Supplementary information: Integrating Climate-Driven Hydropower Variability into Long-Term Energy Planning: A Bolivian Case Study under El Niño and La Niña Scenarios

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ABSTRACT

As climate change effects become more evident worldwide, quantifying their potential impacts is critical to enable adequate adaptation strategies and facilitate planning efforts. A key aspect in these endeavors is acknowledging and considering the variability of hydro resources availability, which affects several strategic aspects of nations' development, such as energy planning. In this sense, countries heavily reliant on hydropower must assess the implications of this variability to ensure a reliable electricity supply. Considering Bolivia as a case study, the impact of alternative hydro availability scenarios is evaluated through the analysis of extreme weather conditions associated with El Niño and La Niña events. The proposed method uses global precipitation projections downscaled to a regional level, with which three scenarios (Control, El Niño, and La Niña) are developed for 2030, 2040, and 2050. These scenarios are later analyzed using an energy model tailored to Bolivia, developed with PyPSA-Earth. The model is selected for its cost-optimization objective, hourly resolution for dispatch analysis, and spatial granularity, which allows the representation of region-specific conditions, both for hydro resources availability and electrical components. Results indicate that both El Niño and La Niña scenarios show significant reductions in hydropower availability, up to 37% compared to average years, with neither of them being strictly linked to a higher reduction of hydropower generation. Regarding the operation of the system, it is seen that Bolivia's legacy power plants can handle hydrological variability until 2040. However, by 2050, a large deployment of new power plants will be required to cover the decommissioning of flexible thermal units. Finally, battery storage will also play a key role in addressing peak demands and regulating short-term variations in the system, derived by the limited availability of renewable technologies.

1. Results from ENSO signal and historical precipitation comparison

1.1. Results per catchment

1. Analysis for catchment UH-2-28. Hydropower plants: ZON, TIQ, BOT, CUT, SRO1, SRO2*, SAI, CHU*, HAR, CAH, HUA

   El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1993, 1996, 1999, 2004, and 2011 (7 out of 11 El Niño events 63.64%) are tied to annual precipitation below the average, i.e., drought-prone conditions. The lowest annual precipitation accumulated from 1995 to 1996 (994.45 mm) belongs to a moderate El Niño event. Another important value is seen in the cumulated annual precipitation from 1983 to 1984 (1164.16 mm), where the second-lowest annual precipitation is tied to a very strong El Niño event. Additionally, there are 3 out of 10 La Niña events (30%) tied to annual precipitation below the average (1990, 2000, and 2001). Moreover, note that none of them are among the lowest annual precipitation values. Hence, it is more likely that El Niño events will come with large reductions on water availability, perturbing the annual energy production.

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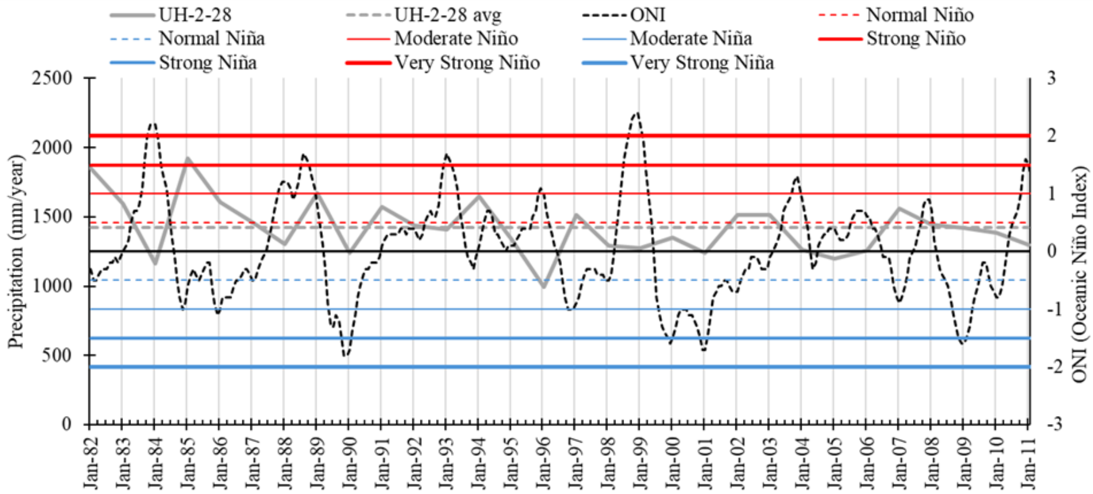


