Modeling hydropower to assess its contribution to flexibility services in the Bolivian power system

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ABSTRACT

Bolivia has an important hydroelectric potential that has the potential to be an important part of future energy supply. This potential is due to the topographic characteristics of the country, composed of two large hydrological systems, the Amazon and La Plata basin, with a power of 34,208.50 MW and 5,359.90 MW respectively. Hydropower has been increasing in the Bolivian territory in recent years, with a tripe objective: guarantee energy sovereignty, industrial development and the export of electrical energy. Today, the power system has a 33 % share of hydraulic component, a 61 % share of thermal component, and the rest of other renewable energy sources. Such a composition makes the system vulnerable to hydrological variations that can affect production costs and flexibility of the energy system. Therefore, this study aims to assess the effects of different rainfall years on the ability of hydropower to generate and store electricity. This is done using the hourly power system simulation software Dispa-SET, primarily developed by the European Commission. For the application of the methodology, the Dispa-Set Bolivia model is taken as a basis. For this study the hydroelectric systems are disaggregated by hydro unit, which allows to include the flows of sub-basins in run-of-the-river plants. The information on water inputs for different years is obtained from the Surface Water Balance of Bolivia 2017, which uses the Soil Moisture method (rainfall-runoff) through the software Water Evaluation and Planning (WEAP), for a period from 1980 to 2016. The model optimizes the system under all hydro years, both with a mid-term scheduling approach and a short-term optimal dispatch and unit commitment approach. Modeling has allowed to obtain a broad vision of different scenarios, where main results show that heavy rainfall years affect the electricity production of hydro plants by impacting the flexibility hydropower can provide to the system. This results in changes on the average production costs, which is quantified by differences in terms of electricity production of hydropower plants.

KEYWORDS

Energy planning, Renewable Energy, Hydropower, Power system modeling, Flexibility.

INTRODUCTION

The reliability and operation of electrical system components can be affected by several factors, mainly climate-related events [1–3]. In the Bolivian electricity system, these factors are called "unforeseen events", which are changes in hydrology, in the demand, and in the unavailability of generating units [4]. These have an impact on marginal costs by showing a difference between the provided costs in the six-monthly schedule and the actual energy dispatch.

Long-term changes in hydrology raise the question of their economic effects in future scenarios. For example, [5] obtains a reduction in hydroelectric energy by the year 2100, which would imply an increase recourse to thermal power plants and would result in additional costs up to 0.05% of GDP. Recourse to thermal power plants can however be largely mitigated by new hydro units: the country has an estimated hydroelectric potential of 39.8 (GW) [6], which is currently exploited by less than 2%.

Bolivia's electricity system currently relies mainly on natural gas as a primary energy source. In 2000, natural gas accounted for 57% of the primary energy produced, and in 2010 this percentage rose to 80% as a result of the significant growth in natural gas exploitation. During the 2000-2010 period, non-renewable energy production increased by 208%, while renewable energy generation only increased by 21%. In the last decade, hydroelectric power generation has been increasing up to 10 percent, and further expansion is planned for the near future [7]. In 2020, the participation of hydroelectric plants in the SIN was 21% with an effective capacity of 734.84 MW.

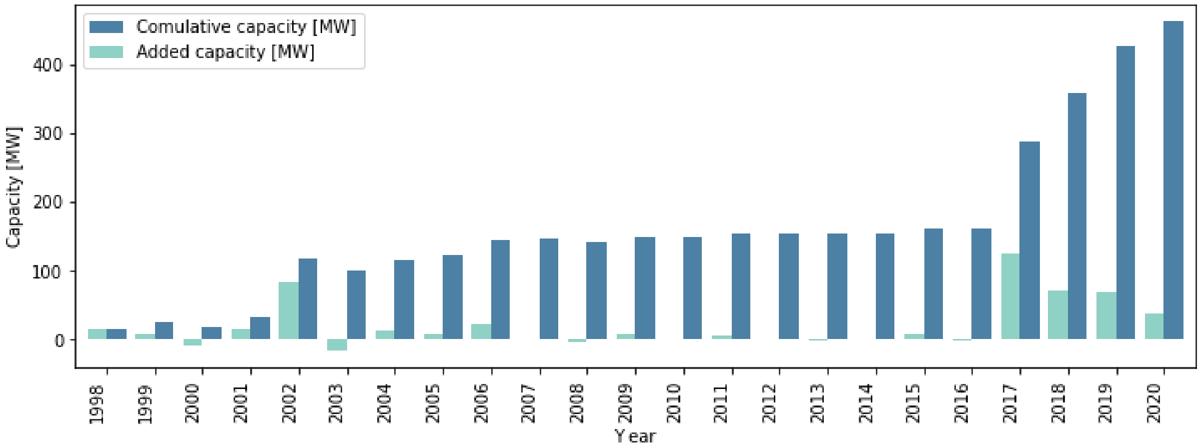

Figure 1: Hydropower growth and development through the years [4].

Figure 1 shows the evolution over time of the increase of power of some units and integration of new hydro units. This growth is a significant asset for the objective of meetings the climate targets, as defined in the National Determined Contributions (NDC) and the Paris Agreement.

Hydroelectricity has multiple benefits, as it is considered as one of the must abundant renewable energy options, it is economically competitive [8], it does not produce greenhouse gases or other air pollution and does not leave waste [9]. Storage capability and rapid response capacity are especially valued to cope with seasonal fluctuations in power demand, and to balance the variable sources (such as wind and solar) [10]. However, this type of energy is limited to changes in hydrology, which has an impact on the provision of reliable electricity and with an optimal generation dispatch, knowing the degree of impact in the face of changes in rainfall patterns will make it possible to broaden the programming horizon of hydropower, which contributes to short-term planning.

In this sense, an analysis of changes in hydrology becomes essential. To that aim, a unit-commitment and power dispatch model Dispa-SET is used to simulate them with different rainfall years, this allows evaluating the flexibility of the electrical system in terms of energy balance, electricity generation costs, and power plant scheduling in the face of different rainfall patterns. This research could also be considered as a basis for evaluating the effects of climate change on hydropower.

THE BOLIVIAN ELECTRICAL SYSTEM

The Bolivian electricity system comprises the National Interconnected System (SIN) and the Isolated Systems (SA) that supply electricity to remote locations. The SIN delivers to the main cities and has an installed capacity of 3318.77 MW in 2020. This system is divided into four defined areas: North (La Paz and Beni), Oriental (Santa Cruz), Central (Oruro and Cochabamba) and South (Potosí, Chuquisaca and Tarija) (see Figure 2). The high voltage transmission system (STI) is the part of the SIN that includes transmission lines of 230, 115 and 69 (kV).

Solar resources Bolivia comprises a strip of territory that receives the largest solar radiation in the world (the southern tropical zone, between parallels 11° y 22°) with radiation values of 5.1 to 7.2 kWh/m2-day in the southwest of the country, while the northeast area has slightly lower values with 3.9-5.1 kWh/m2-day. This feature makes almost 97% of the territory suitable for using solar energy as a primary source of generation [11].

Wind resources In recent years the Bolivian wind atlas was developed [12], which shows annual wind speed measurements at three different heights (20 m, 50 m, 80 m). The wind resource in Bolivian territory seems to be more limited than the solar, the strongest resources are concentrated in five sectors and the first wind farm projects are gradually incorporated: Around the city of Santa Cruz, mostly south and west of the urban center with the projects of "Warnes-El Dorado- San Julian"; In the corridor that goes from east to west between La Paz and Santa Cruz, passing through the north of the department of Cochabamba with the project of "Qollpana I Qollpana II-Qollpana III"; In Tarija and Sucre that goes from north to south with the project of "La Ventolera"; Around the region of Lake Titicaca in the department of La Paz with the project "Titicaca"; Finally, on the southwest border between Chile, Argentina and the department of Potosí; and in the northern corridor between Oruro and the departments of Potosí as possible locations for future projects [12].

