UNIVERSITY OF LJUBLJANA
Faculty of Mechanical Engineering

FEASIBILITY STUDY OF THE OPERATION OF BREŽICE HYDRO POWER PLANT FOR THE IMPLEMENTATION OF HYDROGEN ELECTROLYZERS

ŠTUDIJA IZVEDLJIVOSTI DELOVANJA HIDROELEKTRARNE BREŽICE ZA VGRADNJO ELEKTROLIZERJEV

BACHELOR THESIS – UNIVERSITY GRADE

Marco Cristóbal Rodríguez

Ljubljana, June 2020

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Marco Cristóbal Rodríguez

Mentor: Prof. Dr. Mihael Sekavčnik
Co-mentor: Assoc. Prof. Dr. Boštjan Drobnič

Ljubljana, June 2020

Candidate
Marco Cristobal Rodriguez

VISOKOŠOLSKI STROKOVNI ŠTUDIJSKI PROGRAM I. STOPNJE STROJNIŠTVO: **VS I/796 E**

NASLOV TEME: **Študija izvedljivosti delovanja hidroelektrarne Brežice za vgradnjo elektrolizerjev**

Sodobna oskrba z električno energijo temelji na obnovljivih virih energije, med katerimi je trenutno najbolj razvito izkoriščanje energije vode v hidroelektrarnah. Da bi uporabo fosilnih goriv čim bolj zmanjšali, je potrebno obnovljive potenciale maksimalno izkoristiti. V hidroelektrarnah je za to potrebno zmanjšati količino prelivne vode, ki neizkoriščena teče skozi hidroelektrarno. Pridobljeno energijo pa bi bilo potrebno na primeren način shranjevati za kasnejšo uporabo, npr. s tehnologijami P2G (power to gas) v vodik ali druge pline. V svojem magistrskem delu naj kandidat:

- Pregleda relevantno literaturo o delovanju hidroelektrarn in možnostih shranjevanja presežkov energije s sistemi P2G.
- Predstavi značilnosti obratovanja hidroelektrarne, s poudarkom na posebnostih HE Brežice;
- Analizira podatke o obratovanju HE Brežice in jih ustrezno predstavi;
- Na podlagi rezultatov meritev in razpoložljive dokumentacije iz HE Brežice izpelje poenostavljen matematični model delovanja hidroelektrarne;
- Analizira podatke o količini in frekvenci pojavljanja prelivne vode;
- Na podlagi podatkov oceni energijski potencial prelivne vode ter z izpeljanim modelom delovanja HE oceni količino energije, ki bi jo v obstoječem sistemu lahko s tem pridobili.
- Predstavi možnosti pretvorbe dodatno pridobljene energije v P2G sistemu in oceni količino pridobljenega vodika.

Diplomsko delo je treba oddati v jezikovno in terminološko pravilnem angleškem jeziku. Rok za oddajo tega dela je šest mesecev od dneva prevzema.

1st CYCLE PROFESSIONAL STUDY PROGRAMME IN MECHANICAL ENGINEERING: **VS I/796 E**

TITLE: **Feasibility study of the operation of Brežice hydro power plant for the implementation of hydrogen electrolyzers**

Modern electricity supply is based on renewable energy sources, among which the most developed is currently the use of water energy in hydroelectric power plants. To minimize the use of fossil fuels, it is necessary to maximise the use of renewable potentials. In hydroelectric power plants it is necessary to reduce the amount of overflow water that flows unused through the power plant. However, the produced energy should be stored in a suitable way for later use, e.g. with P2G (power to gas) technologies as hydrogen or other gases. In his master's thesis, the candidate should:

- Review the relevant literature on the operation of hydropower plants and the possibilities of storing surplus energy with P2G systems.
- Present the characteristics of the operation of the hydroelectric power plant, with an emphasis on the special features of HPP Brežice;
- Analyse data on the operation of HPP Brežice and presents them accordingly;
- Based on the results of measurements and available documentation from HPP Brežice, derive a simplified mathematical model of hydropower plant operation;
- Analyse data on the amount and frequency of overflow water;
- On the basis of the data, assess the energy potential of the overflow water and, with the derived model of HPP operation, estimate the amount of energy that could be obtained in the existing system.
- Present the possibilities of converting additional energy obtained in the P2G system and estimate the amount of hydrogen produced.

The bachelor thesis must be written in standard English. It must be submitted within a six-month period after it has been accepted.

Mentor
prof. PhD. Mihael Sekavčnik

Comentor
Assist. Prof. PhD Boštjan Drobnič

I hereby confirm the receipt of the master thesis

Date: 30/04/2020

Student Signature ....

UNIVERZA V LJUBLJANI Fakulteta za strojništvo 14 Ljubljana

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Firstly, I would like to express my gratitude to my Bachelor thesis mentor Prof. Dr. Mihael Sekavčnik for giving me the opportunity to be part of this project. Also for all the guidance and good advice. Thanks to his effort and professionality, confronting the abnormal situation of COVID-19 has been possible in an academic way, and that deserves my most sincere admiration and gratitude.

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To all the friends and people I met these last months I owe all the emotional support, for they have made my stay in Ljubljana my home, and a place I will recall with fondness and warmth. Thanks to their companionship this thesis has been done with joy and dedication, and will be part of my dearest memories.

To conclude, I want to express my gratitude not only for the result of this thesis, but also for the symbolic ending it represents, of all these years of university studies. There were moments of intense delight and also moments of distress. To all the adversities and good memories I owe gratitude, for they have helped me mature and evolve as a person. In all these memories my family and friends are present. To all of you, I owe my most sincere and profound gratitude.

Declaration

1. I, the undersigned Marco Cristóbal Rodríguez, born 19 August 1997 in Vitoria-Gasteiz, a student at the Faculty of Mechanical Engineering at the University of Ljubljana, hereby declare that this final undergraduate thesis titled Feasibility study of the operation of Brežice power plant for the implementation of hydrogen electrolyzers is my own original work created under the supervision of my advisor prof. dr. Mihael Sekavčnik and co-advisor prof. dr. Boštjan Drobnič

2. I hereby declare that the submitted electronic copy of this final undergraduate thesis is identical to the printed copy.

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- I am aware of the potential repercussions concerning my status at the Faculty of Mechanical Engineering at the University of Ljubljana as per the applicable Rules should plagiarism be proven in connection to the submitted final undergraduate thesis.

Ljubljana, 15 June 2020 Signature of the author:______________

Abstract

UDC 621.311.21:519.6(043.2)

Serial No.: VS I/796E

Feasibility study of the operation of Brežice hydro power plant for the implementation of hydrogen electrolyzers

Marco Cristóbal Rodríguez

Keywords: Hydro Power Plant
Hydrology analysis
Numerical Model
Hydro Power Plant Simulation
Hydrogen production

ABSTRACT:

The aim of this thesis is to develop a numerical model of the Brežice HPP in order to analyse the potential of installing hydrogen electrolyzers. To do so, first bibliographic research of hydropower technology is presented, covering theoretical and technical approaches. Then a thorough analysis of the Brežice HPP is introduced, explaining the operating and hydrological situation of the facility. Subsequently, the numerical model is developed from a series of data sets collected from the HPP operator, and presented in forms of mathematical equations and graphics. The validity of the numerical model is then verified with real data and used to analyse the HPP potential to turbine bypass water flow. The results show good correlation between the measured and calculated values obtained with the model, and bypass water flow analysis reveals that power losses are up to a 10 % of the total power output of the HPP. This thesis summarizes the importance of future research on the economic model of the HPP in order to evaluate hydrogen electrolyzers potential.

Povzetek

UDK 621.311.21:519.6(043.2)

Serial No.: VS I/796E

Študija izvedljivosti delovanja hidroelektrarne Brežice za vgradnjo elektrolizerjev

Marco Cristóbal Rodríguez

Keywords: hidroelektrarna
analiza hidrologije
numerični model
simulacija obratovanja hidroelektrarne
proizvodnja vodika

POVZETEK:

Cilj diplomskega dela je razviti numerični model delovanja hidroelektrarne Brežice, ki bi omogočil analizo potenciala prigraditve elektrolizerjev za proizvodnjo vodika. V ta namen je najprej predstavljen pregled literature o tehnologiji vodnih elektrarn, ki zajemajo teoretične in tehnične pristope. Sledi podroben opis HE Brežice, ki prikaže obratovalno in hidrološko stanje objekta. V nadaljevanju je razvit numerični model delovanja elektrarne na podlagi časovnih vrst obratovalnih parametrov, ki jih je zagotovil operater HE in so predstavljeni v obliki matematičnih enačb in grafično. Veljavnost numeričnega modela je preverjena s primerjavo z izmerjenimi podatki, model pa je nato uporabljen za analizo potenciala pretvorbe prelivne vode v dodatno električno energijo. Rezultati kažejo dobro povezavo med realnimi in teoretičnimi vrednostmi, pridobljenimi z modelom. Analiza pretoka prelivne vode pa kaže, da so izgube energije do 10 % celotne proizvedene energije v HE. Ta disertacija kaže tudi na pomen prihodnjih raziskav na ekonomskem modelu HE, ki upošteva tudi oceno potenciala vodikovih tehnologij.

Table of contents

List of figures

List of tables

List of symbols used

Symbol	Unit	Meaning
A		First constant of parabolic correlation
B		Second constant of parabolic correlation
C		Third constant of parabolic correlation
e	%	Error of the model
f	Hz	Frequency of the generator
F	N	Force
g	m/s^2	Acceleration of gravity
h	m	Theoretical water head
H	m	Effective head
H_2	Nm^3	Volume of hydrogen
h_f	m	Head loss
m		Coefficient of losses of velocity along vanes
m	kg	Mass
n	rpm	Turning speed
p		Number of magnetic poles
p	Pa	Pressure of water
P	W	Power in SI
Q	m^3/s	Water flow
R^2		Adjusted coefficient of determination
V	m/s	Velocity of water
W	N	Weight of the striking water in vanes
W	J	Work
Z	m	Water level
γ	N/m^3	Specific weight
η		Efficiency
θ	^{o}	Angle of deflection
ρ	kg/m^3	Density of water

List of acronyms used

Acronym	Meaning
A	After
AM	Ante Meridiem
B	Before
CO_2	Carbon Dioxide
e.g.	Exempli Gratia
EE	Energy Efficiency
EU	European Union
HESS	Hidroelektrarne na spodnji Savi
HFC	Hydrofluorocarbons
HPP	Hydropower plant
LINEST	Linear Estimation
LVL	Level
m a.s.l.	Meters above the sea level
PEM	Proton Exchange Membrane
PFC	Perfluorocarbons
PM	Post meridiem
RES	Renewable energy sources
SI	International System
STDEV	Standard deviation
TPP	Thermoelectric power plant
US	United States
WF	Water Flow

1. INTRODUCTION

1.1. Background

Energy is one of the most important needs of human society. From the most ancient necessities such as fire to cook food and heating, horse power to cultivate the lands and travel, to the modern and high demanding energy demand of electricity, fuel for vehicles heating and so on. It is unspeakable that energy is a basic need and that obtaining it and transforming it so that it is usable for the society is among the most important task of human activities.

Energy storage is one of the major limitations of the energetic perspective of modern human society. The very laws of thermodynamics explain the complex task of transforming natural processes into useful energy, and how this energy tends to disperse irreversibly. Thus, it is the task of energy engineers to find different ways to store energy in efficient ways that will allow society to be less dependent of energy transience, also allowing the efficient implementation of renewable sources that are strongly climate dependent, and giving solution to the increasing need of electric energy storage in the transport sector. With the depletion of fossil fuel resources and the increasing pollution effects in environmental perspective, there is an urgent need to find solutions that will make it possible to go for a different energy system that fulfils the current needs of modern society. Emissions of Carbon Dioxide (CO_2), sulphur and nitrogen compounds, hydrofluorocarbons (HFC) and perfluorocarbons (PFC) are to be reduced and controlled, for global warming and other several environmental impacts threaten the well-being of humankind and nature.

Current research is strongly focused in the development of efficient means to store energy, and while there is presently not sufficient technology in factual use, there are different methods that have positive future perspective: hydro-pumped water plants, hydrogen cells, molten salts and flywheel energy storage among others.