Figure 1: ENSO signal comparison to historical precipitation for Catchment UH-2-28

2. Analysis for catchment UH-2-34. Hydropower plants: CHJ, YAN

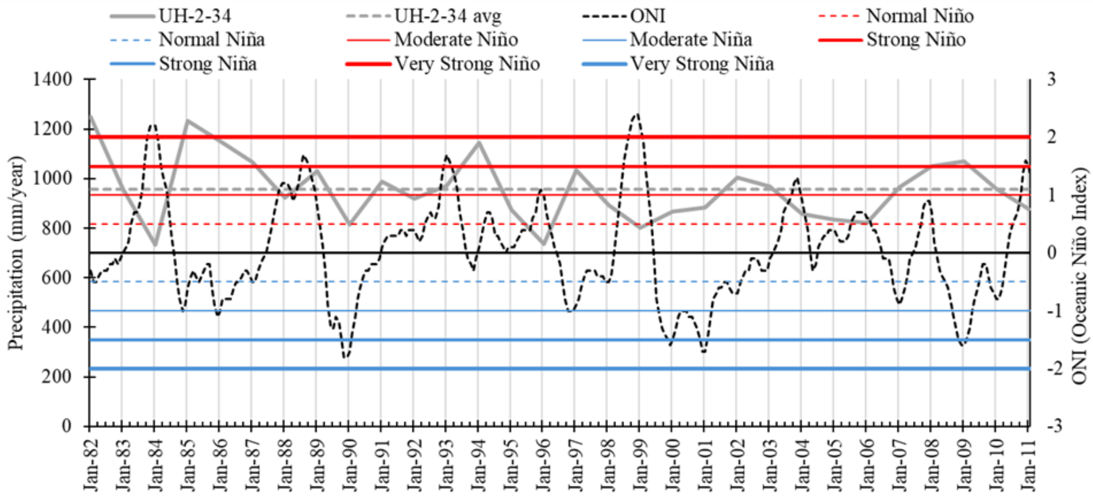


Figure 2: ENSO signal comparison to historical precipitation for Catchment UH-2-34

El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1996, 1999, 2004, 2006, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (7 out of 11 El Niño events 63.64%). The lowest annual precipitation accumulated from 1983 to 1984 (732.52 mm) belongs to a very strong El Niño event. Another important value is seen in the cumulated annual precipitation from 1995 to 1996 (736.64 mm), where the second lowest annual precipitation is tied to a moderate El Niño event. Additionally, there are 3 out of 10 La Niña events (30%) tied to annual precipitation below the average. Moreover, note that none of them are among the lowest annual precipitation values. Hence, it is more likely that El Niño events will come with large reductions on water availability, perturbing the annual energy production.

