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A comparitive analysis of hydropower production during extreme weather events. The case study of three European countries: Spain, Sweden and Slovenia

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Abstract

Water and energy are intricately connected, for example, water from a river is directly used to move the turbines that generate electricity in a hydropower plant. This is the reason why hydropower plants are vulnerable to extreme climate events, like droughts and floods, that affect the available water in the river. When it comes to renewable energy in Europe, electricity produced by hydropower is one of the commonly used sources, and hence there is the need to improve our understanding of these extreme weather conditions that affect the water availability.

The aim of the study is to analyse the impact of extreme events like low and high discharge events on electricity production in three hydropower plants in Slovenia, Spain, and Sweden. The power plant selected in Slovenia is the Mariborski Otok hydropower plant located in the Drava River, whereas the power plants selected in Spain and Sweden are the Alcantara hydropower plant located in the Tagus River and Stornorrfors hydropower plant located in the Ume älv river. Global Flood Awareness System (GLoFAS) is used to provide near real time river discharge data or the total water inflow data for the hydropower plants. The extreme events like low and high discharge events are selected based on this river discharge data and the electricity production from the hydropower plants is analysed.

Results suggest that out of the three case studies, the hydropower plant in Spain is most vulnerable to extreme weather events and the hydropower plant in Sweden deals with the low and high discharge events better and is not affected much by these weather extremes. The hydropower plant in Slovenia also deals with extremes better but not to the degree that Sweden does. These results indicate that, in the future, dams should be built in temperate climates because extreme climate events have less impact on the hydropower production on those climates.

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1.Introduction

The European Commission proposed the European Green Deal which aims for a climate neutral Europe by 2050 (Gøtske & Victoria, 2021). This envisioned goal can be accomplished by using renewable sources of energy like hydropower, wind and solar (Gøtske & Victoria, 2021). Of the three, hydropower has been an important renewable energy for decades as it has various benefits that wind and solar do not have. For instance, It has reached levels of technological maturity (Kougias et al., 2019), it releases less greenhouse gas emissions per unit of energy produced, it can be adapted as per the demand of the consumer, and it can store a vast amount of electricity with the help of reservoirs at minimal cost (Luis et al., 2013). For over a century, hydropower has supplied electricity and storage facilities to central power systems and mechanical energy since ancient times for the development of civilization (Kougias et al., 2019).

During the first half of last century in Europe, hydropower has substantially contributed to the industrial development and welfare making it a significant renewable source of energy in the region (Hydropower Energy, n.d.). In 2020, Europe had an installed hydropower capacity of 254 GW and 676 TWh was generated by hydropower in the complete hydrological year. Also, the hydropower capacity rose by 3 GW across the European region in 2020 (IHA, 2020).

The most significant aspect in hydropower generation is the run-off, as it is directly used in moving the turbines of hydropower plants (Khaniya et al., 2020). The run-off and river discharge depend on different parameters like precipitation or groundwater flows which vary daily and monthly (Kaunda et al., 2012a). Thus, it is very likely that hydropower would be impacted by climate change in varying degrees due to changes in precipitation, temperature, wind speed and solar irradiation that affect the run-off of rivers (Yalew et al., 2020).

It becomes very important to understand how climate change would affect the availability of the water for hydropower. A proxy of those scenarios is to study how extreme events of the past, like floods and droughts have affected hydropower's production (Arriagada et al., 2019). Research today has mainly focused on estimating hydropower potential or determining the ideal locations for hydropower projects without taking into considering the variability and historical trends of the water resources (Arriagada et al., 2019). Hence, a very important question that needs a good understanding is what the impact of extreme events on the hydropower development would be (Khaniya et al., 2020).

The impact of extreme events like droughts and floods on the electricity production by these three power plants is analysed in this study.

The countries that would be looked upon in this study are Spain, Sweden, and Slovenia. All the three countries are a part of the European Union and represent different climatic regions. Sweden is the country most dependent on hydropower for their electricity generation (45%), whereas Slovenia is less dependent on hydropower with Spain being the least because of the weather conditions. The hydropower plant selected in Slovenia called Mariborski Otok hydropower plant located in the Drava River. The Spanish hydropower plant is the Alcantara hydropower plant located in the Tagus River. The Swedish hydropower plant is the Stornorrfors hydropower plant located in the Ume älv river.

For this study, there is the need to estimate the amount of water flowing in a particular river basin. However, to obtain rivers’ discharge data is a huge challenge due to lack of observations in space and time. This gap is bridged by the GLoFAS-ERA5 reanalysis data as it provides near real time river discharge (Harrigan et al., 2020). The GLoFAS-ERA5 reanalysis data is a climate dataset, which includes the discharges of several European rivers.

Below are a few studies which have performed research on climate variability affecting the available water and hydropower generation.

1.1 Previous Research

(Lehner et al., 2005) used a water model called WaterGAP to analyze the effects of global change on hydropower in Europe. The WaterGAP model provides with the discharge calculations based on current and future climate and water use. The results show that Scandinavia and northern Russia show an increase in their developed hydropower potential of 15–30%. The region’s most prone to a decrease in developed hydropower potential are Portugal and Spain in southwestern Europe, as well as Ukraine, Bulgaria, and Turkey in the southeast, with decreases of 20–50%. For the whole of Europe, the gross hydropower potential is estimated to decline by about 6% by the 2070s, while the developed hydropower potential shows a decrease of 7–12%.

(van Vliet et al., 2016) used a multi-model ensemble to show the climate change impacts on global hydropower and cooling water discharge potential. Three hydrological models were used (PCR-GLOBWB, VIC-RBM and WaterGAP2) to produce streamflow and water temperature simulations and they are forced with bias-corrected climate data under RCP 2.6 and RCP 8.5. The results show that gross hydropower potential and cooling water discharge potential will increase in Central Africa and India whereas its decrease is expected in the USA and Europe.

(Wagner et al., 2017) analysed the impacts of climate change on the water availability in the Alpine region and the electricity production by the hydropower power plants till the year 2050. Four regional climate model simulations are used from the ENSEMBLES project to provide temperature and precipitation data for the hydrological model. The results showed that the average annual electricity generation of the hydropower plants for the period 2031–2050 compared to 1961–1990 for the whole Alpine region is estimated to decrease slightly for all climate scenarios considered, whereas in Austria two scenarios result in slight increase and other two in slight increase.

2.Research Aim and Questions

The main objective of the study is to understand how much the electricity generation of the hydropower plants in Spain, Sweden and Slovenia is affected during the extreme events that occurred during a certain period of time. Extreme event like floods and droughts will be identified among different years in these regions and the functioning of these power plants during these periods will be understood.

The main research question can be formulated as:

How do different discharge extremes affect the hydropower electricity production in three different climatic regions in Europe?

Sub-questions are:

1. What is the electricity production during a dry and wet period of representative hydropower plants in Spain, Sweden, and Slovenia?
2. Do low discharge events affect hydropower electricity output of the plants?
3. What are the differences among the three climatic regions in Europe?

3. System Analysis

This chapter describes the countries and the hydropower plants investigated in the study.

3.1. Hydropower plants

Hydropower utilises the innate energy of moving water to generate electricity. This energy is harvested by directing the water through different types of turbines, which converts the energy of the water to mechanical energy (to be later transformed into electricity with the use of a generator). The hydropower plants use different types of turbines like Kaplan, Francis, Cross flow, and Pelton each functioning at different efficiencies for the hydroelectric generation (Elbatran et al., 2015).

The construction of hydropower plants vary depending on the use of the powerplant and the geographic location of the plant (Rosen & Assad, 2021). The most common way to classify the hydropower plants are based on the levels of water impoundment. The hydropower plants are classified into three types based on the way they divert the river's flow which are dammed hydropower plants, run-of-river hydropower plant and in-conduit hydropower plants (Vaca-Jiménez et al., 2019). Dammed hydropower plants and run-of-river hydropower plants are described below.

3.1.1. Dammed hydropower plants

The dammed hydropower plant uses a dam to stop the river flow, creating a reservoir that stores water. This storage can be used to deal with water availability fluctuations of the river, as water can be released whenever required. Dammed hydropower plants are reliable as the reservoirs can be used to regulate the flow into the powerplant, thus controlling the electricity produced. Hence, dammed hydropower plants can be used for supplying both base and peak loads (Kumar et al., 2012).

Moreover, dammed hydropower plants can use reservoirs as buffers to produce electricity constantly during extreme events. Hence, they can delay the effect of the extreme event, whereas other renewables like solar and wind have an immediate effect on the electricity production.

The powerhouse which consists of turbines and generators are usually situated at the dam toe or sometimes downstream connected to the reservoir. Figure 1 shows an example of a dammed hydropower plant.

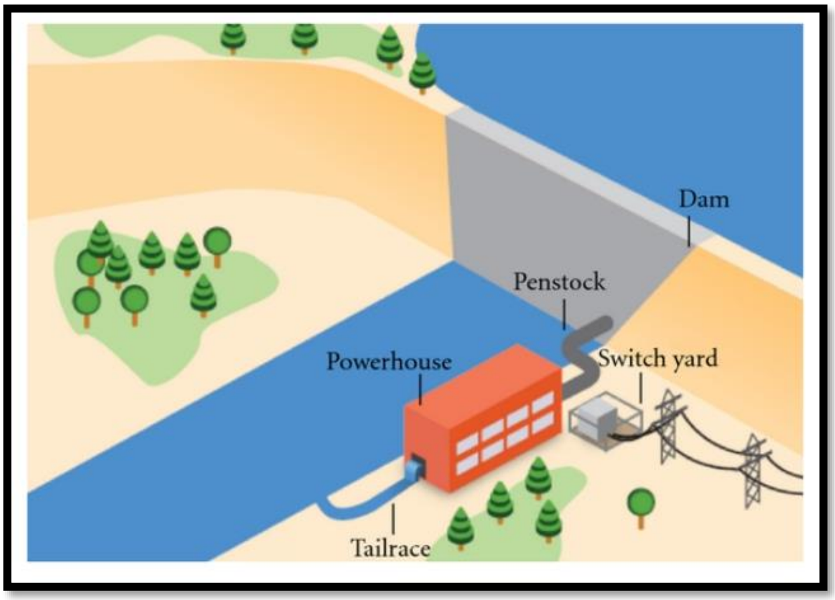


Figure1: Pictorial representation of a Dammed Hydropower plant(Kumar et al., 2012)

3.1.2. Run-of-river hydropower plants

Run-of-river hydropower plants use the flow of the river to generate electricity without any substantial impoundment. They deviate the river flow with the help of small weirs that create small ponds, called pondages, before the weirs. Thus, they have very small storage when compared to dammed hydropower plants. These hydropower plants are more vulnerable to floods and droughts than the dammed hydropower plants as the water intake depends on the flow of the rivers, which is prone to seasonal, monthly or even daily variations.(Kumar et al., 2012). Figure 2 shows an example of a run-of-river hydropower plant.

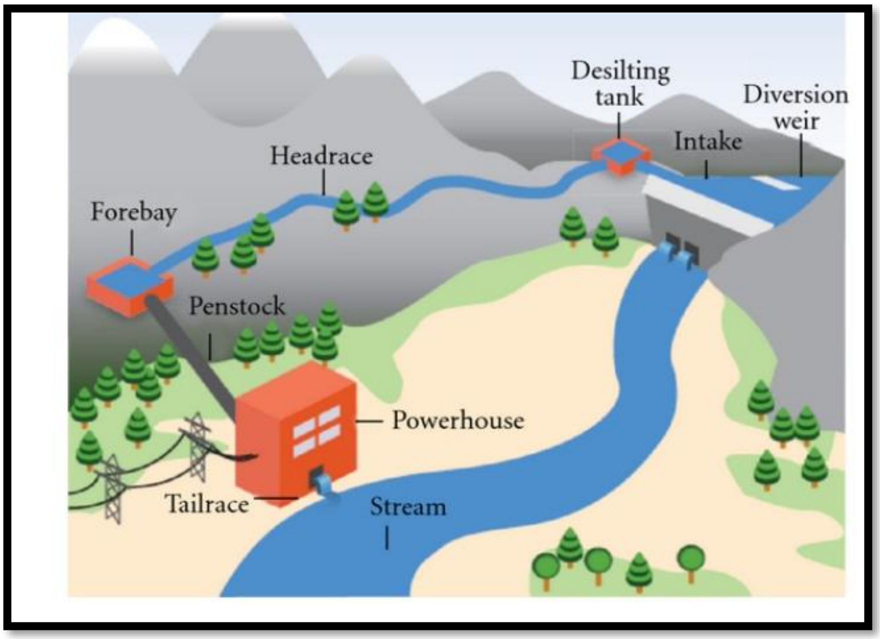


Figure 2: Pictorial representation of a run-of-river hydropower plant(Kumar et al., 2012)

3.2. Hydropower in Europe

In 2020, Europe generated 676 TWh of electricity by hydropower in the complete hydrological year contributing to 13% of the total electricity share (IHA, 2020). The countries investigated in Europe for the study are Spain, Sweden, and Slovenia. They represent different climatic regions in Europe.

3.2.1. Hydropower in Spain

Spain uses different type of energy sources to produce electricity. Figure 3 shows that in 2020 Spain has produced 12.1% of electricity from hydropower. Overall, 34.43% of the electricity is produced by fossil fuels of which 26.01% is by natural gas, 6.03% by oil, and 2.39% by coal. The rest of the electricity is produced by other renewables:22.11% from nuclear, 20.91% from wind,7.87% from solar and 2.59% from other renewables (Ritchie & Roser, 2020).