Hydrogen molecule is rather interesting in terms of energy storage. It can be turned into energy both by electrolysis and combustion with high performance rates, producing no harmful or polluting gases, and giving water as the only product. It can also be stored and transported, although it is highly explosive and must be contained cautiously. The main limitation of hydrogen technology is the means in which the hydrogen molecule, which is not naturally present in nature, is obtained.

In order to produce this hydrogen there are several methods: electrolysis of water, pyrolysis of organic compounds and steam reforming of fossil fuels. Electrolysis of water is among the most important. To do so, and input of energy is needed, so that the molecule of water will divide into a molecule of oxygen and a molecule of hydrogen (Reduction-Oxidation chemical reaction). One possible way to obtain this energy is to equip an already existing power plant with an electrolyzer, so that when there is a higher production than consumption in the electric network, the spare energy can be used to produce hydrogen.

In this Bachelor Thesis it will be studied the feasibility of operating the hydro power plant (HPP) which is already situated on the river Sava (Hydro-power-plant Brežice) together with a electrolyzer for production of hydrogen, thus giving the facility additional functionality.
Hydroelectric energy is based on the principle of obtaining energy out of the potential difference of a stream of water, easily transforming it into electricity by means of a water turbine, attached to an electric generator. For this reason hydroelectric power plants are always located in rivers, reservoirs, dumps… It is the most ancient power plant developed by human to generate electricity, and has been hitherto used as a main source of energy production.

This is due to the several advantages of hydroelectric power plants. It is a renewable source of energy and a primary source. It has the highest performance rates among energy sources, thanks to the use of the electric generator, which usually has a performance rate close to 100 %. The technology used for this energy source is well matured and developed, being strongly reliable. The life time of a hydroelectric power plant is also very high compared to other technologies (high payback time), and the maintenance is considerably low. It can also store energy in great reservoirs. The investment needed for this technology is also smaller compared to a thermal power plant or a nuclear power plant. Asides from technological considerations, hydroelectric power plants are also emissions free, making it a renewable source of energy with low environmental impact.

It is also important to consider the disadvantages of this technology when evaluating the feasibility of it use. These are among the most important: It is usually difficult to locate them close to consumption points, and thus increasing the price of the kWh; it is dependent of the climate, this is, the raining regimes of each year; it requires a very high investment to build a dump and different cost for kWh depending of the power plant type.

There are also environmental impacts to be considered. The most important one being the construction of reservoirs that affect a large area, which must be flooded, thus destroying the previous ecosystem. It is a great impact for flora and fauna, and also a social impact, for many times small populations must be expelled from the basin in where the reservoir will be.

The project is focused on the research of energy storage in the framework of Slovenian electric system, thus giving data on the feasibility of the application of different technologies, and evaluating the functioning of these. For this purpose different constituent projects are being carried out, such as the LCA of a pumped-water energy storage or hydrogen cells. In this Bachelor Thesis a numerical model of a hydropower plant will be developed so that future research can analyse the feasibility of the implementation of electrolyzers to produce hydrogen.

1.2. Objectives

The objectives of this thesis are:

- Bibliographic research of hydropower technology and physic fundamentals.
- Statistical evaluation of hydrology (volume flow data for one-year-period will be provided). Results on water flow regimes and bypass water flow potential are meant to be observed.
- Analysis of the HPP parameters based on the one year data sets provided by the operator in order to detect correlation between water flow, water head and power of the HPP.
- Develop a simplified numerical model that provides power as an output and water head and water flow as input.
- Verify the numerical model out of the data provided by the operators simulating a possible scenario.
- Analyze the water overflow data that goes through bypass and provide descriptive results, using the numerical model to predict the amount of power that could be additionally produced.
- Study the feasibility of implementing the hydrogen electrolyzers using the surplus power that can be obtained from the turbines in points that are not working to their maximum capacity.
- Study the optimal configuration of electrolyzers, both the number of PEMs and the total rated power.
- Provide suggestions for future lines of study about installing hydrogen electrolyzers.

1.3. Methodology

The first step to develop this thesis will be a thorough research of bibliography of hydropower technology and physical fundamentals of hydraulics. A good research work will settle the foundation for quality comprehension of the topic, which is then mandatory to analyse correctly the case at stake.

After the bibliographic research a study of the Brežice HPP will be done, in order to understand the operation of the power plant. For this purpose data sets for year 2019 will be provided by the operators, and then will be sorted, filtered and presented using Microsoft Excel 2010 tools. This data will be the foundation for the development of further steps.

The third step is to obtain analytical and descriptive conclusions out of the obtained data. This mainly comprises the study of water flow regimes, water head and water level difference correlation, water head, flow and power correlation and general averages for year 2019, i.e. power average, maximums and minimums, turbine boundary conditions, turbine regimes, etc Subsequently, once the Brežice HPP has been described by analytical and descriptive means, a mathematical model will be developed using mathematic theory of parameter correlation. To accomplish this, Microsoft Excel 2010 tools will be used.

Once the numerical model has been developed, it will be verified presenting a virtual scenario out of the water flow data for year 2019, and after proving the model valid, it will be used to analyse the energetic potential of the water overflow that is derived through bypass.

Finally, out of the results provided by the model, conclusions will be obtained and presented for future research of the implementation of hydrogen electrolyzers in the Brežice HPP.

1.4. Limitations

The objective of the thesis is to settle the foundation for further analysis of the HPP Brežice by providing a numerical model that can predict the power output in different hypothetic scenarios, in order to understand the feasibility of installing the hydrogen electrolyzers. The calculations of further characteristics of the electrolyzers, the functioning of the same, the economic analysis and the final conclusion of the project are out of the scope of this thesis. This thesis will conclude by verifying that the mathematical model is valid and that it correctly describes (with reasonable accuracy) the functioning of the HPP. Also some calculations of the energy potential of water overflow are provided in the results to provide guidelines for future lines of research, but do not provide with enough profoundness to extract further conclusions.

It should also be pointed out that the calculations are made using data sets of a time spam of only twelve months, because the power plant has been operating only since 2018. This means that hydrological analysis is strongly limited by the amount of data, and that no reasonable statistical approach can be provided. Water flow data is just taken as factual data, but must be clarified that is not representative of any other year, or that it does not represent any tendency or marked behaviour, and that provided values for following years could be completely different.

This sample size limitation also implies that the model will be verified with a scenario made by the same data with which the model was calculated. This reduces the validity of the verification, for following years correlations could not follow current correlations. In this regard the model should prove to have considerable small error so that it can be guaranteed that changes in the value correlations do not affect greatly the final results obtained with the model.

1.5. Outline of the thesis

The thesis has been presented following the normative structure of a bachelor thesis:

- **Introduction:** In this chapter the introductory elements that define the thesis are included. Background presents the current problematics of modern energy perspective and focuses on the role of hydroelectric energy and hydrogen technology in this context. Then objectives and methodology define the scope of the thesis, and how those objectives have been met, by means of the development of the work.

- **Theoretical Background** starts contextualizing hydropower technology by providing historic background and explaining the current situation of hydropower technology in the global, European and Slovenian background. Then some introductory theory of hydraulic physics is provided, sufficient to understand the contents of the thesis. Finally HPP are explained, the constituent elements, the different types and the economical and energetic importance.

- **State of art** will be dedicated to describe the Brežice HPP. It will start by presenting Sava River, which is the river that provides this HPP with water. Afterwards, as this HPP is part of a bigger project of hydropower plants located in the lower Sava River, some basic information will be given for the rest of the power plants. Then the Brežice HPP will be presented and described, providing general and more specific information about elements and working parameters. Subsequently, the parameters that will be used to analyze the power plant will be explained, and then the specific way in which they were provided by the operators will be expounded. The chapter will conclude by providing descriptive information based on the collected data, such as average productions, load duration curve, turbine limits, etc.

- **Numerical model** will present the numerical model that will be calculated out of the previous mentioned parameters. Correlation between water flow, head and power will be analyzed in order to develop the mathematical equations. This will be done both for individual turbines and for the whole power plant. The order that will be follow will be to firstly present the correlation of water head and level difference before and after the power plant. Secondly the water flow will be described. After both water head and flow are defined, both the individual and collective power numerical model will be presented. Finally a shell diagram will be provided using the power values at disposition.

- **Validation of the model** will be used to verify the validity of the numerical model providing a virtual scenario of water flow data from the data sets provided by the HESS operators.

- **Results and discussion** is the chapter in which the results of the model will be presented. These results include the bypass water flow analysis of energy potential and the consequential results for hydrogen electrolyzer installation. The results will be discussed at the same time as they are presented.

- **Conclusions** will present the final closure of the thesis, enumerating the conclusions extracted along the thesis, and providing guidelines for future lines of research.

2. THEORETICAL BACKGROUND

2.1. Historical development

The origin of hydroelectric power goes back to the ancient Greeks, who were the first to transform the power of falling water into useful mechanic energy. They constructed water wheels to grind grain and produce flour. It was not until Middle Age that the hydropower technology finally reached Europe [1].

During the industrial revolution (beginning of 1800's) hydropower energy was used to power textile and different machine technologies, being of vital importance to the development of industries.

In 1831 the discovery of the electric generator by Michael Faraday laid the foundation for the first hydroelectric power plant in 1882. It was located in Appleton, Wisconsin, and began to generate in the aforementioned year, with a rated power of 12.5 kW [2].

In few years the number of hydroelectric power plants in the US increased greatly. In 7 year time the number of them reached 200, and along the 19th century these installations got an increased attention all over the world, which lead to a commercial outbreak of this technology, and the construction of hydroelectric power plants in all suitable areas all around the world.

During the first half of the 20th century hydroelectric energy became the first source of electric energy in the world. In 1936 the largest hydroelectric power plant hitherto was built in the Colorado River: the Hoover Dam, with a rated power of 1345 MW.

In 2008 the Three Gorges Dam was built in China, the largest power plant currently in function, with an installed rated power of 22 500 MW.

2.2. Current state

2.2.1. Global

Although hydroelectric energy is a mature technology and great part of the global available hydroelectric potential sites have already been exploited, the tendency of installed power per year is still growing. Countries with emergent economies like China, India, Brazil or Turkey are among the ones with most new installed power capacity in hydroelectric energy [3].

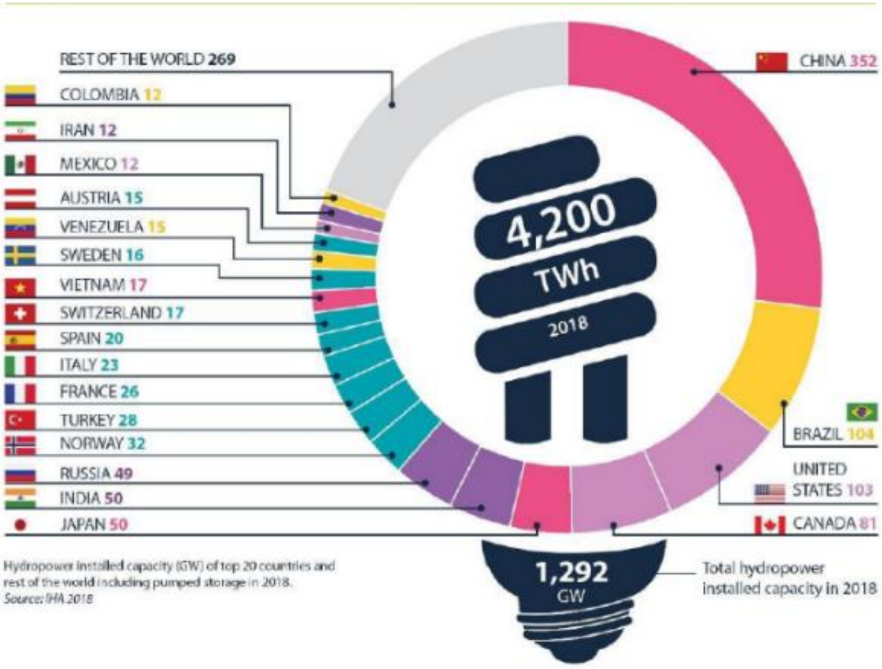

Figure 1. Hydropower installed capacity worldwide [4].

In 2008 the energy generated by hydroelectric energy worldwide reached an estimated value of 4200 TWh, being the highest energy production from a renewable source of energy.

