_Source': sheet.cell_value(12, 2),
              'AF_Source': sheet.cell_value(13, 2), 'ProjectFile': sheet.cell_value(25, 2),
              'TypicalUnitsFile': sheet.cell_value(24, 2), 'WeatherConditions': sheet.cell_value(19, 2),
              'SI_historical': sheet.cell_value(21, 2)}
    startCellProjectsList = 27
    i = 0
    config['ProjectsList'] = []
    while sheet.cell_value(startCellProjectsList+i, 0) != '':
        if sheet.cell_value(startCellProjectsList+i, 2) == 1:
            config['ProjectsList'].append(sheet.cell_value(startCellProjectsList+i, 0))
        i += 1
    return config

def load_ListProjects(configProjects):
    """
    Returns a dataframe with the power plant data of the selected projects

    :param configProjects: Set of variables containing the information from the new projects configuration file
    """
    path_projects = os.path.abspath('../NewProjects/'+configProjects['
```

```
PP_Source']+'.csv')
    projects = pd.read_csv(path_projects, index_col=1)
    return projects[projects.index.isin(configProjects['ProjectsList'])]

def fill_PowerPlantData(configProjects, config):
    """
    Concatenates the 2 power plant files and returns the path to the new merged power plant file

    :param configProjects: Set of variables containing the information from the new projects configuration file
    :param config: Set of variables containing the information from the Dispa-SET configuration file
    """
    plants = pd.read_csv(config['PowerPlantData'], index_col=1)
    projects = load_ListProjects(configProjects)
    for unit in projects.index:
        plants = pd.concat([plants, pd.DataFrame(projects.loc[unit]).T])
        if plants.loc[unit, 'Technology'] == 'HDAM':
            plants.at[unit, 'Fuel'] = 'WAT'
        elif plants.loc[unit, 'Technology'] == 'HPMS':
            plants.at[unit, 'Fuel'] = 'WAT'
        elif plants.loc[unit, 'Technology'] == 'HROR':
            plants.at[unit, 'Fuel'] = 'WAT'
        elif plants.loc[unit, 'Technology'] == 'WTON':
            plants.at[unit, 'Fuel'] = 'WIN'
        elif plants.loc[unit, 'Technology'] == 'PHOT':
            plants.at[unit, 'Fuel'] = 'SUN'
        elif plants.loc[unit, 'Technology'] == 'BATS':
            plants.at[unit, 'Fuel'] = 'ELE'
        for param in projects.columns:
            if pd.isna(plants.loc[unit][param]):
                plants.at[unit, param] = find_TypicalUnits(configProjects, plants, unit, param)
    plants = plants.rename_axis('Units').reset_index()
    plants.insert(0, 'PowerCapacity', plants.pop("PowerCapacity"))
    plants.to_csv(config['PowerPlantData'][:-4]+'_'+configProjects['SimName']+'.csv', mode='w', index=False)
    return os.path.abspath(config['PowerPlantData'][:-4]+'_'+configProjects['SimName']+'.csv')

def find_TypicalUnits(configProjects, plants, unit, param):
    """
    Finds in the Typical_Units csv file the most appropriate value for the missing parameter

    :param configProjects: Set of variables containing the information from the new projects configuration file
    :param plants: Dataframe of the power plant data
    :param unit: Name of the unit with the missing parameter
    :param param: Name of the missing parameter
    """
    typicalUnits = pd.read_csv(os.path.abspath(configProjects['TypicalUnitsFile']), index_col='Technology')
    if isinstance(typicalUnits.loc[plants.loc[unit,'Technology']][param].sum(), str):
        return typicalUnits.loc[plants.loc[unit,'Technology']][param][0]
    else:
```

```python
        return typicalUnits.loc[plants.loc[unit,'Technology']][param].sum()/len(typicalUnits.loc[plants.loc[unit,'Technology']])

def fill_RenewablesAFFile(configProjects, config):
    """
    Concatenates the 2 availability factor files and returns the path to the new merged availability factor file

    :param configProjects: Set of variables containing the information from the new projects configuration file
    :param config: Set of variables containing the information from the Dispa-SET configuration file
    """
    projects = load_ListProjects(configProjects)
    AvailabilityFactors = pd.read_csv(config['RenewablesAF'], index_col=0)
    AF_projects = pd.read_csv(os.path.abspath('../NewProjects/'+configProjects['AF_Source']+'.csv'), index_col=0)
    for unit in projects.index:
        if projects.loc[unit, 'Technology'] == 'WTON' or projects.loc[unit, 'Technology'] == 'PHOT':
            AF_unit = pd.DataFrame(AF_projects.loc[:,unit]).set_axis([unit], axis=1, inplace=False)
            AvailabilityFactors = pd.concat([AvailabilityFactors, AF_unit.set_index(AvailabilityFactors.index)], axis=1)
    # return AvailabilityFactors
    AvailabilityFactors.to_csv(config['RenewablesAF'][:-4]+'_'+configProjects['SimName']+'.csv', mode='w')
    return os.path.abspath(config['RenewablesAF'][:-4]+'_'+configProjects['SimName']+'.csv')

def yearWeatherCondition(configProjects, config):
    """
    Uses historical data to calculate the hydropower available capacity and returns the extreme condition years

    :param configProjects: Set of variables containing the information from the new projects configuration file
    :param config: Set of variables containing the information from the Dispa-SET configuration file
    """
    SI_folder = os.path.abspath(configProjects['SI_historical'])
    path_plants = os.path.abspath(config['PowerPlantData'])
    plants = pd.read_csv(path_plants, index_col=1)
    dates = os.listdir(SI_folder)
    startYear = int(dates[0][0:4])
    stopYear = int(dates[-1][0:4])

    capHydro = plants.loc[(plants['Technology'] == 'HDAM') | (plants['Technology'] == 'HDAMC') | (plants['Technology'] == 'HROR')]['PowerCapacity']
    totCapByYear = pd.DataFrame()
    for year in range(startYear, stopYear+1):
        SIAvByYear = pd.read_csv(SI_folder + '/' + str(year) + '.csv', index_col=0).sum()
        totCapHydroByYear = (SIAvByYear*capHydro).sum()
        totCapByYear[str(year)] = [totCapHydroByYear]
    if configProjects['WeatherConditions'] == "WorstCase":
        return totCapByYear.T.idxmin().iloc[0]
```

```
    elif configProjects[’WeatherConditions’] == "BestCase":
        return totCapByYear.T.idxmax().iloc[0]
    else:
        return (totCapByYear.T-totCapByYear.T.median()).abs().sort_values(0)[:1].iloc[0].name
```

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