3. Analysis for catchment UH-2-31. Hydropower plants: MIG, ANG, CHO, CRB, UMA, PLD

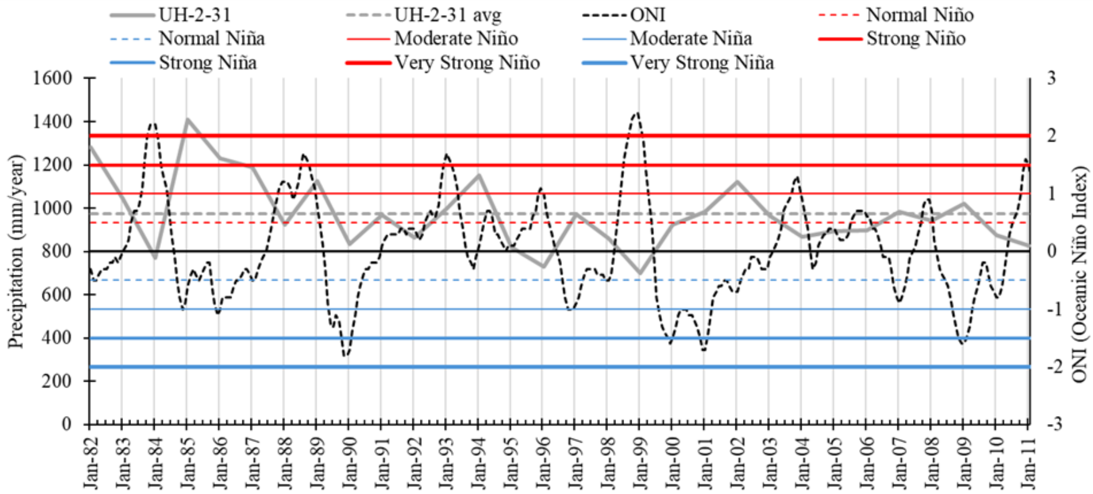


Figure 3: ENSO signal comparison to historical precipitation for Catchment UH-2-31

El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1996, 1999, 2004, 2006, 2008, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (8 out of 11 El Niño events 72.73%). The lowest annual precipitation accumulated from 1998 to 1999 (700.09 mm) belongs to a very strong El Niño event. Another important value is seen in the cumulated annual precipitation from 1995 to 1996 (729.72 mm), where the second lowest annual precipitation is tied to a moderate El Niño event. Additionally, there are 3 out of 10 La Niña events (30%) tied to annual precipitation below the average. Moreover, note that none of them are among the lowest annual precipitation values. Hence, it is more likely that El Niño events will come with large reductions on water availability, perturbing the annual energy production. Please note that this catchment is almost identical to UH-2-34 due to the geography, topography, and hydro climatology.

4. Analysis for catchment UH-2-40. Hydropower plants: QHE

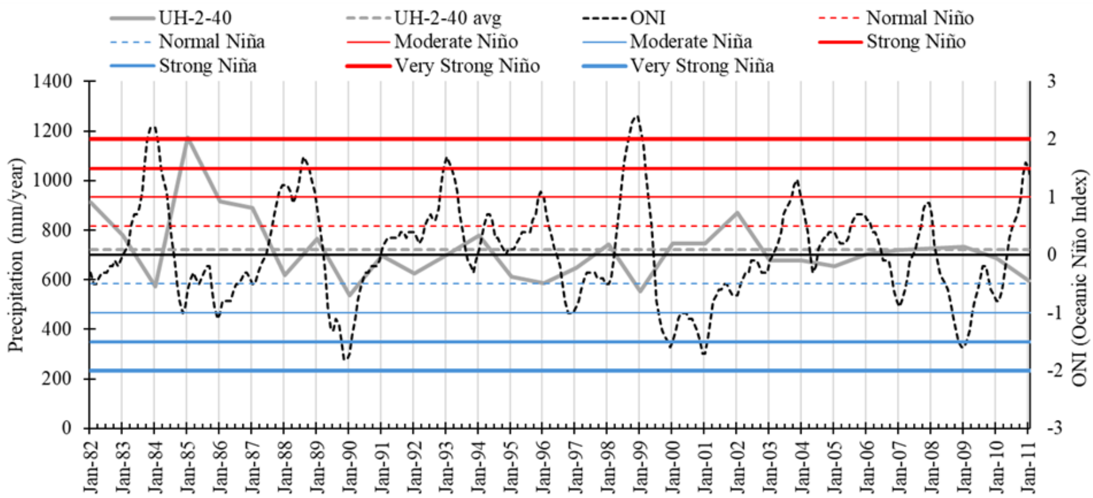


Figure 4: ENSO signal comparison to historical precipitation for Catchment UH-2-40

El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1996, 1999, 2004, 2006, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (7 out of 11 El Niño events 63.64%). The lowest annual precipitation accumulated from 1998 to 1999 (553.29 mm) belongs to a very strong El Niño event. Additionally, there are 2 out of 10 La Niña events (20%) tied to annual precipitation below the average. Hence, it is more likely that El Niño events will come with large reductions on water availability, perturbing the annual energy production. However, the lowest annual precipitation of the series (537.42 mm, from 1989-1990) is tied to a strong La Niña event. Therefore, caution must be exerted in this catchment in the attribution of the reduction in water availability and the El Niño/La Niña events.

