The Impact of Drought on Hydropower Generation:

A Case Study of Spain

by

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Abstract

This research investigates the impact of drought on hydropower generation in Spain, a country heavily reliant on renewable energy source . The study utilizes the Standardized Precipitation Index (SPI) to quantify drought severity and analyse its relationship with monthly hydropower generation data from 2015 to 2023. The findings reveal a strong correlation between SPI-3 and SPI-6 (3-month and 6-month precipitation deficits) and hydropower output, indicating the vulnerability of this sector to drought. The analysis of six major hydropower-producing regions further shows significant generation losses during prolonged dry spells. The research underscores the urgent need for Spain to diversify its renewable energy mix, enhance hydropower infrastructure, and implement adaptive water management strategies to ensure energy security in the face of climate change.

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PREFACE

Spain, a country renowned for its natural beauty, has taken a commendable step towards a sustainable future by pledging to achieve zero emissions by 2050. The nation has made significant strides in renewable energy, with approximately 50% of its energy consumption coming from clean sources. However, a concerning trend has emerged in recent years - a decline in hydropower output, coinciding with unprecedented climate events in the Mediterranean region. This research aims to shed light on the impact of drought on hydropower generation in Spain, providing crucial insights for a resilient and sustainable energy future.

Acknowledgement

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Chapter: 1 Introduction

The most pressing challenge confronting humanity today is undoubtedly climate change, an undeniable consequence of human activities (IPCC, 2021). Across the globe, the catastrophic consequences are evident in the alarmingly rapid melting of glaciers , devastating cloudbursts , droughts , record-breaking temperatures, heatwaves, flood and widespread wildfires (Akhtar, 2020 ;Kuwayama et al., 2019; Dimitrakopoulos et al., 2011; Młyński et al., 2024). These events serve as stark reminders of the profound transformation our climate system is undergoing.

The primary culprits behind this transformation are greenhouse gas emissions, such as carbon dioxide and methane. These emissions create a blanket of heat-trapping gases in the atmosphere, leading to a dangerous rise in average global temperatures (IPCC, 2021). One of the most concerning consequences of this warming trend is the increased frequency and intensity of droughts and heatwaves (Brás et al., 2021). These extreme weather events have a devastating impact on agriculture, triggering a cascade of negative effects (Kuwayama et al., 2019). Reduced crop yields and livestock losses threaten food security and drive up food prices, potentially leading to increased human and animal mortality. The combination of dry conditions and high temperatures creates ideal conditions for wildfires, resulting in the destruction of property and natural resources (Richardson et al., 2022). Energy generation is also disrupted, as hydropower production suffers from water scarcity, and thermal power plants struggle to maintain optimal operating temperatures (Killingtveit & Hamududu, 2012). Moreover, water quality deteriorates as pollutants become concentrated in shrinking waterways, harming ecosystems and posing risks to human health (Mosley, 2015).

The 2012 drought in the USA and the Australian mega-drought from 2001 to 2010 stand as chilling examples of the devastating consequences of prolonged dry spells (Cobon et al., 2019). On the other end of the spectrum, the 2021 flood in Germany serves as a sobering reminder of the destructive power of extreme rainfall events, underscoring the urgent need to address climate change (Ludwig et al., 2023).

Drought is a recurrent and frequently catastrophic event that presents serious problems for ecosystems, water resources, and agriculture (Nath et al., 2017). Drought is characterized by a sustained lack of precipitation and can take many different forms, each with unique consequences (Mishra & Singh, n.d). Below-average rainfall, or meteorological drought, frequently comes before agricultural drought, which is characterized by a lack of soil moisture that inhibits crop growth (Mishra & Singh, n.d.). Reduced streamflow and groundwater levels, which are indicators of a hydrological drought, can affect ecosystems and human water availability (Van Loon, 2015). Effective mitigation and adaptation methods depend on having a thorough understanding of the kind and intensity of drought.

The impacts of climate change are not uniformly distributed; certain regions are disproportionately affected. The Mediterranean, encompassing countries such as Italy, Spain, Portugal, and Greece, is particularly vulnerable (Noto et al. ,2023). The escalating frequency of droughts and heatwaves in this region underscores its susceptibility. The Mediterranean's unique location between arid and temperate climates makes it highly sensitive to shifts in global atmospheric circulation patterns, resulting in significant alterations in precipitation and temperature (Giorgi & Lionello, 2008).

In the global effort to mitigate climate change, renewable energy sources like hydropower are gaining traction due to their reduced greenhouse gas emissions. Hydropower stands out, offering flexibility and reliability thanks to its reliance on stored water reservoirs (Egré & Milewski, n.d.). These plants utilize flowing water to spin turbines, converting mechanical energy into electricity (Egré & Milewski, n.d.). Conventional storage hydropower employs dams to create reservoirs for electricity generation during peak demand, while run-of-river plants harness the natural flow of rivers without the need for reservoirs (Egré & Milewski, n.d.). Pumped storage acts as a battery, storing potential energy by pumping water to a higher reservoir during low demand and releasing it to generate electricity during peak periods. However, hydropower's reliance on water makes it vulnerable to droughts, which can reduce precipitation and impact water availability.

This research aims to develop a model that predicts hydropower generation based on severity of drought. This research will investigate the extent to which drought impacts hydropower generation and explore whether this relationship can be quantified through a case study of Spain. The rationale behind choosing Spain is because of a fall in hydropower generation in last few years (shown in image below). Spain has the fourth largest installed hydropower capacity in Europe (European Rivers Network, n.d.). This research holds academic value for several reasons because by improving the prediction of hydropower generation, we can better integrate renewable energy sources into the power grid. This also allows us to understand the vulnerabilities of our energy infrastructure and develop adaptation strategies. Hydropower's dispatchable nature makes it a valuable tool for smart grid management. With accurate predictions, governments can strategically utilize this renewable energy source to meet rising electricity demands, especially for cooling needs during increasingly heatwaves. This approach can help keep carbon footprints low and contribute to a more sustainable future.

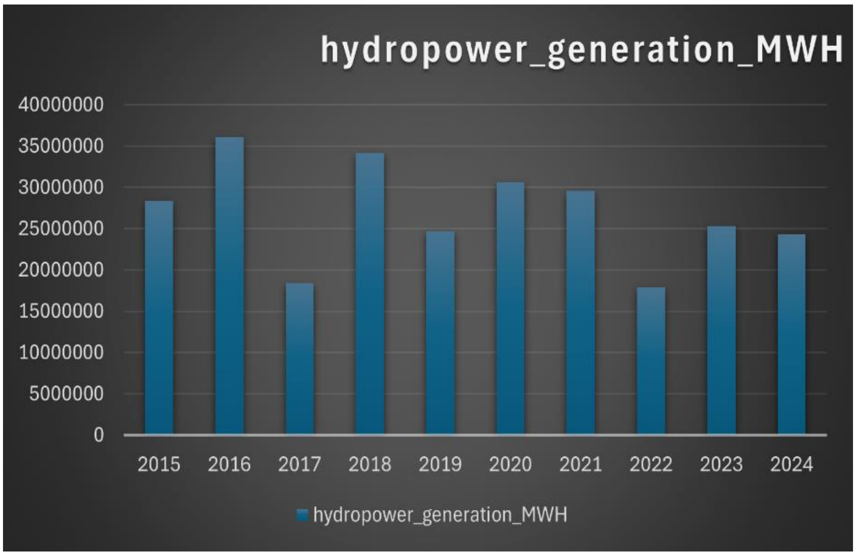


Figure 1 Annual Hydropower_ generation in Spain

1.1 Research Background

Numerous studies have assessed the impact of drought on various sectors, including hydropower generation. For instance, a hydrological study in Brazil by Cuartas et al. (2022) revealed that hydropower systems are vulnerable to drought, particularly during the 2014-2015 event. Similarly, Kilic (2024) investigated the effects of drought on hydropower production in Europe and predicted significant decreases in output under future climate scenarios. While previous research has explored 'drought impacts on sectors like agriculture and health, frequency of heatwaves in different parts of the world', a focused investigation using drought indicators to evaluate drought's influence on Spanish hydropower generation is lacking (Wilhite et al., 2007). This analysis is particularly crucial given the increasing threat of climate change to water resources and energy systems, especially in drought-prone regions like the Mediterranean (Valo, 2024). By quantifying drought's impact on hydropower, this research aims to inform policymakers and support the development of effective strategies for sustainable water and energy management in Spain.

1.2 Relevance of the Research

The urgency of addressing climate change is underscored by numerous international conferences and agreements, such as the annual COP meetings, where commitments to carbon neutrality and global temperature control are made. Spain, along with other countries, has made significant pledges to reduce its greenhouse gas emissions and transition to be carbon neutral by 2050 (Spain unveils climate law to cut emissions to net zero by 2050, 2020). As nations race to decarbonize their economies while maintaining growth, the shift towards renewable energy sources becomes increasingly crucial.

However, the reliability of these sources, particularly hydropower, is threatened by the escalating frequency and severity of droughts, a direct consequence of climate change.

Hydropower contributes approximately 7% of Spain's electricity generation (Cruz & Arribas, 2023). Its dependence on water availability renders it susceptible to disruptions caused by drought. Recent droughts have exposed this vulnerability, with decreased hydropower generation coinciding with increased energy demands for cooling during heatwaves. This dual challenge of rising energy needs and dwindling hydropower output poses a significant dilemma for policymakers in Spain.

Quantifying the impact of drought on hydropower generation is essential for informed decision-making and the development of effective mitigation and adaptation strategies. The unique topographical variations across Spain's autonomous communities required a region-specific approach. Therefore, a comprehensive study assessing the impact of drought on hydropower generation in each autonomous community is very crucial.

This research seeks to fill this knowledge gap by providing a nuanced understanding of drought's implications for hydropower in Spain. By employing the Standardized Precipitation Index (SPI) and hydrological modelling, this study aims to quantify the magnitude of drought-induced hydropower deficits and inform policymakers about the vulnerabilities and potential solutions within each autonomous community. Such region-specific insights will enable the formulation of targeted water management policies and promote sustainable energy practices

1.3 Research question(s)

1.3.1 Primary Research Question

Quantifying the Impact

To what extent does drought severity, as measured by the Standardized Precipitation Index (SPI) at various timescales (3-month & 6-month), affect monthly hydropower generation in each autonomous community of peninsular Spain between 2015 and 2023?

Regional Variations

Are there significant differences in the sensitivity of hydropower generation to drought across different autonomous communities, and can these differences be explained by variations in hydro-climatic conditions, reservoir capacities, or hydropower plant characteristics?

1.3.2 Secondary Research Question

Identifying Resilient Regions

Which regions in peninsular Spain exhibited minimal to no discernible impact on monthly hydropower generation during the 2015-2023 period, even in the face of drought events?

Chapter 2: Literature review

2.1 Climate Change and Drought in Spain

The Iberian Peninsula, where Spain is located, has been recognized as a climate change "hotspot" due to its vulnerability to the impacts of global warming (Solaun & Cerda, 2017). The region is expected to experience significant shifts in precipitation patterns, leading to an overall decrease in water availability and an increased frequency and severity of droughts. The Intergovernmental Panel on Climate Change (IPCC) has projected a potential reduction in runoff of 6 to 36% by the 2070s compared to the baseline period of 1961-1990 (Solaun & Cerda, 2017). The study by researchers further emphasizes the regional disparities in these impacts, highlighting Southern Spain as particularly susceptible to decreased water resources. In my view, to see the big picture, we need to consider the entire Iberian Peninsula region of Spain because precipitation in the northern part of Spain can also impact southern Spain.

2.2 Drought

There is no common definition of draught on which researchers and organization have agreed upon. According to UN Convention to Combat Drought and Desertification defines drought as "the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems" and According to Palmer described a "drought as a significant deviation from the normal hydrologic conditions of an area” (Singh, 2018). in simple terms, it's basically a period when there's much less rainfall than usual in a particular area. There are mainly four types of drought(Singh, 2018).

Meteorological Drought: This type focuses on the lack of precipitation over a specific region and time. It's essentially a deficit in rainfall compared to the average (Singh, 2018).

Hydrological Drought: This refers to when there's not enough surface or subsurface water (like in rivers, lakes, or groundwater) to meet the usual needs (Singh, 2018).

Agricultural Drought: This is about a lack of soil moisture, which can lead to crops ailing. It's connected to both rainfall shortages and how much water is evaporating from the soil (Singh, 2018).

Socio-economic Drought: This happens when the demand for water (for drinking, industry, etc.) is higher than the available supply due to weather-related reasons (Singh, 2018).

Droughts have far-reaching consequences, impacting agriculture, increasing the frequency of wildfires, degrading water quality, and affecting energy generation (Kuwayama et al., 2019; Dimitrakopoulos et al., 2011; Młyński et al., 2024). Previous research has investigated the impact of hydrological drought on water resource formation in the upper Vistula river basin in Poland (Młyński et al., 2024). This research established a clear relationship between the Standardized Precipitation Index (SPI), a widely used drought index, and the hydropower potential of rivers (Młyński et al., 2024). This highlights the vulnerability of hydropower generation to drought. As countries strive to reduce their carbon footprint and transition towards renewable energy sources, more country-specific research is needed to address potential energy crises arising from drought conditions and ensure a stable energy supply.

2.3 Drought Index

In many previous researches, in order to measure the severity of drought ,researchers used various drought indices. Drought indices are crucial for evaluating the impact of droughts. They are derived from meteorological data and offer insights into the intensity, duration, severity, and spatial extent of droughts. They are predominantly based on precipitation data, often combined with other meteorological elements like temperature and soil moisture. Some of the widely used indices are :

2.3.1 The Palmer Drought Severity Index (PDSI)

PDSI is a widely used tool for measuring drought. It uses precipitation and temperature data to assess moisture conditions. PDSI has been modified and adapted for various purposes but has limitations. It might not be ideal for hydrological droughts and makes certain assumptions that can lead to inaccuracies. Despite criticisms, PDSI remains valuable due to its extensive testing, sensitivity to climate variables, and ability to compare different regions (Wang et al., 2022).

2.3.2 Reconnaissance Drought Index (RDI)

RDI is a drought index that considers both precipitation and potential evapotranspiration. It provides a more comprehensive assessment of drought conditions, especially in regions with high temperatures and varying water demands. The RDI can be calculated for different time periods and is particularly useful for agricultural drought assessment and communicating information about climate anomalies to diverse audiences (Tsakiris et al., 2007).