In 2019 approximately 21.8 GW were installed of hydroelectric power, including almost 2 GW of pumped-storage hydroelectricity, which increases the total global installed capacity to 1292 GW.

In 2018 East Asia and the Pacific region where the ones to increase their hydroelectric potential the most (9169 MW), followed by countries in South America (emergent economies) (4855 MW). Countries in South and Central Asia follow with an installed power of 3962 MW. The installed capacity in Europe is 2202 MW, followed by Africa (1009 MW) and North and Central America (620 MW).

Figure 2. New installed capacity by region [4].

Since the mid-20th century the rate of increase of "new installed power capacity of hydroelectric energy" has remained constant in a global overview. Nonetheless, when analyzing by regions, the increase in installed capacity is strongly dependent of the depletion of available locations for hydrological exploitation. In countries of Europe and United States the growth is considerably smaller for most of the hydrological potential is already in use.

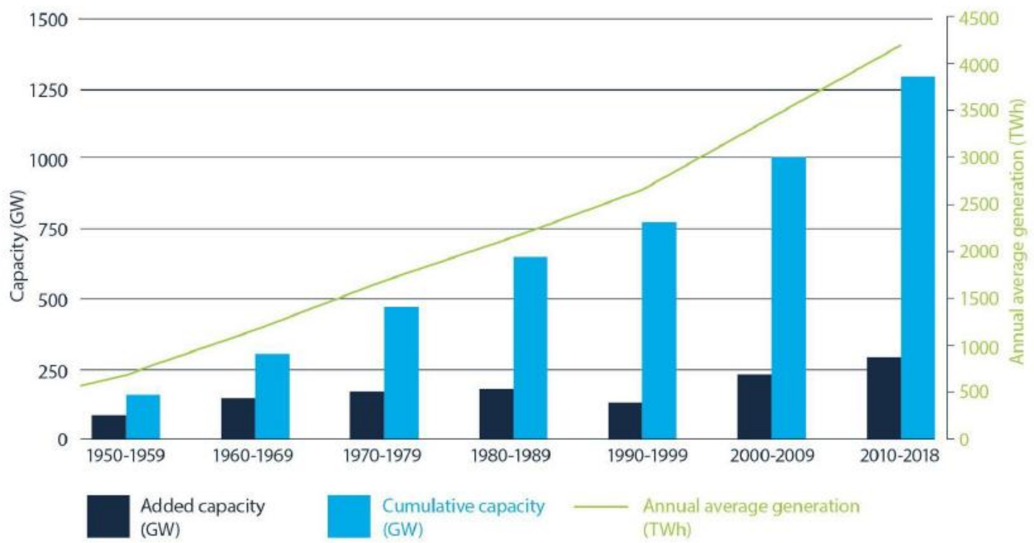

Figure 3. Hydropower growth through the decades [4].

2.2.2 European Union

In the European background the installation of renewable sources such as hydroelectric power is of greatest interest, for it will help to reach the environmental objectives set in the respective climate summits, and the legal framework settled by the European Union to reduce climate change. The targets for the year 2020 were the following:

- 20 % cut in greenhouse gas emissions (from 1990 levels)
- 20 % of EU energy from renewables
- 20 % improvement in energy efficiency

These objectives were settled in 2007 by European leaders and enacted in legislation in 2009. This objectives are translated into a national approach in the means of national actuation programs different for each EU country, to stablish an operation path to follow in the achievement of the development of renewable sources of energy (RES).

For this reason the implementation of renewable sources of energy such as hydroelectric energy are of upmost importance. In the following figure the installed hydroelectric power capacity for some EU countries is visible.

Table 1. Total installed capacity by country

Country	**Total installed capacity (MW)**
Norway	32 256
Turkey	28 358
France	25 519
Italy	22 926
Spain	20 378
Switzerland	16 948
Sweden	16 466
Austria	14 535
Germany	11 258
Portugal	7 347

In 2018 Norway was the country with the highest installed capacity (32256 MW). Turkey followed closely (28358 MW), although the later had a higher increase rate in installed capacity (1085 MW in 2018), being the country in Europe with the fastest increase rate. France, Italy and Spain follow with similar installed capacities among them (20378-25519 MW) [4].

2.2.3 Slovenia

Slovenia, as part of the European Union, shares together with the neighbouring countries the same targets towards climate and environmental protection. The energy actuation plan is covered in the National Renewable Energy Action Plan (Ministry of Economy) and National Energy Program (IJŠ4) [5]. The aforementioned documents do not foresee any active increase in RES and energy efficiency (EE) in a long-term in regard to energy industry development. Moreover the documents do not include any practical measures to implement the changes that could help reach the targets settled in the EU (20/20/20). In Figure 4. it is possible to see the electricity consumption per capita and the share of renewable sources of energy in electricity production in Slovenia. Between years 2000 and 2005 a clear increase in energy consumption is visible, which remains approximately constant till 2008, when there is a reduction in energy consumption due to the economic crisis (usually economic growth and energy consumption go together). The share RES decreased between 2000 and 2007, however since 2007 it has steadily increased. This is the result of both increase of RES and decrease in fossil fuels consumption. The current Slovenian energy strategy does not focus on the reduction of fossil fuel production, and it is foreseen to install a 600 MW thermoelectric power plant (TPP).

In the hydroelectric aspect, Slovenia commissioned the 45 MW Brežice project during 2018. It is the fourth of a five project cascade along the Sava River, which include the already completed Boštanj, Blanca and Krško projects and the planned 28 MW Mokrice project, a further 10 kilometres downstream.

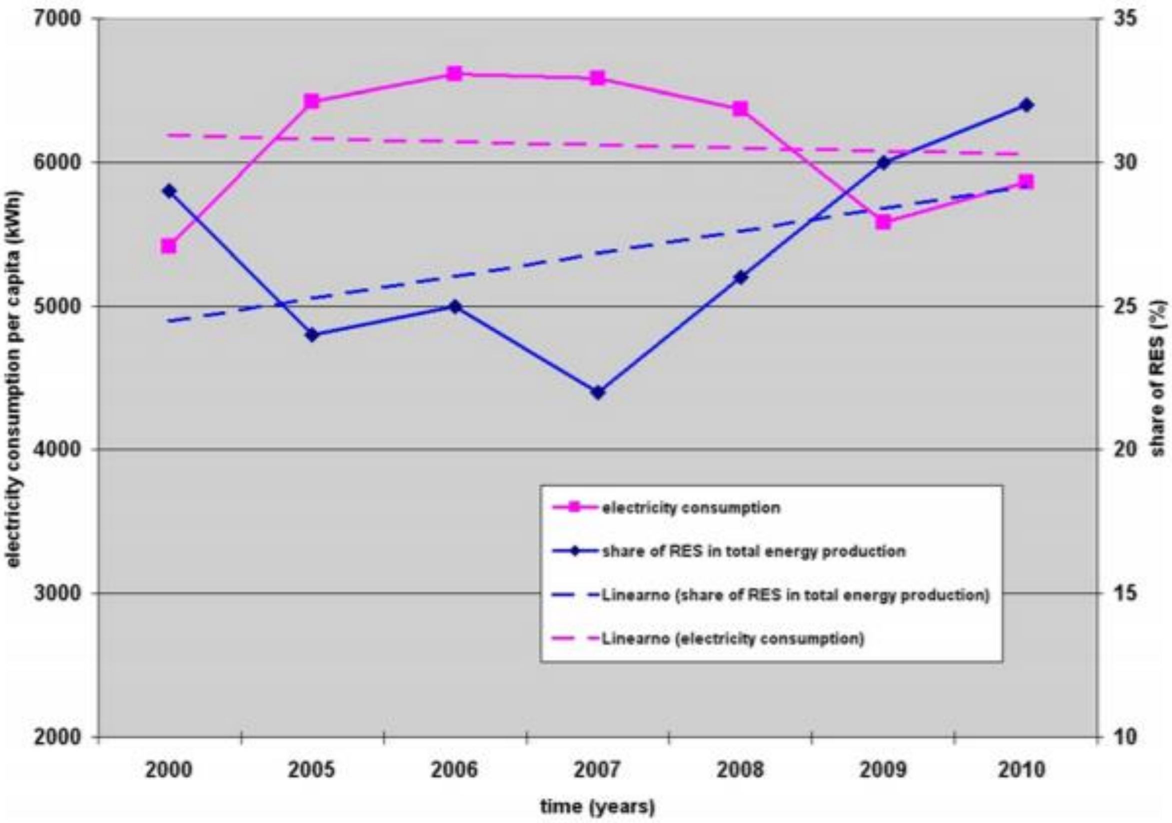

Figure 4. Electricity consumption and RES in total energy production in Slovenia [6].

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2.3. Physical and technical concepts in hydropower

2.3.1. Introduction

The analysis of the physics involved in hydropower can be approached in different ways. There are several processes to be analysed and that have respectively different approaches: the general process of potential differential in a water stream, the functioning of the turbine and its geometry, the functioning of the electric generator, energy losses…

The focus of this thesis is not on the technical aspects of the technology of hydroelectric power, but rather on its functioning and statistical data for optimizing the working regimes. For this reason only the topics of upmost interest for the project will be approached in the physical concepts; that is the energetic consideration of the water stream potential differential and some general approach to the turbines.

2.3.2. Hydraulics in hydropower

- **Energy-work approach**

The "Energy-Work approach" is one of the most elementary approaches to the hydraulic phenomena. It derives from the simple Newtonian Laws of dynamics and energy balance in a deferential portion (d*V*) of water.

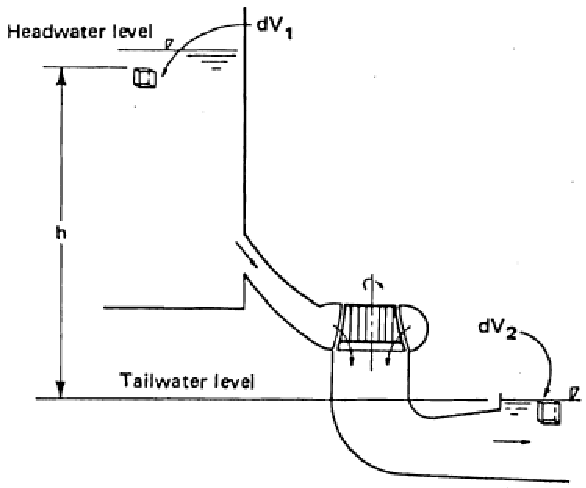

Figure 5. Diagram for developing turbine theory [7].

$$F = m \cdot a \tag{2.1}$$

$$W = \mathrm{d}V \cdot \rho \cdot g \tag{2.2}$$

$$W = F \cdot d \tag{2.3}$$

$$\mathrm{d}W = \mathrm{d}V \cdot \rho \cdot g \cdot h \tag{2.4}$$

Where:
m = mass, kg
a = acceleration, m/s²
W = weight, N
W = work, J
dW = work done by elemental mass of fluid
dV = elemental volume of fluid
g = acceleration of gravity
ρ = density of water
h = vertical distance moved by the elemental volume of water

Equation (2.4) stands for the difference of energy between the differential portion of fluid 1 ($\mathrm{d}V_1$) and differential particle of fluid 2 ($\mathrm{d}V_2$). If the differential particle of fluid moves in a differential unit of time ($\mathrm{d}t$) then the differential discharge of fluid is noted as:

$$\mathrm{d}q = \frac{\mathrm{d}V}{\mathrm{d}t} \tag{2.5}$$

Where
dq = elemental discharge
dt = diferential time

Power is the rate of energy (or work) per unit of time (P). Considering the aforementioned equations power can be noted as:

$$\mathrm{d}P = \frac{\mathrm{d}W}{\mathrm{d}t} \tag{2.6}$$

Substituting in Equation (2.4):

$$\mathrm{d}P = \frac{\mathrm{d}V \cdot \rho \cdot g \cdot h}{\mathrm{d}t} \tag{2. 7}$$

$$\mathrm{d}P = \frac{\mathrm{d}q \cdot \mathrm{d}t \cdot \rho \cdot g \cdot h}{\mathrm{d}t} \tag{2. 8}$$

$$\mathrm{d}P = \mathrm{d}q \cdot \rho \cdot g \cdot h \tag{2. 9}$$

Where
dP = elemental amount of power

Integrating the elemental power components the equation is as follows:

$$P = Q \cdot \rho \cdot g \cdot h \tag{2. 10}$$

Where
Q = water flow, m³/s

This is only the theoretical result, since performance of the turbine and various elements must be considered (η), resulting in the following:

$$P = Q \cdot \rho \cdot g \cdot h \cdot \eta \tag{2. 11}$$

- **Bernoulli energy equation approach**

Bernoulli approach derives from the use of the "Bernoulli Energy Equation", which is an energetic simplification from Reynolds Transport Theorem, commonly used to analyse energy balances in fluid dynamics. It is based on the mathematical development in terms of energy grade lines and hydraulic grade lines. The Bernoulli equation is as follows:

$$\frac{V_1^2}{2g} + \frac{p_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + Z_2 = constant \qquad (2.\ 12)$$