5. Analysis for catchment UH-2-56. Hydropower plants: KAN, MIS

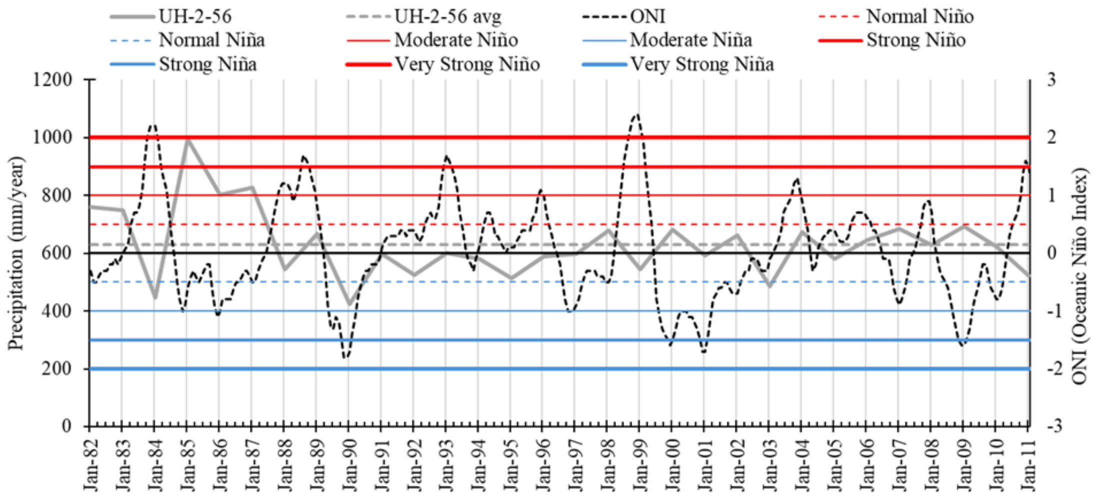


Figure 5: ENSO signal comparison to historical precipitation for Catchment UH-2-56

El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1993, 1996, 1999, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (6 out of 11 El Niño events 54.55%). One of the lowest annual precipitation accumulated values, 1983 to 1984 (445.86 mm), belongs to a very strong El Niño event. Additionally, there are 3 out of 10 La Niña events (30%) tied to annual precipitation below the average. Moreover, note that the lowest annual precipitation (425.05 mm accumulated from 1989 to 1990) in the basin belongs to a strong La Niña event. Hence, attributing drought conditions to either El Niño or La Niña event seems difficult. Although, it is more likely (54.55 vs 30 %) that El Niño will come with a reduction in water availability.

6. Analysis for catchment UH-2-54. Hydropower plants: SIS, COR, SJS, SJE

   El Niño events (regardless of the intensity of the anomaly) in the years 1989, 1996, 2006 and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (4 out of 11 El Niño events 36.36%). The lowest annual precipitation accumulated value, 1988 to 1989 (1737.71 mm), belongs to a decaying El Niño event. On the other hand, there are 4 out of 10 La Niña events (40%) tied to annual precipitation below the average. Since the lowest precipitation values has been detected during a decaying El Niño event and the probability of having drought conditions during La Niña events is larger (40 vs 36.36 %), it is more likely that a drought event will come under La Niña year.

7. Analysis for catchment UH-2-58. Hydropower plants: SEH, JUN

   El Niño events (regardless of the intensity of the anomaly) in the years 1989, 1996, 2006 and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (4 out of 11 El Niño events 36.36%). The lowest annual precipitation accumulated value, 1988 to 1989 (1737.71 mm), belongs to a decaying El Niño event. On the other hand, there are 4 out of 10 La Niña events (40%) tied to annual precipitation below the