2.3.3 US Drought Monitor (USDM)

USDM is a weekly map illustrating drought location and intensity across the US. It employs five drought categories (D0-D4) determined by integrating various drought indicators, both objective and subjective (Wang et al., 2022). The USDM's strength lies in its 'convergence of evidence' approach, combining short and long-term indicators like precipitation, temperature, and soil moisture (Wang et al., 2022). However, it's worth noting that the input data for these indicators have varying periods of record, potentially impacting drought assessments. The USDM serves as a valuable tool for drought monitoring, offering a comprehensive picture of drought conditions across the country.

2.3.4 Standardized Precipitation Evapotranspiration Index (SPEI)

SPEI is a drought index that considers both precipitation and evapotranspiration, offering a more comprehensive assessment of drought severity than indices based solely on precipitation. It calculates the difference between precipitation and potential evapotranspiration over a given period, standardizes it using a probability distribution, and expresses the result in standard deviations (Al Moteri et al., 2024). Positive SPEI values indicate wetter conditions, while negative values signify drier conditions. The magnitude of the SPEI value reflects the severity of the drought or wet period. The SPEI is valuable for various applications, including drought monitoring, agricultural planning, and water resource management, as it accounts for both water supply (precipitation) and demand (evapotranspiration) (Al Moteri et al., 2024).

2.3.5 Crop Moisture Index (CMI)

CMI evaluates short-term moisture conditions based on weekly temperature and precipitation. It compares variables to long-term averages and modifies them with empirical relations (Heim, 2002). However, CMI may increase with higher potential evapotranspiration, contradicting natural phenomena. Additionally, its rapid response to short-term changes might not accurately reflect long-term conditions. Despite these limitations, CMI is useful for monitoring agricultural droughts during warm growing seasons.

2.3.6 Standardized Precipitation Index (SPI)

SPI is a versatile tool for monitoring and analysing drought conditions. It works by comparing the current precipitation at a location to its historical precipitation records, transforming this comparison into a standardized value. It quantifies precipitation deficits based on historical data (Mishra & Desai, 2005). It's calculated by fitting a location's long-term precipitation record to a probability distribution ,which is then transformed into a standard normal distribution with a mean of zero (Edward & Mckee, 1997). This allows us to understand how unusual the current precipitation is relative to what's typically expected. The SPI's key strength is its flexibility in analysing different timescales. By calculating SPI values for various periods (2-month, 3-month,6-month,12-month,24-month), it can monitor both short-term impacts like soil moisture crucial for agriculture, and long-term concerns such as groundwater levels and reservoir storage (Mishra & Desai, 2005). Different SPI timeframes are chosen based on the specific water resource being monitored. Short-term SPI values are used for soil moisture, while long-term SPI values are used for reservoir and groundwater levels.

While calculating SPI it is crucial to understand that the length of precipitation records (for reliable results we need precipitation data of at least 30 years)impacts SPI values significantly. Similar record lengths produce similar SPI results, while discrepancies arise with differing lengths. Understanding these numerical differences is crucial when interpreting SPI for decision-making. Correct selection of distribution is also important for probability distribution. The choice of probability distribution affects SPI values, with options available gamma, Pearson Type III and lognormal (Edward & Mckee, 1997).However, challenges arise, biased fitting for long time scales due to limited data length, especially in finer spatial resolutions, and non-normally distributed SPI values in dry climates with frequent zero precipitation, leading to potential errors in simulating precipitation distributions. So it is very important to take these points into consideration while employing SPI for drought measurement. If the SPI value is negative, it means it's drier than usual. If it's positive, it's wetter than usual. When it's 0, it indicates normal rainfall for that area.

SPI Range	**Drought Class**
2 or more	Extremely wet
1.5 - 1.99	Very wet
1 - 1.49	Moderately wet
0.99 - 0.0	Normal
0.0 to -0.99	Near normal
-1 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

Table 1 : Drought classification according to SPI Values

2.4 Impact of drought on hydropower generation

In a research a paper published in 2022, there was a research conducted in Brazil to investigate the impact of previous droughts on hydropower generation (Cuartas et al., 2022). The objective of the study was to enhance the understanding of hydrological drought patterns in Brazil, the factors that influence them, and the impact these droughts have on the nation's hydropower plants. Brazil is heavily reliant on hydropower, which accounts for about 64% of its electricity generation. The severe drought that struck the Southeast region of Brazil in 2014 and 2015 had a profound and lasting impact on numerous river basins, leaving them in a critical state that persists to this day.

Cuartas et al. (2022) employed three primary drought indices—the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), and the Standardized Streamflow

Index (SSFI)—to assess and quantify hydrological drought severity across 20 selected basins. The SPI evaluates drought based solely on precipitation deficits, while the SPEI incorporates both precipitation and potential evapotranspiration, providing a more comprehensive assessment of drought conditions by accounting for the influence of temperature. The researchers calculated these indices at different time scales (12, 24, 36, and 48 months) to capture the varying temporal dynamics of drought events.

The study revealed that Brazil has experienced an increase in the frequency and intensity of hydrological droughts in recent decades, particularly in the period from 2010 to 2021. The impact of these droughts on hydroelectricity generation has been substantial, with significant reductions observed in most regions except for the North (Cuartas et al., 2022). This exception in the North highlights the importance of considering regional variations in factors such as installation capacity, topography, and geography when assessing the impact of drought on hydropower generation. The Mid-West, Southeast, and Northeast regions, which collectively hold 71% of Brazil's total installed hydropower capacity, have been hit the hardest, raising serious concerns about the country's energy security (Cuartas et al., 2022). The study also underscored the role of deforestation in specific regions, contributing to local warming and potentially reducing rainfall, which further intensifies drought conditions. The findings of this research are highly informative and encourage further research into the impact of drought on countries that heavily rely on hydropower and have been significantly affected by drought in recent decades, such as those in the Mediterranean region**.**

2.5 Research Gap

Spain, situated on the Iberian Peninsula with territories extending beyond, is experiencing the effects of climate change alongside the Mediterranean region and the globe. Rising temperatures drive increased power demand for cooling, emphasizing the need to shift away from fossil fuels. To achieve its goal of zero emissions by 2050, Spain is actively phasing out its reliance on these sources.

In 2022, renewable energy accounted for 42.2% of Spain's power consumption, a decrease from the previous year due largely to a significant drop in hydropower production (Cruz & Arribas, 2022). The figure provided below illustrates a clear downward trend in annual hydropower generation. Hydropower, constituting 7% of Spain's energy generation in 2022, is a crucial clean energy source with a long history of use. Its key advantage lies in its ability to produce electricity on demand, as long as water is available, unlike solar power which requires batteries for energy storage. The recent decline in hydropower production is a cause for concern.

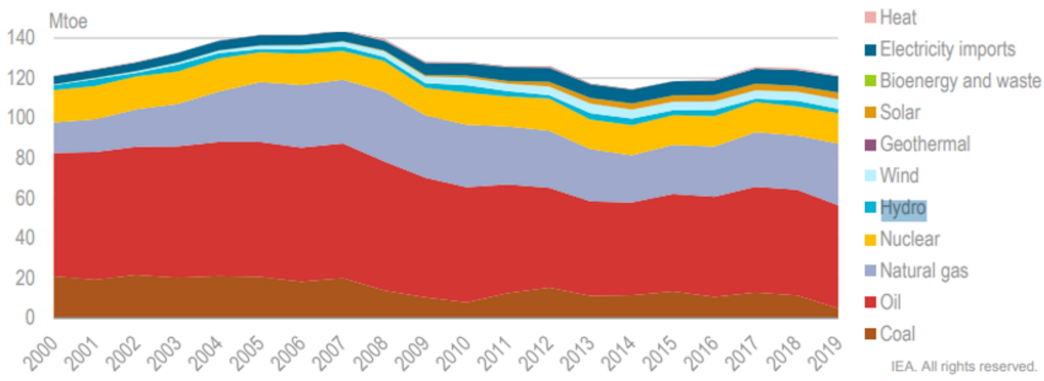


Figure 2: Power Generation in Spain(International Energy Agency, 2021*)*

A potential link exists between the multiple droughts Spain has experienced and the decrease in hydropower generation. The spring heatwave of 2023 in the western Mediterranean was intensified by a persistent, severe drought affecting the region for years (Lemus-Canovas et al., 2024). While the effects of prolonged drought on various aspects of human life are known, the impact on hydropower, a renewable resource reliant on water, remains a research gap that this study aims to address.

The necessity to phase out fossil fuels to achieve carbon neutrality further highlights the importance of understanding the challenges facing hydropower. While hydropower currently contributes 7% of Spain's energy, its potential as a clean and reliable source necessitates a deeper investigation into the relationship between drought and its production capacity.

In this study, we will assess the impact of drought on hydropower generation using the Standardized Precipitation Index (SPI), a widely recognized and accepted tool within the scientific community. By examining all 15 autonomous communities in the Spanish peninsula that generate hydropower, we aim to gain a comprehensive understanding of how drought has affected each region and Spain as a whole. This will be achieved by analysing SPI data over both short and long time periods, providing insights into the varying effects of drought on hydropower production across different temporal scales.

Chapter 3: Research Methodology

3.1 Study area

This research investigates the impact of drought on hydropower generation in Spain. We selected 15 out of 19 autonomous communities for analysis, specifically focusing on those located on the Spanish peninsular, which represents a sufficiently large sample to provide a comprehensive understanding of the drought's impact on hydropower generation across the country. The Canary Islands, an integral part of Spain, were not included in this analysis despite their hydropower generation potential. This exclusion is due to the relatively small scale of their hydropower installed capacity(2 MW) and their remote location in the far southwest of the country. The list of selected communities is provided below.

S.No.	Autonomous Community	Hydropower Installed Capacity in Megawatt (Acc. To REE)
1	Andalucía	623 MW
2	Aragón	1334 MW
3	Principado de Asturias	806 MW
4	Cantabria	99 MW
5	Castilla-La Mancha	651 MW
6	Castilla y León	4398 MW
7	Cataluña	1922 MW
8	Comunidad de Madrid	109 MW
9	Comunidad Valenciana	642 MW
10	Extremadura	2277 MW
11	Galicia	3732 MW
12	La Rioja	52 MW
13	Región de Murcia	35 MW
14	Comunidad Foral de Navarra	238 MW
15	País Vasco (Basque Country)	178 MW

Table 2: Hydropower Install Capacity of Each Autonomous Community.

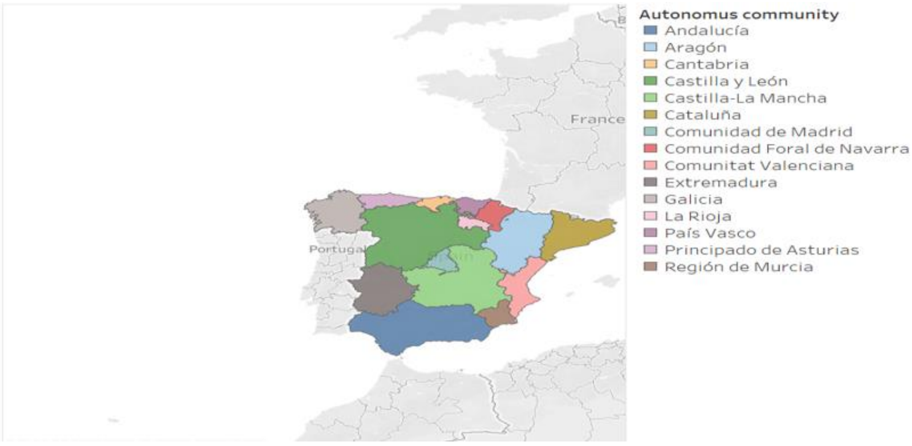


Figure 3 : Delineation of Study Area

3.2 Datasets

In this study, we utilized data procured from reliable and authoritative sources. The data essential for our analysis encompassed hydropower generation records of each autonomus community , global precipitation data , and a shapefile of Spain, enabling to extract precipitation data specific to the targeted autonomous communities.

3.2.1 Precipitation data

For our study, we sourced precipitation data from compiled datasets of the Climatic Research Unit (CRU), established by the University of East Anglia in 1982 (Peterson & Michael, 2008). The CRU has developed a strong and reliable methodology for collecting and processing climate data, resulting in widely-used gridded datasets. Their primary data source is an extensive global network of weather stations operated by National Meteorological Services, which meticulously record various meteorological parameters (Harris, Osborn, Jones, & Lister, 2020). The Climate Research Unit Time Series (CRU TS) dataset, specifically, provides gridded monthly fields of precipitation, temperatures, cloud cover, and other variables covering Earth's land areas from 1901 onwards . The dataset boasts a 0.5° x 0.5° degree resolution, achieved through the analysis of over 4,000 individual weather station records, and offers spatially complete coverage (Harris, Osborn, Jones, & Lister, 2020).we downloaded precipitation data from CRU’s official website . We obtained five files containing global precipitation data. Four of these files cover 10-year periods, while the last one includes data for 3 years, spanning from 1981 to 2023. The precipitation data we downloaded contains monthly precipitation measurements in millimeters (mm). After merging all five files, we have precipitation data at 516 time points(See Appendix B). This is because our dataset spans 43 years, and each year has 12 months, resulting in a total of 516 months of data. The total size of these files amounted to 2.01 GB (See Appendix C).

In this study we used NetCDF , or Network Common Data Form format file which contains precipitation data and sourced from CRU (Peng et al., 2019). It is a versatile file format widely used in geospatial analysis because it effectively manages multidimensional data like temperature or elevation across space and time (What is netCDF?, n.d.). Its self-describing nature, incorporating metadata about variables and units, makes it easy to understand. Furthermore, NetCDF's array-oriented structure enables efficient handling of large datasets, crucial in the domain of geospatial data analysis. In a NetCDF file, we utilize columns named “longitude”, “ latitude”, “ time”, “ precipitation”, along with a spatial component. Longitude and latitude pinpoint the geographic location, while time specifies the month and year. Precipitation indicates the amount of rainfall, in millimeters, at that particular time and location.

▼Coordinates:

lon	(lon)	float32	-179.8 -179.2 ... 179.2 179.8
lat	(lat)	float32	-89.75 -89.25 ... 89.25 89.75
time	(time)	datetime64[ns]	1981-01-16 ... 2023-12-16
spatial_ref	()	int64	0

▼Data variables:

pre	(time, lat, lon)	float32	dask.array<chunksize=(120, 360, 720), meta=...
long_name :	precipitation		
units :	mm/month		
correlation_dec...	450.0		
stn	(time, lat, lon)	float64	dask.array<chunksize=(120, 360, 720), meta=...
mae	(time, lat, lon)	float32	dask.array<chunksize=(120, 360, 720), meta=...
maea	(time, lat, lon)	float32	dask.array<chunksize=(120, 360, 720), meta=...