Where:
V_1 = water velocity at point 1
p_1 = water pressure at point 1
γ = specific weight of water
Z_1 = potential head at point 1 referenced to the datum
V_2 = water velocity at point 2
p_2 = water pressure at point 2
Z_2 = potential head at point 2
hf = head loss in flow passage between points 1 and 2

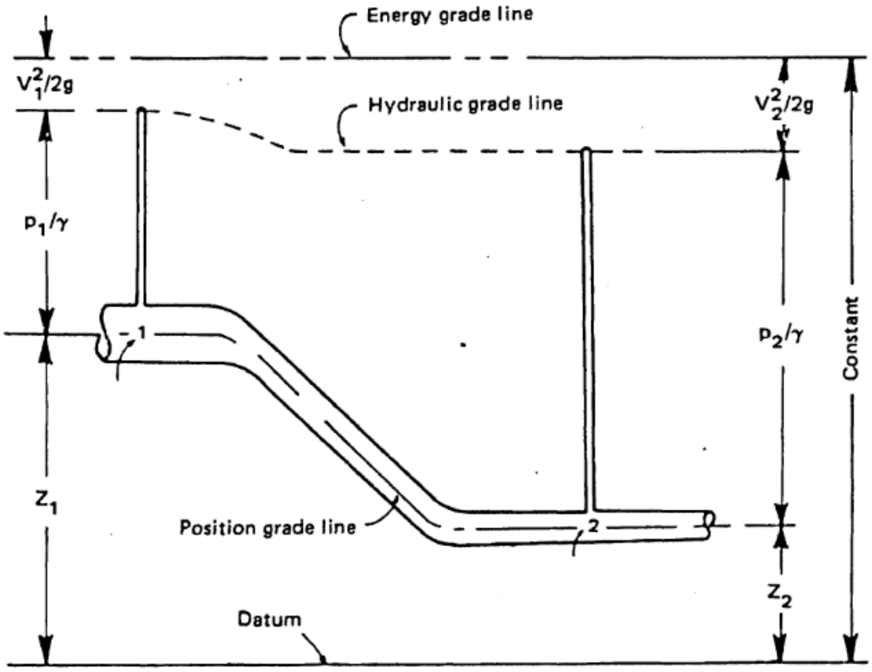

Figure 6. Bernoulli diagram relating energy grade lines and hydraulic grade line [7].

Each term of the Bernoulli equation refers to different types of energy that a confined fluid possesses: $V^2/2g$ as for kinetic energy, P_1/γ as for pressure energy and Z_1 as for potential energy. The Bernoulli equation states that the sum of these terms remains constant for a confined moving fluid along the path of that fluid. For this to be true there are some considerations to be made. The most important one is the condition of reversibility. It must be admitted that the process is reversible, that is, that in the hypothetic case of reversing the process, this could be possible, or in terms of entropy, the entropy differential between state A and B should be zero. This reversible conditions are translated in terms of having an adiabatic process (process in which the control volume does not exchange energy with the surroundings) and ignoring effects of non-laminar flow (turbulence). The aforementioned, in mathematical interpretation, implies that any change at any of the parameters in the equation at certain point, must be compensated by another parameter in that very same point. This is for example the phenomena that can be easily appreciated in the Venturi effect, where a narrow section of conduction increases the speed of water at expense of its pressure:

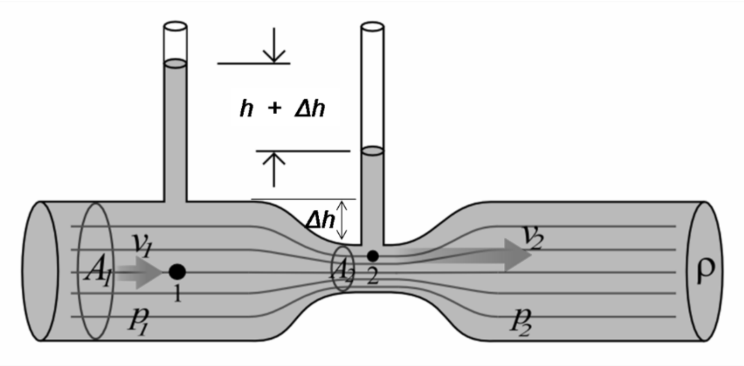

Figure 7. Venturi effect [8].

In the real approach there are some losses that must be taken into account, which are related to the friction between the water stream and the walls of the conduction, and minor losses in corners, internal elements like valves, filters, turbines… This losses are introduced in the equation like an additional term, usually represented by h_f, and referred to as *head losses*. In Figure 8 they are represented as a grade line lower to the Gross Head, and delimit the actual *Effective head*.

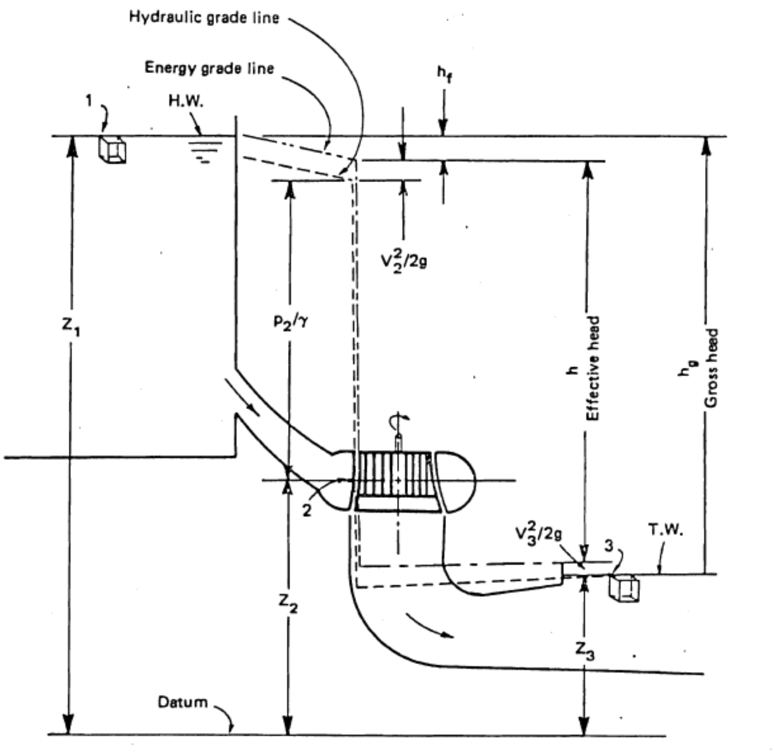

Figure 8. Grade line diagram for effective and gross head [7].

In terms of the equation, for a hydropower installation which takes water from point 1 (at the surface of the water input) to point 2 (at the entrance of the turbine) the equation is noted as follows:

$$\frac{V_1^2}{2g}+\frac{p_1}{\gamma}+Z_1=\frac{V_2^2}{2g}+\frac{p_2}{\gamma}+Z_2+h_f \qquad (2.\ 13)$$

The Bernoulli equation from point 2 (entrance of the turbine) to point 3 (surface of the water at the exit of the conduction) would be as follows:

$$\frac{V_2^2}{2g}+\frac{p_2}{\gamma}+Z_2=\frac{V_3^2}{2g}+\frac{p_3}{\gamma}+Z_3+h \qquad (2.\ 14)$$

To analyse the real case of a hydraulic power plant there are some simplifications to be made, that are acceptable for the case of study for the little impact of its parameters. This simplifications are to consider the pressure in p_1 and p_3 equal to zero, for they are open to the atmosphere and they have atmospheric pressure (in the relative pressure measuring). Also the water velocity in point 1, V_1, where the water is supposed to be remnant is considered zero.

Solving for p_2/γ the equation is as follows:

$$\frac{p_2}{\gamma}=Z_1-\frac{V_2^2}{2g}-Z_2-h_f \qquad (2.\ 15)$$

Solving for h in the Equation (2. 14) the result is:

$$h=\frac{V_2^2}{2g}+\frac{p_2}{\gamma}+Z_2-\frac{V_3^2}{2g}-Z_3 \qquad (2.\ 16)$$

Substituting p_2/γ in the previous equation the result is:

$$h=\frac{V_2^2}{2g}+\left(Z_1-\frac{V_2^2}{2g}-Z_2-h_f\right)+\left(Z_2-\frac{V_3^2}{2g}-Z_3\right) \qquad (2.\ 17)$$

$$h=Z_1-Z_3-h_f-\frac{V_3^2}{2g} \qquad (2.\ 18)$$

This result is the *effective head*, which stands for the actual energy that can be transformed into work, and that is not lost into friction and general losses, represented in Bernoulli equation as an energy line lower to the Gross head line. Now the Equation (2. 11) of the previous "Energy-Work approach" can be combined with Equation (2. 18), substituting the *effective head* in the height, H, of the previous.

2.3.3. Physical phenomena in turbine

The turbines are the elements that transform the kinetic energy of water into mechanical energy that can be transferred to the axis of the electric generator. The physics involved in this are related to the dynamic action of water on the buckets and vanes of the turbine, and it is essential for the derivation of different turbine constants [7].

- **Kinetic Theory**

Figure 9. represents the action of a water jet against a vane or bucket and illustrates the section of the water stream deriving through the shape of the blade. The equation that describes the jet action (in terms of force) of the water is as follows:

$$F = \frac{W \cdot v}{g} \cdot (1 - m \cdot \cos\theta) \tag{2. 19}$$

Where:
F = dynamic force on the vane
W = weight of water striking vane
g = acceleration of gravity
v = relative velocity of the jet of water with respect to the moving vane
m = coefficient accounting for loss of velocity moving across vane
ϑ = angle of deflection of jet from the original jet direction

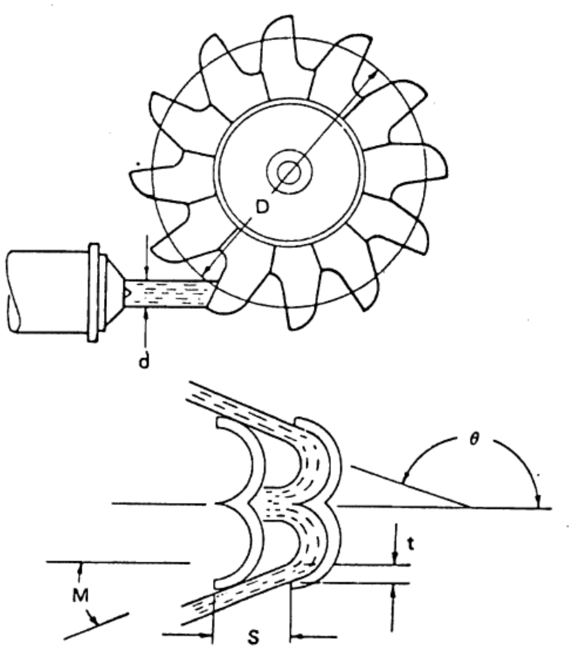

Figure 9. Action of water jet against Pelton turbine bucket [7].

Theoretically the optimum angle of deflection is 180º, for the $m{\cdot}\cos\theta$ would be valued zero and the force done in the bucket would be maximum. Nonetheless, for technical purposes the angle of the bucket is generally 165º, so that the water stream does not collide against the previous bucket and can be expelled.