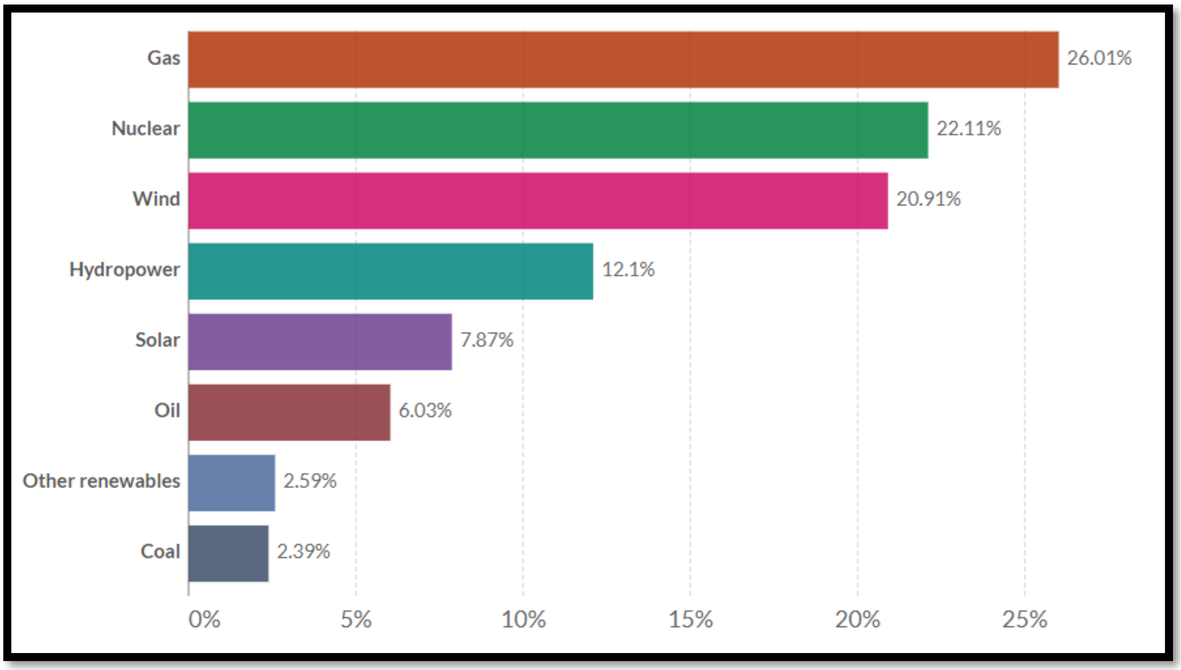


Figure 3: Share of hydropower among other sources of electricity in Spain (Ritchie & Roser, 2020)

In 2020, Spain produced 31.9 TWh of electricity through hydropower (Ritchie & Roser, 2020). The electricity produced by hydropower was higher than the electricity produced by solar but lower than electricity produced by wind, nuclear and gas. The electricity produced by hydropower in Spain has declined from 42.3 TWh in 2010 to 31.9 TWh in 2020. The total installed capacity of hydropower in 2020 was 20409 MW (IHA, 2020). In Spain the sporadic nature of rainfall and river flow cause periods of drought in summer seasons and seasonal variations (Berga, 2006).

Spain is a country with many reservoirs located across the whole region that are used for various purposes like electricity generation, irrigation for agriculture, and other human activities. Approximately 1150 reservoirs are situated in Spain which have a total storage capacity of $56*10^9$ m^3 and roughly 1270 dams are constructed across these reservoirs (Berga, 2006). In Europe, Spain has the largest number of dams, and it is ranked fourth in the world for the number of large dams located in the country. Table 1 shows the list of large hydropower plants, the river they are located and their installed capacity.

Table 1: Characteristics of major powerplants in Spain (Berga, 2006) (Thomas Bigorda, n.d.)

Hydropower Plant	River	Capacity (MW)
Aldeadávila	**Douro**	1243
Alcantara	**Tagus**	915
Villarino	**Tormes**	857
Muela	**Júcar**	630
Saucella	**Duero**	520
Cedillo	**Tagus**	500
Sallente	**Flamicell**	468
Mequinenza	**Ebro**	384

3.2.2. Alcantara Hydropower Plant

The Alcantara hydropower plant, also called the J.M Oriol hydropower plant is located in the Cáceres province of Spain (DBpedia, n.d.). It is situated in the western part of Spain on the Tagus River and is owned and operated by the Iberdrola company. The powerplant is operational since 1969. (Global Energy Observatory, n.d.). The Tagus River is 1009 km long and it is located at the centre of the Iberian Peninsula. 73% of the river is in Spain and the rest in Portugal (López-Moreno et al., 2009). The Alcantara hydropower plant is located near the border of Spain and Portugal, and it consist of a reservoir which has a storage capacity of $31.62*10^8$ m^3 making it the 2nd largest reservoir in Europe (López-Moreno et al., 2009). Among the dams situated in large reservoirs in Spain, the Alcantara dam is 130 meters in height and has the highest installed capacity (JRC Hydro-power database, 2019).

The Alcantara hydropower plant has an installed capacity of 915MW making it the second largest hydropower plant in Spain in terms of installed capacity (Global Energy Observatory, n.d.). The Alcantara dam is a buttress dam which regulates the flow of the Tagus River and has a hydraulic head of 130 m (López-Moreno et al., 2009). The power station is equipped with four Francis turbines for its electricity generation which aids in an annual generation of about 1850 GWh (*ENTSO-E Transparency Platform*, n.d.). Figure 4 shows the Alcantara Hydropower plant (J.M Oriol Hydropower plant).

Figure 4: Alcantara Hydropower plant (J.M Oriol Hydropower plant)(Google Maps, n.d.)

3.2.3. Hydropower in Sweden

Sweden mostly uses hydropower for their production of electricity. Figure 5 shows that in 2020, 44.56% of the electricity is produced by hydropower (Ritchie & Roser, 2020). Other renewables comprise of 22.81% of the electricity mix. Electricity from fossil fuels like oil, natural gas and coal is very terse: 1.76% from oil and a mere 0.23% and 0.2% from natural gas and coal respectively (Ritchie & Roser, 2020).

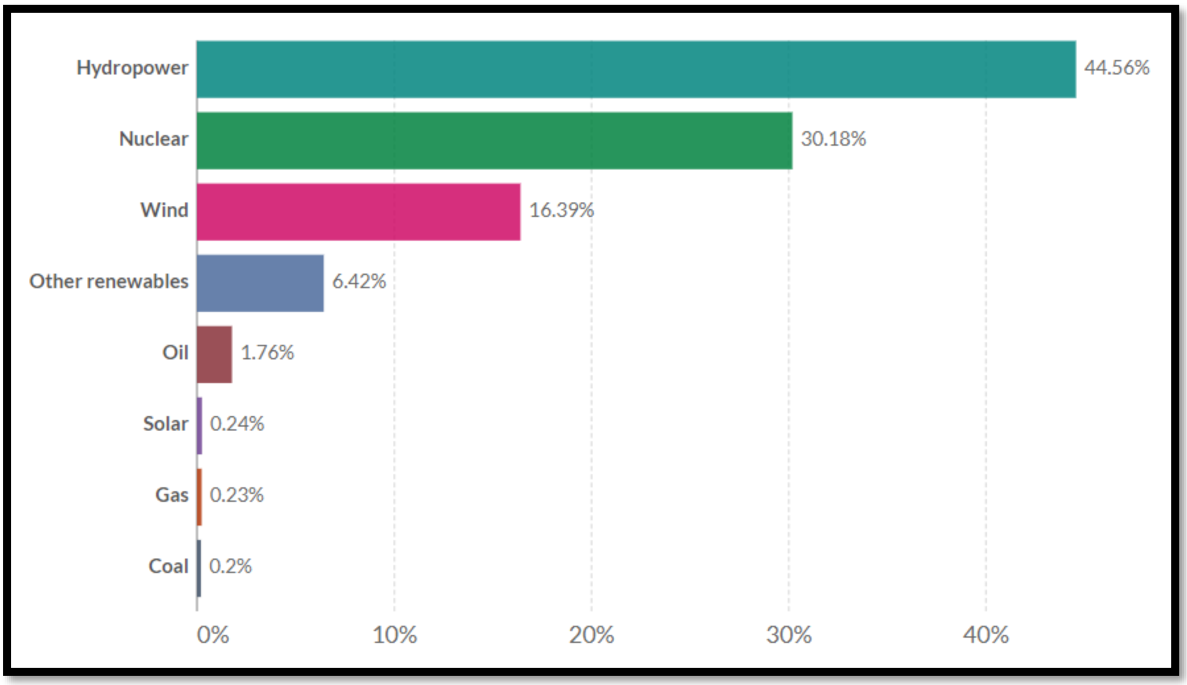


Figure 5: Share of hydropower among other sources of electricity in Sweden (Ritchie & Roser, 2020)

In 2020, Sweden produced 74.15 TWh of electricity through hydropower (Ritchie & Roser, 2020). Sweden's electricity mix is dominated by hydropower and is higher than all the other sources of energy which signify that hydropower plays a significant role in its electricity production. The electricity produced by hydropower in Sweden has increased from 66.4 TWh in 2010 to 74.15 TWh in 2020 (Ritchie & Roser, 2020). The total installed capacity of hydropower in 2020 was 16478 MW (IHA, 2020).

Sweden has around 2000 hydropower plants scattered across the whole country including smaller hydropower plants having a capacity of around 100 KW and larger hydropower plants with a capacity of more than 100 MW (Byman, 2015). The majority of the working hydropower plants in Sweden uses dams and reservoirs to produce electricity (Byman, 2015). Table 2 shows the largest hydropower plants in Sweden with their maximum installed capacity (Vattenfall, 2022).

Table 2: Characteristics of major powerplants in Sweden (Vattenfall, 2022)

Hydropower Plant	River Stream	Capacity (MW)
Harsprånget	Lule älv	818
Stornorrfors	Ume älv	599
Letsi	Lule älv	483
Messaure	Lule älv	463
Porjus	Lule älv	417
Ligga	Lule älv	342
Vietas	Lule älv	325
Ritsem	Lule älv	304
Porsi	Lule älv	282

3.2.4. Stornorrfors Hydropower Plant

Sweden completed the construction of Stornorrfors hydropower plant in 1958 (Vattenfall, 2022). It is situated in the northern part of Sweden by the Ume älv River and is owned and operated by the Vattenfall company (Vattenfall, 2022). The Ume älv River is a long river whose origin starts from the mountainous region near the Norwegian border and flows south easterly to the Bothnian Bay which is 450 km from the river origin (Rivinoja et al., 2001). There are a few hydropower plants along this river which are used for the generation of electricity out of which Stornorrfors is situated at the end of the river in Sweden. The Stornorrfors hydropower plant in Sweden when compared to other powerplants generates most electricity in Sweden

The Stornorrfors hydropower plant has an installed capacity of 599 MW making it the second largest hydropower plant in Sweden (HydroFlex, n.d.). The Stornorrfors dam is located 4km from the power station and has a hydraulic head of 75m (Vattenfall, 2022). The reservoir and the power station are attached with the help of a canal. The power station is equipped with four Francis turbines for its electricity generation which aids in an annual generation of about 2256 GWh (ENTSO-E Transparency Platform, n.d.). Figure 6 shows the Stornorrfors dam.

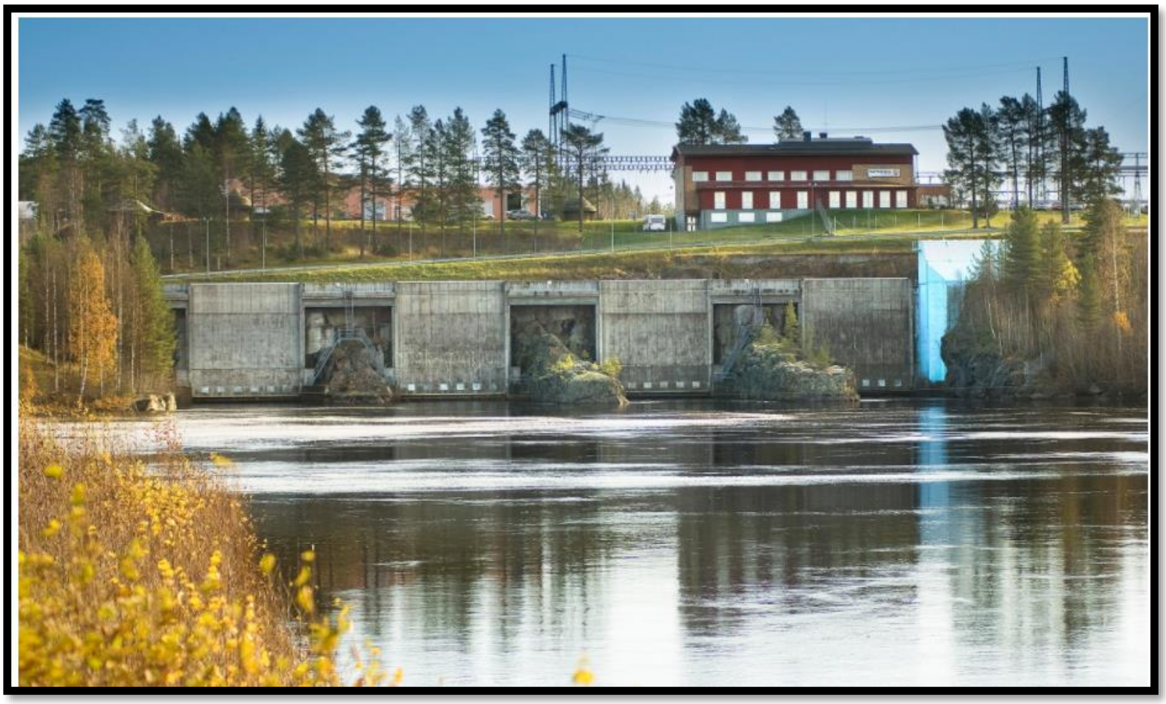


Figure 6: Stornorrfors dam (Vattenfall, 2022)

3.2.5. Hydropower in Slovenia

Slovenia uses different types of energy sources to produce electricity. It is seen from figure 7 that in 2020 Slovenia has produced 29.87% of electricity from hydropower energy. Nuclear, solar and wind comprise of 37.31%,1.71% and 0.04% of the electricity mix respectively. Electricity produced by fossil fuels like coal and natural gas is 25.81% and 3.52% respectively. Overall, 29.4% of the electricity is produced by fossil fuels and the rest by renewables and nuclear energy (Ritchie & Roser, 2020).