Figure 4 : metadata about variables in netcdf file

3.2.2 Hydropower generation data

Red Eléctrica de España (REE), the sole transmission system operator in Spain, holds a critical role in managing the nation's power grid (Generation, 2024). They maintain comprehensive data on electricity generation, consumption, and infrastructure, making them an invaluable resource for research (Moriana & Collantes, n.d.). For our analysis, we collected REE's open data, specifically focusing on monthly hydropower gene (Generation, 2024) ration figures for each autonomous community. This data, available in diverse formats like Excel and JSON, offers flexibility for analysis. The granularity of monthly data, measured in megawatt-hours (MWh), allows for insights into seasonal trends in hydropower production. The hydropower generation data collected spans from the year 2015 to March 2024 for each autonomous community.

The data's potential extends to trend analysis, climate impact studies, and forecasting. It's worth noting that while REE is a reliable source, data completeness and interpretation nuances should be considered. In sum,this dataset provides a strong foundation for understanding hydropower's role in Spain's evolving energy landscape.

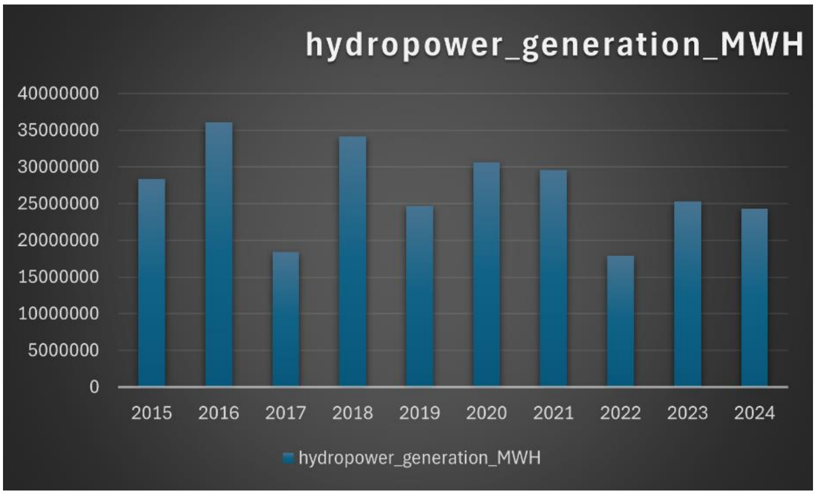


Figure 5 : Spanish Hydropower Production Over Time

3.2.3 Spain's geometrical boundaries dataset

The CRU stored global precipitation data is stored in a NetCDF file, utilizing longitude and latitude coordinates to precisely record rainfall measurements for any location on earth. In a so-called Shapefile that information is saved in the "geometry" column . Shapefiles are a geospatial vector data format used in Geographical Information System(GIS) to store and represent geographical features and their associated attributes A shapefile defining a country's boundary then is used to extract precise precipitation data from a NetCDF file (Vector maps and cartographic and topographic bases, n.d.). "Xarray" library was used to load the NetCDF, while Geopandas handled the shapefile. After ensuring both are in the same Coordinate Reference System (CRS), the "Rioxarray" library clipped the NetCDF data based on the Spain's shape, extracting precipitation information specific to that region.In the context of studying precipitation across Spain's autonomous communities, they provide a crucial spatial framework for linking rainfall data to specific regions. Each autonomous community is represented as a polygon or multipolygon within the shapefile, defining its boundaries and allowing for precise overlay and analysis of precipitation measurements (for reference see "Figure 6"). This enables researchers to calculate average precipitation, identify areas of high or low rainfall, and visualize spatial patterns (Langley, et al., 2015).

Shapefiles' geometric precision corresponding to a specific area is key to their utility. Polygons, representing the closed boundaries of each autonomous community, accurately capture their unique shapes and spatial extents. These polygons, along with associated attribute data like community names and area code, offer a rich canvas for geospatial analysis. This Shapefile also contains the Information in respective columns as "Official Code of Autonomus Community ","Official Name of Autonomous Community", "Local Name of Autonomous Country", "ISO 3166-2 Feature Code", "Iso3166-3 Area Code". This Shapefile is of 876 KB.

```
    year acom_code                        acom_name acom_area_c  \
0   2022        19  Ciudad Autónoma de Melilla               ESP
1   2022        13           Comunidad de Madrid             ESP
2   2022        15  Comunidad Foral de Navarra               ESP
3   2022        07                Castilla y León            ESP

               acom_type acom_name_l acom_iso316  \
0   autonomous communities       None          ML
1   autonomous communities       None          MD
2   autonomous communities       None          NC
3   autonomous communities       None          CL

                                             geometry
0   POLYGON ((-2.95264 35.32030, -2.95052 35.31849...
1   MULTIPOLYGON (((-3.53972 41.16504, -3.53670 41...
2   MULTIPOLYGON (((-2.42058 42.48923, -2.42353 42...
3   MULTIPOLYGON (((-6.98576 41.97104, -6.98665 41...
```

Figure 6 : Columns and records in a Shapefile

3.3 Data Processing and Analysis

The majority of the data processing and analysis, encompassing data cleaning, integration, manipulation, exploration, and visualization, was conducted within the Google Colab environment using the power and versatility of Python programming(see Figure7). While Python served as the primary tool for data analysis, Excel and Tableau were also strategically employed for specific tasks where their user-friendly interfaces proved advantageous.

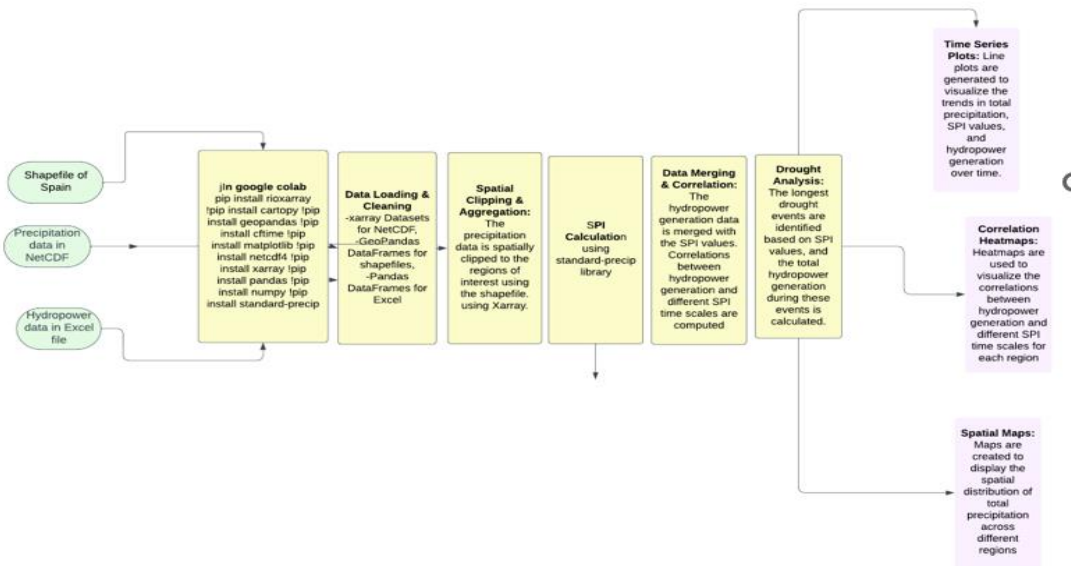


Figure 7: Visualisation of Data Pipeline

3.3.1 Data Integration and Cleaning

Excel was utilized for the initial stages of data exploration and cleaning. Its intuitive interface and powerful data manipulation capabilities enabled efficient handling of tasks such as: inspecting the data to gain an understanding of its structure, identifying potential errors, and assessing overall quality; performing basic data cleaning operations, including handling missing values, removing duplicates, and correcting inconsistencies; and restructuring or transforming the data to prepare it for further analysis and integration with other datasets.

3.3.2 Geospatial Data Handling

Rioxarray is a powerful library specifically designed for handling geospatial raster data. It seamlessly integrates with the xarray library, providing a labelled, multi-dimensional array data structure that significantly simplifies working with raster datasets. Rioxarray enabled crucial operations such as(See Appendix B)

- **Reading and writing raster data**
  Rioxarray efficiently reads and writes raster data in various formats, including Geo TIFF and NetCDF, preserving essential geospatial metadata.
- **Manipulating raster data**
  The library facilitated cropping, resampling, reprojection, and other essential raster data manipulation tasks.
- **Visualizing raster data**
  Rioxarray integrates well with visualization libraries like Matplotlib, allowing for the creation of informative maps and plots.

Cartopy is a specialized library designed for creating publication-quality maps. It offers a wide range of cartographic projections and features for adding map elements such as coastlines, borders, and gridlines. Cartopy was likely used to generate visually appealing and informative maps for data visualization and presentation.

Geopandas is a library that extends the capabilities of pandas to handle geospatial vector data. It provides data structures and functions for working with points, lines, and polygons, enabling operations such as spatial joins, overlays, and distance calculations. Geopandas was instrumental in integrating and analysing vector datasets, such as shapefiles containing administrative boundaries or hydrological features.

3.3.3 Climate Data Management

NetCDF4 is a library that provides essential functionality for reading and writing NetCDF files, a common format for storing climate and meteorological data. It enables efficient access to the multi-dimensional arrays and metadata contained within these files (See Appendix B).

Xarray is a powerful library that builds upon the NetCDF4 library, offering a labeled, multi-dimensional array data structure that significantly simplifies the analysis of climate data. Xarray enables crucial operations such as:

Data selection and indexing Xarray's powerful indexing capabilities allow for the selection of specific time periods, spatial regions, or variables of interest within the climate datasets.

Data aggregation and computation

This library facilitates the calculation of statistics, temporal aggregations (e.g., monthly or annual averages), and spatial operations on the climate data.

Data visualization

Xarray seamlessly integrates with visualization libraries like Matplotlib, enabling the creation of informative plots and maps to explore and communicate climate patterns.

3.3.4 Numerical Computation and Data Analysis

NumPy is a fundamental library for numerical computation in Python. It provides essential tools for array manipulation and mathematical operations, including Array Creation and Manipulation(See Appendix B). NumPy arrays efficiently store and manipulate numerical data, enabling operations such as reshaping, slicing, and element-wise calculations. Mathematical Operations, this library offers a wide range of mathematical functions for performing calculations on arrays, including statistical analysis & linear algebra.Pandas is a powerful data analysis library that offers high-performance data structures and tools for data manipulation and exploration. It was utilized for tasks such as:

Data Cleaning and Transformation

Pandas DataFrames provided a flexible structure for cleaning and transforming data, including handling missing values, filtering data based on conditions, and aggregating data by groups.

Data Exploration and Analysis

The library offered functions for calculating descriptive statistics, performing group-wise operations, and exploring relationships between variables.

Data Integration

Pandas facilitated the merging and joining of different datasets based on common keys or indices.

3.3.5 Drought Analysis

The **standard-precip** library, specifically designed for drought analysis, streamlined the calculation and analysis of the Standardized Precipitation Index (SPI). This widely-used metric quantifies drought severity based on precipitation deviations from long-term averages. The library offered functions for calculating SPI values at various time scales (1, 3, 6, 12 and 24 months), classifying drought severity based on SPI values, and analyzing drought patterns, such as identifying drought duration and intensity (see Appendix B).

3.3.6 Data Visualization

Tableau

While Python libraries like Matplotlib and Seaborn offer extensive visualization capabilities, Tableau was employed for generating specific graphs due to its intuitive drag-and-drop interface and interactive features. Tableau's user-friendliness facilitated the creation of visually appealing and insightful visualizations for data exploration and communication.

Python Visualization Libraries

Python's rich ecosystem of visualization libraries, including Matplotlib and Seaborn, was leveraged for creating a variety of plots, charts, and maps within the Google Colab. These libraries offered control over visualization elements, enabling the creation of customized and publication-quality graphics (see Appendix B).

3.4 Drought Analysis using the Standardized Precipitation Index (SPI)

For our research we need to measure drought through precipitation data and we used Standard Precipitation Index(SPI) to find out the magnitude of drought. A popular meteorological drought index that measures precipitation shortfalls over a range of time periods is the SPI. By converting precipitation data into a probability distribution, it makes it easier to estimate the severity of droughts and to compare data from different climate zones (Edward & Mckee, 1997).For this research we took the percipitation data of 43 years (for reliable results we need precipitation data of at least 30 years) begining from 1981 to 2023.

In our study, we employed the Standardized Precipitation Index (SPI) to characterize meteorological drought across multiple time scales. Specifically, we calculated SPI values for moving average of 1, 3, 6, 12, and 24 months, allowing us to assess short-term, seasonal, and long-term drought patterns. We employed different time scales of the SPI to assess the sensitivity of hydropower generation capacity in each autonomous region(Pramudya & Onishi, 2018). This is because some regions' hydropower generation may be more sensitive to short-term droughts, while others may be impacted by longer droughts. The reasons for this variability can be numerous, including factors such as the size of water reservoirs.

The selection of these time scales aligns with the availability of hydropower generation data, spanning from 2015 to 2024. To ensure temporal overlap with precipitation data, we restricted our SPI analysis to the period from 2015 to 2023.

The choice to utilize 43 years of precipitation data for SPI calculation is rooted in the desire to achieve a smooth and reliable fit to the gamma distribution, which underlies the SPI methodology. A lengthier data record allows for the detection and classification of various drought intensities, improving the reliability of the estimated parameters and providing a wider range of SPI values.

For calculating SPI, we leveraged the Python library "standard-precip". This library streamlines the analytical process and maintains conformity to established scientific standards by making it easier to calculate SPI values over various time scales. Utilizing this library improves our research's reproducibility even more, offering future validation and expansion of our conclusions.SPI’s severity can be measured through its value . We utilized the generally accepted SPI criteria, where values is below 0 indicate the beginning of drought conditions, to categorize drought occurrences and their severity. The degree of the drought is closely correlated with the magnitude of the negative SPI number, with progressively lower values denoting more severe drought conditions. Please refer to the table below for a good illustration of the drought classifications based on SPI values.

SPI Value Range	SPI Category
≥ 2.00	Extremely wet
1.50 - 1.99	Severely wet
1.00 - 1.49	Moderately wet
0 >SPI	Drought

Table 3 : SPI values Categorisation

3.4.1 Identifying Optimal SPI Time Scales

To determine the most suitable common Standardized Precipitation Index (SPI) time scales for assessing drought impact on hydropower generation across all regions, we employed Pearson correlation analysis. This statistical method quantifies the strength and direction of the linear relationship between two variables. In our study, we calculated Pearson correlation coefficients between various SPI time scales (SPI-1, SPI-3, SPI-6, SPI-12, and SPI-24) and corresponding hydropower generation data in MWH. A higher absolute value of the correlation coefficient (‘r’, has range from-1 to1+) indicates a stronger association between a specific SPI time scale and hydropower generation.