- **Similarity Laws**

The following epigraph will only be covered descriptively, for it is not of upmost interest to the scope of this thesis to profound in practical considerations of the build-up of the turbine. Nonetheless it is important to mention and briefly explain the purpose of the Laws of Similarity.

The Laws of Similarity are used to characterize the turbine performance of different turbine size and type. Given already built turbines of similar geometry and linear ratio, it provides the possibility to predict the functioning of a non-built turbine of a similar design. This is often called “the homologous nature of turbines”.

To turbines of different size which have a common geometric ratio and linear dimension correspondence the name of homologous is given. Those turbines are expected to have proportional power outputs, speeds, and flow specifications and usually share same efficiencies. The laws of similarity are thus given in the form of the so-called *turbine constants*, which are formulas derived from fundamental concepts of hydraulic and mechanics theory [7].

2.4. Hydroelectric power plants

As a previous step to the development of the project it has also been considered important to explain the functioning and characteristics of hydraulic power plants, and introduce some basic concepts about the machinery of the before: turbines and generators.

As it has been said before, the basis of hydraulic power plants is to use hydraulic energy and transform it into mechanic energy by the means of a turbine, and then transform the mechanic energy into electric energy by means of the generator.

The hydraulic principle is based on the potential energy that a mass of water possesses in the natural basin of a river given for the level difference. In this fall of water between the two levels of the water basin, the stream is used to propel the turbine, connected to the generator which produces electric energy [9].

2.4.1. Components

Now the components of a hydroelectric power plant will be explained, in order to give further understanding of the project in study. This elements have been chosen for they are the general elements that hydroelectric power plant might have. Some of them are specific for a type of hydroelectric power plant.

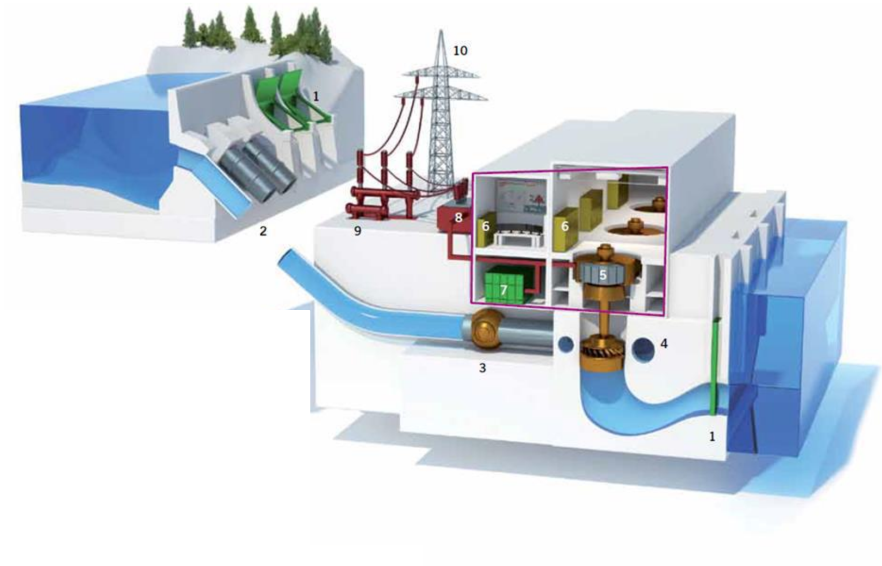

Figure 10. Scheme of a HPP. Elements [9].

- **Dam**

The dam is an essential element for some types of hydroelectric power plants. It has the function to contain the water of a river and store it in the reservoir. The construction of the dam creates a water level before contention different to the water level after contention, thus creating a level difference useful to turbine the water stream and produce energy. The shape of the dam is strongly dependent on the landscape and orography and on the course of the water of the area where the reservoir is to be constructed. Depending of the materials to be used, dams can be classified into two major types, concrete dams and earthen dams. There are more materials to be used, but these are the most important [10].

Concrete dams are the most resilient and the most used ones. Depending on the structure they can be classified into:

- Gravity dam: These are really long lasting and do not need maintenance. Their height is limited by the resistance of the landscape. They have triangular shape and a wide basement that goes thinner as it goes upper.

- Arch dam: The wall of this type of dam is curved in the form of an arch. The pressure of the water is almost entirely transmitted towards the walls of the valley where the dam is, thanks to the effect of the arch shape. When situation is favourable, the arch dam needs less concrete to be built than the gravity dam, but it is sometimes difficult to find places where they can be constructed.

- Buttress dam: It is made of a wall that holds the water and a series of buttresses or pillars of triangular shape that hold the contention wall and transmit the pressure of water towards the basement. They are generally used in terrains with low stability and are not cheap to build [11].

- **Conductions**

The water reaches the turbines through a complex system of canalizations. In the case of channels, there can be dug in the soil channels and channels of solid structures made of concrete. Their construction is always dependent on the conditions of the landscape. Sometimes the best option is to construct a penstock when the soil conditions are not the best, although the investment is bigger. The last part of the conduction of water from the charge chamber to the turbines is done by a penstock. For the construction of these pipes steel is used in the case of hydraulic jump up to 2000 meters and concrete for the case of up to 500 meters [11].

- **Intake**

The water intake is the element that gathers the water and allows it to head to the turbines chamber. The water intake is located in the wall of the dam where it is contact with the stored water of the reservoir. They are equipped with gates that regulate the water intake and racks and filters to prevent unwanted object that could damage the vanes to go though such as branches, logs, animals, etc.

- **Surge tank**

In transitory regimes of change of load in the turbine the valves of the power plant are opened or closed, creating and increase or decrease in pressure all along the penstock. This is the so-called water hammer phenomenon, which threatens to damage the conductions if they are not resistant enough. To prevent this damage in the conductions something is needed to alleviate the variation of pressure.

One of the main methods to cushion this pressure variations is to use a surge tank, which consists of a reservoir or tank opened to atmosphere. When there is a pressure increase the water level rises, transforming the pressure into potential energy, serving as a sort of spring to absorb the mechanic impulse of the transitory effect of the water hammer phenomenon. When there is a reduction of pressure the level of water in the tank goes down compensating the low pressures of the pipe. During one transitory there are usually several and consequential increases and decreases of pressure, due to the compression effect of water (although water is usually regarded as a non-compressible fluid, this is an approximation that for the case of water conductions in power plants is not valid, and compression phenomena of water must be taken into account).

In the case of open channels surge tanks are not necessary, for the pressure of the water is atmospheric. In the case of close conductions the water pressure is high and surge tanks are necessary to limit the abnormal conditions, although there are some other methods to prevent the suffering of the conduits, for example a fore bay.

The location of the surge tank depends on the size of the power plant. Whereas in small power plants the surge tank is usually at the inlet of the turbine, in medium and high head power plants the size of the surge tank would be excessive. The usual location is in between the penstock and the pressure tunnel. It is also important that the surge tank is as closest as possible to the power station and as closest as possible to the ground level to reduce the size of the tower.

- **Turbine**

The turbine is the element that receives the high energetic water and transforms kinetic energy into mechanical energy. It is at the end of the pressurize conduit and then releases the water back. It is coupled with the generator which transforms mechanical energy into electric energy that then is connected to the electric system.

- **Gear box**

It is a box of gears attached between the electric generator and the shaft of the turbine. It is installed in those cases in which it is needed to increase the speed of the shaft in order to reduce the number of magnetic poles in the electric generator.

$$p = \frac{f \cdot 60}{n} \qquad (2.\ 20)$$

Where:
p = number of poles
f = frequency of the generator (Hz)
n = turning speed of the shaft (rpm)

Reducing the number of magnetic poles the size of the electric generator is smaller, thus reducing the costs.

- **Electric generator**

The electric generator is a rotatory electric machine that transforms mechanic energy into electric energy. Generators are usually divided into two groups: alternators, which produce alternate electric current (usually in three-phase) and dynamos, which produce direct electric current. There are two different types of alternators that can be found in a hydropower plant, the asynchronous generator and the synchronous.

- Synchronous generator
The main characteristic of the synchronous generator is that it has a spinning speed strictly defined by the frequency and the number of pole pairs. According to the way of producing the excitation there are two types of synchronous generators: excited and with permanent magnets [12].

The synchronous generators of excitation are made by a rotor with mechanized gaps on the periphery that allow to twine a coil around itself, which circulates a direct current responsible to create the magnetic field that allows the rotor to work. This induced magnetic field allows to regulate the intensity of itself, which increases the operational possibilities. On the contrary, brushes are needed to power the current in the rotor, producing losses and maintenance problems. Besides the coil has considerable Joule losses.

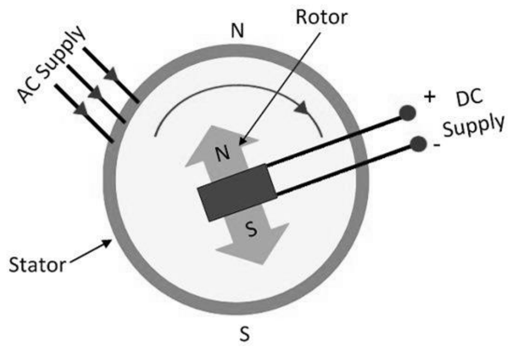

Figure 11. Synchronous motor [13]

The synchronous generator with permanent magnets has two clear advantages. On the first place there is no need for the brushes that power the coil and there are not as many Joule losses as in the previous. This advantages make the performance of this generator higher. In the other hand the magnets allow to have smaller poles, which is of great use in the multipole generators. As a disadvantage it has the problem of control loss for the magnets cannot vary their intensity, and this control limits the operating point of the machine. To finish with, this generator is less capable of producing high power.

- Asynchronous generator

The most used types of asynchronous generator are the coiled rotor and the squirrel-cage rotor. The squirrel-cage rotor consists of a cage shaped structure, which two circular joints and longitudinal bars that go from one top to the other. The bars are made of conductive material, usually copper or aluminium. The endings of these bars are short-circuited by means of the conductive tops of it, which are called short-circuit rings. The advantages of the asynchronous squirrel-cage rotor generator are that it is pretty solid, cheaper to build and less heavy than similar asynchronous machines. Also the maintenance of this generator is considerably easier and cheaper [12].

The asynchronous generator with coiled rotor consists of a three-phase winding around the rotor quite similar to the winding in the stator. The three phases are usually connected in star configuration, and the other three free endings are connected to conducting rings, isolated from each other and from the shaft. Over this conducting rings there are some graphite brushes. One of the advantages of this generator is that external resistances can be connected to this conducting rings in order to reduce the starting currents, which by default tend to be too high. It also allows to improve the characteristics of the torque and to control the spin speed of the rotor. As disadvantages, the construction of this type of generator is more expensive due to the used materials and for the assembly. It is also heavier, more complex, and voluminous and requires higher maintenance.

2.4.2. Types of hydropower plants

Hydroelectric power plants can be classified according to different criteria. The main two criteria are classifying according to the rated power and according to the characteristics of the hydroelectric power plant.

HPP classification according to rated power

- Micro hydropower plant: Up to 100 kWs
- Small hydropower plant: Less than 10 MWs
- Large hydropower plant: Less than 30 MWs

The criteria of rated power is not strictly defined, and the ranges differ from one source to another. The given ranges in this case are given by the U.S. Department of Energy [14].

HPP classification according to facility type

- **Impoundment**

This is the most common type of hydroelectric facility. The main characteristic is the construction of a dam that creates a reservoir of water that allows to control the water level. Water is passed through the turbines to produce electricity and also to control the water level of the reservoir.

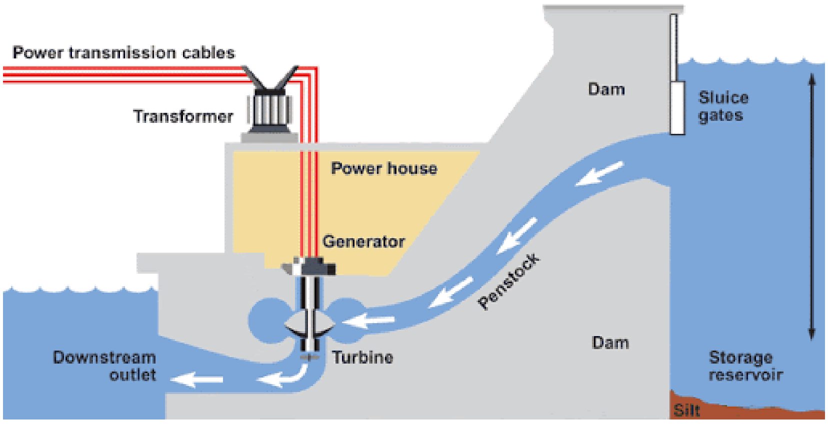

Figure 12. Impoundment HPP scheme [15].