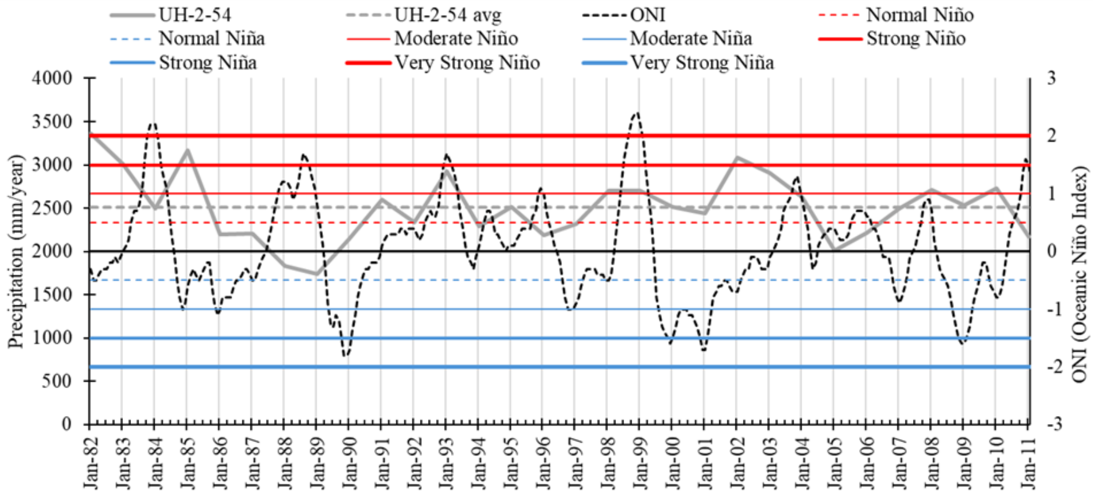


Figure 6: ENSO signal comparison to historical precipitation for Catchment UH-2-54

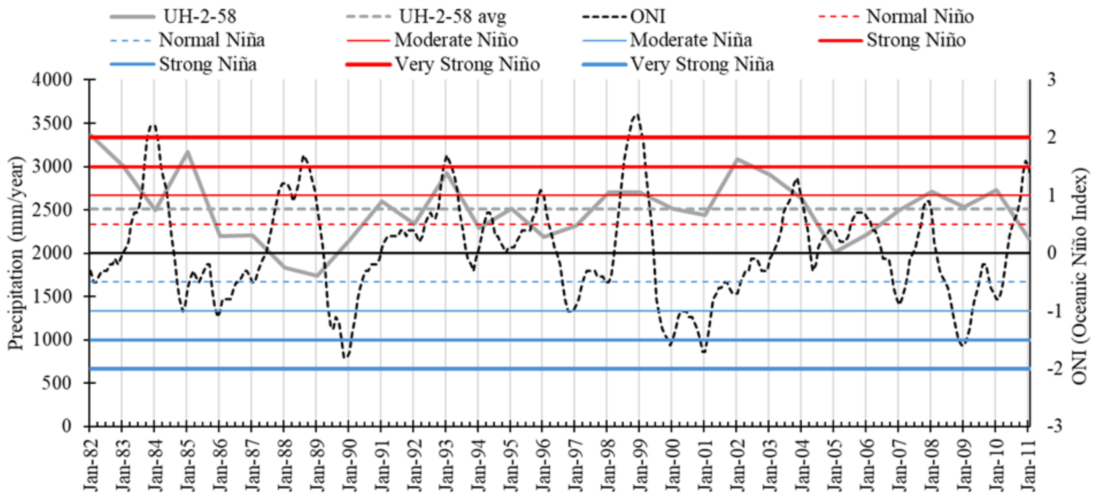


Figure 7: ENSO signal comparison to historical precipitation for Catchment UH-2-58

average (1986, 1990, 1997, and 2001). Since the lowest precipitation values has been detected during a decaying El Niño event and the probability of having drought conditions during La Niña events is larger (40 vs 36.36 %), it is more likely that a drought event will come under La Niña year. Please note that this catchment is almost identical to UH-2-54 due to the geography, topography, and hydro climatology.

8. Analysis for catchment UH-3-14-3. Hydropower plants: KIL, LAN, PUH*

   El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1988, 1999, 2004, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (5 out of 11 El Niño events 45.45 %). Additionally, there are 4 out of 10 La Niña events (40%) tied to annual precipitation below the average. The lowest annual precipitation value (208.34 mm) is tied to a strong La Niña event (year 1990). Therefore, caution must be exerted in the attribution of El Niño/La Niña to drought-prone conditions in this basin.