Our analysis revealed that SPI-3 and SPI-6 consistently exhibited the strongest correlations with hydropower generation across the majority of the autonomous communities in Spain. We completed this analysis with the help of Python programming(See Appendix B).We identified these time scales as the most suitable for evaluating the impact of drought on hydropower generation within the context of this study.

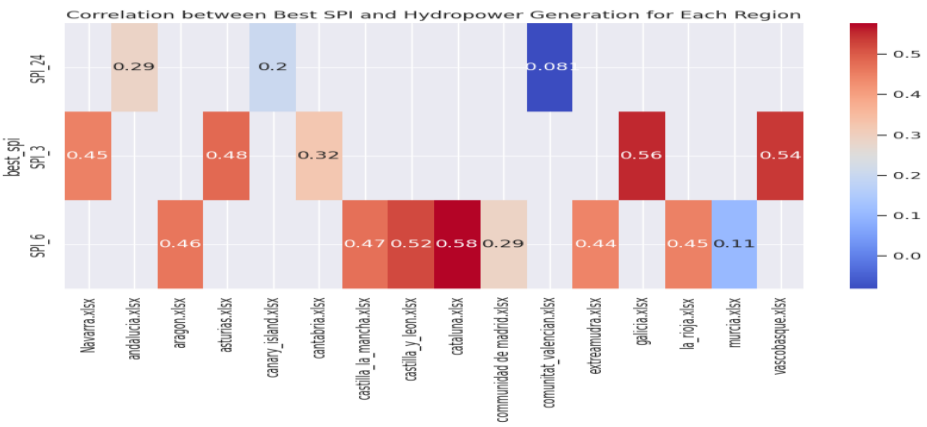


Figure 8: Correlation between Best SPI and Hydropower generation for Each region

Chapter 4 : Results and Discussion

In this chapter, we present the final results of our comprehensive research, "The Impact of Drought on Hydropower Generation: A Case Study of Spain." We delve into the core questions raised by this study, focusing on 6 of the 15 autonomous communities in detail. (Results for the remaining 9 can be found in Appendix D.) Our selection of communities included the 5 largest hydropower producers, along with one additional community(Comunidad Foral de Navarra) chosen for its variability.

Castilla y León emerges as the leading hydropower producer with a substantial 4398 MW installation capacity, followed by Galicia, Extremadura, Cataluña, and Comunidad Foral de Navarra (see table 4).

Our analysis revealed that the 3-month and 6-month Standardized Precipitation Index (SPI-3 and SPI-6) are the most effective indicators for assessing drought severity in the majority of these communities. These SPIs exhibit a strong correlation with hydropower generation, making them valuable tools for evaluating drought's impact on energy production(See chapter 3; section 3.4.1). Moreover, these SPIs differentiate between short-term (SPI-3) and long-term (SPI-6) drought vulnerability, providing crucial insights for assessing the resilience of hydropower systems to different drought scenarios.

Our results focus on SPI-3 and SPI-6 for evaluating drought severity in each community. By examining these SPIs, we can gain a comprehensive understanding of the relationship between drought conditions and hydropower generation, enabling us to develop informed strategies for managing water resources and ensuring energy security.

In addition to assessing drought severity, we will also investigate the longest drought events, defined as periods where either SPI value is 0 or below for an extended duration. This will allows us to explore the nature of hydropower generation in each community and its resilience to prolonged dry spells. By identifying the communities most susceptible to lengthy droughts, we can prioritize targeted interventions to improve their drought resilience and mitigate the potential impacts on hydropower production.

S.no.	**Autonomous Community**	**Hydropower Installed Capacity in MW**	**Hydropower Production in MWH(Monthly Averages)**
1	Castilla y León	4398	600055.4
2	Galicia	3732	581274.8
3	Extremadura	2277	146456.6
4	Cataluña	1922	317470.8
5	Aragón	1334	239117.7
6	Comunidad Foral de Navarra	238	39969.16

Table 4: Hydropower generation & installed capacity.

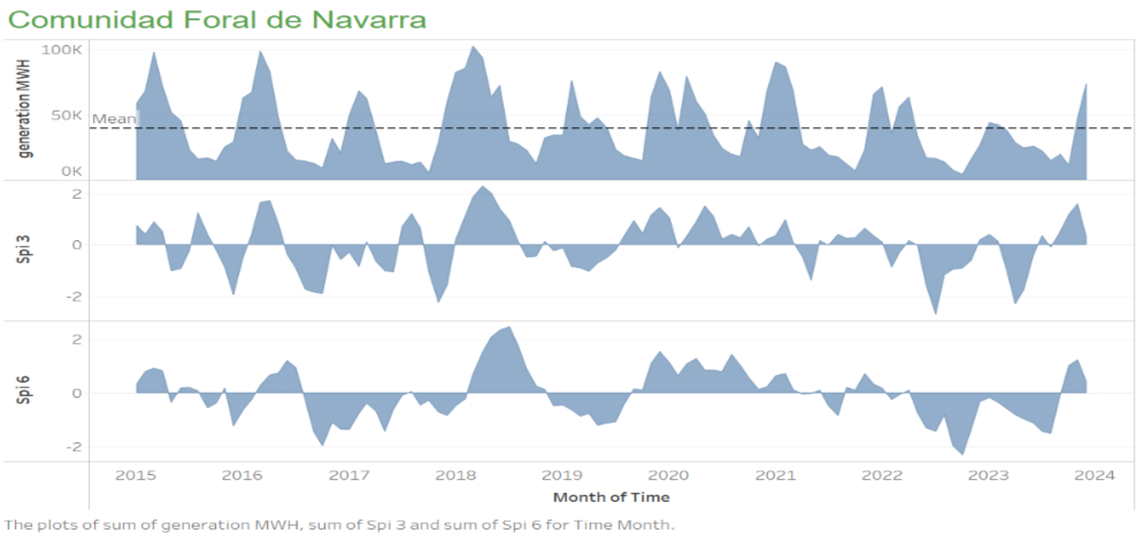
To quantify the impact of drought, measured by SPI3 and SPI6, on hydropower generation, we will calculate the deviation in hydropower output from its average. This mathematical approach will reveal the extent of power loss due to drought, providing valuable insights for adaptation strategies. By subtracting the average hydropower generation from the actual output during drought periods, we can determine the specific amount of power that has been compromised. This data will enable a more precise assessment of the drought's impact on energy production and inform the development of targeted mitigation measures.

Mathematical Equation to calculate the downfall in hydropower generation during drought.
Total Standard Deviation (SD) = (Drought Period in Months * Monthly Average Hydropower Generation) - Actual Power Generation during Drought

4.1 Results of selected Autonomous community

4.1.1 Comunidad Foral de Navarra(Navarre)

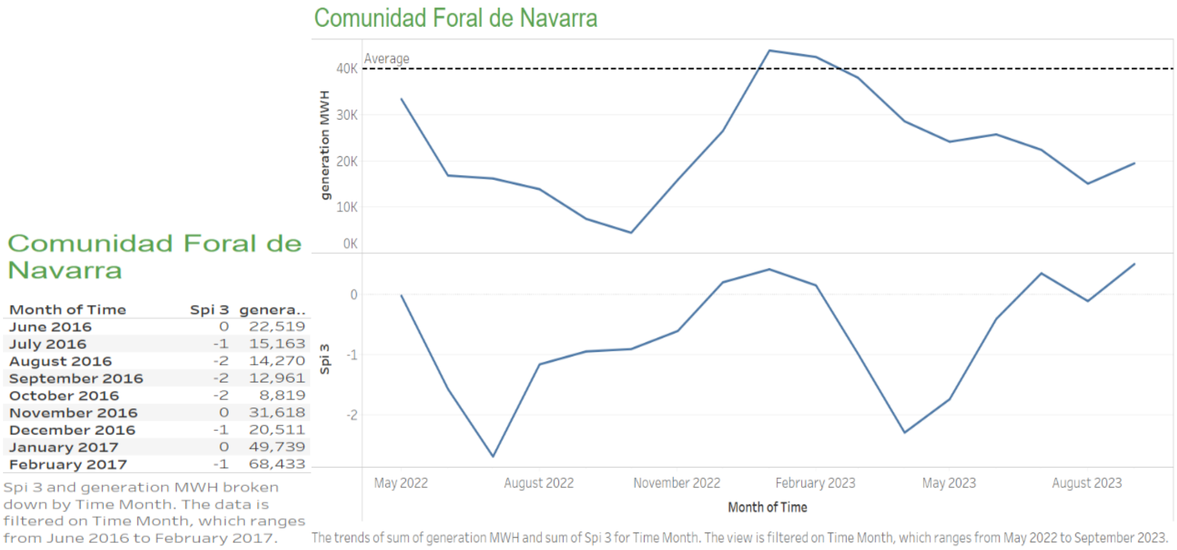
Average Hydropower generation= 39969.16 MWH
The autonomous region of Navarre in northern Spain, steeped in history and perhaps most famous for the annual Running of the Bulls in its capital, Pamplona, also holds a significant role in renewable energy production (Incentives: Navarre, Spain, 2016). With an installed hydropower capacity of 238 MW, Navarre generates an **average of 39,969.19 MWh** of electricity monthly.
However, as our analysis reveals, hydropower generation in Navarre is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a corresponding decrease in hydropower output. This trend is evident in Graph 1, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the average generation level.



Graph 1 : The Impact of Drought on Hydropower Generation in Navarra

SPI-3
To gain a deeper understanding of how drought affects hydropower generation in Navarre, we'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from June 2016 to February 2017, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans nine months.
Calculation
SD = (9 months * 39,969.16 MWh/month) - 244,032.57 MWh
SD = 115,689.87 MWh
Interpretation

The substantial total standard deviation of **115,689.87 MWh** underscores the severe impact the drought had on hydropower generation in Navarre.This trend can also be seen in Graph 2.



Month of Time	Spi 3	genera..
June 2016	0	22,519
July 2016	-1	15,163
August 2016	-2	14,270
September 2016	-2	12,961
October 2016	-2	8,819
November 2016	0	31,618
December 2016	-1	20,511
January 2017	0	49,739
February 2017	-1	68,433

Graph 2 : The Impact of Drought(SPI-3) on Hydropower Generation in Navarra

SPI-6

In Navarra, we'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from May 2022 to September 2023, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Seventeen months.

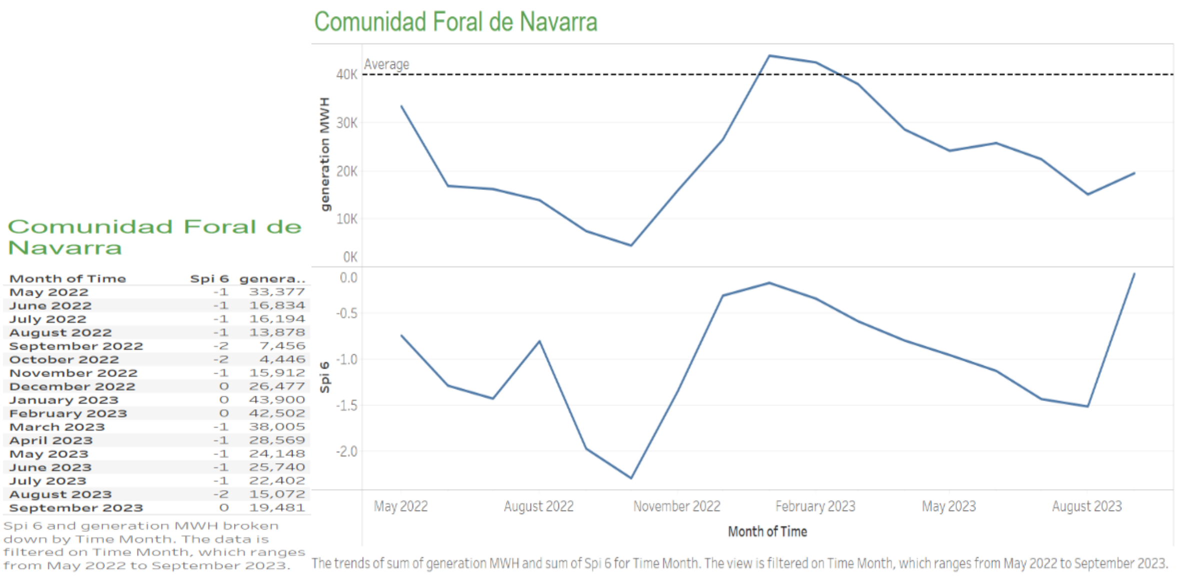
Calculation

SD = (17 months * 39,969.16 MWh/month) – 394392.5872 MWh

SD = 285083.13MWh

Interpretation

The substantial total standard deviation of **285083.13MWh** underscores the severe impact the drought had on hydropower generation in Navarre.. This trend can also be seen in Graph 3.