Hydro resources A study carried out by the consulting company Poyri shows the important hydroelectric potential of the country and identifies 216 potential new projects, without considering the projects that are under construction and operation. This study also identifies 23,170 rivers, according to the topographic, hydrological and river network review of the country; in addition to a remaining usable technical potential of about 40 (GW) [6]. In spite of the huge hydroelectric

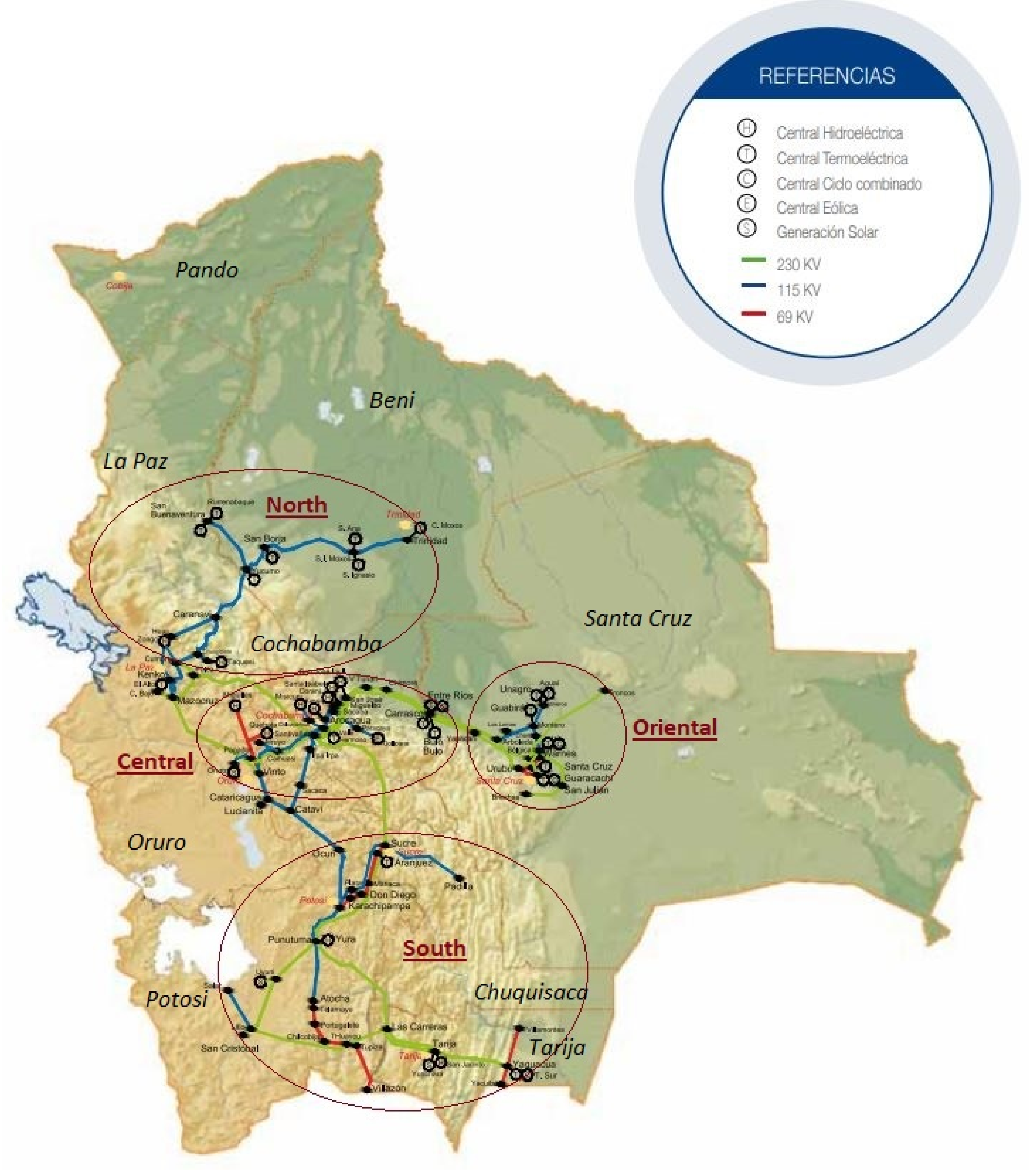

Figure 2: The SIN layout at 2020 [4].

potential, its exploitation is still relatively limited, with 493 MW in 2016. Since 2017, however, an uptake of the hydroelectric sector has been stated, with the entry into operation of Misicuni, San Jose 1 and the increase in the capacity of Corani and San Jose 2 [13].

By 2020 it has an installed power of 734.83 MW, and hydroelectric park that would be composed of water systems with power stations (Zongo, Taquesi, Yura and Quehata), and water systems with power stations with reservoir (Corani, Miguillas, San Jacinto and Misicuni) and a power station whose operation depends on drinking water supply in the city of Cochabamba (Kanata) [4].

The Corani Hydroelectric power plant is the oldest in Bolivia, since it entered into operation in 1967 with two generation units, implemented two more units in 1980 and incorporated in 2018 a fifth unit, which increased its total generation capacity to 64 MW. Downstream of the Corani Hydroelectric Power Plant, is the Santa Isabel Hydroelectric Power Plant, which began operating with two generation units in 1973. It incorporated two units in 1981 and installed its fifth unit in 1983, achieving a total generation capacity of 91 MW. The third use of this cascade is the San José 1 Hydroelectric Power Plant, which began operations in 2018, injecting 55 MW; In April 2019, the San José 2 Hydroelectric Power Plant, entered into commercial operation, constituting the fourth use of this same cascade, contributing 69 MW to the SIN [14].

San Jacinto Hydroelectric Power Station consists of two generating units, each equipped with two Francis type turbines with horizontal axis. The hydraulic use is through the contributions of the rivers Tolomosa and Molino [15]. In 2019 the Hydroelectric Plant contributed to the SIN with a maximum power of 7.6 MW and a power generated of 21.0 GWh which means a reduction of 16.9% compared to 2019 [4].

Interconnected National System in 2020 (Baseline)

The National Interconnected System (SIN) supplies electrical energy to all departments of Bolivia except Pando. The energy consumption in the SIN is distributed mainly in the Oriental areas (Santa Cruz) with 38.1%, North with 23.4% (La Paz 21.3% and Beni 2.1%) and the rest of the SIN with 38.5%. Total demand in the SIN is approximately 95% of total demand in the country [4]. In this work, the characteristics of the SIN with data for the year 2020 are considered as the baseline scenario.

It is important to note that 2020 corresponds to period of low demand, with a reduction of up to 40% in daily energy demand and up to 20% in power during the peak demand period from 21 March due to the national quarantine imposed by the Central Government to contain COVID-19. In addition, this situation made it necessary to take operational measures in periods of low demand to adequately regulate the voltage in the STI, by disconnecting transmission lines in 230 (kV) and 115 (kV). The energy consumption recorded in 2020 reached the value of 8,725.4 GWh which is 3.9% lower than the year 2019 [4]. 2020 is also characterized by the commissioning of new generating capacities, which are included in Table 1.