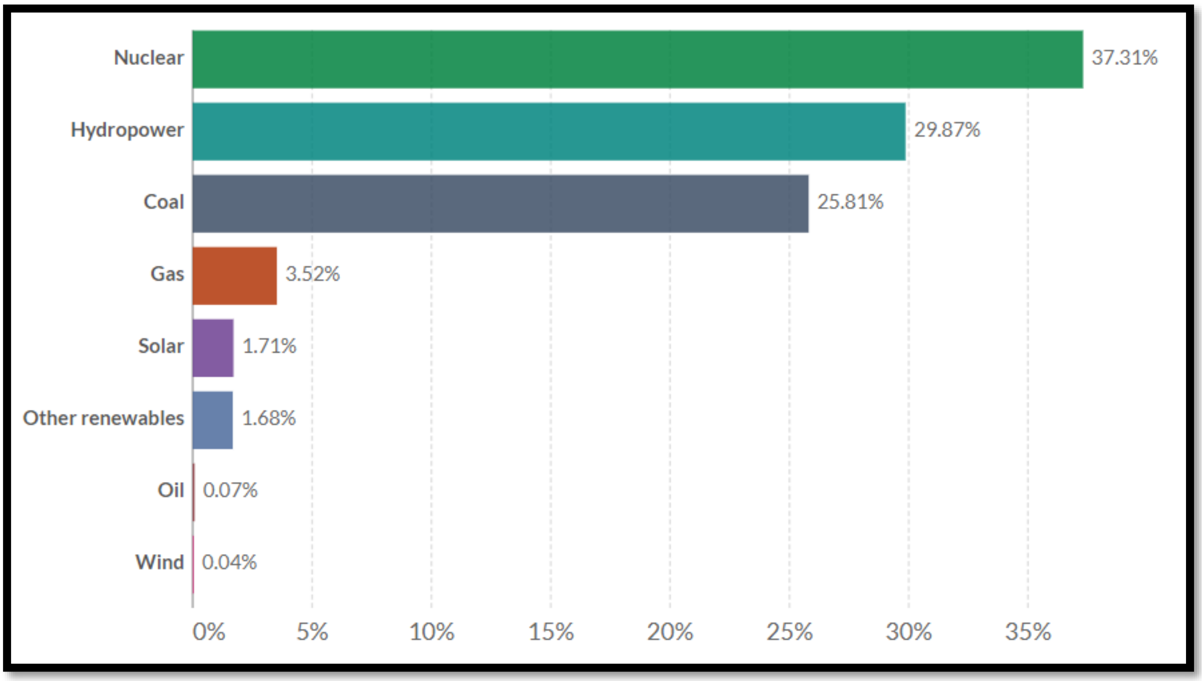


Figure 7: Share of hydropower among other sources of electricity in Slovenia (Ritchie & Roser, 2020)

In 2020, Slovenia produced 5.07 TWh of electricity through hydropower (Ritchie & Roser, 2020). The electricity produced by hydropower is higher than other renewables like solar and wind energy and more than electricity produced by fossil fuels. This indicates that hydropower is one of the important sources of electricity produced in Slovenia. The electricity produced by hydropower in Slovenia has increased from 4.52 TWh in 2010 to 5.07 TWh in 2020. The total installed capacity of hydropower in 2020 was 1524 MW (IHA, 2020).

Slovenia is a country rich in water resources with multiple lakes, rivers, and aquifers (Danielson & Leflaive, 2019). It has various rivers like Drava, Sava, Soča, Mur, and many more making it abundant in rivers with a length of 28,000 km of river network in the country (Danielson & Leflaive, 2019) (Negm et. al., 2020). The two longest rivers in Slovenia are the Drava River and Sava River which are a part of the Black Sea basin (Negm et. al., 2020). The hydropower plants in Slovenia use the natural flow of the rivers to produce electricity, making them run-of-river hydropower plants. Of all the rivers flowing through Slovenia, the Drava River is the most water abundant river with highest producing electricity from hydropower in Slovenia with eight large and four small hydropower plants (Dravske elektrarne Maribor, 2020). Table 3 shows the largest hydropower plants with their installed capacity on the Drava River.

Table 3: Characteristics of major powerplants in Slovenia (Dravske elektrarne Maribor, 2020)

Hydropower Plant	River Stream	Capacity (MW)
Zlatoličje	577	136
Formin	548	116
Ožbalt	305	73.2
Vuhred	297	72.3
Mariborski Otok	270	60
Fala	260	58
Vuzenica	247	55.6
Dravograd	142	26.2

3.2.6. Mariborski Otok Hydropower plant

Slovenia completed the construction of the Mariborski Otok hydropower plant in 1948(Dravske elektrarne Maribor, 2020). It is located in the north-eastern part of Slovenia by the Drava River and is owned and operated by the company Dravske Elektrarne Maribor (Dravske elektrarne Maribor, 2020). The Drava River is a 719 km long river whose origin starts from the southern alps in Italy and then flows through Austria, Slovenia, Croatia, and Hungary (Stunjek et al., 2020). There are various hydropower plants located along the Drava River out of which Mariborki Otok is situated after the Fala Hydropower plant in Slovenia (Dravske elektrarne Maribor, 2020). The Drava River in Slovenia is the most abundant river with highest producing electricity from hydropower in Slovenia (Dravske elektrarne Maribor, 2020). Some of the hydropower plants have reservoirs to store water, out of which the hydropower plant in Mariborksi Otok has the largest reservoir when compared to others.

Mariborksi Otok is the lowest lying run-of river hydropower plant on the Drava River chain in Slovenia. It utilizes a hydraulic head of 14.2m for its electricity production and has an installed capacity of 60 MW (Dravske elektrarne Maribor, 2020). It uses Kaplan turbines for its electricity generation and has an annual power production of 270 GWh (Dravske elektrarne Maribor, 2020). Figure 8 shows the Mariborksi Otok hydropower plant.

Figure 8: Mariborksi Otok Hydropower plant (Dravske elektrarne Maribor, 2020)

3.3. Description of the Climate model

Estimating the amount of water flowing in the rivers is an important factor for hydrologists to study the hydrology of different countries over the world and to monitor and access premature warnings of hydrological extremes such as floods and drought (Lavers et al., 2019).

There exist some numerical weather prediction models which help to calculate run-off in separate grid cells, but they do not have the ability to provide river discharge data at catchment scales. Hence, they have limited use in observing and predicting extreme events like floods and droughts (Harrigan et al., 2020).

To tackle this problem, a new model called the GloFAS-ERA5 was introduced which essentially combines the river routing scheme to a land surface model to produce river discharge data. The GloFAS-ERA5 produces river discharge forecasts at a daily time step (Harrigan et al., 2020). The river discharge in this model is developed by combining data from the ERA-5 land global reanalysis dataset, and the LISFLOOD hydrological river routing model (Hersbach et al., 2020) (Harrigan et al., 2020) giving river discharges as output. ERA-5 land data uses an enhanced land data assimilation system to replicate variables like soil, moisture, soil temperature, snow density and snow temperature. It then calculates the surface water and energy fluxes at each grid cell (Harrigan et al., 2020). The LISFLOOD river discharge model has various inputs like topography, river network, land use, irrigation and in-situ river discharge observations which represents the lakes and the reservoirs (Harrigan et al., 2020). Finally, the GloFAS-ERA5 combines these two to give us river discharges at different locations.

The GloFAS-ERA5 river discharge model is useful in 86% of the catchments. It has high performance in countries like Central Europe, Brazil, and the west coast of the United States. The performance of the model is rather low in Africa, some parts of Thailand, Mexico, and the southern part of Spain (Harrigan et al., 2020). The efficiency of the model essentially depends on the catchment areas. If the catchment area is less than 10,000 km^2 the model performs poorly and if the catchment area is more than 500,000 km^2 the performance is highest (Harrigan et al., 2020). One of the main limitations of the model is that it does not consider anthropogenic activities, i.e. the external human activities .The model does take into consideration major dams but apart from that any other human activity in the catchment area is not taken into consideration which might affect the model (Harrigan et al., 2020).

4.Method and Data

The method used to assess the hydropower production of the hydropower plants in Europe consist of five different steps

1. Selection of the case study areas in Europe.
2. Calculation of the modelled total water inflow into the reservoir expressed in energy units.
3. Determination of the historical electricity production by the hydropower plants.
4. Allocation of a correction factor to make modelled total water inflow comparable to historical electricity production.
5. Selection of the extreme events (high and low discharge).

Figure 9 shows an overview of the method used in this study.

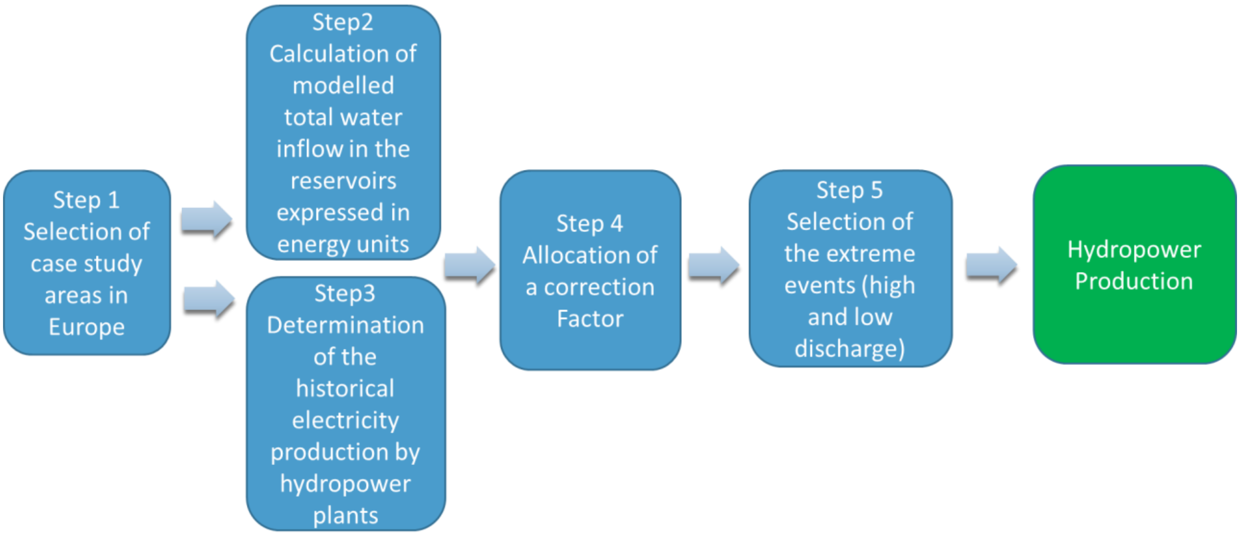


Figure 9: Overview of the method used in the study

Step 1 – Selection of the case study areas in Europe

Step 1 selects the hydropower plants in Spain, Sweden and Slovenia that were analysed in this study. First different hydropower plants in Spain and Sweden based on their installed capacity were looked upon. The hydropower plants in these countries which are representative of the largest capacity were collected. The list of hydropower plants in Spain and Sweden with their installed capacity is shown in the system discerption. In case of Slovenia, different hydropower plants were collected which are representative of the largest reservoir. The list of hydropower plants in Slovenia are shown in the system description. Later based on the availability of the electricity data of the hydropower plants, the three hydropower plants in the countries are chosen.

Step 2 - Calculation of modelled total water inflow into the reservoirs expressed in energy units

Step 2 determines the total water inflow at the river basin for the three case studies assessed. The total water inflow is then converted into energy units (GWh) so it can be compared to the historical electricity output of each power plant. Two sub-steps are made in this step.

(a) Determination of the total river water inflow

For the total river water inflow or the river discharge, this study uses the GLoFAS-ERA5 reanalysis dataset which consists of the modelled discharges of the rivers for the whole globe in the form of a variable called river discharge (m^3/s) (Harrigan et al., 2020). Based on coordinates of the studied river basins and the year for which the data needs to be extracted, the total water inflow in m^3/s averaged per day can be determined. Python was used for the extraction of the data. The coordinates for the river basins in Alcantara (Spain), Stornorrfors (Sweden) and Mariborksi Otok (Slovenia) are (39.73, -6.80), (63.85,20.05), (46.46,15.59) respectively. The time range for the data of the Spanish, Swedish and the Slovenian hydropower plants are 2015-2020, 2016-2020 and 2008-2020 respectively. The time range for the total river water inflow should be same as the time range for historical electricity output of each power plant as they need to be compared. ENTSO-E which is the database for production data only provides data for the years 2014-2020 out of which data for 2014 in case of the Alcantara hydropower plant, and data for 2014 and 2015 in case of the Stornorrfors hydropower plant were missing. Hence, the time range is 2015-2020 for the Spanish hydropower plant and 2016-2020 for the Swedish hydropower plant. Dravske elektrarne Maribor is the database which provides data for the Slovenian hydropower provides data from the year 2008-2020. Hence, that time range was chosen for Mariborski hydropower plant. The river flow that is extracted from the dataset is in the form of daily data, so it provides the discharges in the river basins averaged over a day.

Figure 10 shows the global mean daily river discharge network which is modelled with the help of GLoFAS-ERA5 reanalysis dataset.

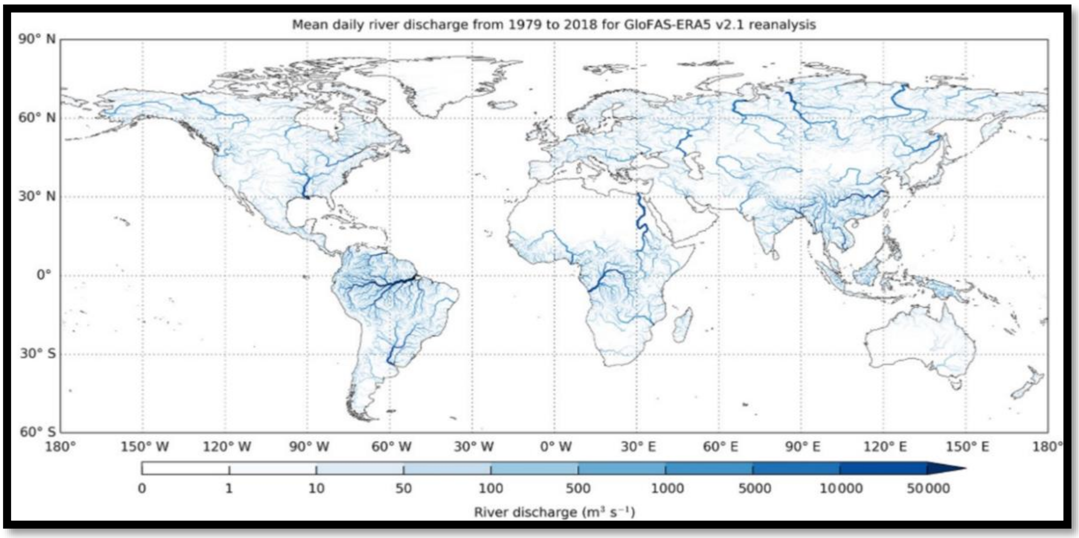


Figure 10: Global mean daily river discharge network (Harrigan et al., 2020)

(b) Conversion of the total water inflow into Energy units

After determining the daily total water inflow of the three river basins for the respective time ranges, the study converts them into Energy units (GWh) by adopting a formula from (Prodanovic et al., 2019) as:-

$$P = \rho * Q * g * h * \eta \tag{1}$$

where, P is the power generated from the hydropower plant in Watts.

ρ is the density of water (kg/m^3) which is 1000 kg/m^3, g is the acceleration of gravity (m/s^2) which is 9.81 m/s^2, h is the head of the hydropower plant, which is considered to be constant throughout the studied period. In this case, the head is 130m for the Alcantara hydropower plant (Spain), 75m for Stornorrfors hydropower plant (Sweden) and 14.2m for Mariborski Otok (Slovenia) (Dravske elektrarne Maribor, 2020.). η is the efficiency of the turbine used at the power plant which is set to 90% in case of Francis turbines and 85% in case of Kaplan turbines (Kaunda et al., 2012b). The type of turbines used for each case are described in the System Analysis. Q is the river discharge (m^3/s) which in this case is the daily total water inflow calculated in the previous step.