Month of Time	Spi 6	genera..
May 2022	-1	33,377
June 2022	-1	16,834
July 2022	-1	16,194
August 2022	-1	13,878
September 2022	-2	7,456
October 2022	-2	4,446
November 2022	-1	15,912
December 2022	0	26,477
January 2023	0	43,900
February 2023	0	42,502
March 2023	-1	38,005
April 2023	-1	28,569
May 2023	-1	24,148
June 2023	-1	25,740
July 2023	-1	22,402
August 2023	-2	15,072
September 2023	0	19,481

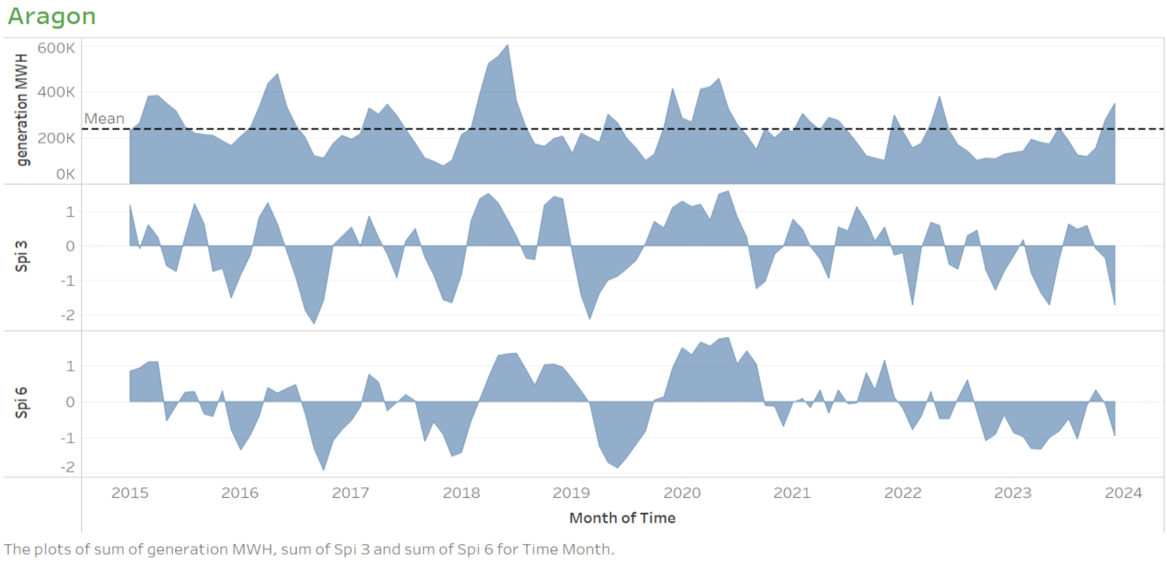
Graph 3 : The Impact of Drought(SPI-6) on Hydropower Generation in Navarra

4.1.2 Aragon

Average Hydropower Generation=239117.7 MWH

Aragon with an installed hydropower capacity of 1334 MW, Aragon generates an average of 239117.7 MWh of electricity monthly.

However, as our analysis reveals, hydropower generation in Aragon is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a decrease in hydropower output. This trend is evident in Graph 4, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the mean generation level.



Graph 4 : The Impact of Drought on Hydropower Generation in Aragon

SPI-3

To gain a deeper understanding of how drought affects hydropower generation in Aragon, we'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from January 2019 to August 2019, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans seven months.

Calculation

SD = (7 months * 239117.7 MWh/month) – 1656180.39 MWh

SD = 17643.51 MWh

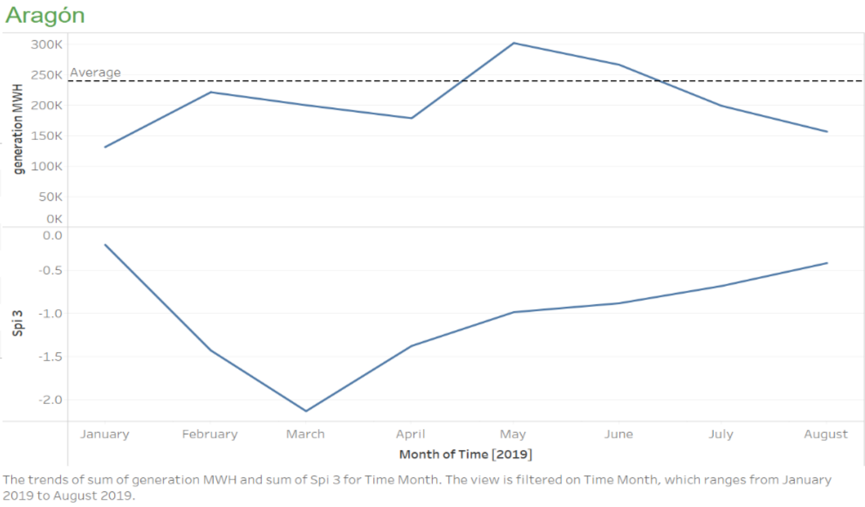
Interpretation

The substantial total standard deviation of **17643.51 MWh** underscores the severe impact the drought had on hydropower generation in Aragon.This trend can also be seen in Graph 5.

Aragón

Month of Time	Spi 3	genera..
January 2019	0	131,495
February 2019	-1	221,430
March 2019	-2	200,133
April 2019	-1	178,687
May 2019	-1	302,077
June 2019	-1	266,471
July 2019	-1	199,161
August 2019	0	156,726

Spi 3 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from January 2019 to August 2019.



Graph 5 : The Impact of Drought (SPI-3)on Hydropower Generation in Aragon

SPI-6

In Aragon, we'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from September 2022 to September 2023, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans thirteen months.

Calculation

SD = (13 months * 239117.7MWh/month) – 1958915.065 MWh

SD = 1149615.035MWh

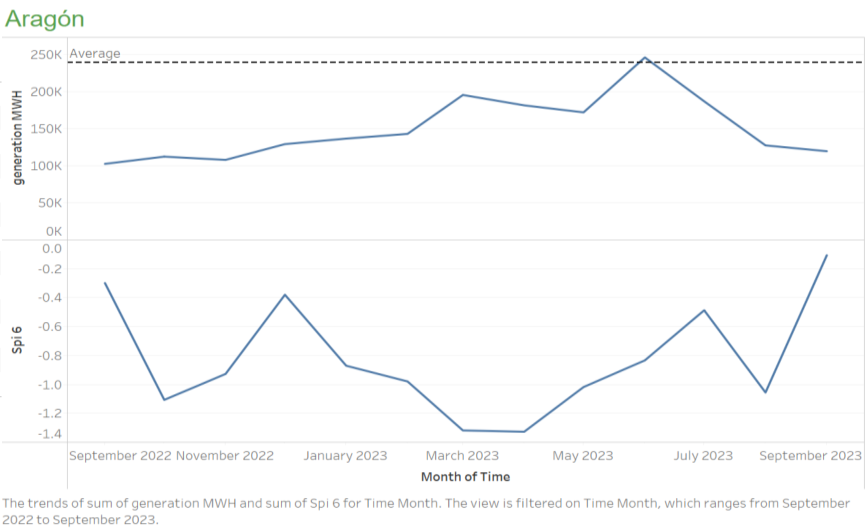
Interpretation

The substantial total standard deviation of **1149615.035MWh** underscores the severe impact the drought had on hydropower generation in Aragon. This trend can also be seen in Graph 6.

Aragón

Month of Time	Spi 6	genera..
September 2022	0	102,444
October 2022	-1	112,200
November 2022	-1	107,823
December 2022	0	129,037
January 2023	-1	136,498
February 2023	-1	142,896
March 2023	-1	195,311
April 2023	-1	181,341
May 2023	-1	171,895
June 2023	-1	245,918
July 2023	0	186,751
August 2023	-1	127,313
September 2023	0	119,489

Spi 6 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from September 2022 to September 2023.



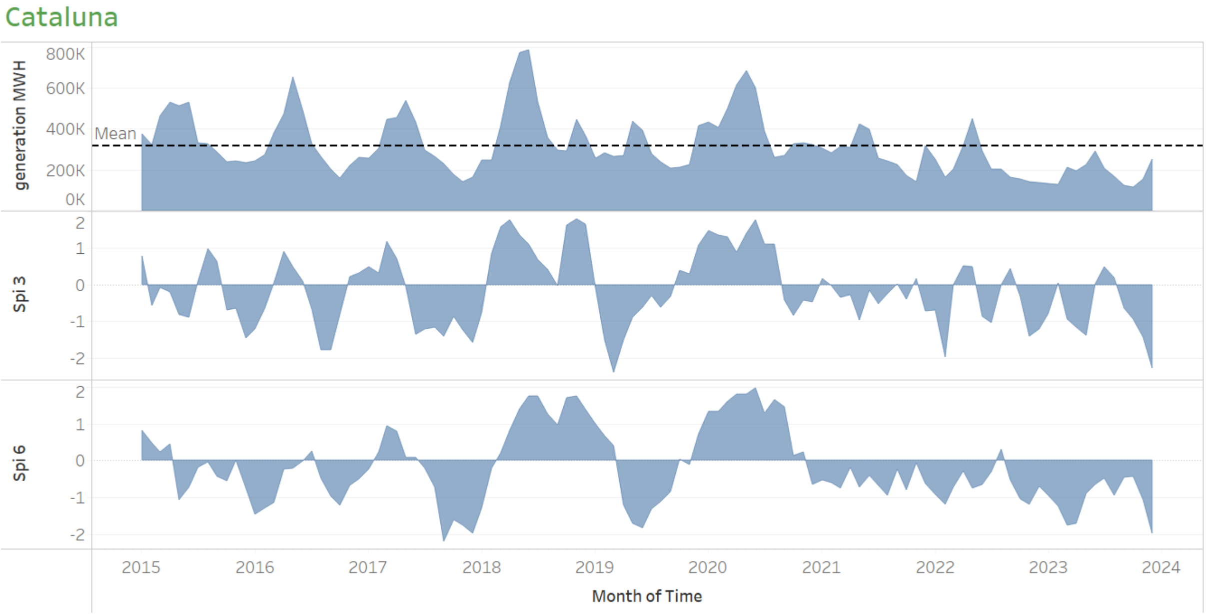
Graph 6: The Impact of Drought (SPI-6) on Hydropower Generation in Aragon

4.1.3 Cataluña

Average hydropower generation=317470.8

Cataluña with an installed hydropower capacity of 1922 MW, Cataluña generates an average of 317470.8 MWh of electricity monthly.

However, as our analysis reveals, hydropower generation in Cataluña is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a decrease in hydropower output. This trend is evident in Graph 7, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the mean generation level.



The plots of sum of generation MWH, sum of Spi 3 and sum of Spi 6 for Time Month.

Graph 7 : The Impact of Drought on Hydropower Generation in Cataluña

SPI-3

We'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from May 2017 to January 2018, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Nine months.

Calculation

SD = (9 months * 317470.8 MWh/month) – 2488039.613 MWh

SD = 369197.58 MWh

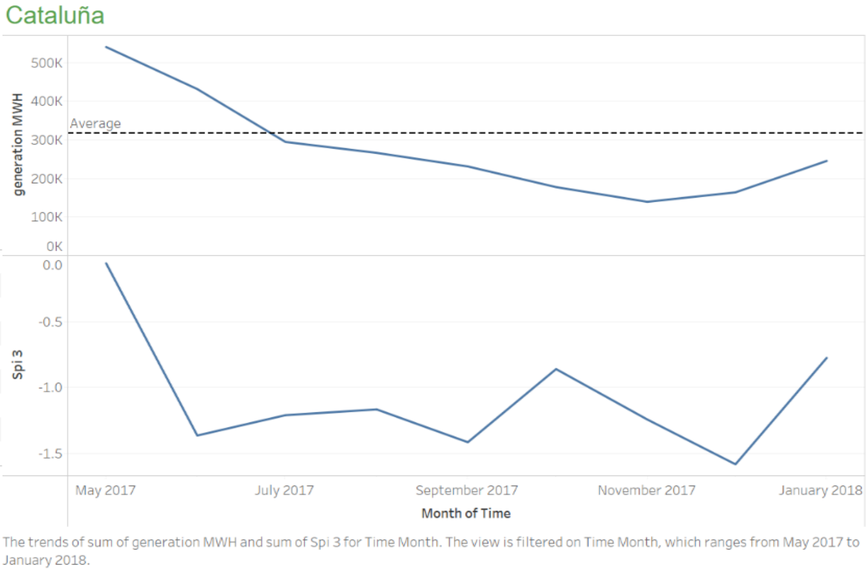
Interpretation

The substantial total standard deviation of **369197.58 MWh** underscores the severe impact the drought had on hydropower generation in Cataluña. This trend can also be seen in Graph 8.

Cataluña

Month of Time	Spi 3	genera..
May 2017	0	540,088
June 2017	-1	431,167
July 2017	-1	294,266
August 2017	-1	266,008
September 2017	-1	230,861
October 2017	-1	177,422
November 2017	-1	139,349
December 2017	-2	163,785
January 2018	-1	245,093

Spi 3 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from May 2017 to January 2018.



Graph 8 : The Impact of Drought(SPI-3) on Hydropower Generation in Cataluña

SPI-6

We'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from December 2020 to July 2022, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Twenty months.

Calculation

SD = (20 months * 317470.8 MWh/month) -5584059.95 MWh

SD = 765356.05 MWh

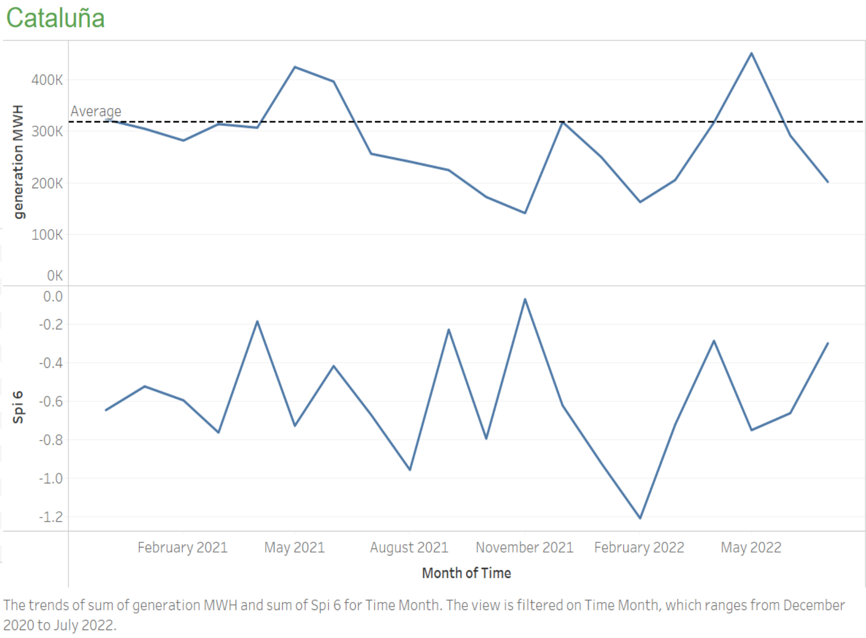
Interpretation

The substantial total standard deviation of **765356.05 MWh** underscores the severe impact the drought had on hydropower generation in Cataluña.This trend can also be seen in Graph 9.

Cataluña

Month of Time	Spi 6	genera..
December 2020	-1	322,966
January 2021	-1	304,810
February 2021	-1	281,953
March 2021	-1	313,922
April 2021	0	306,887
May 2021	-1	424,622
June 2021	0	396,508
July 2021	-1	256,178
August 2021	-1	240,942
September 2021	0	224,538
October 2021	-1	172,299
November 2021	0	141,041
December 2021	-1	317,869
January 2022	-1	249,639
February 2022	-1	162,486
March 2022	-1	205,283
April 2022	0	317,341
May 2022	-1	451,515
June 2022	-1	291,586
July 2022	0	201,675

Spi 6 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from December 2020 to July 2022.