The average annual marginal cost for 2020 was 18.74 (US/MWh) (without tax), with a minimum monthly average of 15.12 (US/MWh) and a maximum monthly average of 21.74 (US/MWh). Events not foreseen in the programming (changes in hydrology, in demand and in the unavailability of generating units), have affected the marginal costs showing a difference of 1.73% more of the energy dispatch between the costs predict in the semiannual programming and the programmed [4].

MATERIALS AND METHODS

For this study, the configured model of Dispa-SET_Bolivia is used, initially developed in 2016 with data from the SIN of the same year. The model was configured to carry out short and

Table 1: Power generation fleet in the SIN in 2020 [16].

Zone	**System**	**Central name**	**Units**	**Power MW**
North	Taquesi System	HDAM	2	89.19
	Zongo System	HDAM	21	188.04
	Quehata Central	HDAM	2	1.97
	kenko	GTUR GAS	2	
	El Alto		2	46.19
	Trinidad	GTUR OIL	19	25.28
	Rurrenabaque		1	1.8
	Yucumo		1	0.35
	San Borja		2	1.8
	Say		2	1.62
	San Ignacio de Moxos		2	0.73
	San Buenaventura	GTUR BIO	1	5
Central	Miguilla System	HDAM	9	21.11
	Corani System	HDAM	10	280.35
	Misicuni System	HDAM	3	120
	San Jose 1 y 2	HDAM - HROR	4	124
	Kanata	HROR WAT	1	7.54
	Valle Hermoso	GTUR GAS	8	107.65
	Carrasco		3	122.94
	Bulo Bulo		3	135.41
	Entre Rios		4	105.21
	Entre Rios	COMC GAS	3	376.98
	Oruro I	PHOT SUN		50.01
	Quollpana I & II	WTON WIN	10	27
Oriental	Guaracachi	COMC GAS	3	192.92
	Warnes		2	248.1
	Guaracachi	GTUR GAS	5	126.72
	Santa Cruz		2	38.07
	Warnes		5	195.56
	Unagro	GTUR BIO	1	14.22
	Guabira		1	21
	IAG		1	5
South	Yura System	HDAM	7	19.04
	San Jacinto	HROR WAT	2	7.6
	Aranjuez	GTUR GAS	10	33.76
	Karachipampa		1	
	Del Sur		4	147.55
	Del Sur	COMC GAS	2	232.32
	Uyuni_Colchak	PHOT SUN	21	60.06
	Yunchara		2	5
SIN	All centrals	All technologies	184	3187.09

long-term projection studies for the implementation of new unconventional energy sources such as solar-PV and wind-onshore. Although the Dispa-SET_Bolivia model has been updated both in data and with projections towards an energy transition, it is still necessary to continue updating the model. Therefore, one objective of this study is to expand the information regarding the hydropowers.

The aim of this study is not only to provide more information on hydroelectric power stations, but also to analyze the flexibility of the system in the face of different rainfall years. For that purpose, this study uses both a hydrological model that allows obtaining the time series of inflows of hydro units and an energy dispatch and commitment model that allows simulating the hydroelectric system in terms of system flexibility in the different rainfall years.

The energy dispatch and commitment model is simulated for two scenarios, the first is a simulation of the configured model of Bolivia with hydroelectric systems, disaggregated by hydro plants and with data from the SIN for 2020. This scenario is referred to as "Baseline". The second consists of varying the time series inflows of hydro plants in the Baseline, allowing to assess the influence of different rainfall years in the electrical system in terms of production. The following sections describe the configurations, architecture and parameters used for both models.

Dispa-SET Bolivia

Dispa-SET is an open-source model for unit commitment and economic dispatch, originally developed for the European power system. The goal of the Dispa-SET model is to optimize the short-term operation of large-scale power systems, with high level of details and at an hourly time step resolution, solving the unit commitment problem (UC/D). The objective function of this model minimizes the total costs of the power system, which consist of start-up, shut-down, fixed, fixed, variable, ramping, transmission-related and load shedding costs [17]. The main model inputs are detailed hereunder. The interested reader can refer to [18] for more details on the modelling framework itself.

The model is set up in a non-clustering mode so that all units are considered individually in such a way that the participation of each hydroelectric plant can be observed during the modeling period, which is one year. To avoid a requirement in computational terms, the optimization horizon of the short-term dispatch optimization is three days with an overlap of one day.

Power plants data Specific techno-economic data is provided for each power plant installed in the system. This includes the type of power plant, the technology, the area where the unit is located (zone), the power capacity, together with more detailed technical data (ramping rates, part-load efficiencies, etc.). This information is described in Table 1.

Load curve A single load curve is provided per zone, which integrates the demand of all sectors, this data is extracted from [19].

Variable renewable energy generation. This section receives information on the availability factor of renewable energy sources in the electricity system. The availability factor is the ratio of instantaneous to installed renewable power. Therefore, for the case study the SIN has sources of solar PV, wind and run-of-the-river plants.

Power plant outages. Outages factor refers to scheduled and unplanned interruptions of generation units and varies from 0 (no outage) to 1 (total outage). The available power is therefore given by the nominal capacity multiplied by (1_outage factor) [17]. Historical average unavailability of the SIN is 4% [20], and the POES takes 7% for thermal units and 4% for hydro units [20,21]. In this work, since no detailed outages times series are available, a constant value of 7% is assumed for all units.

Grid data. Because of the relative simplicity of the grid in Bolivia, the country is divided into four zones whose cross-border flows are limited by a net transfer capacity (no DC power flow is implemented in the current version of the model). The maximum capacity of transmission lines are obtained from [20, 21]. Figure 2 provides the total nominal values of each interconnector; the maximum flow registered in 2020 was 264.45 MW from Central to Oriental area [22].

Time series inflows. In this section, the availability of water resources are added in terms of storage level and inflows or "scaled inflows". "Scaled inflows" are defined as serial exogenous time for each energy storage unit and are expressed as a fraction of the nominal power of this unit [23]. The net generation of hydropower connected to the SIN in 2020 was 9,212.4 (GWh) (see Table 2).

Hydrological model

In 2018, the study The Superficial Water Balance of Bolivia (BHSB) was published, which was generated using the hydrological modelling software Water Evaluation And Planning System (WEAP) [24] and requires climate and soil and land cover data. The BHSB considered the main macrobasins of the country including the Altiplano basin, the Plata basin, and the Amazon basin having defined 95 hydrographic units (UHs) (see Figure 3) combining levels 6, 7 and 8 of HydroBasin [25], of which calibrated balances were obtained in 77 closure basins.

The BHSB covers the modeling period from 1980 to 2016 on a monthly scale. The main results of the BHSB are precipitation, actual evapotranspiration, runoff, specific flow rate and runoff coefficient for the different UH, which were obtained using the Soil Moisture (SM) method and only in some UH was the flood module of the hydrological model WEAP used. The flood module allowed to represent the flood dynamics, since it simulates the movement of water between the river and the flood plains using a surface storage component in the UH ("catchment"). While SM is a uni-dimensional two-bucket soil method with an accounting scheme based on empirical functions describing evapotranspiration, surface runoff, sub-surface runoff, and deep percolation of a basin, that is, the method allows the characterization of the impact of the land cover and the soil type in the hydrological processes, for more details on [26].

For the present study, BSHB surface runoff results are used as input data for the Dispa-SET model, which requires high time-resolution input data. Therefore, the hydrological model of the BHSB is reduced to a daily time resolution, which is the minimum scale of recorded hydrometric data in most of the rivers of Bolivia. The time downscaling involves a series of procedures such as: the adaptation of the model for a daily simulation, estimation of the flow coefficient and finally the calibration and validation of the model.