Next, the calculation of electricity produced by the hydropower plants, E, in GWh, is calculated as:

$$E = \frac{P}{10^6} * \frac{n}{1000} \tag{2}$$

Where, P is the power generated in W, 10^6 is the factor used to convert W to MW, n is the number of hours the hydropower plant is running and 1000 is the factor used to convert MWh to GWh. An assumption is made that the hydropower plants are running 24 hours a day. Next the study generates the daily total water inflow in Energy units (GWh/day) for the three power plants in Spain, Sweden, and Slovenia for their respective time ranges.

Step 3 - Determination of the historical electricity production by the hydropower plants

Step 3 determines the historical electricity production by the three hydropower plants. It also consists of two sub-steps:

(a) Historical electricity production of Alcantara and Stornorrfors hydropower plants
For the dammed hydropower plants in Spain and Sweden, the historical electricity production data is retrieved from the European Network of Transmission System Operators for Electricity European Network of Transmission Systems Operators for Electricity (ENTSO-E Transparency Platform, n.d.). It provides the daily electricity produced in MWh for both the Alcantara hydropower plant and Stornorrfors hydropower plants.

(b) Historical electricity production of Mariborski Otok
For the Mariborksi Otok hydropower plant, the historical electricity production data (GWh) is retrieved from Dravske elektrarne Maribor which is the company that owns the power plant (Dravske elektrarne Maribor, 2020). The electricity production data is in the form of monthly data, so it gives the electricity produced by the hydropower plant in all the 12 months over the year. The data on the electricity production is available for the time range 2008-2020.

Step 4 - Allocation of a correction factor to make modelled total water inflow comparable to historical electricity production.

The modelled total water inflow in energy units and the historical electricity production by the hydropower plants need to be compared for further analysis. Hence, a correction factor is introduced to make them comparable.

It is crucial to make sure that the historical electricity production (outflow) and the total water inflow in energy units are of the same scale as the results are based on the accuracy of the data. Hence a correction factor, based on water balance, is allocated to make sure that both the data are on the same scale. A factor will be assigned for both the hydropower plants in Spain and Sweden. The factor will not be assigned for the hydropower plant in Slovenia, as the GLoFAS-ERA5 reanalysis dataset is able to simulate the total water inflow very accurately when compared to the historical electricity production data. This can be seen in the figure 22 in the appendix A.

The water balance indicates that the total water flowing into the reservoirs is also flowing out. To do this, a factor is assigned, and it is multiplied to all the values of the modelled water inflow. This way the trend predicted by the modelled inflow does not change but only the scale as we are multiplying the factor throughout the time-period considered. Equation 3 shows the allocation of the correction factor:

$$Correction\ factor = \frac{Historical\ electricity\ production}{Modelled\ total\ water\ inflow\ in\ energy\ units} \tag{3}$$

For the Alcantara hydropower plant in Spain, the

Correction factor = 4613/ 12568 = 0.36.

for the Stornorrfors hydropower plant in Sweden, the

Correction factor = 11846/ 16371 = 0.72.

Hence, all the values of the modelled water inflow will be multiplied by these correction factors to make the water balance in the system.

Step 5 - Selection of the extreme events (high and low discharge)

Step 5 selects extreme high and low discharge events(floods and droughts) for the three case studies for analysis of the hydropower production. In order to do this the Standardized Precipitation Anomalies (SPA) is used (Lamb, 1982). This formula helps in identifying the outliers of climate data, which in this case are high and low discharge events. The formula is given below (Lamb, 1982),

$$SPA_b^i = \frac{Q_b^i - \overline{Q_b}}{\sigma_b} \tag{4}$$

Here,Q_b^i is the total water inflow or river discharge data from GLoFAS-ERA5 reanalysis dataset for basin b for a period, at year *i.* $\overline{Q_b}$ and σ_b are the mean and standard deviation of the total water inflow data of basin b for the period considered. On the one hand, If the SPA factor > 1, then that period is selected as a high discharge event (wet period). On the other hand, If the SPA factor < 1, then that period is selected as a low discharge event (dry period). The total water inflow data or the discharge data used in the formula is retrieved from the GloFAS-ERA5 dataset (Harrigan et al., 2020). The years included for this statistical analysis is from the year 1979 to year 2020, which is a 42-year period. The extreme events will be determined among this 42-year period for the three case studies.

The discharge data are available in the form of daily data (water discharge per second averaged over a day). This is converted into total amount of discharge per day by the equation below:

$$Q_{Day} = Q * 24 *3600 \tag{5}$$

Here, Q_{Day} is the total amount of discharge in a day in m^3, Q is the discharge data averaged over a day in m^3/s and 3600 converts seconds to days.

Once the total amount of discharge in a particular day is calculated, the same is done for all the days from the year 1979 to 2020. For this analysis a particular month is selected as an extreme period hence, discharges per day are summed according to different months. The calculation for the total discharge in January in 1979 is shown as an example in the equation below:

$$Q\ [\text{January } 1979] = Q\ (01\text{-}01\text{-}1979) + Q\ (02\text{-}01\text{-}1979) + Q\ (03\text{-}01\text{-}1979)\ldots. + Q\ (31\text{-}01\text{-}1979) \tag{6}$$

Here, Q is the total water inflow data or river discharge data.

Similarly, discharge is calculated for all the months for the years 1979 – 2020. Once all the monthly discharges are calculated for all the years, the mean and the standard deviation are determined and then placed in the above formula to get the SPA factor.

For example, the factor for the month January 1979 can be determined by calculating the mean and standard deviation over the basin considered for the 42-year period and placed in the SPA formula for the factor. It is shown below as:

$$\overline{Q_b} = \frac{[\mathrm{Q(Jan{-}1979)} + \mathrm{Q\ (Jan{-}1980)}\ \ldots\ldots\ldots{+}\mathrm{Q\ (Jan{-}2020)}]}{42} \tag{7}$$

Here, $\overline{Q_b}$ is the mean discharge for January, Q is the total water inflow data or river discharge data.

Similarly, the standard deviation is calculated, and both mean and standard deviation values are put in the SPA formula to determine the factor and based on that it is selected if it is a high discharge or a low discharge event.

5. Results

This chapter presents the main results of this study on the impact of weather extremes on the electricity generation of three hydropower plants in Spain, Sweden, and Slovenia.

5.1. Hydropower Plants Annual Electricity Production

Figure 11 shows the annual production of three hydropower plants: Alcantara in Spain, Stornorrfors in Sweden, and Mariborski Otok in Slovenia, during a wet, dry and an average year.

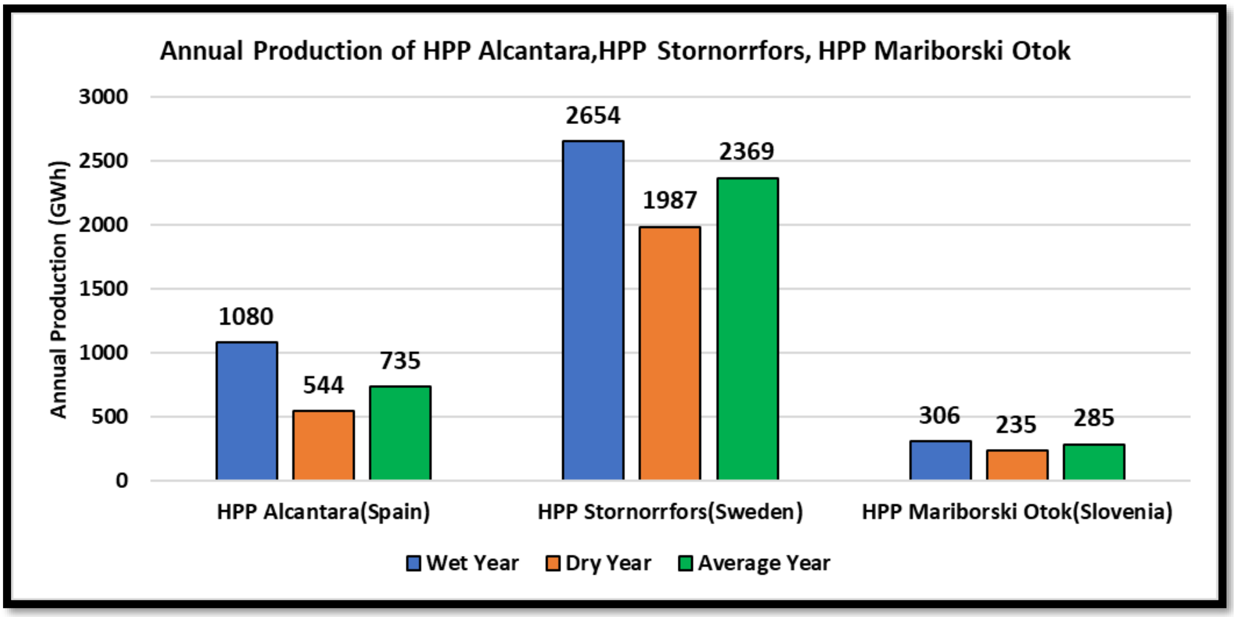


Figure 11: Annual Production of HPP Alcantara, HPP Stornorrfors, and HPP Mariborski Otok in Spain, Sweden, and Slovenia during a wet, dry and an average year

Figure 11 shows that the difference between the annual production during a wet and dry year in Spain is 50%, the difference between the annual production during a wet and dry year in Sweden is 25% and the difference between the annual production during a wet and dry year in Slovenia is 23%. The differences between the annual production during a wet and average year in Spain, Sweden, and Slovenia is 32%, 11%, 7% respectively. Figure 27 in the appendix c shows there is a similar variability between the total water inflow in energy units during a wet and dry year in Spain, Sweden, and Slovenia as 54%, 23% and 24%, respectively. Thus, the extreme events affect the electricity production of the hydropower plant in Spain more than the power plants in Sweden and Slovenia.

5.2. Hydropower Plants Capacity Factors

The capacity factor can be defined as ratio of the annual generation of a power plant divided by the product of the capacity and the number of hours over a given period (output if it operated at full capacity) (MORALESPEDRAZA, 2019). Figure 12 show the capacity factor of the hydropower plants during a wet, dry and an average year.

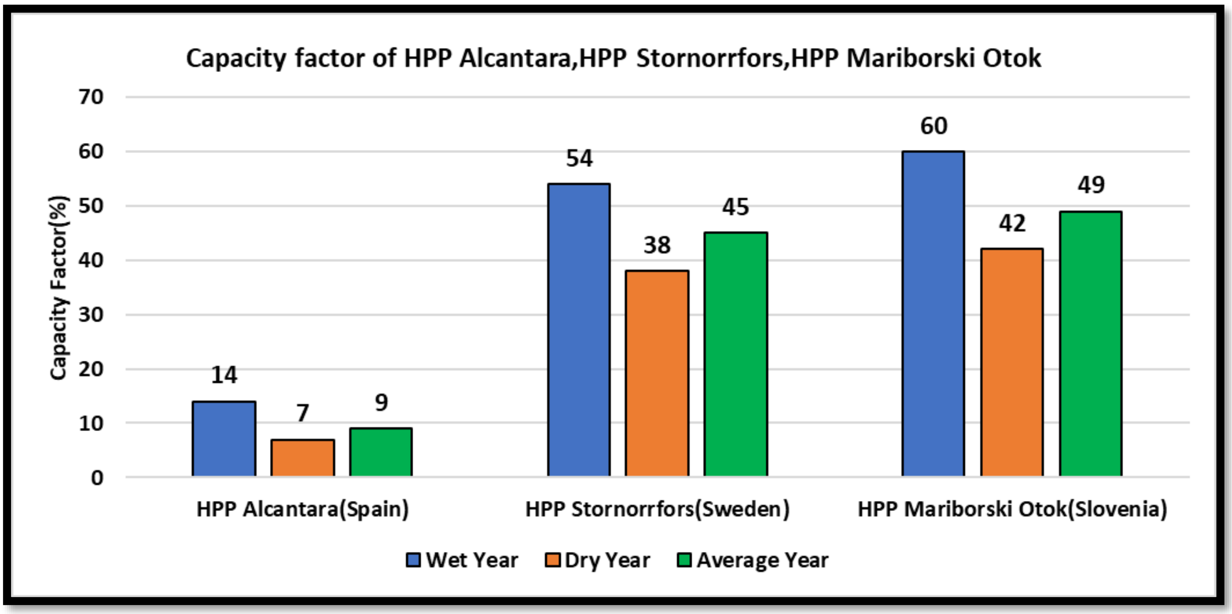


Figure 12:Capacity Factor of HPP Alcantara, HPP Stornorrfors, and HPP Mariborski Otok in Spain, Sweden, and Slovenia during a wet, dry and an average year

Figure 12 shows that the capacity factors of the Alcantara hydropower plant during a wet year is 14% and during a dry year is 7%. During an average year the capacity factor is 9%. This shows that the electricity production by the hydropower plant is very low compared to its installed capacity, which likely means that the hydropower plant was oversized. It is also possible that there is not enough water available in the reservoirs to produce that much electricity or perhaps it is built like that to use seasonal storage. It is observed that the difference in capacity factor during a wet and dry year is 50% which seems to indicate that the electricity production of the Alcantara hydropower plant is affected by extreme events. The figure 5.2 also shows the capacity factor of the Stornorrfors hydropower plant during a wet year is 54% and during a dry year is 38% and the capacity factor of the Mariborski Otok hydropower plant during a wet year is 60% and during a wet year is 42%. Since the global average capacity factor for hydropower plants is around 40% (Eia, 2011). This indicates that the hydropower plants in Sweden and Slovenia perform well and are not affected by the extreme events to the same degree that the Spanish hydropower plant does.

5.3. Modelled total water inflow in energy units (2015-2020) and Historical production (2015-2020) at Alcantara hydropower plant in Spain

Figure 13a-c shows the modelled total water inflow in energy units and the historical production at HPP Alcantara in Spain during a dry, wet and average year.