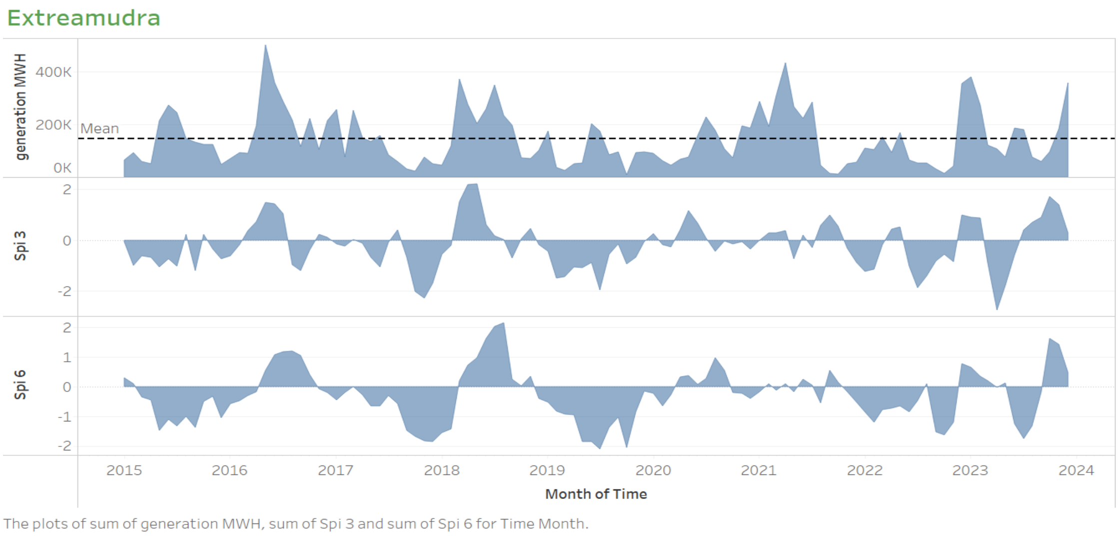
Graph 9 : The Impact of Drought(SPI-6)on Hydropower Generation in Cataluña

4.1.4 Extremadura

Average Hydropower Generation=146456.6 MWH

Extremadura with an installed hydropower capacity of 2277 MW, Extremadura generates an average of 146456.6 MWh of electricity monthly.

However, as our analysis reveals, hydropower generation in Extremadura is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a decrease in hydropower output. This trend is evident in Graph 10, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the mean generation level.



Graph 10 : The Impact of Drought on Hydropower Generation in Extremadura

SPI-3

We'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from December 2018 to December 2019, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Thirteen months.

Calculation

SD = (13 months * 146456.6 MWh/month) – 1197202.46 MWh

SD = 706733.34 MWh

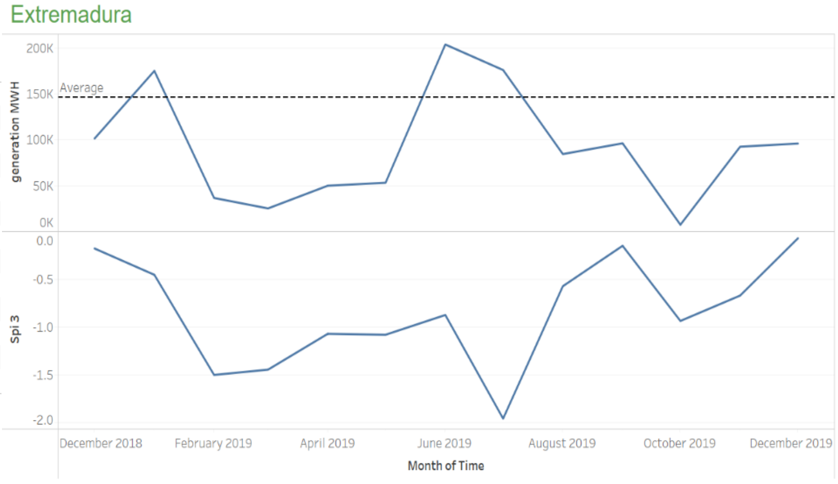
Interpretation

The substantial total standard deviation of **706733.34 MWh** underscores the severe impact the drought had on hydropower generation in Extreamudra.This trend can also be seen in Graph 11

Extremadura

Month of Time	Spi 3	genera..
December 2018	0	101,369
January 2019	0	174,997
February 2019	-2	36,586
March 2019	-1	25,196
April 2019	-1	49,937
May 2019	-1	53,161
June 2019	-1	203,768
July 2019	-2	175,945
August 2019	-1	84,396
September 2019	0	96,130
October 2019	-1	7,417
November 2019	-1	92,410
December 2019	0	95,890

Spi 3 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from December 2018 to December 2019.



The trends of sum of generation MWH and sum of Spi 3 for Time Month. The view is filtered on Time Month, which ranges from December 2018 to December 2019.

Graph 11 : The Impact of Drought(SPI-3) on Hydropower Generation in Extremadura

SPI-6

We'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from December 2018 to March 2020, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Sixteen months.

Calculation

SD = (16 months * 146456.6 MWh/month) – 1393170.77 MWh

SD = 950134.83 MWh

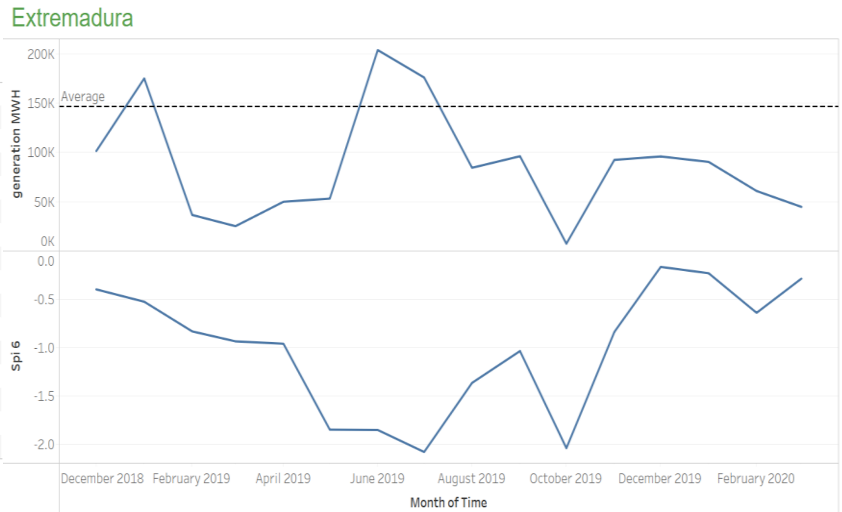
Interpretation

The substantial total standard deviation of **706733.34 MWh** underscores the severe impact the drought had on hydropower generation in Extremadura.This trend can also be seen in Graph 12.

Extremadura

Month of Time	Spi 6	genera..
December 2018	0	101,369
January 2019	-1	174,997
February 2019	-1	36,586
March 2019	-1	25,196
April 2019	-1	49,937
May 2019	-2	53,161
June 2019	-2	203,768
July 2019	-2	175,945
August 2019	-1	84,396
September 2019	-1	96,130
October 2019	-2	7,417
November 2019	-1	92,410
December 2019	0	95,890
January 2020	0	90,354
February 2020	-1	60,865
March 2020	0	44,750

Spi 6 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from December 2018 to March 2020.



The trends of sum of generation MWH and sum of Spi 6 for Time Month. The view is filtered on Time Month, which ranges from December 2018 to March 2020.

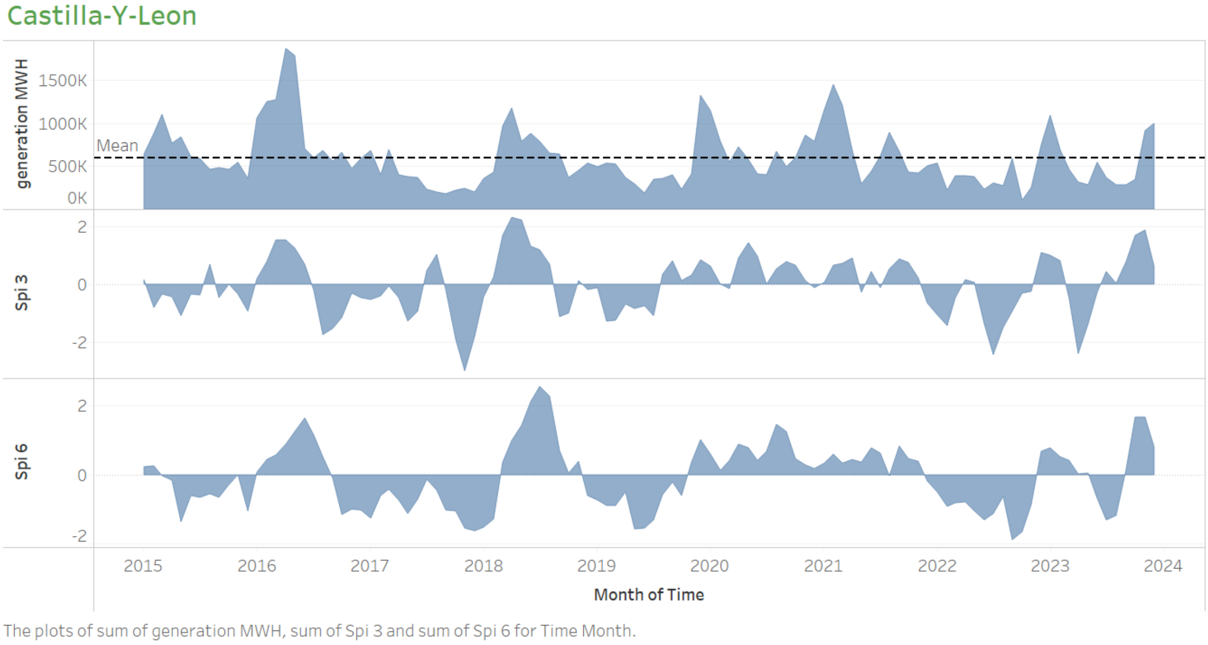
Graph 12 : The Impact of Drought(SPI-6) on Hydropower Generation in Extremadura

4.1.5 Castilla y Leon

Average hydropower generation=600055.4 MWH

Castilla y León with a highest installed hydropower capacity of 4398 MW, Castilla y Leon generates an average of 600055.4 MWh of electricity monthly.

However, as our analysis reveals, hydropower generation in Castilla y León is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a decrease in hydropower output. This trend is evident in Graph 13, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the mean generation level.



Graph 13 : The Impact of Drought on Hydropower Generation in Castilla y León

SPI-3

We'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from July 2016 to June 2017, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Twelve months.

Calculation

SD = (12 months * 600055.4 MWh/month) – 6471390.33 MWh

SD = 729274.47MWh

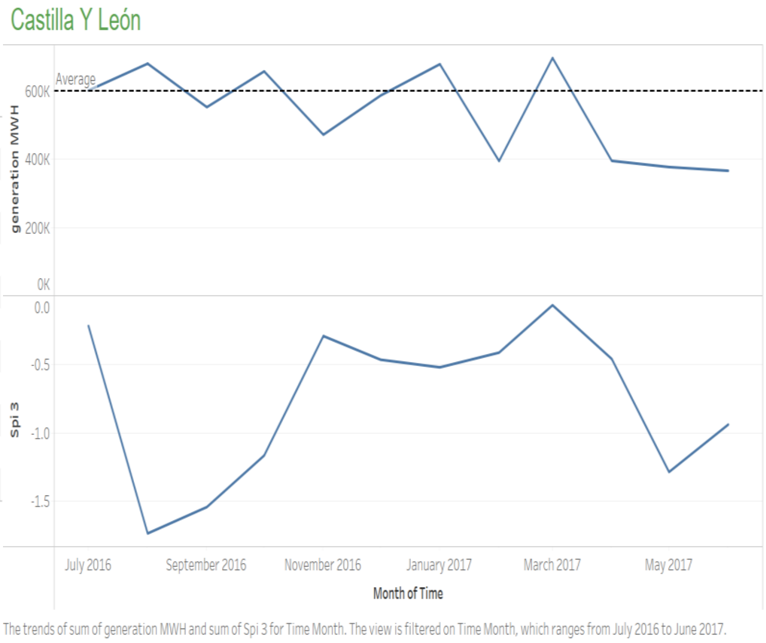
Interpretation

The substantial total standard deviation of **729274.47 MWh** underscores the severe impact the drought had on hydropower generation in Castilla y León.This trend can also be seen in Graph 14.

Castilla Y León

Month of Time	Spi 3	genera..
July 2016	0	602,820
August 2016	-2	681,432
September 2016	-2	553,720
October 2016	-1	658,743
November 2016	0	472,717
December 2016	0	587,930
January 2017	-1	679,865
February 2017	0	395,351
March 2017	0	698,082
April 2017	0	396,041
May 2017	-1	377,772
June 2017	-1	366,917

Spi 3 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from July 2016 to June 2017.



Graph 14 : The Impact of Drought(SPI-3) on Hydropower Generation in Castilla y Leon

SPI-6

We'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from September 2016 to Feb 2018, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Eighteen months.

Calculation

SD = (18 months * 600055.4 MWh/month) –7231768.26MWh

SD = 3569228.94MWh

Interpretation

The substantial total standard deviation of **3569228.94 MWh** underscores the severe impact the drought had on hydropower generation in Castilla y León.This trend can also be seen in Graph 15.

Castilla Y León

Month of Time	Spi 6	genera..
September 2016	0	553,720
October 2016	-1	658,743
November 2016	-1	472,717
December 2016	-1	587,930
January 2017	-1	679,865
February 2017	-1	395,351
March 2017	0	698,082
April 2017	-1	396,041
May 2017	-1	377,772
June 2017	-1	366,917
July 2017	0	228,640
August 2017	0	195,024
September 2017	-1	177,555
October 2017	-1	217,231
November 2017	-2	239,169
December 2017	-2	202,933
January 2018	-2	355,848
February 2018	-1	428,232

Spi 6 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from September 2016 to February 2018.