Table 2: Power generation hydropower in the SIN in 2020 [16].

Zone	System	Central name	Power MW
Central	Corani System	CORANI	65.24
		SANTA ISABEL	91.11
		SAN JOSE 1	124.00
	Kanata Central	KANATA	7.54
	Misicuni System	MISICUNI	120.00
	Miguillas System	MIGUILLAS	2.55
		ANGOSTURA	6.23
		CHOQUETANGA	6.20
		CARABUCO	6.13
North	Zongo System	ZONGO	11.04
		TIQUIMANI	9.72
		BOTIJLACA	6.81
		CUTICUCHO	22.97
		SANTA ROSA	17.59
		SAINANI	10.50
		CHURURAQUI	25.39
		HARCA	25.85
		CAHUA	28.02
		HUAJI	30.15
	Taquesi System	CHOJLLA	38.40
		YANACACHI	50.79
	Quehata Central	QUEHATA	1.97
South	Yura System	KILPANI	11.49
		LANDARA	5.15
		PUNUTUMA	2.40
	San Jacinto System	SAN JACINTO	7.60

Adjustment to the BHSB model. The BSHB model is modified only in climatic variables, such as relative humidity, wind speed, and sun hours, which are originally multi-year averages and the same which are used on a daily basis through a repeat of fixed values per month and are projected by cycles for all years. While the precipitation and temperature variables have a data set at daily level developed using the Gridded Meteorological Assembly Tool (GMET) in the BHSB. GMET is a more realistic representation of precipitation statistics by considering time-invariant spatial parameters and a network of point measurement stations, method described in [27].

Runoff coefficient. The estimation of precipitation with the GMET product presents uncertainty associated to several factors such as observed data records, data filling process, density and distribution of stations in the country, and also to the same GMET algorithm. GMET's rainfall grid was generated using data from 385 stations in Bolivia, Peru, Brazil, Paraguay, Argentina, and Chile. In addition, 12 sampling points taken from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) product to cover the Madre de Dios region [28]. The mentioned sources of uncertainty affect the amount of runoff and the relation between runoff

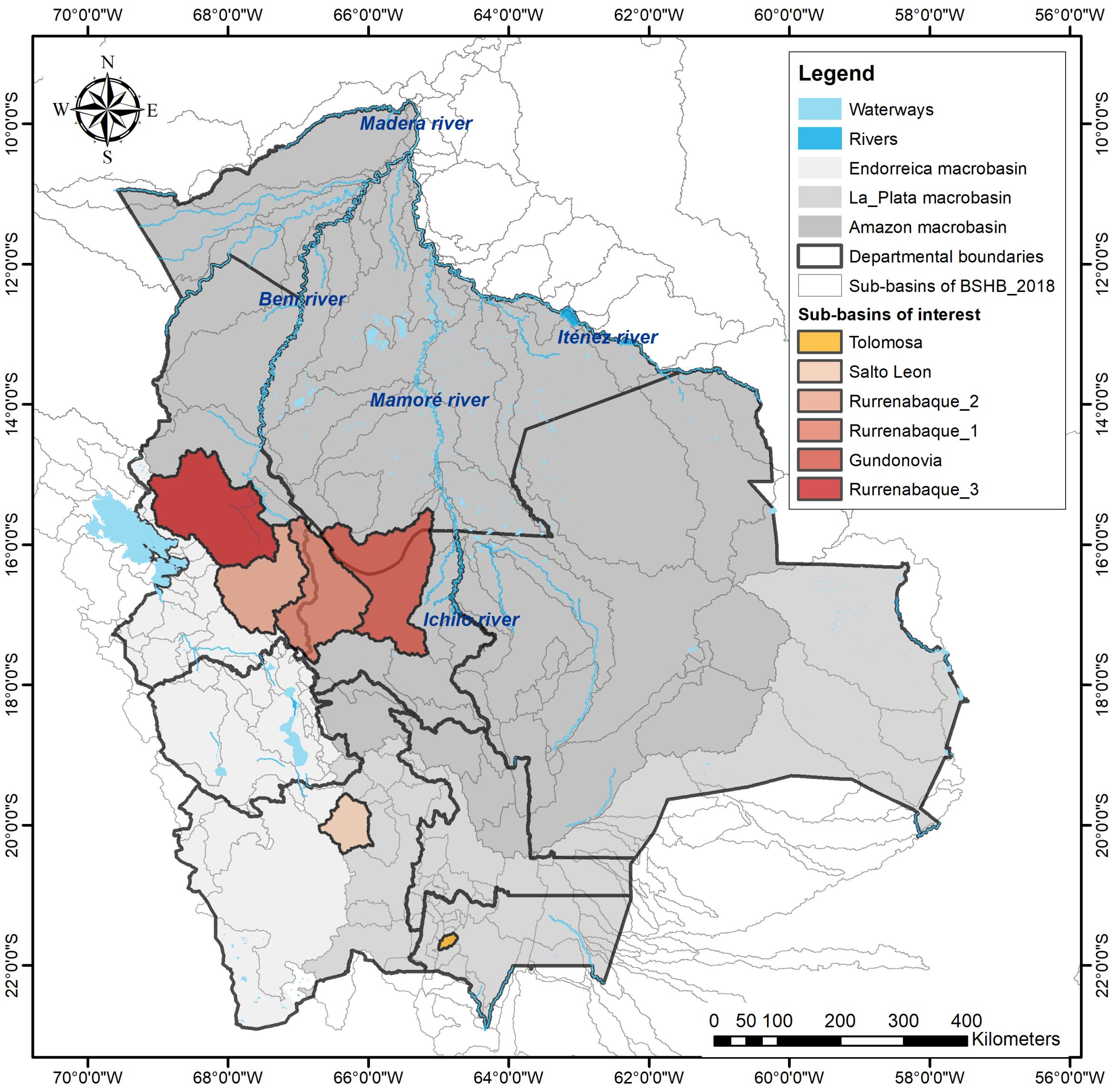

Figure 3: Division of hydrographic units for the Superficial Water Balance of Bolivia 2018.

and precipitation at the basin scale. Therefore, in the BSHB study, an uncertainty analysis was performed and precipitation correction factor (PCF) were applied in the basins El Sena, Rurrenabaque, Puerto Villarroel, Matto Grosso, Pimenteiras, and Pedras Negras. These basins correspond to those in which CHIRPS sampling points have been included and where the observed data were underestimated.

For the same reasons, the present study implements a methodology to calibrate and validate the precipitation time series. A runoff coefficient (CR) is determined in each hydrometric station considering all the basins that drain their waters towards that point. CR allows to know the relationship between direct runoff and the average intensity of precipitation in a storm [29]. The Table 3 shows the CR and PCF values obtained for the BSHB hydrological model and the corrected values.

Table 3: Correction factors and Runoff coefficients.