9. Analysis for catchment UH-3-2. Hydropower plants: SJA

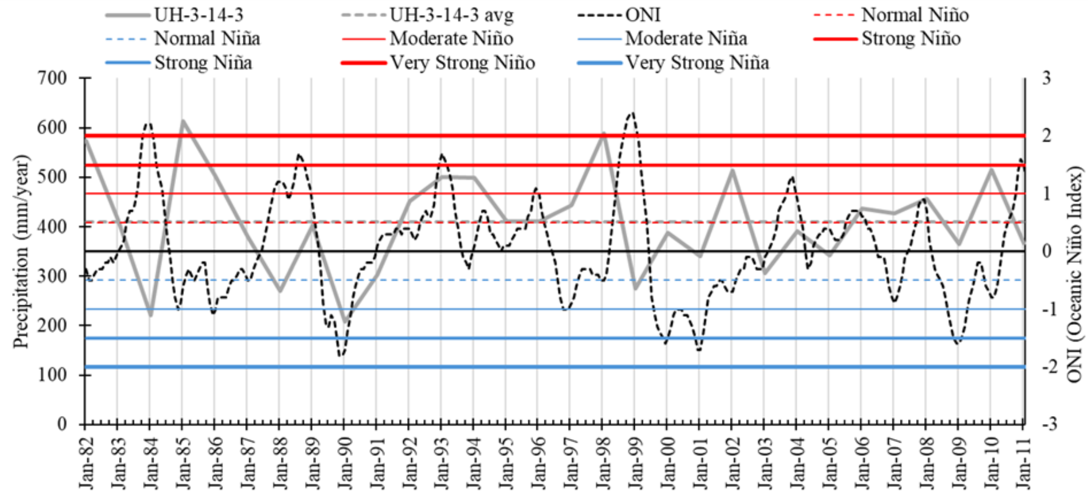


Figure 8: ENSO signal comparison to historical precipitation for Catchment UH-3-14-3

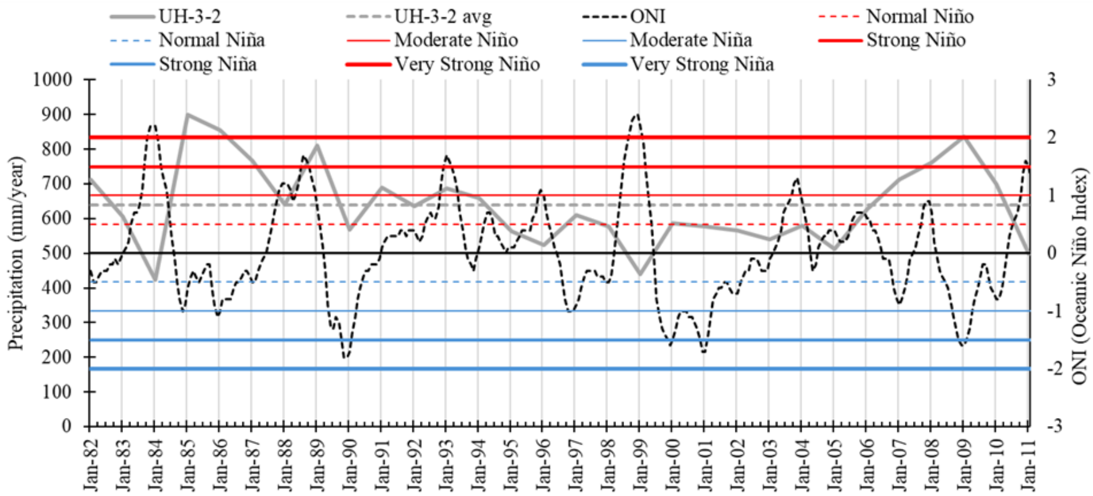


Figure 9: ENSO signal comparison to historical precipitation for Catchment UH-3-2

El Niño events (regardless of the intensity of the anomaly) in the years 1984, 1996, 1999, 2004, 2006, and 2011 are tied to annual precipitation below the average, i.e., drought-prone conditions (6 out of 11 El Niño events 54.55 %). Additionally, there are 5 out of 10 La Niña events (50%) tied to annual precipitation below the average (1990, 1997, 2000, 2001, and 2002). The lowest annual precipitation value (422.35 mm) is tied to a very strong El Niño event (year 1984) and the second lowest value (1999) is also tied to a very strong El Niño event. Therefore, it is more likely that a drought event will come under El Niño conditions.