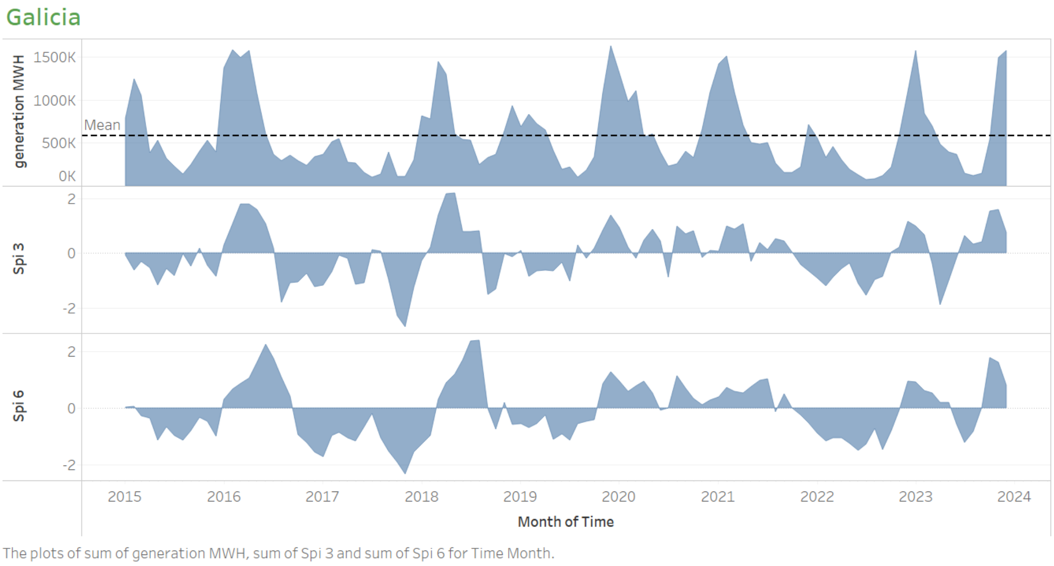
Graph 15 : The Impact of Drought (SPI-6) on Hydropower Generation in Castilla y León

4.1.6 Galicia

Average Hydropower generation=581274.8 MWH

Galicia with an installed hydropower capacity of 3732 MW, Galicia generates an average of 581274.8 MWh of electricity monthly.

However, as our analysis reveals, hydropower generation in Galicia is closely linked to drought conditions. When the SPI values dip below 0, indicating drought, there's a decrease in hydropower output. This trend is evident in Graph 16, which presents monthly hydropower output data from 2015 to 2023 alongside SPI-3 and SPI-6 values. During drought periods, the monthly hydropower output falls below the mean generation level.



Graph 16 : The Impact of Drought on Hydropower Generation in Galicia

SPI-3

We'll focus on a period of significant drought as indicated by the SPI-3 index. Specifically, we'll examine the hydropower output from August 2016 to June 2017, when the SPI-3 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Eleven months.

Calculation

SD = (11 months * 581274.8 MWh/month) – 3630706.90MWh

SD = 2763315.9MWh

Interpretation

The substantial total standard deviation of **2763315.9 MWh** underscores the severe impact the drought had on hydropower generation in Galicia.This trend can also be seen in Graph 17

Galicia

Month of Time	Spi 3	genera..
August 2016	-2	294,515
September 2016	-1	351,977
October 2016	-1	293,351
November 2016	-1	241,093
December 2016	-1	335,098
January 2017	-1	361,410
February 2017	-1	510,617
March 2017	0	550,991
April 2017	0	271,859
May 2017	-1	265,250
June 2017	-1	154,546

Spi 3 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from August 2016 to June 2017.

Graph 17 : The Impact of Drought (SPI-3) on Hydropower Generation in Galicia

SPI-6

We'll focus on a period of significant drought as indicated by the SPI-6 index. Specifically, we'll examine the hydropower output from October 2016 to Feburary 2018, when the SPI-6 value was at or below zero, signaling a longest drought event beteween 2015-2023. This period spans Seventeen months.

Calculation

SD = (17 months * 581274.8 MWh/month) – 5727103.448MWh

SD = 4154568.16MWh

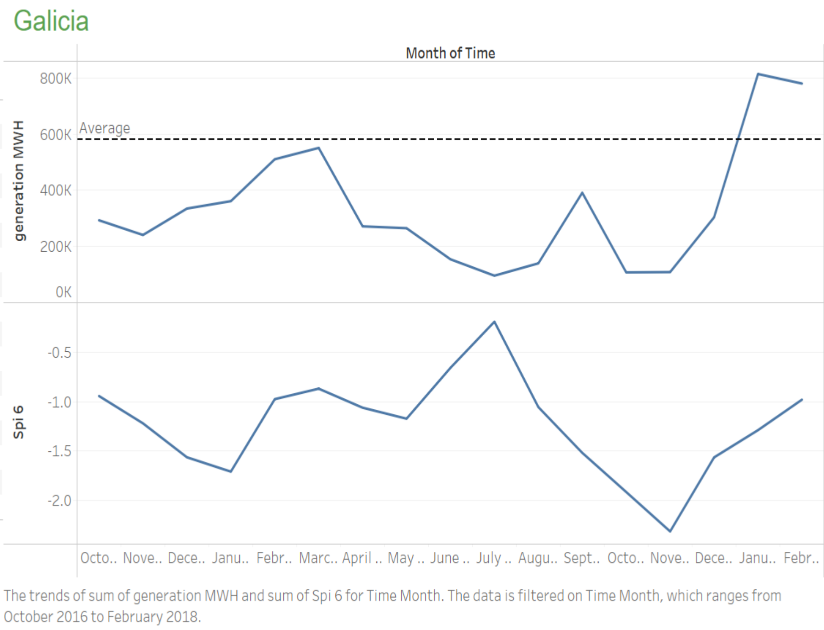
Interpretation

The substantial total standard deviation of **4154568.16MWh** underscores the severe impact the drought had on hydropower generation in Galicia.This trend can also be seen in Graph 18

Galicia

Month of Time	Spi 6	genera..
October 2016	-1	293,351
November 2016	-1	241,093
December 2016	-2	335,098
January 2017	-2	361,410
February 2017	-1	510,617
March 2017	-1	550,991
April 2017	-1	271,859
May 2017	-1	265,250
June 2017	-1	154,546
July 2017	0	96,242
August 2017	-1	140,151
September 2017	-2	391,559
October 2017	-2	107,999
November 2017	-2	109,027
December 2017	-2	303,875
January 2018	-1	813,978
February 2018	-1	780,057

Spi 6 and generation MWH broken down by Time Month. The data is filtered on Time Month, which ranges from October 2016 to February 2018.



Graph 18 : The Impact of Drought (SPI-6) on Hydropower Generation in Galicia

4.2 Discussion

Across the six autonomous communities studied, the results unequivocally demonstrate a shortfall in hydropower generation during drought periods. Regions like Castilla y León and Galicia, with substantial hydropower infrastructure, were hit particularly hard during the extended droughts of 2016-2017 and 2022-2023. These findings align with prior research in the Mediterranean region, highlighting the prolonged dry spells occurred during 2015-2019 (Mathbout et al., 2021).
The substantial standard deviation values observed underscore the severity of drought's impact on energy production. This is consistent with existing literature indicating that drought can lead to significant reductions in hydropower output, potentially threatening energy security (Cuartas et al., 2022; Kilic, 2024).
Regional disparities in drought impact and hydropower generation loss are evident. Castilla y León and Galicia experienced substantial losses during drought events, highlighting the vulnerability of regions heavily reliant on hydropower. However, it's important to note that hydropower generation isn't always directly correlated with very short and least severity. For example, in January and February of 2018, when the 6-month Standardized Precipitation Index (SPI-6) for Galicia was -1, indicating s drought, the region produced more hydropower than its monthly average (see Graph 18). This suggests other factors besides drought can influence hydropower output.
The overall trend is clear: prolonged drought leads to a decline in hydropower generation across all 15 autonomous regions studied(See Appendix D). Galicia, with the second highest hydropower installed capacity, experienced the most significant losses in both SPI-3 and SPI-6 long drought events. Interestingly, Aragon, despite having less hydropower capacity than Extremadura, lost more energy during SPI-6 prolonged drought event, further highlighting the complex interplay of factors influencing hydropower production.
This research confirms the findings of previous studies in Brazil, Portugal, and other European regions, demonstrating that drought significantly impacts hydropower generation in Spain(Sousa et al. 2019; Cuartas et al., 2022; Młyński et al., 2024). It contributes to the growing body of knowledge on the nexus between climate change, drought, and renewable energy. The use of the SPI provides a standardized and scientifically rigorous approach for assessing drought severity and its impact on hydropower production. The focus on Spain, a country particularly susceptible to climate change, adds to the relevance and applicability of the research.
In sum, this study stresses the urgent need to develop adaptive strategies to reduce the impact of drought on hydropower production. Diversifying energy sources and improving water management practices are essential steps toward ensuring energy security in a changing climate.

S.no.	**Autonomous Community**	**Longest drought event between 2015-2023.(SPI-3)**	**Total Hydropower Generation loss due to longest drought event between 2015-2023(SPI-3)**	**Longest drought event between 2015-2023.(SPI-6)**	**Total Hydropower Generation loss due to longest drought event between 2015-2023(SPI-6)**
1	**Castilla y León**	July 2016-June 2017	729274.47MWH	Sep 2016-Feb 2018	3569228.94 MWH
2	**Galicia**	Aug 2016-June2017	2763315.9 MWH	Oct 2016-Feb 2018	4154568.16 MWH

3	**Extremadura**	Dec 2018-Dec2019	706733.34 MWH	Dec 2018-March 2020	950134.83 MWH
4	**Cataluña**	May 2017-Jan 2018	369197.58 MWH	Dec 2020-July2022	765356.05 MWH
5	**Aragón**	Jan 2019-Aug 2019	17643.51 MWH	Sep 2022-Sep2023	1149615.035 MWH
6	**Comunidad Foral de Navarra**	June 2016-Feb 2017	115689.87 MWH	May 2022-Sep 2023	285083.13 MWH

Table 5 : Overview of Regional Hydropower Losses During Extended Drought Periods in Spain.

Chapter 5: Conclusion and Recommendations

Climate change poses a significant threat to humanity, with its repercussions evident in our daily lives. Extreme weather events such as incessant rain, prolonged droughts, heatwaves, and wildfires are becoming more frequent due to the emission of greenhouse gases (Perkins-Kirkpatrick & Lewis, 2020 ; Roca Villanueva et al., n.d.). In response, nations are striving to reduce their emissions to meet the targets outlined in the Paris Agreement (King & van den Bergh, 2019). The energy sector, a major contributor to carbon emissions, is undergoing a transformation as countries increasingly adopt renewable energy sources like solar, wind, and hydropower.

Hydropower stands out as a flexible and reliable renewable energy source. Developing countries, in particular, are investing in hydropower projects due to their vast untapped potential (Robinson, 1997). However, hydropower generation is inherently reliant on water availability, making it susceptible to the impacts of droughts and climate change. Previous studies have highlighted the adverse effects of drought on hydropower generation in countries like Brazil, Portugal, and the USA. However, Spain, a nation heavily reliant on hydropower to meet its energy demands and situated in the climate-vulnerable Mediterranean region, has not yet been the focus of such research(Sousa et al. 2019; Cuartas et al., 2022; Młyński et al., 2024). This gap in knowledge underscores the importance of investigating the specific impact of drought on Spain's hydropower sector.

To investigate the impact of drought on hydropower generation in Spain, we utilized the Standardized Precipitation Index (SPI), a widely recognized drought indicator that quantifies precipitation deficits. Our analysis focused on the period from 2015 to 2023, for which comprehensive hydropower generation data was available.

Our findings revealed a strong correlation between SPI-3 and SPI-6 (representing 3-month and 6-month precipitation deficits) and monthly hydropower generation across all of Spain's autonomous communities. This indicates that short- to medium-term drought conditions exert a substantial influence on the country's hydropower output.

To further understand the impact of severe drought events, we identified the longest continuous periods where SPI-3 and SPI-6 were at or below zero, signifying drought conditions and analysed hydropower generation during the longest time period drought. We then conducted a focused analysis on six regions with substantial hydropower installed capacity: Galicia, Extremadura, Navarra, Castilla y León, Catalonia, and Aragon. This targeted approach allows for a more nuanced understanding of the specific vulnerabilities and resilience of these key hydropower-producing regions in the face of drought. Our analysis unequivocally demonstrates that all six regions experienced a significant decline in hydropower generation due to drought conditions. Furthermore, we observed a substantial loss of hydropower output during prolonged drought periods, highlighting the critical need for proactive measures to mitigate the impacts of drought on Spain's hydropower sector.

In this study, we employed the Standardized Precipitation Index (SPI) s a drought indicator, which primarily focuses on precipitation deficits to quantify drought severity. However, it is important to recognize that the availability of water in reservoirs is influenced by multiple factors beyond precipitation, including temperature, actual evapotranspiration, and potential evapotranspiration.

The CRU precipitation data utilized in this study is generated by converting precipitation station data into a gridded format at a 0.25-degree spatial resolution through interpolation techniques (Peterson & Michael, 2008). However, previous research has indicated that this interpolation process can introduce biases, particularly in regions with sparse station coverage.

Due to limitations in the availability of hydropower generation data, our analysis was conducted at a regional scale using monthly averages. However, to ensure adequate energy supply during drought periods, a more granular analysis using weekly or even daily hydropower generation data is crucial(Młyński et al., 2024).. Such high-resolution data would enable a more precise assessment of the immediate impacts of drought on hydropower production and facilitate the development of more effective and responsive drought mitigation strategies.

The Mediterranean region, including Spain, is particularly vulnerable to climate change impacts like drought and heatwaves(Tuel & Eltahir, 2020). This region also heavily relies on hydropower. Therefore, it is crucial to conduct more detailed research tailored to this specific context. Furthermore it is important to analyse hydropower generation data at a weekly or even daily level to understand the short-term impacts of drought and enable proactive responses. Utilization of drought indices like the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates temperature data, to provide a more comprehensive assessment of drought's effects on water availability and hydropower(Mishra & Singh, n.d).

Leverage the strong correlation between SPI and hydropower generation to establish early warning systems that predict potential hydropower shortages. These systems could inform water resource management decisions, energy planning, and demand-side management strategies to ensure grid stability during drought events. For instance, if the SPI indicates an impending drought, water managers can prioritize water allocations for essential uses like drinking water and agriculture, while energy planners can implement load shedding or demand response programs to reduce electricity consumption.

To overcome the limitations and potential biases associated with CRU precipitation data, especially in regions with sparse station coverage, consider using multiple sources of precipitation data. This could include radar-based precipitation estimates, satellite-derived precipitation products, or data from denser observational networks(Germann et al., 2006).

Integrating precipitation data with other hydrological variables, such as evapotranspiration, runoff, and soil moisture, can enhance the accuracy and comprehensiveness of drought models(Mishra & Singh, n.d). This allows for a more holistic understanding of the water cycle and its interactions with hydropower generation. By combining precipitation data with information on other hydrological processes, researchers can develop more robust and reliable drought assessments.