- **Diversion or run-of-river**

The water is deviated from the natural course by canals or penstocks to pass it though the turbines to produce electricity. It may or may not need the construction of a dam.

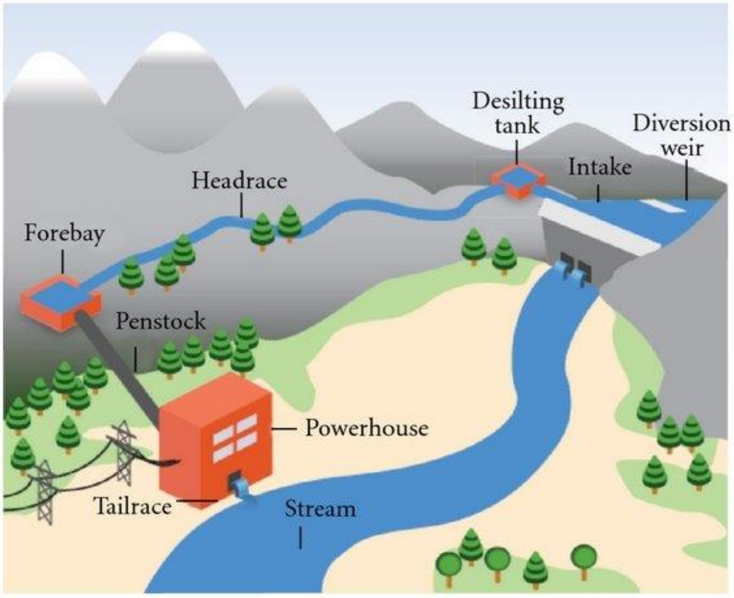

Figure 13. Diversion or run of river HPP scheme [16].

- **Pumped storage**

This type hydroelectric power plant works as a battery to store energy in the form of potential energy. When there is a surplus of energy, from any different source like wind energy, solar energy, hydropower and so on, water can be pumped from a lower reservoir to a higher level reservoir. This allows that when there is a need of energy, or when the electric market has the highest prices for energy, water can be passed by back to the turbines to produce electricity.

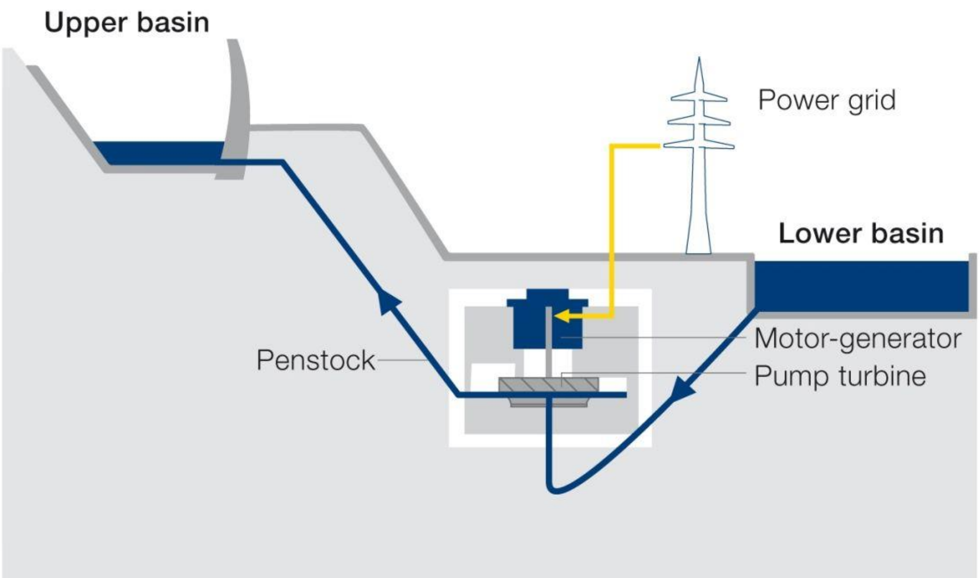

Figure 14. Pumped storage HPP scheme [17].

2.4.3. Types of water turbines

The turbine is key in the functioning of the power plant and it is one of the most complex elements of it. The turbine is the responsible to turn kinetic energy into mechanic energy, and for this reason it is of upmost importance to choose the best fitting turbine, in order to get the highest performance rates possible out of the water source. The design of the turbine implies complex calculations of geometry, hydraulics and mechanics. There are some rules to typify the function of turbines, as the aforementioned similarity laws.

There are also different ways to classify hydraulic turbines. In the following table there are three different criteria to classify them:

- According to the flow path of the liquid.
- According to pressure change.
- According to the direction of the shaft.

Table 2. Classification of turbines according to different criteria.

FLOW PATH OF THE WATER		PRESSURE CHANGE		DIRECTION OF THE SHAFT	
Axial Flow	Water enters the impeller parallel to the shaft	**Impulse**	The collision of water and the direction of spin of the impeller goes is coincidential to the point where the water impact the vanes.	**Horizontal**	Axis parallel to the ground
Radial Flow	Water enters the impeller in radial direction	**Reaction**	The spinning of the impeller does not concur with the direction of entrance and exit of water. It uses the kinetic and pressure energy to move the impeller. Pressure is lower at the exit than at the entrance.	**Vertical**	Axis perpendicular to the ground
Tangential Flow	Water hits the impeller tangentially			**Tilted**	Axis forming certain angle with the ground

- **Pelton turbine**

Pelton turbine is also known as tangential hydraulic wheel or Pelton wheel. It is a tangential turbine, of impulse and usually horizontal. It has a specific working conditions that make it more suitable for certain conditions: big hydraulic jumps, superior to 200m and small water flow. The design is simple, compact and wheel shaped. The main elements are the buckets, deflectors, or split movable vanes located around its periphery.

The water surrounds the turbine by a channel called distributor that allows the water to enter the impeller tangential to the vanes. Along the distributor there are different wholes that give entrance to the water in the impeller chamber.

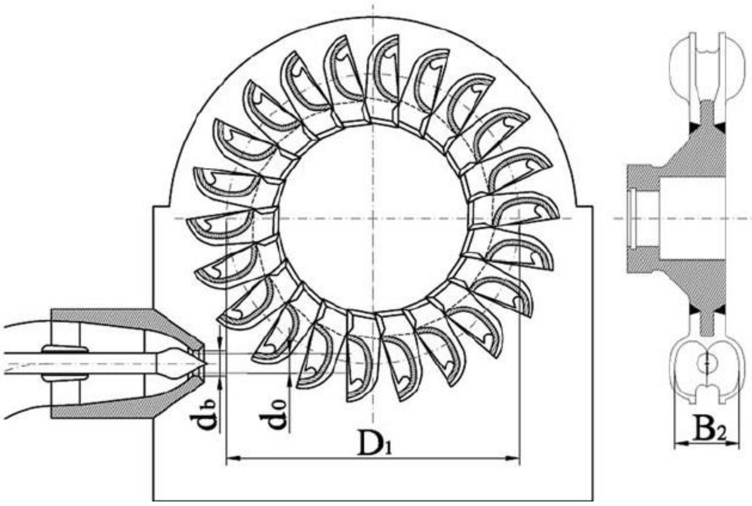

Figure 15. Pelton turbine scheme [18].

- **Francis turbine**

Francis turbine is a radial-axial turbine of reaction and usually with vertical shaft, although it can also have horizontal shaft. It can be designed for a varied range of hydraulic jump heights and water flows, being suitable for jumps of 2 meter high up to hundreds of meters. Nonetheless it is usually installed for intermediate jumps of less than 200 meters. In terms of the water flow it ranges from 2 to 200 cubic meters per second.

The water flow in the turbine entrance is controlled by the distributor, which are some guiding vanes of circular shape around the impeller. To allow the variation of flow in the turbine this vanes have free movement. In this kind of turbines water enters the impeller in perpendicular direction to the axis of the turbine, and leaves the chamber parallel to the axis.

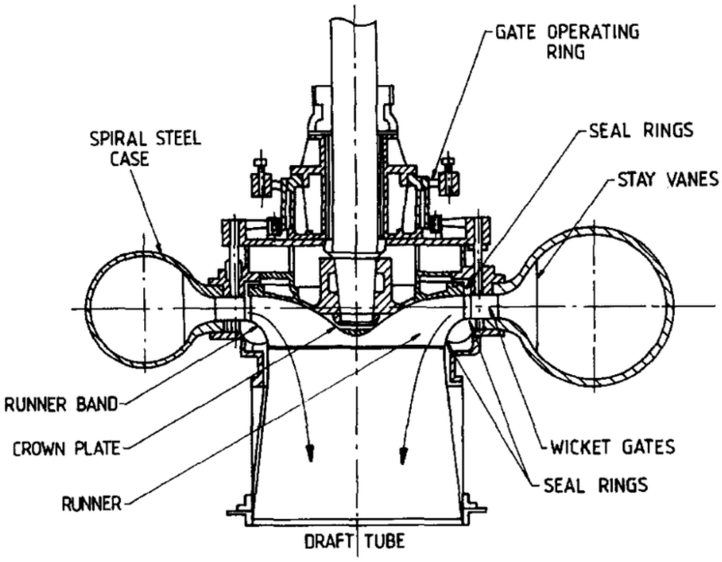

Figure 16. Francis turbine scheme [19][18].

- **Kaplan turbine**

Kaplan is a radial-axial pure reaction turbine, usually of vertical axis. The range of use of this turbine is much more specific in comparison to the Francis turbine: usually short distance hydraulic jumps of up to 50 meters and big water flows that easily overpass the 15 cubic meters per second.

The vanes of the impeller in the Kaplan turbines are always movable and have helical shape, while the vanes of the distributor can either be fixed or movable. If both vanes are movable the turbine is usually referred as a “True Kaplan”; if only the vanes in the impeller are movable, the turbine is said to be “Semi-Kaplan”. Semi-Kaplan turbines can either be axial or radial flow, while the conventional Kaplan are always of axial flow.

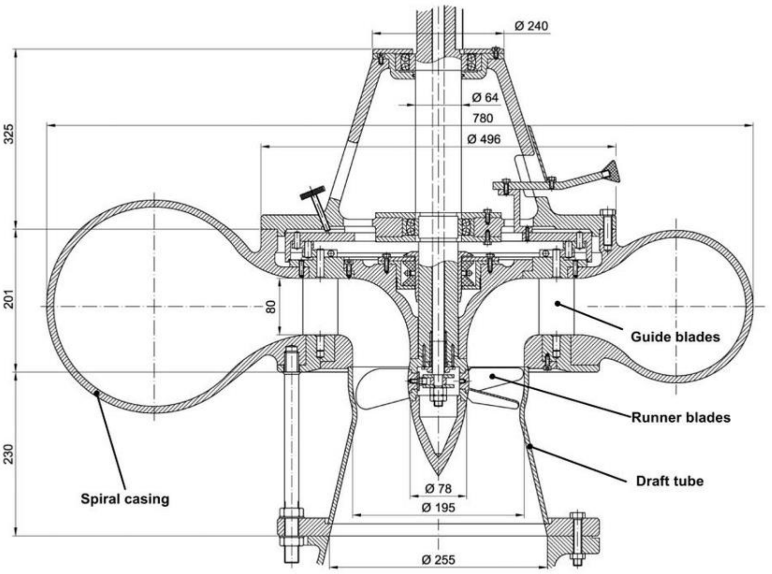

Figure 17. Kaplan turbine scheme [20].

2.4.4. Economy and energy market in hydropower plants

The construction of hydraulic power plants must be extremely precise and optimized in order to reduce costs, both for the magnitude of the project and for the limited resources and natural enclaves. The investment capital is very high in the beginning, although then the lifespan of the power plants is really long (50, 100 or even more years). On the opposite the costs associated to maintenance and exploitation are relatively low. For these reasons project decisions must be taken thoughtfully and after a thorough research of all the available possible solutions [22].