Control station name	**Runoff Coefficient**			
	BSHB (2018)		**Modified**	
	PCF	**RC**	**PCF**	**RC**
Rurrenabaque	1.38	0.58	1.38	0.58
Penha Amarilla	1	0.46	1	0.46
Portachuelo dos Estrellas	1	0.47	1	0.47
La Sena	1.1	0.59	1.2	0.59
Riberalta	1	0.55	1	0.55
Cachuela Esperanza	1	0.53	1	0.53
Paraiso	1	0.45	1	0.45
Abapo	1	0.42	1	0.42
Puerto Pailas	1	0.43	1	0.43
Angostura	1	0.21	0.8	0.27
La Belgica	1	0.22	0.8	0.28
Puente Eisenhower	1	0.10	0.8	0.12
El Carmen	1	0.24	0.8	0.28
Puerto Villarroel	1.6	0.85	1.8	0.76
Santa Rosa del Chapare	1	0.64	1	0.52
Camiaco	1	0.45	1	0.52
Gundonovia	1	0.45	1	0.45
Los Puentes	1	0.59	1	0.59
San Borjita	1	2.19	1	2.20
Puerto Siles	1	0.57	1	0.49
Matto Grosso	1	0.21	0.8	0.26
Pimenteiras	0.9	0.21	0.8	0.24
Pedras Negras	0.9	0.19	0.8	0.21
Principe	1	0.23	0.8	0.28
Camapamento More	1	0.20	1	0.24
Guayaramerin	1	0.84	1.2	0.90

Calibration and validation. According to the BHSB hydrological model report, the most sensitive parameters influencing the Soil Moisture (SM) Method in WEAP are the resistance to flow (RRF), the storage capacity in the root zone (SWC), the conductivity in the root zone (RZC) and the preferential flow direction (PDF). The same parameters were identified with medium and high sensitivity in the study carried out by [30] for four Amazon basins. The rest of the parameters of the SM method show a low sensitivity and therefore not calibrated in the present analysis.

Before starting the calibration process of the hydrological model on a daily scale, a first simulation is performed by inserting the precipitation correction factors determined in the previous section (see Table 3), the results show an overestimation of the outflows in some basins. Since this cannot be resolved by improving the soil model, an additional calibration is performed regarding the connection with the aquifer in order to better represent underground losses.

Table 4 shows the values of the adjustment metrics Nash-Sutcliffe modeling efficiency (NSE) and Percent Bias (PBIAS) obtained after calibration for the main tributaries of the main rivers.

Table 4: Performance evaluation of the daily hydrological model.

Mean river	**Tributary river**	**Station Capacity**	**NSE**	**PBIAS**
Beni River	Cachuela Esperanza river	Q_Cachuela esperanza	0.68	8%
Mamore River	Puerto Siles river	Q_Puerto Siles	0.76	5%
Amazonas River	Amazonas river	Q_Campamento More	0.50	10%
	Amazonas river	Q_Guayaramerin	0.53	9.8%
	Amazonas river	Q_Abuna	0.64	11%
	Amazonas river	Q_Porto Velho	0.51	15%

Time series. Time series of daily inflows for each hydropower are extracted from the daily hydrological model by relation of contribution areas on the area of the whole basin to which they belong. Figure 3 shows the six sub-basins where all hydropower operating by 2020 are located, as follows: Corani system and Kanata Central are inside the Gundonovia sub-basin; Misicuni system and Quehata central are inside the Rurrenabaque 1 sub-basin; Taquesi and Miguillas system are inside the Rurrenabaque 2 sub-basin; Zongo system is inside the Rurrenabaque 3 sub-basin; finally Yura and San Jacinto system are inside the Salto Leon and Tolomosa sub-basin respectively.

The Kanata central is not related to any basin because the flow destined to generation depends on the supply of drinking water, therefore, the flow is extracted from the CNDC [31] for 2003 until 2015, period of available data, and for remaining years of the modeling period data year 2020 is replicated, the same procedure is carried out for the plants of the Miguillas system because the water collection system to generate energy is unknown.

RESULTS AND DISCUSSION

Important simulation results include the total production of electricity and production costs for the 2020 baseline with the data year 2020 and different historical rainfall years. The variation of the reservoir level profiles was also obtained.

Since the water levels in the reservoirs are known [32] for the year 2020 (Baseline), a mid-term hydro scheduling is not simulated and the historical values are taken as reference. Example results of the short-term unit commitment problem are shown in the dispatch plots (Figure 6 and Figure 5) for the second week of the month of January [33] and August, which are the rainiest month and the driest months, respectively.

Baseline

The baseline simulates the Bolivian electricity system of 2020, building upon previous works [34,35]. For this study, the Dispa-SET_Bolivia model is modified in the hydroelectric generation component. In this sense, hydroelectric systems are disaggregated by hydro units, this has allowed to obtain an annual energy production of 264.82 (TWh) a value similar to that reported by the CNDC with 249.45 (TWh).

At the level of hydro units, the results also show good agreement with the reported data in terms of power output for each hydro unit (see Figure 4). This confirms the ability of the model to reproduce the conditions of the electrical system in terms of hydropower for the baseline.

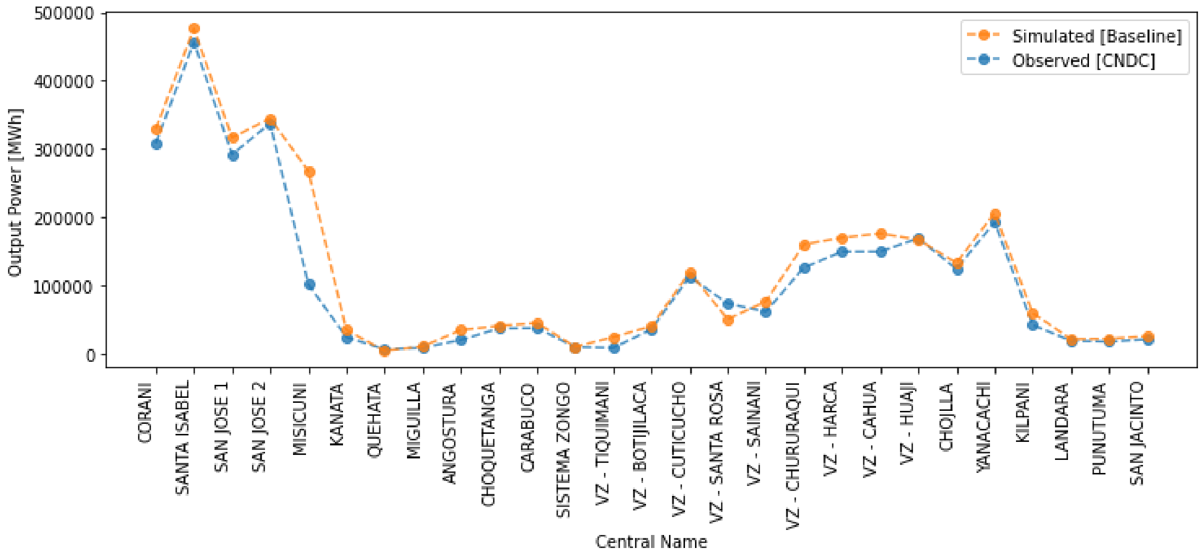

Figure 4: Comparison between observed and simulated values.

Table 5 highlights the main simulation results, the average electricity cost for the baseline is 5.49 (EUR/MWh). There is load shedding in all zones, with a maximum of 36.64 (MWh) for the oriental zone. This zone has an energy consumption of 38% of the total and its demand is mostly covered by thermal and imported energy this could be the possible cause of congestion between the transmission line $CE \Rightarrow OR$ with 550 hours.

Table 5: Main results of all SIN in 2020.

Zone	Peak Load	Net transfer capacities	Total load shedding (TMWh)	Maximum load shedding (MWh)	Load Shifted	Curtailment	Maximum Curtailment
CE	403.48	-1.79	2.88E-04	19.59	3.89E-02		
NO	394.12	0.81	1.42E-04	19.13	3.76E-02	3.63E-05	1.20
OR	754.87	0.89	2.55E-04	36.64	6.51E-02		
SU	277.54	0.09	1.03E-04	13.47	2.59E-02	7.03E-06	0.64

Figure 5 and Figure 6 show that the current Bolivian generation park is clearly dominated by conventional thermal technologies except for the north zone, where hydropower predominates in the wet season the latter being complemented by importations during the dry season (line $CE \Rightarrow NO$).