5.3 Conclusion

This case study significantly addresses a pressing research gap by meticulously examining the relationship between drought, measured through the Standardized Precipitation Index (SPI), and hydropower generation in Spain. The findings underscore the necessity of adopting proactive strategies to mitigate the impacts of drought on this renewable energy source.

Diversification of the renewable energy mix emerges as a vital measure, reducing reliance on hydropower during periods of water scarcity and ensuring a consistent supply of clean energy.

Additionally, upgrading existing hydropower generation capacities and implementing technological advancements can enhance their efficiency and resilience to drought conditions.

These insights hold immense value for policymakers, enabling them to formulate effective water management strategies and tailor responses based on the specific vulnerabilities and drought thresholds of each autonomous community. This will contribute to building a more resilient hydropower sector and ensuring a sustainable energy future for Spain.

This research lays a robust foundation for future investigations into the complex interplay between drought and hydropower generation. Further studies could delve deeper into the weekly or even daily variations in this relationship, considering plant-specific parameters such as reservoir size and local topography. This granular analysis would facilitate even more precise assessments of drought impacts and inform targeted adaptations in the hydropower sector.

By proactively addressing the challenges posed by drought, Spain can strengthen its hydropower infrastructure and harness its full potential while navigating an increasingly unpredictable climate. This research not only contributes to the advancement of scientific knowledge but also paves the way for informed decision-making that will foster a sustainable and secure energy landscape in the years to come.

Appendices

Appendix A :Approved Draft Proposal

FT MScBA - Draft Proposal – Thesis Project

Attention: you will have to use at least **10 academic sources** (from scientific journals) for this proposal. You will mainly use those for the description of the Research Problem and Theoretical Relevance.

Name	**Ashutosh Bhardwaj**
Research Problem	**Topic** Impact of drought on hydropower generation: A case study of Spain **Introduction** Hydropower is a major source of renewable energy, but its generation is highly dependent on water availability. Climate change is causing more frequent and severe droughts in many regions, including Spain, which is a significant producer of hydropower. This research aims to investigate how droughts have affected hydropower generation in Spain and to develop a model for predicting future impacts. **Background** Numerous studies have investigated the impact of droughts on hydropower generation in various regions. For instance, Luz Adriana et al. (2022) examined the effects of the 2014/2015 drought on hydropower in Brazil, while Sean Turner et al. (2022) analyzed the impacts of the 2021 droughts on US hydropower generation. However, to our knowledge, no research has specifically focused on the impact of droughts on hydropower generation in Spain. -

Aims and Objectives	To understand this vulnerability, we developed a simple linear regression model to predict hydropower generation at a monthly scale. This research aims to provide insights into the vulnerability of hydropower in Spain to drought conditions. The findings can be valuable for policymakers and energy providers as they develop strategies for a more resilient and sustainable electricity grid.
Research Question	How has drought historically impacted hydropower generation in Spain? And what is the relationship between hydropower generation and precipitation at different timescales (e.g., monthly, quarterly, annually)?

Theoretical Relevance	This research holds both theoretical and practical relevance. **Theoretical Relevance:** This study contributes to the academic understanding of the relationship between drought and hydropower generation. It aims to develop a statistical model to predict the impact of droughts on hydropower generation in Spain, which can be applied to other regions with similar climatic conditions. This will enhance our knowledge of the vulnerabilities of renewable energy sources to climate change and inform the development of more accurate energy models.

	Practical Relevance: The findings of this research have significant practical implications for policymakers, energy providers, and stakeholders in the energy sector. By understanding the vulnerability of hydropower to droughts, they can develop strategies to mitigate the impacts of droughts on electricity generation. This could involve diversifying energy sources, improving water management practices, or investing in more droughtresistant hydropower technologies. Ultimately, this research can contribute to a more resilient and sustainable energy system in Spain.

Research Design, Methodology and Data Sources	The overall strategy to address the research questions involves analysing the historical impact of droughts on hydropower generation in Spain at a monthly scale. This will be achieved by examining monthly precipitation data from the Climate Research Unit (CRU) and observed hydropower generation data from Red Eléctrica de España (REE). The research will investigate the impact of meteorological drought on hydropower generation in the region. Drought periods will be identified using the Standardized Precipitation Index (SPI), a widely used metric that quantifies the severity of drought by standardizing precipitation anomalies. The SPI is particularly well-suited for this study due to its ability to assess drought conditions across the entire country. To examine the relationship between drought and hydropower generation, a simple linear regression model will be employed, with antecedent precipitation as the independent variable and monthly hydropower generation as the dependent variable. A multi-linear regression model can be used to explore the influence of other relevant factors if needed. To ensure the robustness of the results, a sensitivity analysis will be conducted, evaluating the impact of different drought thresholds and time scales. Comparative analysis will be performed to contrast hydropower generation during drought periods (defined as SPI below -1.0) with generation during non-drought periods. This will provide valuable insights into the extent to which drought affects hydropower production.

	The data used in this research will be monthly gridded precipitation data from CRU and monthly hydropower generation data from REE. The CRU dataset provides a comprehensive record of precipitation levels across Spain, while the REE dataset includes information on both reservoir and run-of-river hydropower generation.

References Used in the Proposal	• Kumar, M. N., Murthy, S. C., Sai, M. S., & Roy, P. S. (2009, September). On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. *METEOROLOGICAL APPLICATIONS, 16*(3). doi:10.1002/met.136 • Bonnin, J. (2022, October 12). What's a Dispatchable Energy Credit and What Does It Accomplish? Retrieved from pcienergysolutions: https://www.pcienergysolutions.com/2022/10/12/whats-a-dispatchableenergy-credit-and what-does-it-accomplish/ • Batool, S., Guo, J., Wang, Y., Soomro, S. e.-h., & Tayyab, M. (2024). How does the climate change efect on hydropower potential,. *Applied Water Science*. doi:10.1007/s13201-023-02070-6 • Cuartas, L. A., Cunha, A. P. M. D. A., Alves, J. A., Parra, L. M. P., DeusdaráLeal, K., Costa, L. C. O., ... & Marengo, J. A. (2022). Recent hydrological droughts in Brazil and their impact on hydropower generation. *Water*, *14*(4), 601. • Giorgi, F., & Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change, 63*(2-3), 90-104. doi:https://doi.org/10.1016/j.gloplacha.2007.09.005

	• Gleick, P. (2017). Impacts of California's five-year (2012-2016) drought on hydroelectricity generation. *Pacific Institute.* • Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2013). Updated highresolution grids of monthly climatic observations – the CRU TS3.10 Dataset. doi: https://doi.org/10.1002/joc.3711 • Lionello, P., Abrantes , F., Gacic, M., Planton, S., & Trigo, R. (2014, August 17). The climate of the Mediterranean region: research progress. *Reg Environ Change, 14*. doi:10.1007/s10113-014-0666-0 • *red electrica*. (2024, March 21). Retrieved from In 2023, Spain implemented the largest installed solar photovoltaic power system in its history: https://www.ree.es/en/press-office/news/press-release/2024/03/in-2023spaim-implemented-the-largest-installed-solar-photovoltaic-power-system-inits-history#:~:text=In%20Spain's%20national%20ranking%2C%20wind,%2C%20and%20hydropower%20(13.6%25). • Ronningen, F. (2024, November 8). *Spain's renewable power generation to top 50% in 2023*. Retrieved from Rystad Energy: https://www.rystadenergy.com/news/spain-s-renewable-power-generation-totop-50-in-2023-surpassing-european-neighbor

- Turner, S., Voisin, N., & Nelson, K. (2022). Revised monthly energy generation estimates for 1,500 hydroelectric power plants in the United States. *Scientific Data, 9*. doi:https://doi.org/10.1038/s41597-022-01748-x

Project Planning – this needs to be filled in as well!

Please take your time for this and envision the upcoming months: what are the different steps that I need to take to write a chapter, how many times do I want to send a document to my supervisor for revision, how long does it take before I have gathered enough interviews or respondents? Etc. Think in weeks, not in months!

Activity			Extra Info
Date			
1-5June	Finalizing the draft proposal		
7-14 June	Adjust the feedback from the draft proposal		Feedback
16-28 June	Data collection and interpretation		Feedback
1-7 July	Data modelling	Will make changes according to feedback.	

8-12 July	**Writing Introduction**	**Will make changes according to feedback.**	
14-24 July	**Writing thesis: Result and funding**		**Feedback**
25-31 July	**Writing thesis: Discussion and conclusion**	**Adjust result and findings to feedback of supervisor**	
4-10 August	**Finalize recommendation and outcomes**		**Feedback**
11-15 August	**Write the executive summary and finalize the outcome**	**Adjust recommendation and outcomes to feedback of supervisor**	
16-23 August	**Implement the last feedback of the supervisors**	**Finalize thesis**	
24-28 August	**Final adjustment and handing in**		

Feedback Track Coordinator – to be filled in by your Track Coordinator

General comments	Yes a nice topic, worth further investigation
Is it achievable?	Yes.
Specific issues that you should address	None.

Appendix B : Data Analysis, Cleaning & Processing

This script was used to find the longest drought event for each autonomous community a hydropower energy was generated in those event.

```
# Replace 'your_file.xlsx' with the actual filename
df = pd.read_excel('/content/drive/MyDrive/final file of spi&hydro/cataluna.xlsx')

pd.set_option('display.max_rows', None)
pd.set_option('display.max_columns', None)

# Convert `time` column to datetime
df['time'] = pd.to_datetime(df['time'])

# Filter data where `SPI_3` is less than 0
drought_periods = df[df['SPI_6'] < 0].copy()

# Created a new column `drought_group` to group consecutive rows where `SPI_3` is less than 0
drought_periods['drought_group'] = drought_periods['time'].diff().dt.days.gt(31).cumsum()

# Group by `drought_group` and count
drought_duration = drought_periods.groupby('drought_group')['time'].count()

#  maximum value
longest_drought_group = drought_duration.idxmax()
```

ps://colab.research.google.com/drive/1F4muk6swaSRR15MFV7Z5pon55wRIYs5T#scrollTo=qrud4BWhPkOP&printMod

/08/2024, 14:47 Data Analysis Script - Colab

```
# Filter the data where `drought_group` equals to the `drought_group` value
longest_drought = drought_periods[drought_periods['drought_group'] == longest_drought_group]

# Sum of `generation_MWH` column for the filtered data
total_generation = longest_drought['generation_MWH'].sum()

#  minimum and maximum of the `time` column for the filtered data
drought_start = longest_drought['time'].min()
drought_end = longest_drought['time'].max()

# Print the results
print(f"Longest drought period: {drought_start} to {drought_end}")
print(f"Total hydropower generation during the drought: {total_generation} MWh")
```

```
Longest drought period: 2020-12-01 00:00:00 to 2022-07-01 00:00:00
Total hydropower generation during the drought: 5584059.956 MWh
```

This script was used to findout the best SPI for each region through pearson correlation.

```
# Directory containing your Excel files
data_dir = '/content/drive/MyDrive/final file of spi&hydro'

# List of all Excel files in the directory
files = [f for f in os.listdir(data_dir) if f.endswith('.xlsx')]

# Initialize a dictionary to store results
results = {}

# Iterate through each file
for file in files:
    # Load data
    data = pd.read_excel(os.path.join(data_dir, file))

    # Calculate correlations for each SPI
    correlations = data[['SPI_1', 'SPI_3', 'SPI_6', 'SPI_12', 'SPI_24']].corrwith(data['generation_MWH'])

    # Identify the SPI with the highest absolute correlation
    best_spi = correlations.abs().idxmax()
    best_corr = correlations[best_spi]

    # Store results
    results[file] = {'best_spi': best_spi, 'correlation': best_corr}

# Create a DataFrame from the results dictionary
results_df = pd.DataFrame.from_dict(results, orient='index')

# Visualize correlations using a heatmap
plt.figure(figsize=(10, 6))
sns.heatmap(results_df.pivot_table(index='best_spi', columns=results_df.index, values='correlation'), annot=True, cmap='coolwarm')
plt.title('Correlation between Best SPI and Hydropower Generation for Each Region')
plt.show()
```

This script is used to calculate SPI-1,3,6,12,24.

```
from standard_precip.spi import SPI
from standard_precip.utils import plot_index

rainfall_data = pd.read_excel('/content/monthly_precipitation_vasco.xlsx')

spi = SPI()

spi_1 = spi.calculate(
    rainfall_data,
    'time',
    'precipitation',
    freq="M",
    scale=1,
    fit_type="lmom",
    dist_type="gam"
)


spi_3 = spi.calculate(
    rainfall_data,
    'time',
    'precipitation',
    freq="M",
    scale=3,
    fit_type="lmom",
    dist_type="gam"
)
spi_6 = spi.calculate(
    rainfall_data,
    'time',
    'precipitation',
    freq="M",
    scale=6,
    fit_type="lmom",
    dist_type="gam"
)
spi_12 = spi.calculate(
    rainfall_data,
    'time',
    'precipitation',
    freq="M",
    scale=12,
    fit_type="lmom",
    dist_type="gam"
)
spi_24 = spi.calculate(
    rainfall_data,
    'time',
    'precipitation',
    freq="M",
    scale=24,
    fit_type="lmom",
    dist_type="gam"
```

In this script we plot a graph of precipitation data over last 43 years.

```
# Aligned the CRS system of shape and netcdf file.
data = data.rio.write_crs(4326)
#checking the CRS again

print(data.rio.crs)
print(spain.crs)
data.rio.set_spatial_dims(x_dim="lon", y_dim="lat")


# Clipping the NetCDF data to the regions.
clipped_dataset = data.rio.clip(spain.geometry, spain.crs)#use ''region_shape'' for  seeing information related to each autonomous comm
print(data['time'])

# Select the variable  to analyze
precipitation_data = clipped_dataset['pre']

# Calculating total precipitation over the time period and for each grid cell
total_precipitation_time = precipitation_data.mean(dim='time') #temporal mean
total_precipitation_grid = precipitation_data.mean(dim=['lat', 'lon']) #spatial mean

# Plotting total precipitation over time
plt.figure(figsize=(10, 6))
total_precipitation_grid.plot()
plt.title(f'Total Precipitation Over Time in {region_name}')# use ''region_name'' for finding for a specific region
plt.xlabel('Time')
plt.ylabel('Total Precipitation (mm)')
plt.show()
```

Appendix C : Hydropower Generation and SPI related data of each Autonomous Community.

hydropower%20and
%20SPI%20values%2

georef-spain-comunidad-autonoma-millesime.shp

Appendix D: Drought and Hydropower Generation Analysis of Autonomous Communities.

SPI Graph.pdf

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