The variables to take into account are multiple, but the main question is up to which point the obtained production justifies the costs of the implementation of the hydraulic power plant. There is an evident technic limit as to which resources are depleted. Nonetheless, before reaching that limit there is usually an economic limitation. These are the main things to take into account:

- Where is the damn located and which dimensions.
- Which water flow will the power plant use and how to dimension the conductions.
- Which section should the pressurize water pipe have.
- Whether to construct an interior (subterranean) or exterior power plant.
- Which rated power will the power plant have.
- How many turbines to install.
- How to divide the water needs for irrigation, power production and water supply.

There are usually two considerations in the economic analysis of the power plant. One is the technical optimization and the other is the economical optimization.

The technical optimization consists on giving the most economical solution to a technical problem among all the different technical possibilities. It is understood for this consideration that all the basic parameters are already solved and fixed and that productivity is not going to be affected by the chosen solution. For example, given a location and height of a dam, the technical optimization would consist in finding the most convenient type of dam, in economic terms. Another example is that given the level difference and the water flow for a channel, to find the best type of coating, diameters, tracing…

The economical optimization implies combined considerations of costs and production. The aim is to compensate the initial investment for a given solution, with the profit obtained all along the lifespan of the power plant. This optimization is the one that ultimately defines the scale and scope of the project. While in the technical optimization just engineering is needed, in the economic optimization also the help of economists is needed. To proceed it is usual to choose a sole variable of decision and take the others as fixed. Nevertheless the actual problem is usually rather complex and more than one variable analysis is needed. One example is to determine the most convenient dam height, reservoir capacity, installed power, surface to irrigate…

When constructing a power plant it is also very important to consider the grid capacity to which the power plant will be connected, also because it defines the amount of power that can be sold in the electricity market.

Another and very important element to consider is the electricity market. It is very important to understand the functioning in order to operate the hydroelectric power plant. One of its main characteristics is the impossibility to store big amounts of energy, which makes it a really fluctuating and volatile market, with hourly arrangements of sales, different levels of availability of production, compensation of reactive energy and so on.

3. SAVA RIVER: POWER POTENTIAL

3.1. Hydrology of Sava River

The Sava is a river that flows through Western Europe and crosses Slovenia, Croatia, Bosnia-Herzegovina and Serbia, until it discharges in the Danube River in Belgrade. It is 945 km in length and has a river basin of 95 719 km^2. It is among the longest rivers that discharge in the Danube, just after river Tisza.

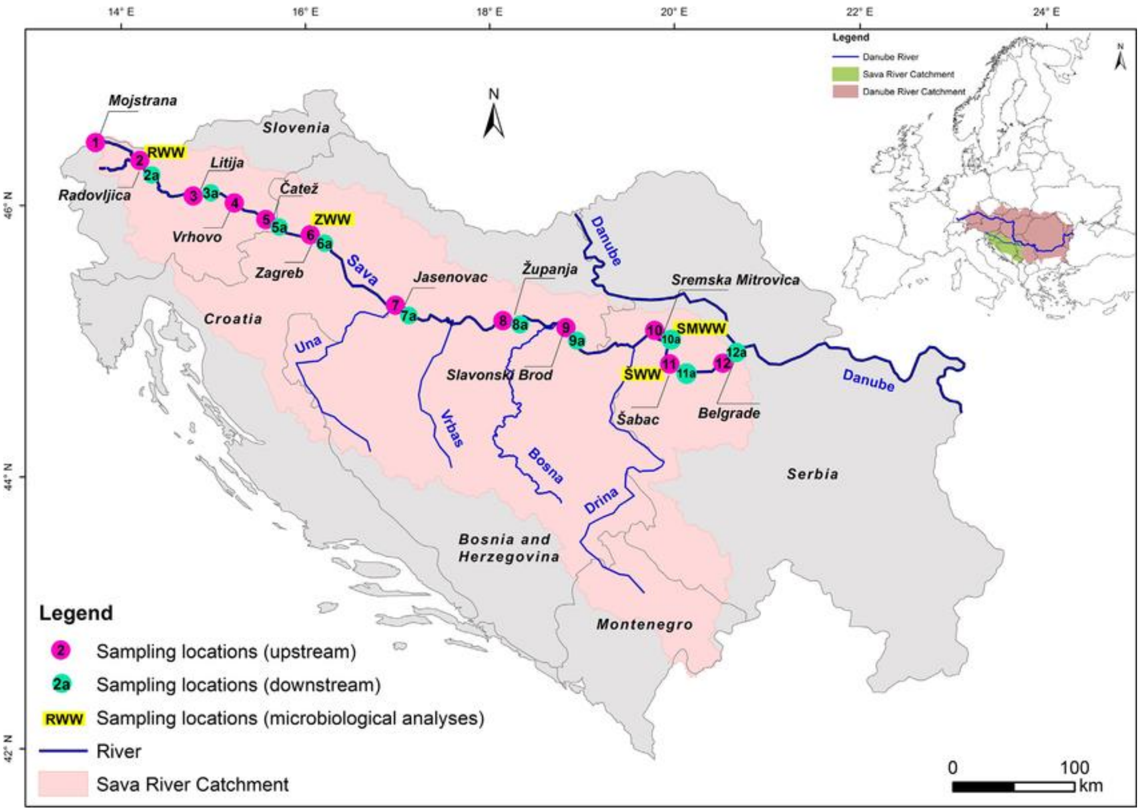

Figure 18. Map of the Sava River and tributaries [24].

River Sava originates from the conjunction of two different rivers: Sava Dolinka and Sava Bohinjka, that come together in the Slovenian localities of Lesce and Radovljica. It drains a total surface of 95 719 km^2 including the 115 km^2 at the north of Albania. The average water flow of the river is 1513 m^3/s, and the depth varies between 28-30m between the localities of Hrtkovci and Bosut in Serbia.

Between 1977 and 1980 several federal agreements were signed in order to regulate the water flow of the river, to prevent floods, the construction of hydroelectric power plants, the construction of the infrastructure to make the river navigable until Zagreb and the protection of the water quality. Nonetheless, the project did not finish in time, also because of the dismantlement of Yugoslavia in 1991.

Sava River is navigable nowadays along 593 km, from the discharge in the Danube until the discharge of the Kupa and Sisak. Small sized boats can navigate up the river until the city of Zagreb, but the plans to make it fully navigable were discarded. The navigability also varies depending on the weather conditions. As well as the water navigation, the Savas basin also lays a natural way for the land transport. Both the railway and the highway that lead from Belgrade to Zagreb and routes for oil and natural gas pipelines from Croatia to Serbia. For all this activities involving the river, the basin is highly populated and the water is considerably polluted.

The Sava River is also considered the political boundary of the northeast of the Balkan Peninsula. Before the dissolution of Yugoslavia the Sava was considered all itself the boundary, which included in the Balkan territories part of the lands of the region of Italian Trieste. After 1991 the boundary was determined by the divisor line of Sava-Kupa until the Adriatic.

3.1.1 Hydrology

The annual average water flow of the river increases in as much as the tributary rivers discharge in the Sava. The following are the average flows immediately after each of the mentioned tributaries:

Table 3. Water flow of the Sava River after each tributary.

TRIBUTARY	AVERAGE FLOW (m3/s)
Sava Bohinjka and Sava Dolinka	45
Krka	317
Sutla	340
Kupa and the Una	880
Vrbas	990
Bosna	1 180
Confluence in Belgrade	1 564

The highest flow rate registered was 6 007 m^3/s in May 2014 in Slavonski Šamac gauging station. Along the Sava River there are 22 reservoirs that hold together an amount of 5 000 000 m^3. There are four of them directly situated on the Sava. Most of the biggest water reservoirs of the Sava are located in the Drina catchment, the largest of them being 0.88 km^3.

This is the reservoir of Mratinje Dam in Montenegro, Lake Piva. The main use of the reservoirs is for hydroelectric power plants and electricity generation. There are other secondary uses such as supplying drinking water, industrial water resource and for irrigation and food production.

Potable water supply and industrial water supply are also covered by groundwater derived from the Sava River. Groundwater is also of upmost importance for the preservation of aquatic ecosystems. There are 41 identified groundwater bodies in the domains of the Sava basin. The size of them ranges from 97 to 5 186 km^2 [24].

3.1.2 Electric power generation

Along the Sava River there are 18 hydroelectric power plants exceeding the rated power production of 10 MW. Most of the facilities located in Slovenia are located in the river itself, and in other countries mainly in the tributary rivers. The annual total production of these hydroelectric power plants together with all the ones smaller than 10 MW sum up to 2 497 GWh and a common rated power of 41 542 MW.

Another important use of the rivers water is to serve as coolant in thermoelectric power plants and nuclear power plants, which happens to be the main use of the Sava Rivers water.

3.2 Hydroelectric power plants on the lower Sava River

In the figure below the hydroelectric power plants located in the lower Sava can be seen along its length. Brežice is forth in row, just before the discharge of River Krka.

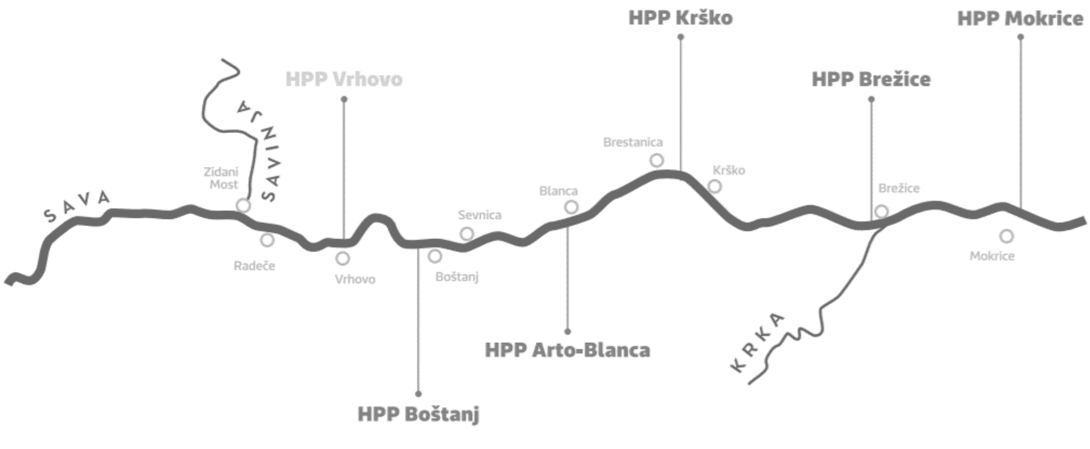

Figure 19. chain of HPPs along the lower Sava River [25].

The purpose of the company Hidroelektrarne na spodnji Savi (HESS) is to build a chain of hydroelectric power plants in the course of the Sava River, that can contribute to the increase of renewable installed power capacity in Slovenia. It is a big scale project in terms of electricity generation facilities. The aim is to ensure a more reliable supply of electricity and to have a bigger contribution of renewable energy sources. The project consist on five operating hydroelectric power plants that will be operated by HESS: HPP Boštanj, HPP Arto-Blanca, HPP Krško, and HPP Brežice and HPP Mokrice. The last is still not operating, but a National Spatial Plan was approved in August 2013. Together they will hold a rated power capacity of 186.19 MW and an annual average production of 695 GWh [25].

3.2.1 HPP Boštanj

The Boštanj hydroelectric power plant is the first one of the chain of five power plants of the Sava River. It started to operate on June 2006. It is a run-of-the-river and reservoir type and has three bulb-type operating units. It has five spillways and an average annual production of 109 GWh.

Figure 20. HPP Boštanj [25].

Table 4. Technical specifications of HPP Boštanj [25].

Number of generating units	3
Turbine type	Double-regulated horizontal bulb-type Kaplan turbine
Installed plant capacity	32.5 MW (3 x 10.84 MW)
Rated plant discharge	500 m^3/s
Rated head	7.47 m
Average annual output	109 GWh
Headwater elevation	182.20 m a.s.l.
Maximum operating variation of water level	1 m
Mean annual discharge	193 m^3/s
Reservoir capacity	8 x 10^6 m^3
Reservoir live storage	1.17 x 10^6 m^3
Number of spillways	5

3.2.2. HPP Arto-Blanca

Arto-Blanca is the second HPP in the chain of five hydroelectric power plants. It is also a run-of-the-river and reservoir type of facility. It started to operate in November 2008. It has three vertical working units that provide an annual average energy production of 148 GWh. It has five spillways and a rated flow discharge of 500 m^3/s.