1.2. Final remarks ENSO attribution

During El Niño events, basins UH-2-28, UH-2-34, UH-2-31, UH-3-2, and UH-2-56 are more likely to have drought-prone conditions. During La Niña events, basins UH-2-54 and UH-2-58 are more likely to have drought-prone conditions. Catchments UH-2-40 and UH-3-14-3 seem to not be affected by either El/La Niño/Niña events, hence, they are not required in the selection of the pessimistic year. As a result, two configurations were proposed for the analysis:

- Selection of the series based on the assumption that the catchments will face a El Niño event: From the future SSP1-2.6 series, every decade, we chose the year with the lowest annual precipitation based exclusively on the data from basins UH-2-28, UH-2-34, UH-2-31, UH-3-2, and UH-2-56.
- Selection of the series based on the assumption that the catchments will face a La Niña event: From the future SSP1-2.6 series, every decade, we chose the year with the lowest annual precipitation based exclusively on the data from basins UH-2-54 and UH-2-58.

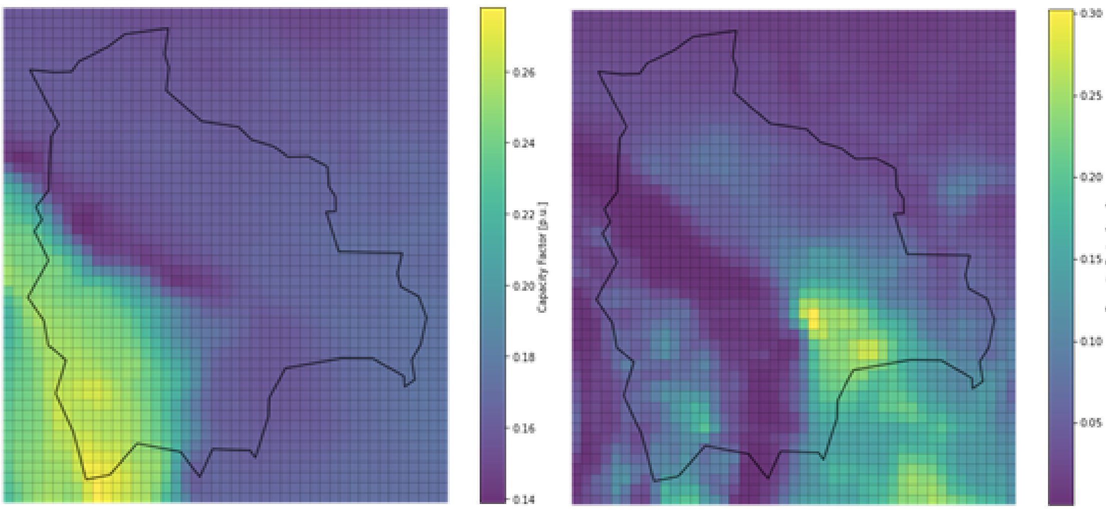
2. PyPSA-Eath adaptations for the Bolivian context

2.1. Data sources

For the adaptation of the PyPSA-Earth to better represent the Bolivian case, information from existing installed capacities is derived from reports of the national energy company ENDE [1], the national dispatch agency CNDC [2], and the electric regulation agency AETN [**?**]. Future/planned installed capacities are extracted from the webpage of the national energy company ENDE, where information from projects under development [3] and under study [4] is available. Fuel costs are extracted from previous national development plans [5], and hydroelectric plant-specific inflow information is extracted from previous studies [6]. A compilation of the investment costs, fuel prices, FOM, efficiencies and lifetimes used in the model is presented in Table 1:

2.2. Model's validation

Similarly, the model's wind and solar resources availability has proven to be consistent and adequately distributed by comparing average availability factors with published data from the Ministry of Energy and Hydrocarbons [7]. A comparison of specific locations from these datasets, transformed into average capacity factors, shows consistency with values observed in existing power plants. This is the case of San Julian (wind) and Uyuni (Solar), located in the regions with the highest potential in the country of their respective technologies. Results from plotting average capacity factors for wind and solar technologies across Bolivia are available in Figure 10.



(a) (b)

Figure 10: Standardized solar (left) and wind (right) capacity factors in Bolivia calculated based on data from Copernicus Climate Change Service.