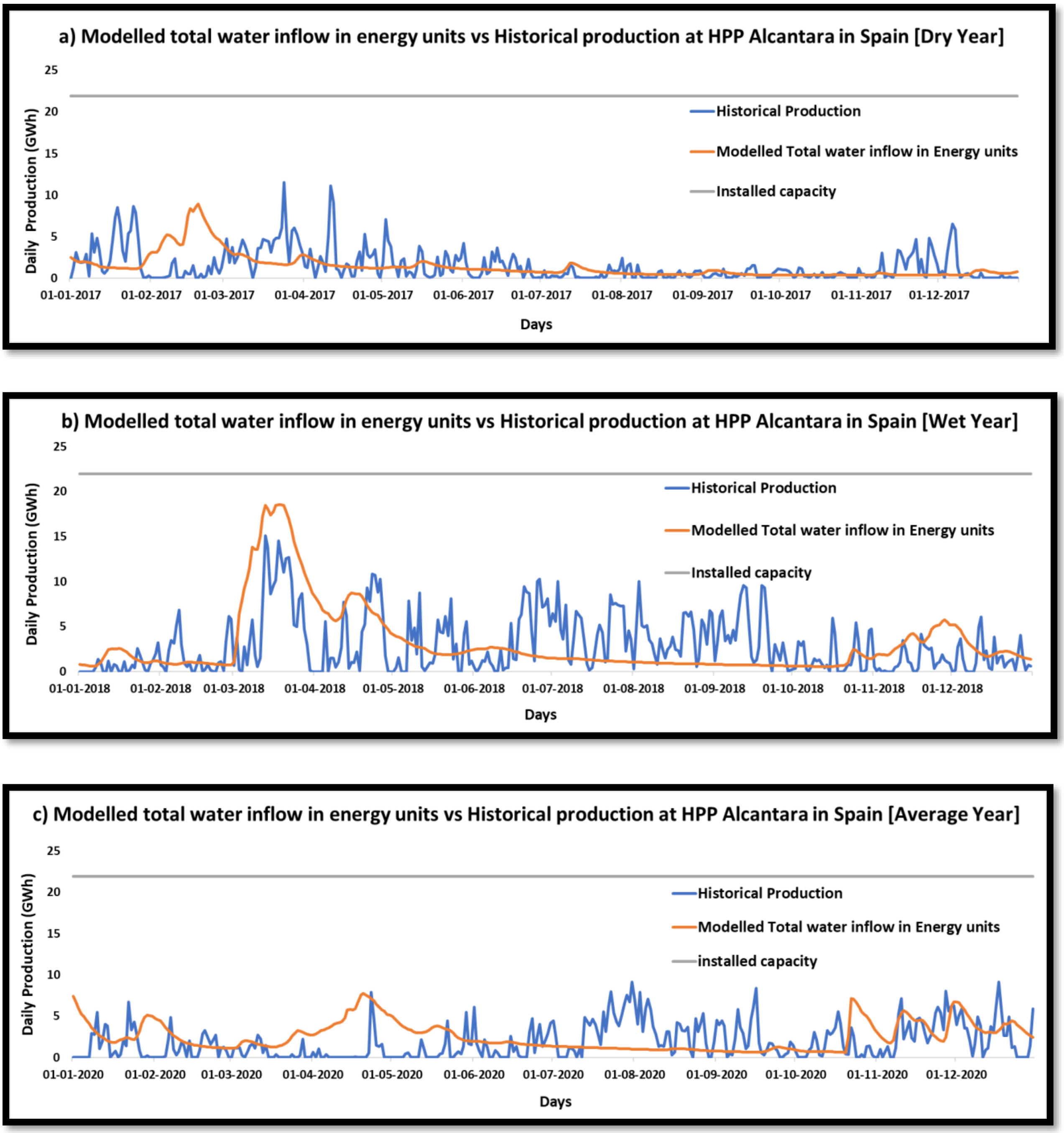


Figure 13:(a-c) Modelled total water inflow in energy unit's and the historical production at HPP Alcantara in Spain for a) Dry year b) Wet year and c) Average year

Figure 13 shows the daily total water inflow in energy units and the daily historical electricity production of the Alcantara hydropower plant in Spain along with the installed capacity for a dry (2017), wet (2018) and an average year (2020). For all the three years the hydropower plant never reaches the maximum production of its installed capacity of 22 GWh. This could indicate that the hydropower plant is oversized and the water available at the location is overestimated. Also, it could be that the hydropower plant is designed to cover the daytime loads which means it does not function at night-time causing it to never reach its maximum production potential. Next, it is observed that the historical production of the hydropower plant does not follow the same trend of the total water inflow in energy units. From figure 13(b) and 13(c), it is observed that the hydropower plant produces a large amount of electricity during the months of June, July, August, and September even though there is not enough water inflow available, which indicates that during this period the hydropower plant uses water from the storage to meet the demands.

5.3.1. Monthly discharge distribution of Spain (1979-2020) and mean monthly hydropower production of HPP Alcantara (2015-2020) in Spain

Figure 14 shows the monthly discharge distribution in Spain for the time-period 1979-2020.

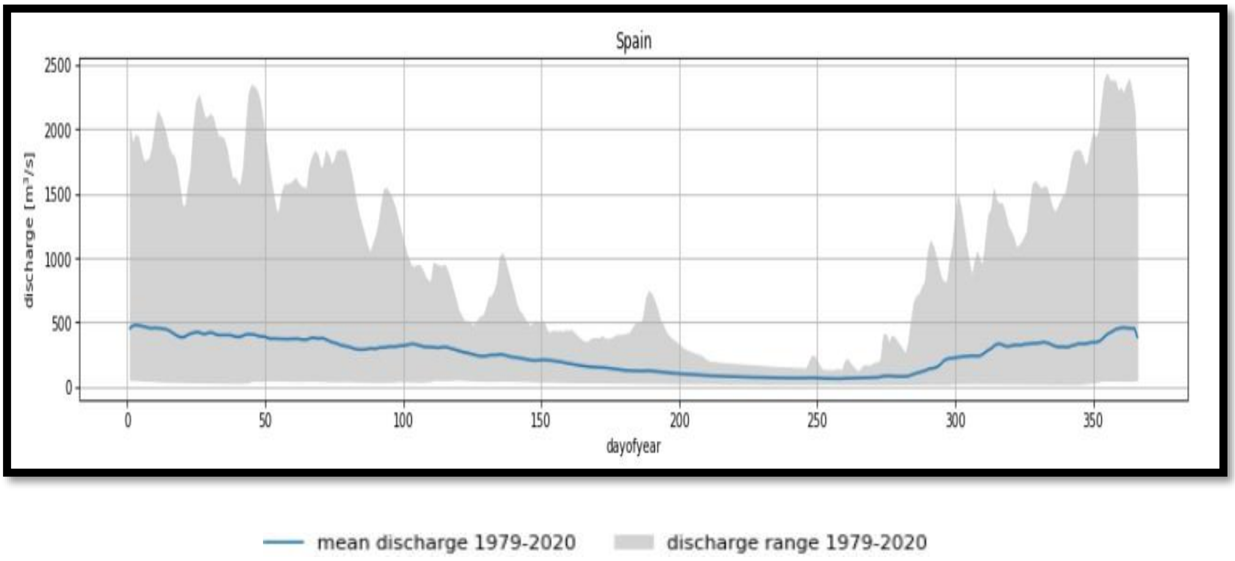


Figure 14: Monthly discharge distribution in Spain

Figure 14 shows that during summer months the water inflow is the lowest during the months of May, June, and July. During the autumn and winter months it is seen that the water inflow is higher when rains start to arrive in Spain. Also, we see that during the winter months there is high variability in discharge.

Figure 15 shows the mean monthly hydropower production of HPP Alcantara in Spain for the period 2015-2020.

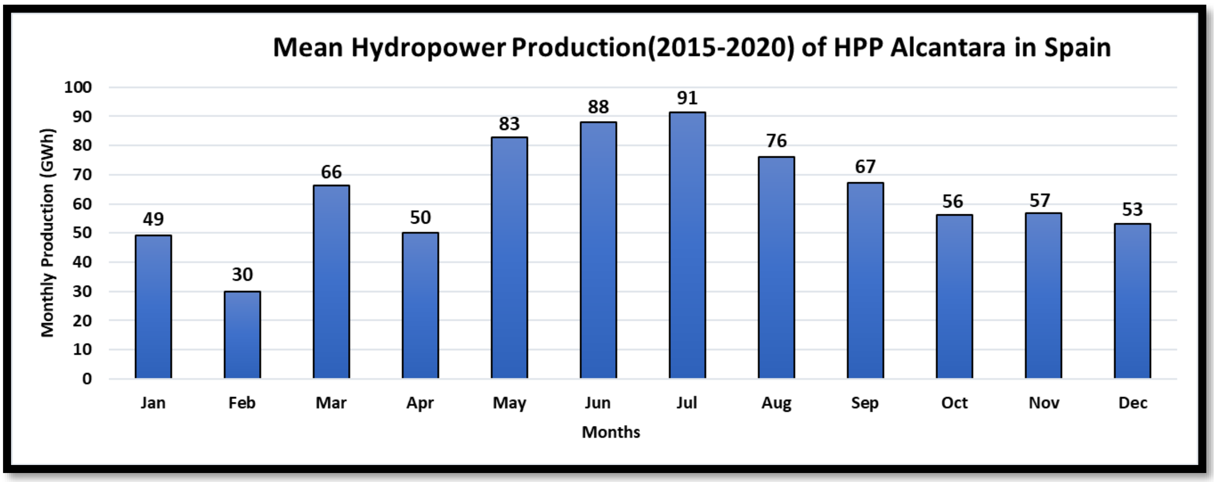


Figure 15: Mean monthly hydropower production for years 2015-2020 of HPP Alcantara in Spain

Figure 15 shows the mean monthly production of the Alcantara hydropower plant throughout the year for the period 2015-2020. It is seen that it has most production during the summer months which are June, July, August, while during the autumn and winter months the production is lower with the least production in the month of February.

5.3.2. Hydropower production during low discharge months at HPP Alcantara in Spain

Figure 16 shows the hydropower electricity production during low discharge months and the yearly production at HPP Alcantara in Spain.

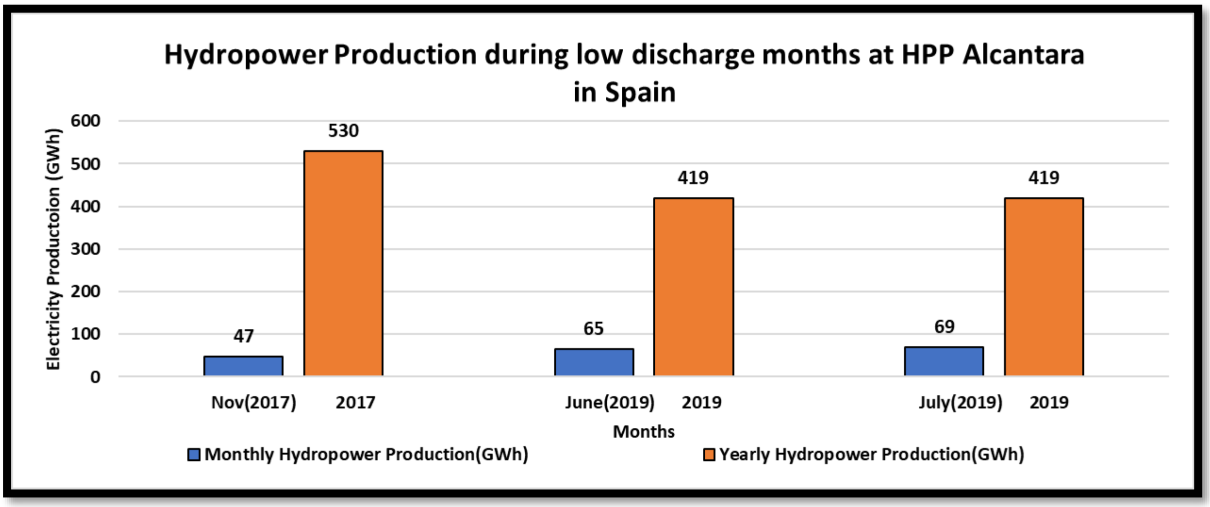


Figure 16: Hydropower production during low discharge months corresponding to the yearly production at HPP Alcantara in Spain

Figure 16 that the period November 2017, June 2019, and July 2019 were low discharge months or dry months, and it is observed that the hydropower plant produces 47 GWh, 65 GWh, and 69 GWh respectively. It is seen that the yearly production by the hydropower plant during 2017 and 2019 is 530 GWh and 419 GWh which is less that what it usually produces on average making them dry years. Hence, it is seen that the dry months in November 2017, June 2019, and July 2019 have an impact on the yearly hydropower production by the Alcantara hydropower plant in Spain.

Furthermore, Figure 16 show a difference in the impact on the annual hydropower production when the extreme event happens during the autumn than when it occurs during the summer. According to the monthly discharge distribution of Spain, shown in Figure 14, during the summer (June, July, August) the total water inflow is significantly smaller than the discharge during autumn (September, October, November). Since the hydropower plant produces more electricity in the summer months when compared to autumn, shown in Figure 15, even though the total water inflow is less, this likely indicates that it uses water from the storage to produce the electricity to meet the demand during summer. During the autumn and winter months the hydropower plant stores the water in the reservoirs to produce during the summer. This suggests that a low discharge event happening in autumn month will have larger implications on the electricity production of the hydropower plant when compared to other months.

5.4. Modelled total water inflow in energy units (2016-2020) and Historical production (2016-2020) at Stornorrfors hydropower plant in Sweden

Figure 17a-c shows the modelled total water inflow in energy units and historical production at HPP Stornorrfors in Sweden during a dry, wet, average year.