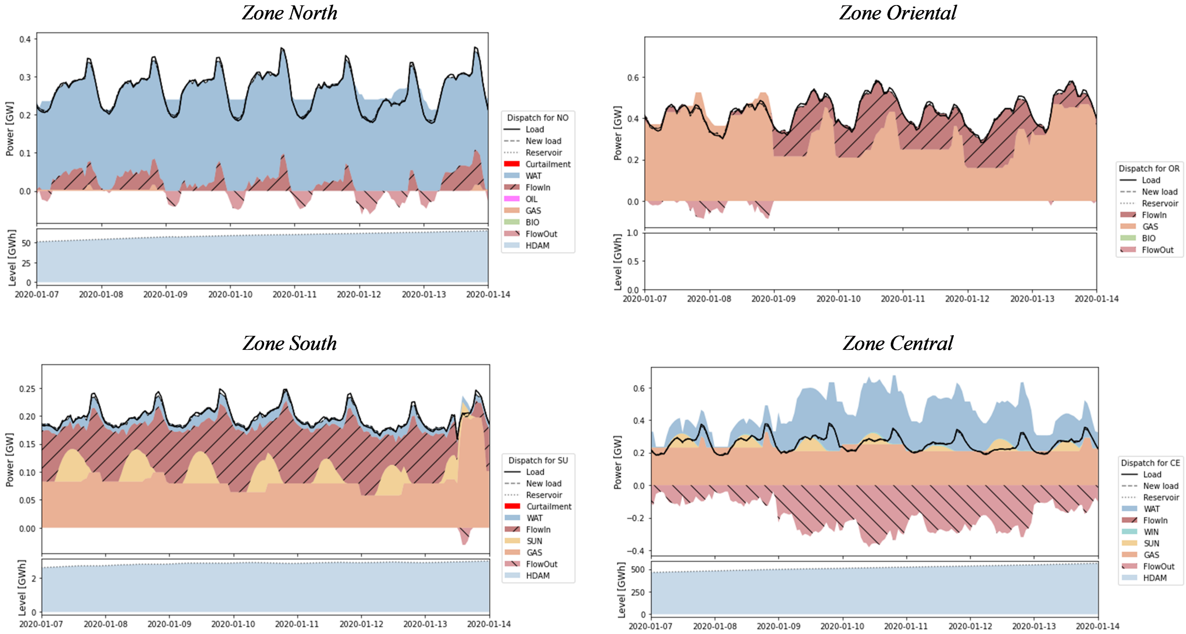

Figure 5: Dispatch results of Baseline for one week (January 7th-14th of 2020); North zone (top left), Oriental zone (top right), South zone (bottom left) and Central zone (bottom right).

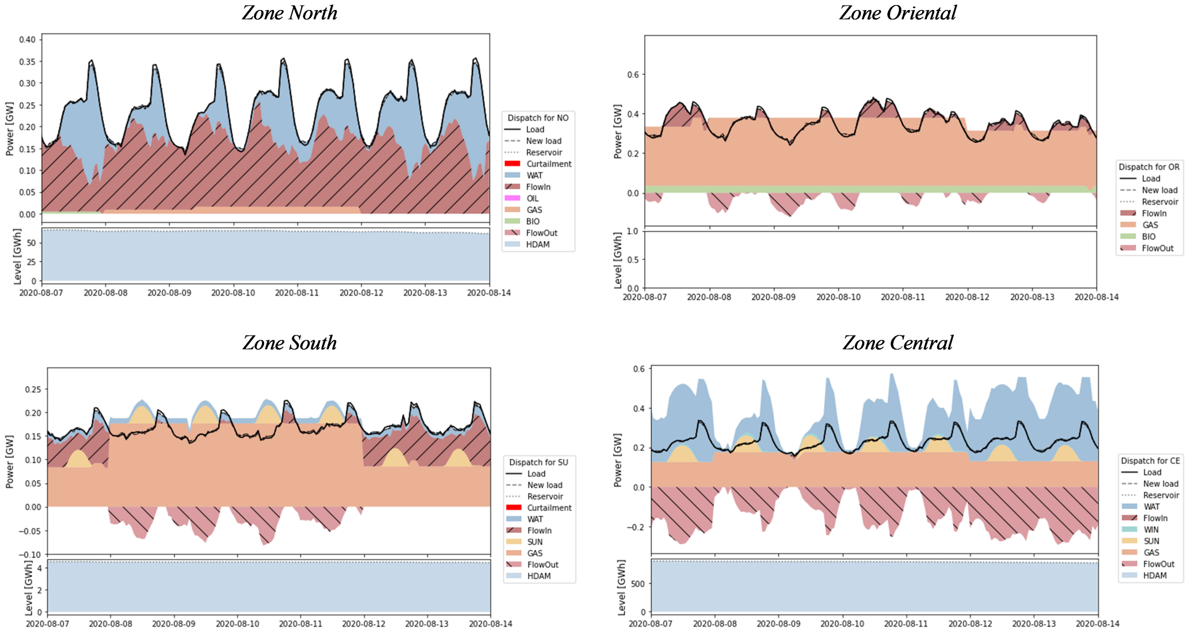

Figure 6: Dispatch results of Baseline for one week (August 7th-14th of 2020); North zone (top left), Oriental zone (top right), South zone (bottom left) and Central zone (bottom right).

Figure 7 shows the calculated level profiles. The graph also shows that the highest level of storage is in the dry season, which means that the reservoirs will be the source of supply to the hydropower during this period. As for dams like San Jacinto and Miscuni it has a limited volume for the generation since they are multi-purpose reservoirs. One aspect to highlight the highest level of reservoir of the Zongo plant that corresponds to the month of August during the dry season, but this is due to the thaw.

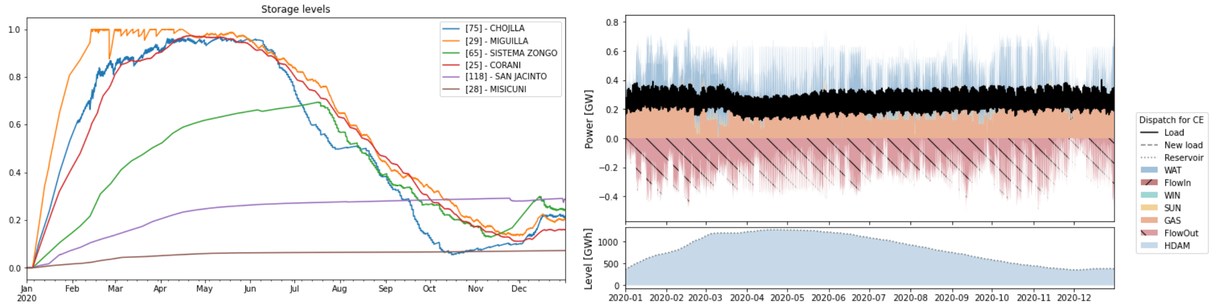

Figure 7: Hydroelectric energy storage level imposed (left); Dispatch and storage level for one year of Central zone - Baseline (right).