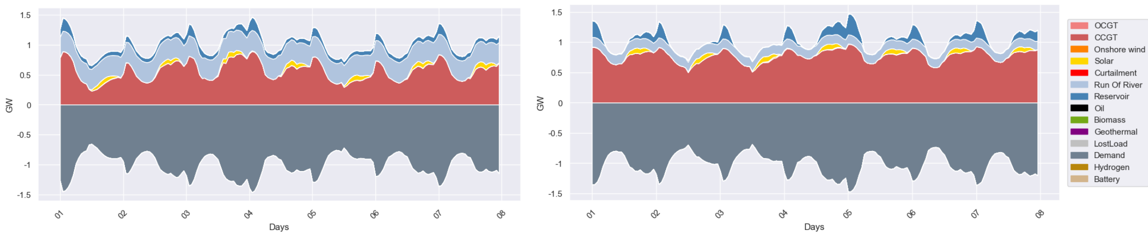
For the case of hydro resources, due to the simplified approach used by the model to transform runoff data into operational inflows for the power plants, results show higher discrepancies. Because of this, inflow information for each hydro power plant is directly fed into the model, as shown in the workflow, to replace the predefined calculations and improve the representation of these power plants.

Simulation results for the year 2020 show that installed capacities are now included and coincide with historical values, thanks to the adaptations made to the workflow. However, due to the optimization premises of the model and the

Technology	Parameter	Value	Unit
battery inverter	efficiency	0,9	
biomass	efficiency	0,2966	
CCGT	efficiency	0,4695	
geothermal	efficiency	0,239	
hydro	efficiency	0,9	
OCGT	efficiency	0,3246	
oil	efficiency	0,369	
ror	efficiency	0,9	
battery inverter	FOM	3	%/year
biomass	FOM	2,32	%/year
CCGT	FOM	2,5	%/year
geothermal	FOM	2,5	%/year
hydro	FOM	1	%/year
OCGT	FOM	3,75	%/year
oil	FOM	1,5	%/year
onwind	FOM	2	%/year
ror	FOM	1	%/year
solar	FOM	3	%/year
biomass	fuel	7	EUR/MWhth
gas	fuel	4,44	EUR/MWhth
oil	fuel	124,5	EUR/MWhth
battery inverter	investment	411	USD/kWel
battery storage	investment	192	USD/kWh
biomass	investment	1716,96	EUR/kWel
CCGT	investment	1281,56	EUR/kWel
geothermal	investment	3772,17	EUR/kWel
hydro	investment	2206,3	EUR/kWel
OCGT	investment	963,31	EUR/kWel
oil	investment	384,6	EUR/kWel
onwind	investment	1629,13	EUR/kWel
ror	investment	2000,26	EUR/kWel
solar	investment	1051,13	EUR/kWel
battery inverter	lifetime	20	years
battery storage	lifetime	15	years
biomass	lifetime	30	years
CCGT	lifetime	30	years
geothermal	lifetime	40	years
hydro	lifetime	80	years
OCGT	lifetime	30	years
oil	lifetime	30	years
onwind	lifetime	30	years
ror	lifetime	80	years
solar	lifetime	25	years

Table 1
Generation technology characterization

simplification of the system, slightly different behaviors can be noticed when reviewing the energy produced by type of technology. The biggest difference is linked to the operation of thermal plants, for which Combined Cycle Gas Turbines (CCGT) are used exclusively in the model, compared to reality, where small fractions of the thermal generation are covered by Open Cycle Gas Turbines (OCGT) and Diesel (Oil) power plants. The use of these technologies can be linked to several aspects like local regulations, prolonged or non scheduled maintenance, or social/human aspects, all of which force a suboptimal operation of the system. Particularly, for the case of thermal units, operators tend to be overly cautious and rely heavily in OCGT units to guarantee the stability of the grid [8].



(a) (b)

Figure 11: Aggregated hourly dispatch modelled during the first week of janurary (a) and July (b) of 2020, corresponding to the rainy and dry seasons respectively

Figure 11 shows the hourly production by technology, simulated by the model for a week of both the rainy (November-February) and dry (March-October) season of the year. Here, the dispatch shows that renewable technologies such as solar, wind, and hydro, both Run-off-River (RoR) and Reservoir, are used at their maximum capacities and that CCGT works as the main regulation technology in the system. This behavior is consistent with the cost characterization in the model, given that renewable technologies (aside from biomass) do not incur variable expenses linked to their operation, which is the case for fuel-based technologies.

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