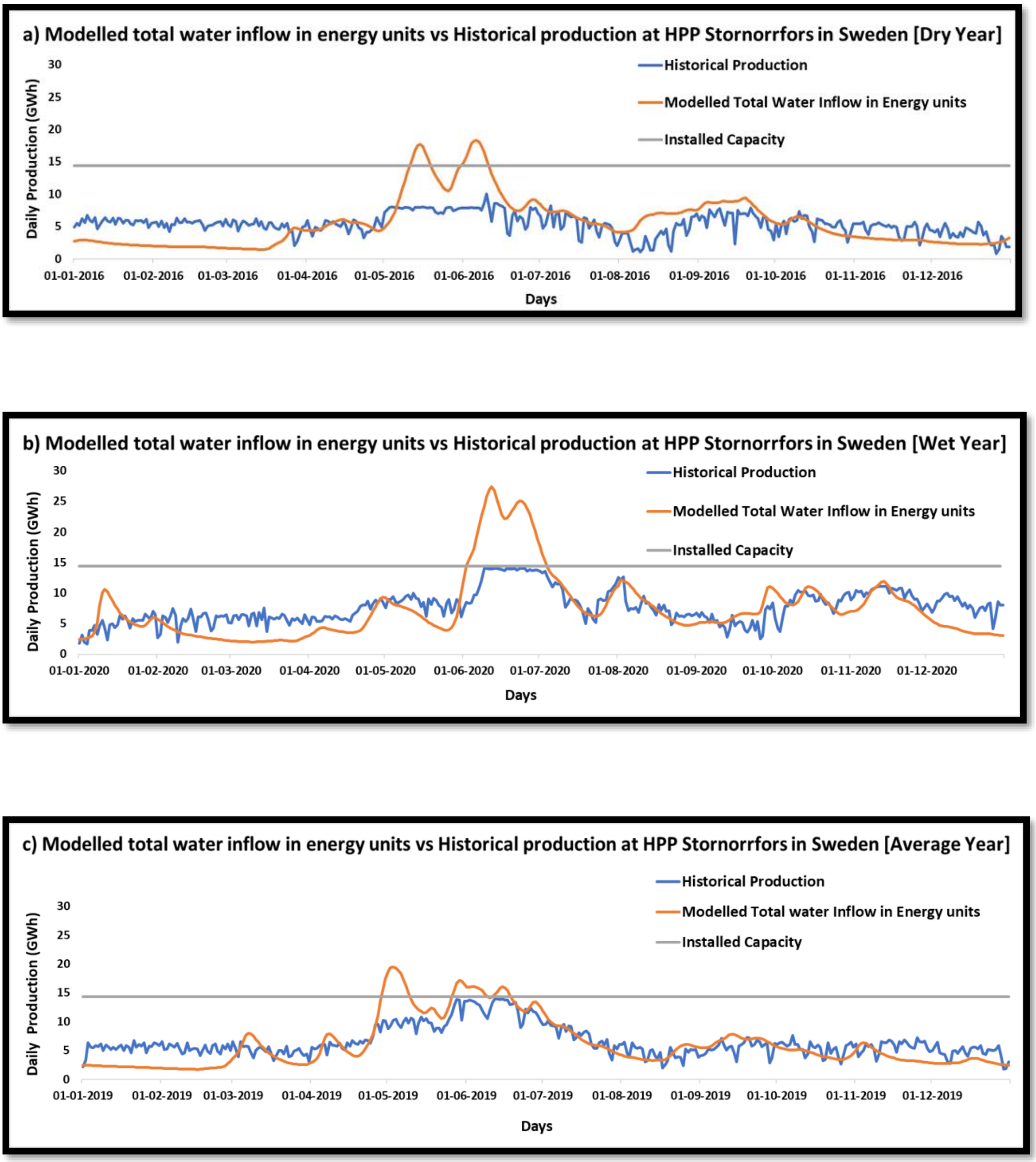


Figure 17(a-c): Modelled total water inflow in energy unit's vs Historical production at HPP Stornorrfors in Sweden for a) Dry year b) Wet year and c) Average year

The figure 17 shows the daily total water inflow and the historical electricity production of the Stornorrfors hydropower plant in Sweden along with the installed capacity for a dry (2016), wet (2020) and an average year (2019). From the figures it is observed that the historical production from the hydropower plant follows the same trend as the total water inflow. This indicates that the hydropower plant produces more electricity during the months with higher water inflow when compared to the months of low water inflow where they produce less electricity. It is also observed from all the three figures above that during the middle of the year (June, July, and August), there is a lot of water inflow available, but the hydropower plant does not produce that much electricity due to the limitation of the installed capacity.

This indicates that the physical limitations of the hydropower plants, such as capacity of the plant, are very important for the production of electricity as more water available for production does not mean that the hydropower plant can just produce that much electricity. Finally, it is observed that during the start and end of the year, i.e., the winter and autumn months, the historical production of the hydropower plant is higher than the total water inflow which indicates that the hydropower plant uses water from the storage to produce electricity during this period.

5.4.1. Monthly discharge distribution of Sweden (1979-2020) and mean monthly hydropower production of HPP Stornorrfors (2016-2020) in Sweden

Figure 18 shows the monthly discharge distribution in Sweden for the time-period 1979-2020.

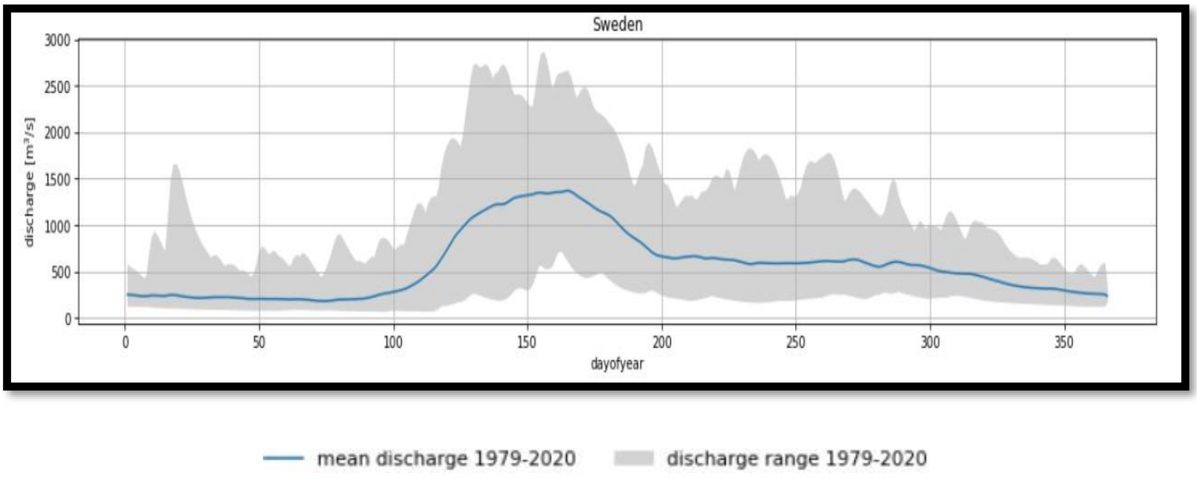


Figure 18: Monthly discharge distribution in Sweden

The figure shows the monthly discharge distribution of Sweden, and it is seen that during summer months the water inflow is the highest during the months of June and July with a peak in the month of June. During the autumn and winter months it is seen that the water inflow is lower.

Figure 19 shows the mean monthly hydropower production of Stornorrfors HPP in Sweden for the years 2015-2020.

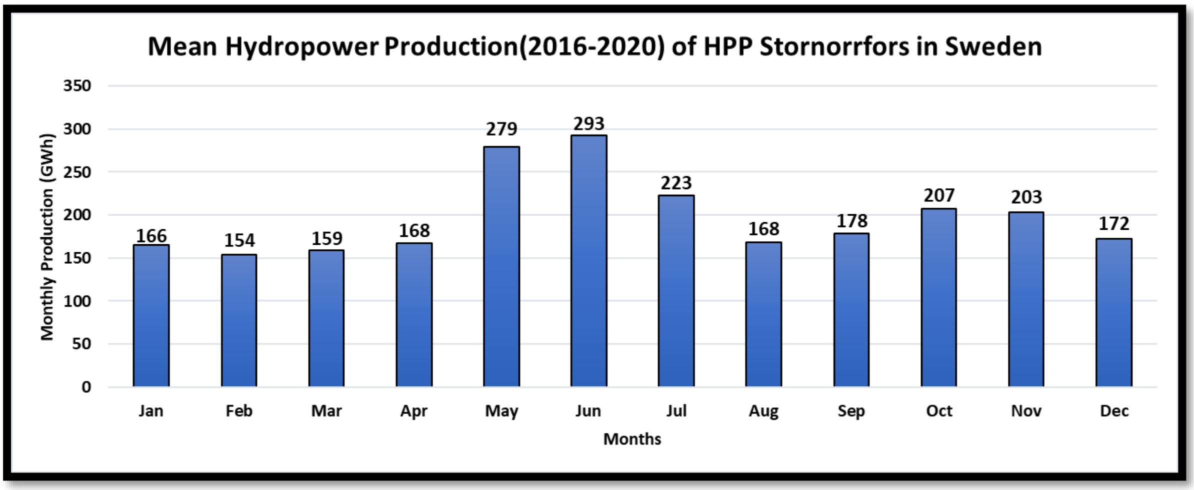


Figure 19: Mean monthly hydropower production for years 2015-2020 of HPP Stornorrfors in Sweden

Figure 19 shows the mean monthly production of the Stornorrfors hydropower plant throughout the year. It is seen that it has most production during the summer months June and July with the highest production during June (293 GWh). The high production in summer is due to the larger total water inflow received in Sweden during that season.

According to the monthly discharge distribution of Sweden in figure 17, during the summer months (June, July, August) the total water inflow is way larger when compared to winter months (December, January, February). Hence, during the winter months the hydropower plant produces lower than what it produces during summer months. During summer months the water inflow is so high even though there is a low discharge month occurring, the hydropower plant receives so much total water inflow that it does not affect the operation of the hydropower plant. Hence, it can be said the low discharge events (dry events) do not affect the hydropower production of the Stornorrfors hydropower plant in Sweden.

5.4.2. Hydropower production during low discharge months at HPP Stornorrfors in Sweden

Figure 20 shows the hydropower electricity production during low discharge months with the yearly production at HPP Stornorrfors in Sweden.

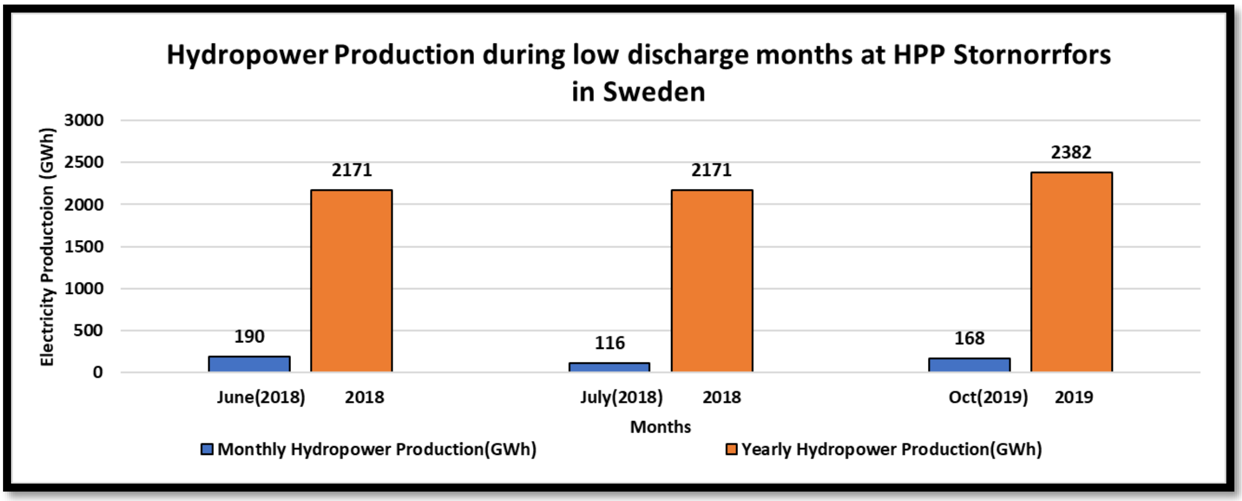
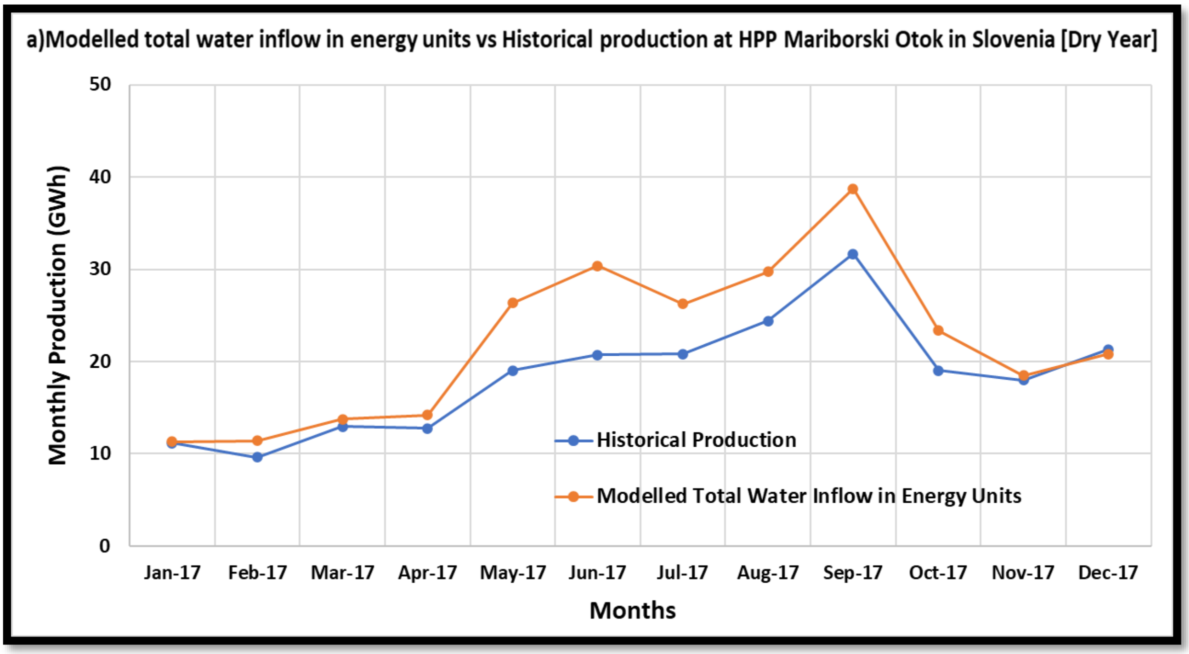


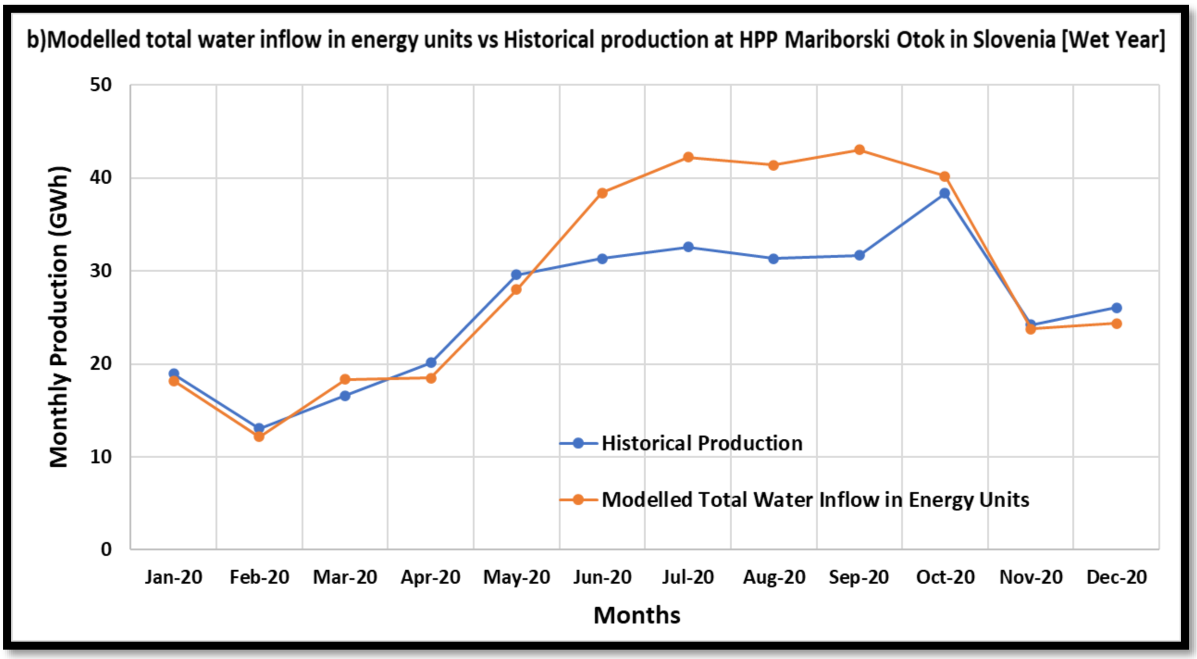
Figure 20: Hydropower production during low discharge months corresponding to the yearly production at HPP Stornorrfors in Sweden

Figure 20 shows the hydropower electricity production during low discharge months with the corresponding yearly production at HPP Stornorrfors in Sweden. The period June 2018, July 2018, and October 2019 were low discharge months or dry months, and it is observed that the hydropower plant produces 190 GWh, 116 GWh, and 168 GWh respectively. It is seen that the yearly production by the hydropower plant during 2018 and 2019 is 2171 GWh and 2382 GWh which is what the hydropower plant usually produces on average. Hence, it is seen that the dry months in June 2018, July 2018, and October 2019 do not have an impact on the yearly hydropower production by the Stornorrfors hydropower plant.