The amount of electricity stored in aggregate from all hydro units in the central zone for a year is shown in Figure 7 on the right, in which highlights the months of April, May, and June are months of increased electricity storage capacity. As for the level of the reservoir, these fluctuate around $\pm15\%$ of the level imposed in the months January, February, and December, months that belong to wet season where the input flows are of greater magnitude than the rest of the year this could cause that the reservoirs receive more water than they can convert into electricity, for the rest of the months it fluctuates between $\pm5\%$ with respect to the level imposed except for the months of April, May, and June where the level of reservoir fluctuates between 0% and 1%.

Historical inflows

In this section, the results of the baseline model are aggregated with different rainfall years to evaluate the flexibility of the Bolivian electrical system. The inflow time series obtained for the historical period reveal to be about twice the turbined flow according to the historical records. This difference indicates that only a part of the water potential of the area is used. Therefore, the series of historical flows correspond to an optimistic scenario in which the 100% of the inflows can be harvested for power generation.

The previously mentioned effect mainly affects the cost of electricity, which is reduced by 17 to 23% compared to the average electricity cost in Baseline (see Table 6). However, the increased flow rate generates more than 220 (TWh) per year of unused energy (curtailment), which is due to a lack of transmission capacity and low demand levels. Congestion mainly occurs in the transmission line $CE \Rightarrow OR$, which indicate the importance of new investments in the grid infrastructure.

For the wet season, the year with the largest of dispatch of hydropower is 1980, which has one of the highest congestion hours on the line $CE \Rightarrow OR$, and the lowest release for this station is 1998 with 4% more than the baseline. Whereas the dry season 2004 and 2005 are the highest and lowest dispatch of hydropower, with a 34 and 17% increase compared to the baseline, respectively. These values indicate that some regions of the country suffered the driest periods of the last 30 years [36, 37].

Results also show that the greater the dispatch of hydroelectric units, the higher the number

Table 6: Main results of the electrical system determined with different rainfall years.

Year	**Average electricity cost (EUR/MWh)**	**Total Load Shedding (TWh)**	**Total shifted load (TWh)**	**Maximum Load Shedding MW**	**Total Curtailed RES (TWh)**	**Maximum Curtailed RES MW**	**Congestion (Hr)**
1980	4.44	8.72E-04	7.93E-02	35.98	10560.44	1.32E-04	1802
1982	4.59	8.13E-04	7.91E-02	38.06	13220.13	1.36E-04	1735
1984	4.32	8.57E-04	7.96E-02	35.26	26032.63	1.33E-04	1927
1985	4.25	6.04E-04	7.95E-02	31.93	6522.33	1.01E-04	1650
1986	4.46	7.51E-04	8.01E-02	35.63	6750.83	1.01E-04	1593
1988	4.52	7.33E-04	7.93E-02	31.78	21919.55	1.39E-04	1475
1990	4.41	7.25E-04	7.93E-02	37.80	221.79	1.97E-06	1576
1992	4.64	1.02E-03	7.81E-02	34.17	228.00	1.97E-06	1388
1994	4.50	8.05E-04	7.91E-02	28.34	970.17	5.04E-05	1343
1995	4.81	9.26E-04	7.90E-02	41.69	1699.73	9.91E-05	1180
1996	4.45	8.20E-04	7.98E-02	41.69	978.62	5.81E-05	1451
1998	4.64	7.06E-04	7.88E-02	40.54	912.32	6.12E-05	1338
2000	4.51	8.13E-04	7.92E-02	30.68	3307.12	9.51E-05	1351
2002	4.22	7.39E-04	7.90E-02	32.81	11493.55	1.21E-04	1529
2004	4.43	6.52E-04	7.93E-02	30.63	289.58	1.63E-05	1433
2005	4.49	1.11E-03	7.93E-02	36.12	1087.88	6.32E-05	1493
2006	4.46	7.96E-04	7.99E-02	26.26	9123.35	9.79E-05	1829
2008	4.59	8.04E-04	7.90E-02	31.64	11101.86	1.25E-04	1656
2010	4.51	8.15E-04	7.91E-02	40.77	418.86	4.55E-05	1171
2012	4.70	7.55E-04	7.91E-02	31.32	6905.03	1.07E-04	1362
2014	4.69	5.98E-04	7.99E-02	31.86	1596.89	8.74E-05	1452
2015	4.39	6.99E-04	7.95E-02	27.99	6627.05	1.01E-04	1752
2020	5.49	7.88E-04	8.38E-02	42.84	43.37	1.20E-06	550

of hours of congestion on the line $CE \Rightarrow OR$. This however allows to reduce the amount of unsatisfied demand (load shedding).

Hydropower power output with different rainfall years ranges from 38 to 77% of the total (see Figure 8. This means, that the electrical system is able to receive a share of hydro units up to 77% of total power output, turning them into the largest energy producers of the electric system.

While by 2020 (baseline) the energy supplied by hydro units ranges between 6 and 23% . and were exceeded in all months of the year by thermoelectric power output even rainy months (wet season) [4, 38].This is because 2020 has been modeled with turbinate flows, which are lower than the flows of the water supply of the basin especially in the wet season.