5.5. Modelled total water inflow in energy unit's (2008-2020) vs Historical production at HPP Mariborski Otok in Slovenia

Figure 21a-c shows the modelled total water inflow in energy units and historical production at HPP Mariborski Otok in Slovenia during a dry, wet and average year.





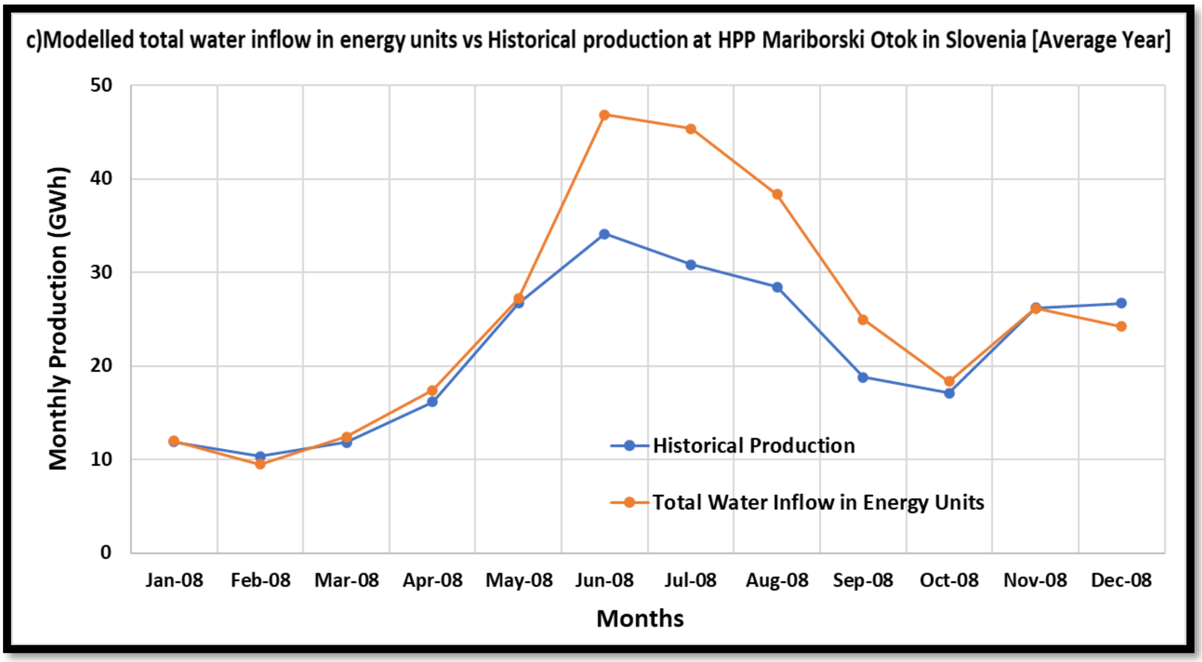


Figure 21: Modelled total water inflow in energy unit's vs Historical production at HPP Mariborski Otok in Slovenia for a) Dry year b) Wet year and c) Average year

It is observed from the figures that the historical production follows the same trend as the total water inflow in energy units. This indicates that the hydropower plant's production matches the inflow: that they produce more electricity during the months of more water inflow and produce less during the months of low water inflow. The figures also show that the water inflow during the months of June, July, August, and September is higher than the historical production. Since this is a run-of-river hydropower plant, the plant just produces according to the water inflow available without any means of storage due to the lack of a reservoir.

6. Discussion

The following section will discuss the limitations, assumptions of the data and model used for the calculations of the results and the implications of the study.

6.1.Historical electricity production data and modelled total water inflow in energy unit’s

The data used to determine the historical electricity production of the hydropower plants were retrieved from the ENTSOE transparency database (ENTSO-E Transparency Platform, n.d.). That database gives the daily production data of the hydropower plants in European countries for the period 2014-2020, but it was seen that it lacked data for some years. For example, for the Alcantara hydropower plant in Spain, the database had missing data for the year 2014 and for the Stornorrfors hydropower plant in Sweden, it had no data for the years 2014 and 2015. Hence, the missing years were not considered and data for the years available were used instead, (2015-2020) in case of Spain and (2016-2020) in case of Sweden. Also, for the Mariborski Otok hydropower plant in Slovenia, the ENTSOE database had missing data for all the years. Hence for the electricity production of the Slovenian hydropower plant, Dravske Elektrarne Maribor platform was used where only monthly production data were available for the years 2008-2020. Therefore, due to lack of availability of production data for some years, the data had to be adjusted accordingly. Also, since the study had missing data, i.e., no electricity production data before 2014 for Spanish and Swedish hydropower plant and no production data before 2008 in case of Slovenian hydropower plant, probably with a larger dataset, say 50 years the study would have been more precise.

For the calculation of the total water inflow the GLOFas-ERA5 river discharge reanalysis dataset was used (Harrigan et al., 2020). Since the data from this source are modelled, they have some limitations and were probably not hundred percent accurate. The GLOFas-ERA5 river discharge reanalysis is skilful in its performance but its accuracy depends on the location of the river basin (Harrigan et al., 2020). Its performance was best in Central European countries but poor in countries like Brazil, Thailand, and Spain (Harrigan et al., 2020). An important limitation of the model is that it does not consider water uses from anthropogenic activities (Harrigan et al., 2020). Therefore, the modelled total water inflow will not have complete precision when compared to the actual measured data.

6.2. Assumptions in calculations

During the calculation of the modelled total water inflow in energy units for the hydropower plants, it was assumed that all the hydropower plants run for 24 hours daily throughout the time-period considered. This is probably not true, as some days of the year, the hydropower might run for 24 hours, but not all the days of the year. If the actual number of hours was considered, the accuracy of the results would have been better. Next, the head of the hydropower plant is considered to be constant through the studied period. This assumption may overestimate the amount of energy passing through the basin, and therefore the difference between energy produced and modelled could be significant be lower. This is particularly true in case of the Alcantara hydropower plant in Spain.

Also, for the efficiency of the turbines of the hydropower plants, it was defined that Alcantara and Stornorrfors hydropower plants are equipped with Francis turbines (efficiency of 90%) and Mariborksi Otok hydropower plant is equipped with Kaplan turbines (efficiency of 85%) was used for the calculations. These assumptions were taken into consideration to help perform the calculations as there was missing data. As the efficiency of the turbines in reality will not always be 90% and 85% for Francis and Kaplan turbines. The efficiency of the turbine depends on the discharge (flow) and head of the potential hydropower (Sosilo et al., 2018). Hence the efficiency of Francis and Kaplan turbines is not always constant and come in a range. If the exact efficiency values were calculated and used the results might have been more accurate.

6.3. Implications of the study

From the results it is seen that the installed capacity of the hydropower plant plays a huge role when it comes to the electricity production. Even though there is water inflow available for a certain amount of electricity production, the turbines of the hydropower plant should have the capacity to produce that much electricity. This shows that the physical limitations of the hydropower plants are very important and should be taken into consideration while modelling current and future hydropower in Europe.

Results show that in the summer months the Alcantara hydropower plant produces more electricity, and it needs to use water stored in the reservoir. This is expected as Spain has a cooling demand and during the summer season the electricity demand goes up because of the use of air conditioners due to high temperatures and increase in population from tourists. The Alcantara hydropower plant in Spain, the low discharge events or the dry events have larger implications on the electricity production during autumn season when compared to other seasons. This is important to take into consideration for current and future modelling of hydropower in Spain.

From the results it is seen that extreme events and climate variability affect Spain to a higher degree than the other two countries, and that Sweden when compared to Spain and Slovenia is most suitable for hydropower generation as it is not affected by weather extremes to the degree of Spain and Slovenia. But in this study, only one hydropower plant is selected as a case study in the countries. For more precision of the results, it would be better to incorporate more hydropower plants in the countries as case studies and determine the results. Selecting hydropower plants in different regions in the same country would help for less uncertain results. Also, in this study the types of the hydropower plants were not taken into consideration. It would be interesting to study how different types of hydropower plants like dammed, run-of-river, and pumped storage hydro plants would compare during extreme weather events.

Extrapolating the results from this study, we can infer that countries with dryer climates (as Spain), like Portugal, Italy and other Mediterranean regions are most likely to be affected by extreme events. Countries in Northern Europe with more temperate climates (as Sweden), like Norway, Denmark, Finland are not so likely to be affected by extreme events and are most suitable for hydropower considering a changing climate.

7.Conclusions

This study investigated the effects of low discharge and high discharge extreme events on the hydropower electricity production in three different climatic regions of Europe. The three countries selected for this study were Spain, Sweden, and Slovenia.

The results show that the difference between the annual production of the hydropower plant in Spain during a wet and a dry year is 50%, whereas in case of the hydropower plants in Sweden and Slovenia the differences are only 25% and 23% respectively. This indicates that the extreme events or the low and high discharge events affect the production of the hydropower plant in Spain much more than the hydropower plants in Sweden and Slovenia.

The hydropower plant in Spain has a very low-capacity factor (9%), which indicates that it is oversized and the water available at the location is overestimated. In case of the Spanish hydropower plant, it is seen that it does not produce with the same trend as the total water inflow. During autumn and winter months the hydropower plant stores water to make sure it has continuous production during other months. Hence, if a low discharge event happens in the autumn season, it has much more implications on the electricity production when compared to other seasons.

In case of the Swedish hydropower plant, it is seen that it produces with the same trend as the total water inflow, the months it has more water inflow it produces more electricity and vice versa. During summer months it stores water in the reservoirs so that it can have continuous production in the autumn and winter months. The results indicate that the hydropower plant in Sweden deals with the low and high discharge events better and is not affected much by these weather extremes to the degree of Spain and Slovenia.

The results of this study show that low discharge events (dry events) have more implications and are more relevant for the electricity production by the hydropower plants than the high discharge events (wet events) because there is a physical limitation of the installed capacity of the power plant, that prohibits a larger production even when more water is available. As more greenhouse gas emissions are emitted, climate change will have a greater impact on electricity production by hydropower plants. Thus, these results play a significant role as they indicate that, in the future, dams should be built in temperate climates because extreme climate events have less impact on the hydropower production on those climates.

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Appendix A

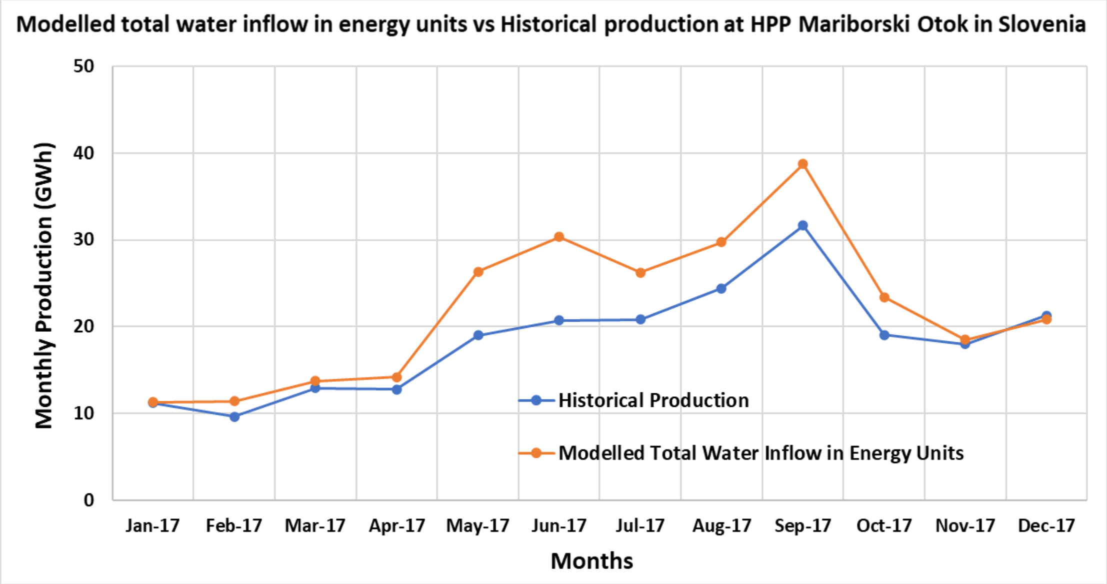
Calculation for allocation of the correction factor

Alcantara Hydropower Plant (Time period – 2015 -2020)		
Modelled total water inflow in energy units	**Actual electricity produced**	**Factor**
12568.28	**4613.12**	$\frac{\mathbf{4613.12}}{\mathbf{12568.28}}$ **= 0.36**

Calculation of the factor for Alcantara HPP in Spain

Stornorrfors Hydropower Plant (Time period – 2016 -2020)		
Modelled total water inflow in energy units	**Actual electricity produced**	**Factor**
16371.05	**11846.92**	$\frac{\mathbf{11846.92}}{\mathbf{16371.05}}$ **= 0.72**

Calculation of the factor for the Stornorrfors HPP in Sweden



Modelled total water inflow in energy units vs Historical production at HPP Mariborski Otok in Slovenia

Figure 22. Total water inflow and historical electricity production at Mariborski Otok HPP(Slovenia)

Appendix B

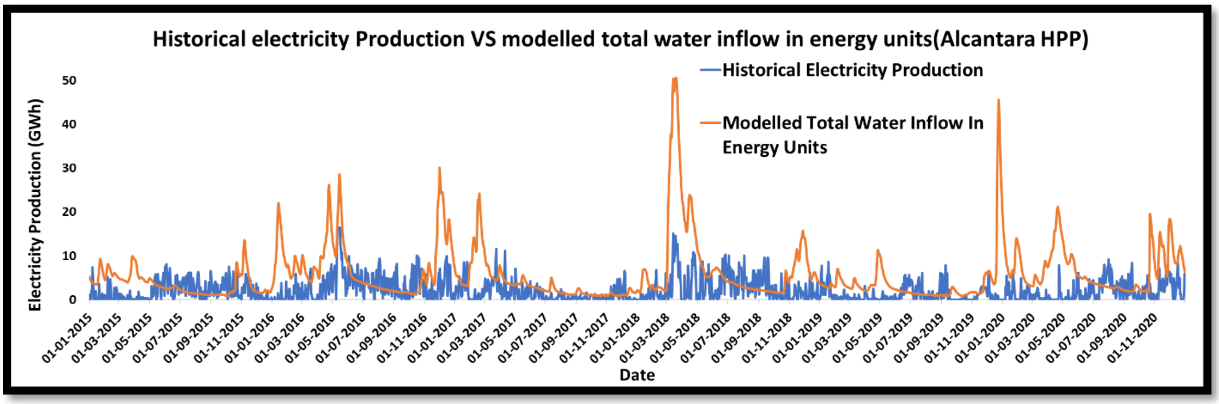


Figure 23. Historical electricity production and total water inflow at Alcantara HPP(Spain)

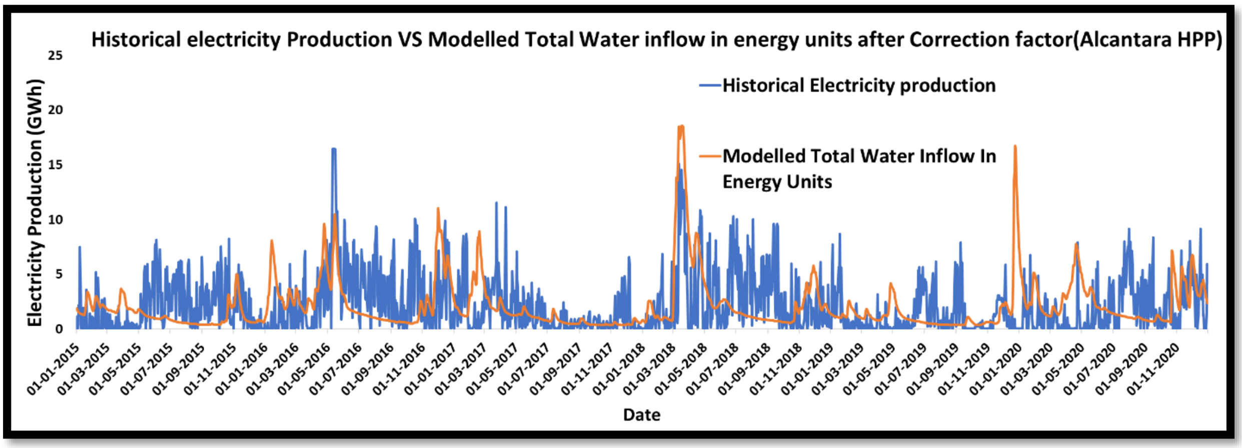


Figure 24. Historical electricity production and total water inflow after correction factor at Alcantara HPP (Spain)

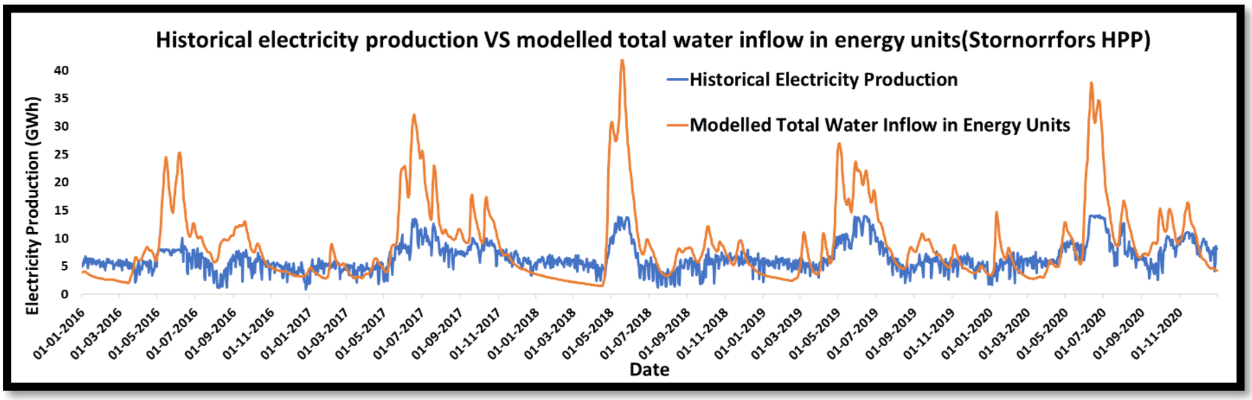


Figure 25. Historical electricity production and total water inflow at Stornorrfors HPP(Sweden)

Appendix C

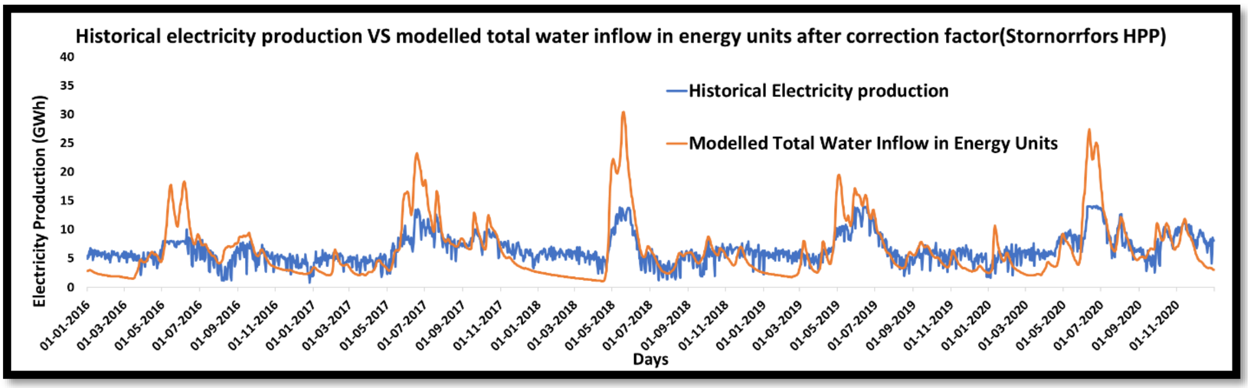


Figure 26. Historical electricity production and total water inflow after correction factor at Stornorrfors HPP(Sweden)

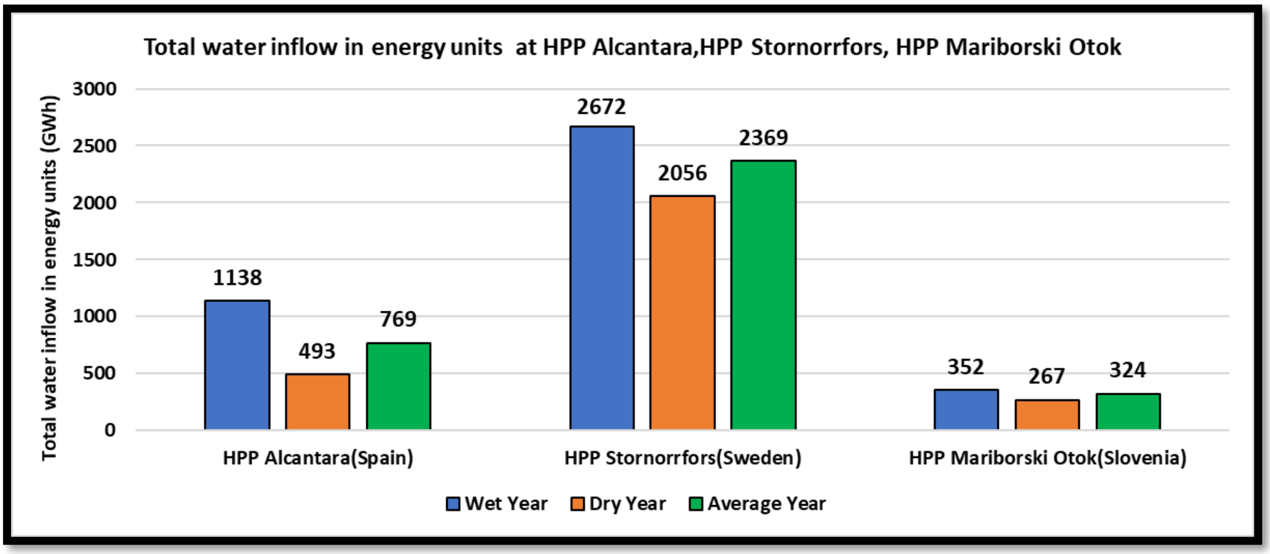


Figure 27. Total water inflow in energy units at HPP Alcantara, HPP Stornorrfors, and HPP Mariborski Otok in Spain, Sweden, and Slovenia during a wet, dry and an average year

Appendix D

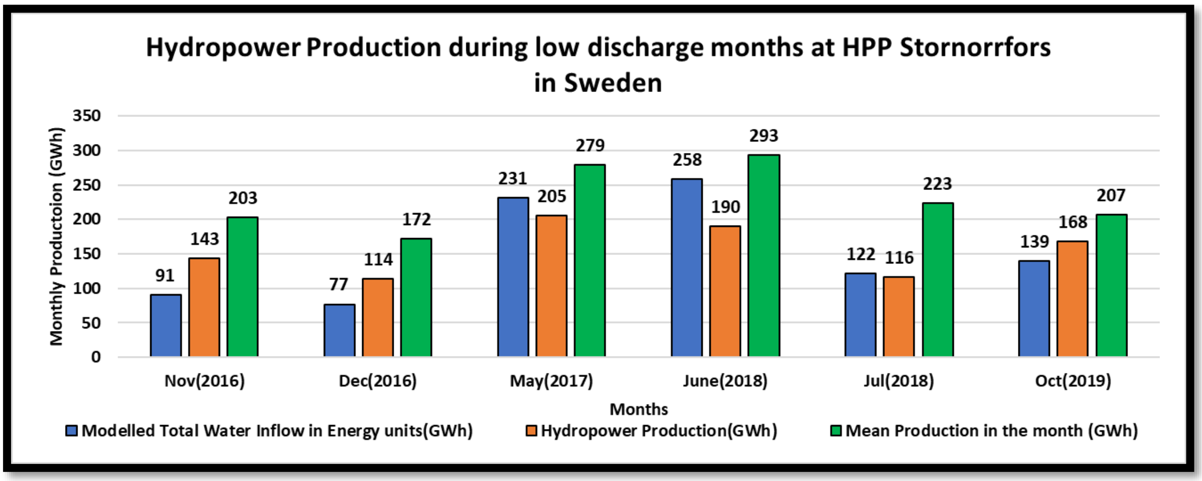


Figure 28. Hydropower production during low discharge months at HPP Stornorrfors in Sweden

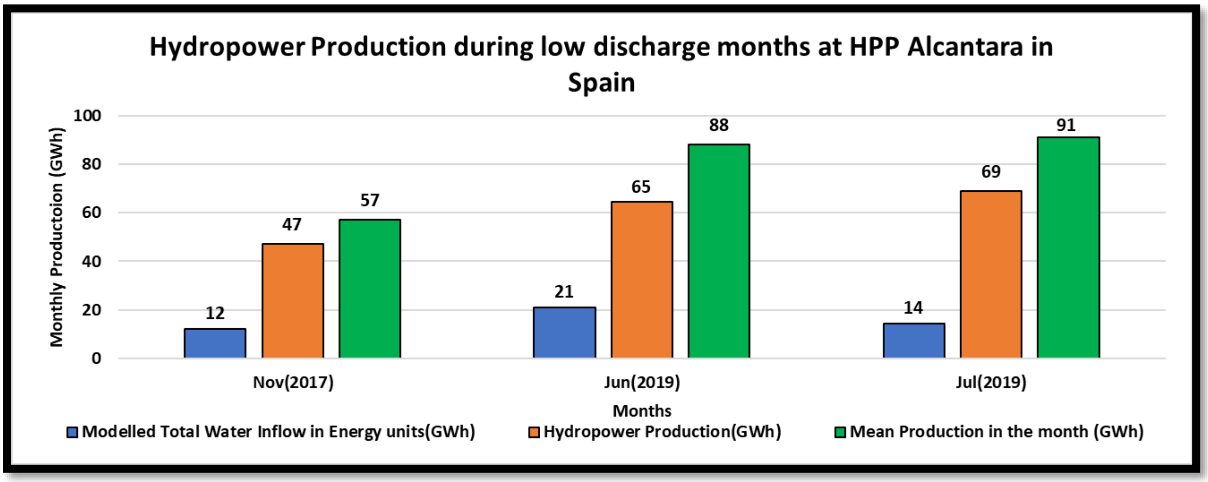


Figure 29. Hydropower production during low discharge months at HPP Alcantara in Spain

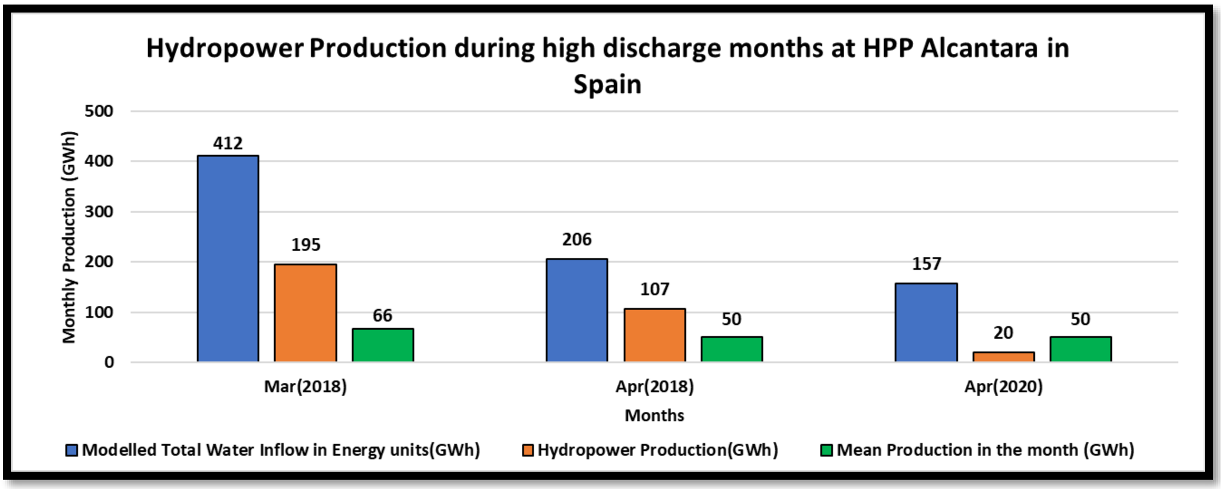


Figure 30. Hydropower production during high discharge months at HPP Alcantara in Spain