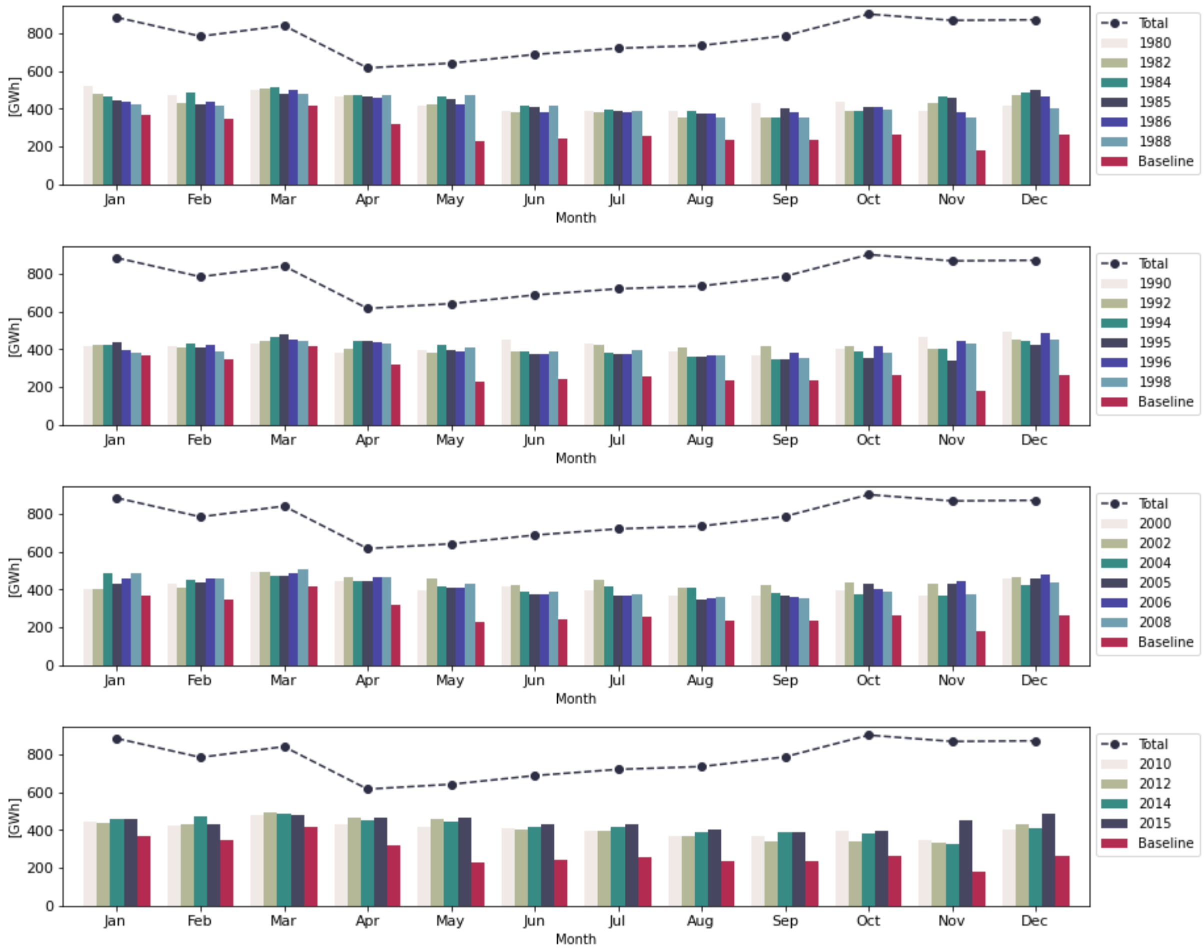

Figure 8: Monthly dispatch of hydropower for different rainfall years.

Figure 9 presents a comparison between the behavior of the reservoirs during the simulations, it is observed that most of the reservoirs located around the central zone (Corani and Misicuni dam) are receiving more water than they can convert into electricity. While in the north zone (Zongo dam), the opposite happens because the water supply is much lower, especially in 1990. As for the rest of the hydro units, they follow the pattern of storing during the wet season for then used of it during the dry season. However, there are slight variations at the beginning and end of the year because the wettest months of the wet season are December and January. On the other hand, this plot shows that the year with the highest water supply for all the plants is for the year 1980 and the years of lower rainfall are 2000, 2010, and 1990.

The Bolivian electricity system has the flexibility to increase power through unconventional sources such as solar-PV and wind-onshore that was demonstrated in previous studies [34, 35]

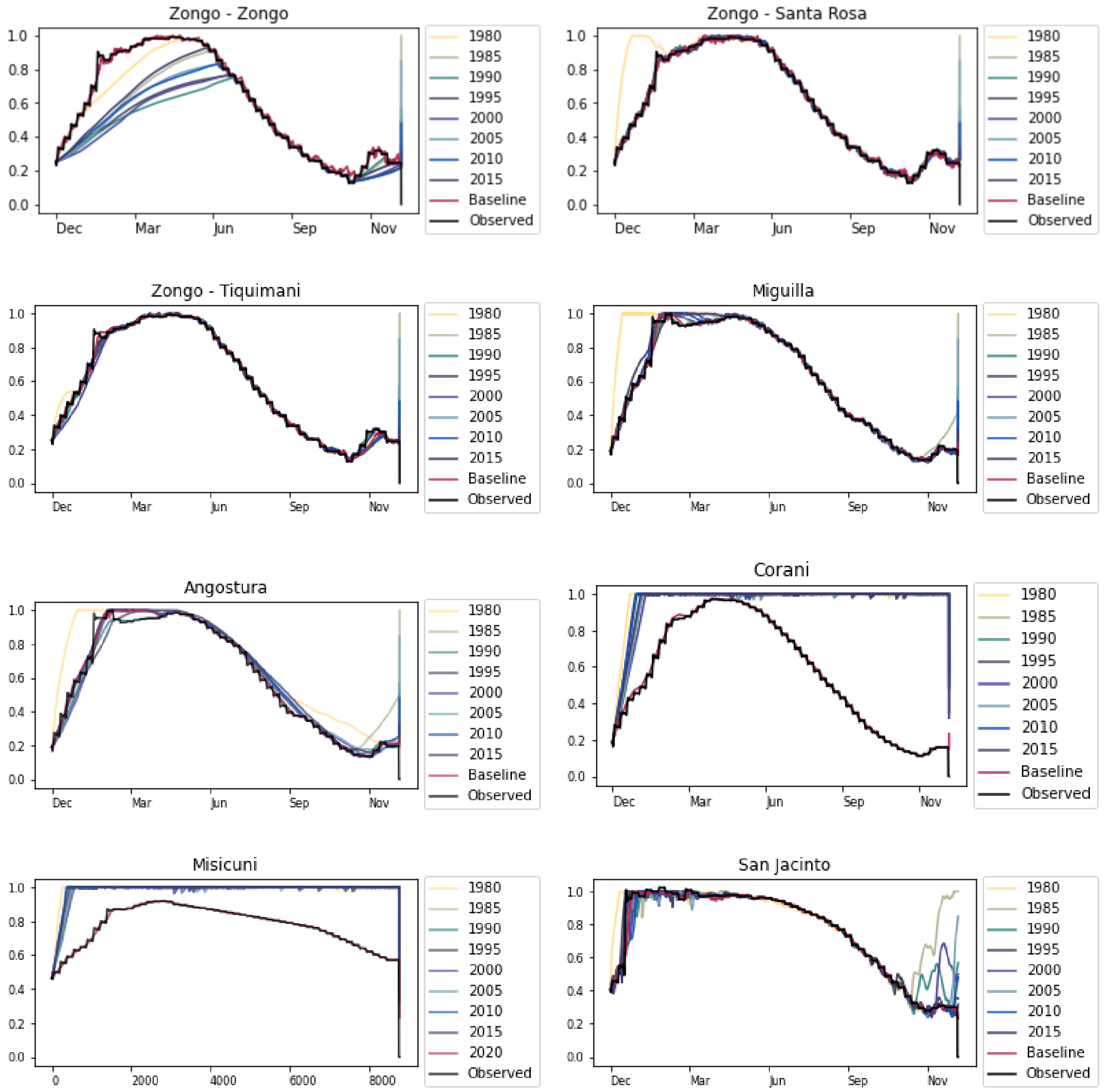

Figure 9: Reservoir levels for all hydro units for the during simulations

and now it is shown that increased hydropower also has a positive impact in economic terms and is more environmentally friendly (CO2 levels are reduced by 15% compared to the baseline).

CONCLUSIONS

This study assesses the effects of different rainfall years on the ability of hydropower to generate and store electricity in the Bolivian electric system through Dispa-SET power system model. The configuration of the model is compiled from Dispa-SET_Bolivia [34, 35] for this model is expanded and updated information about hydropower that were operating by 2020.

This study allowed to obtain the daily flow series for the hydro units of the country for the period 1980 to 2016. To do this, the time resolution of the hydrological model of Bolivia BSHB was improved. This led to modify climatic variables, verification of the runoff coefficient and calibration in the soil parameters: Kc, SWC, DZF and DPF, which showed the highest sensitivity in the model. The goodness-of-fit measure obtained is in the range of good and very good, with better fits in the stations located northwest of the country.

The simulation of Dispa -SET_Bolivia model with different time series of historical inflows has allowed to highlight the fact that the flow destined to the hydroelectric generation is less than half of the water supply of the basin in the wet season. During the rest of the year this value is approximately 10% lower. A better utilization of these hydro resources generate benefits such as the reduction of electricity costs up to 5% compared to the established price for the baseline. In addition, CO2 emissions are reduced by up to 15%. This increased inflow utilization is however not able to cover the entire energy demand of the area despite presenting a high amount of energy not used. This is explained by congestion in the transmission lines. Increasing the voltage and capacity of the $CE \Rightarrow OR$ transmission line could significantly improve the system operation.

Finally, this study allows us to know that the increase in flow in each hydro unit could bring benefits in economic and environmental terms.

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