Figure 21. HPP Arto-Blanca [25].

Table 5. Technical Specification of HPP Arto-Blanca [25].

Number of generating units	3
Turbine type	Double-regulated vertical Kaplan turbine
Installed plant capacity	39.12 MW (3 x 13.04 MW)
Rated plant discharge	500 m^3/s
Rated head	9.29 m
Average annual output	148 GWh
Headwater elevation	174.20 m a.s.l.
Maximum operating variation of water level	1 m
Mean annual discharge	201 m^3/s
Reservoir capacity	9.95 x 10^6 m^3
Reservoir live storage	1.30 x 10^6 m^3
Number of spillways	5

3.2.3. HPP Krško

HPP Krško is the third of the five power plant chain. As the previous it is a run-of-the-river and reservoir type of facility. The characteristics are pretty similar to the previous. It has three vertical working units with five spillways. The average water flow is 500 m^3/s and the annual average energy production is 146 GWh. It was put into work in July 2012.

Figure 22. HPP Krško [25].

Table 6. Technical specifications of HPP Krško [25].

Number of generating units	3
Turbine type	Double-regulated vertical Kaplan turbine
Installed plant capacity	39.12 MW (3 x 13.04 MW)
Rated plant discharge	500 m^3/s
Rated head	9.14 m
Average annual output	146 GWh
Headwater elevation	164.00 m a.s.l.
Maximum operating variation of water level	1 m
Mean annual discharge	205 m^3/s
Reservoir capacity	6.31×10^6 m^3
Reservoir live storage	1.18×10^6 m^3
Number of spillways	5

3.2.4. HPP Mokrice

Mokrice is the last of the five hydroelectric power plants chain. It is still not operating, but the technical characteristics will be similar to the other five power plants. Three working units, five spillways, run-of-the-river and reservoir type with a rated discharge of 500 m^3/s.

Figure 23. Virtual representation of the prospective HPP Mokrice [25].

Table 7. Technical specifications of HPP Mokrice [25].

Number of generating units	3
Turbine type	Double-regulated horizontal bulb-type Kaplan turbine
Installed plant capacity	28.05 MW (3 x 9.35 MW)
Rated plant discharge	500 m^3/s
Rated head	7.47 m
Average annual output	131 GWh
Headwater elevation	141.50 m a.s.l.
Maximum operating variation of water level	1.3 m
Mean annual discharge	261 m^3/s
Reservoir capacity	8.3 x 10^6 m^3
Reservoir live storage	3.4 x 10^6 m^3
Number of spillways	5

3.3. Introduction to the Brežice power plant

The Brežice hydroelectric power plant is the facility in where the project covered in the thesis is being carried out. It is a Slovenian power plant located in the municipality of Brežice, on the riverbed of Sava River. It is one of the six hydroelectric power plants existing all along the Sava River, and one of the most recent (operating since October 2018).

Figure 24. HPP Brežice [25].

It is a hydroelectric power plant of run-of-river type with reservoir and has a rated power of 47.4 MW and three vertical working turbines. The rated discharge is 500 m^3/s though five spillways. The annual average production is 161 GWh, which supposes one percent of Slovenian annual electricity production.

Table 8. Technical specifications of HPP Brežice [25].

Number of generating units	3
Turbine type	Double-regulated vertical Kaplan turbine
Installed plant capacity	47.4 MW (3 x 15.8 MW)
Rated plant discharge	500 m^3/s
Rated head	11.00 m
Average annual output	161 GWh
Headwater elevation	153.00 m a.s.l.
Maximum operating variation of water level	1.1 m
Mean annual discharge	207 m^3/s
Reservoir capacity	19.3 x 10^6 m^3
Reservoir live storage	3.40 x 10^6 m^3
Number of spillways	5

Table 8 shows the general specifications of the Brežice power plant. Nonetheless, it does not show more specific parameters or technical specifications. The following information was provided by the HESS operators, and gives a more precise insight of the power plant.

It is very important to possess information of the elements of the power plant, and understand the distribution of the constituent parts. The best way to present this information is by schemes or blueprints. The following blueprints, Figure 26, represent the section of the power plant from one of the sides. The different elements can be seen and are pointed out. The power plant has five spillways but only three working units. The units take the water by the overture shown in the blueprints, and then canalizes it to the Kaplan turbine. The turbine is coupled with the generator, formed by rotor, which is coupled to the axis of the turbine, and stator, which is embedded around the chamber of the rotor. Then the electric connections carry the current to the transformers station. Once the water is used in turbine it exits the power plant by the spillway. Then there are all the auxiliary systems: engine to open and close the gate, refrigeration systems, measuring systems, lighting, etc.

Another important element that must be described is the turbine and its characteristics. As it has already been said, the turbine is Kaplan type. The maximum capacity of each turbine is 15.66 kW, and has a maximum performance of 94.6 %. A good way of representing the values of a turbine is the shell diagram. The shell diagram for these turbines is provided below:

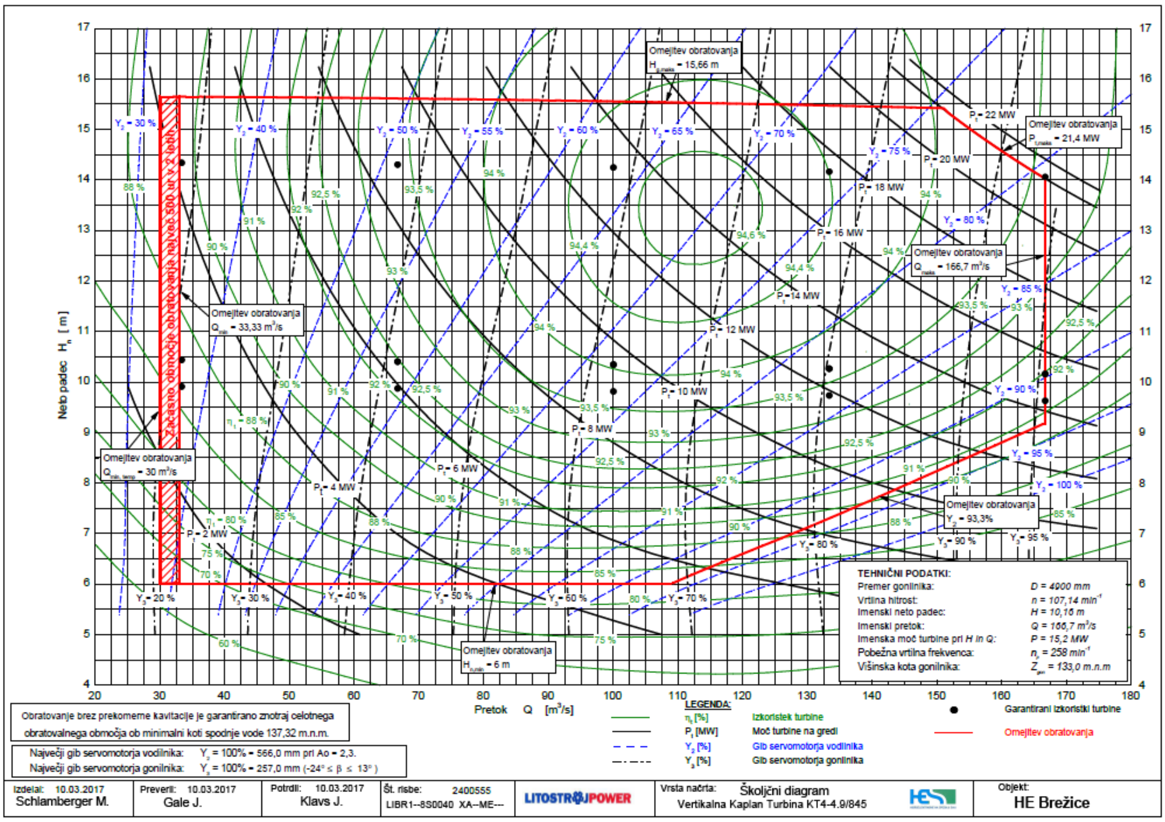

Figure 25. Shell diagram of the Kaplan turbine of the HPP

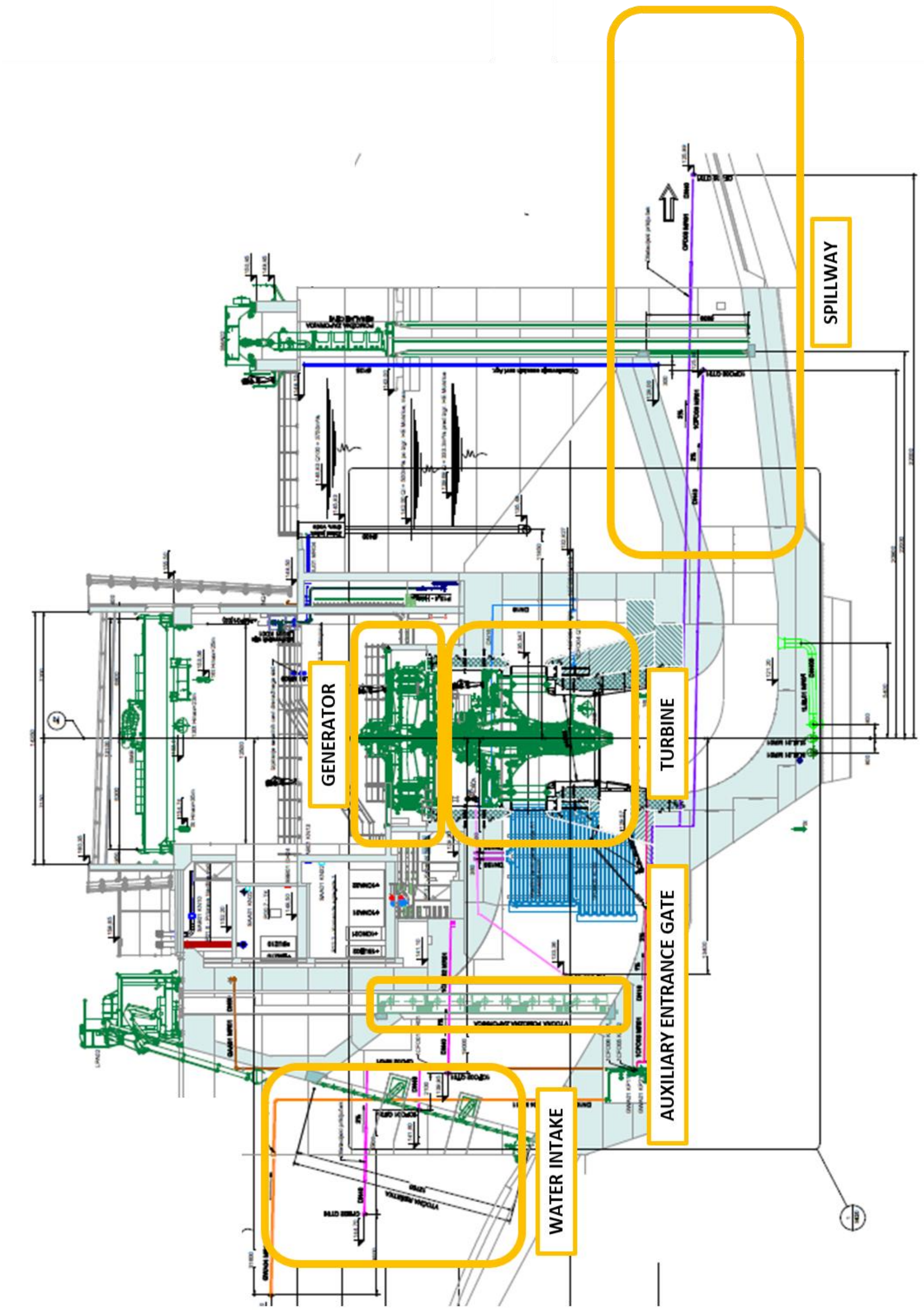

Figure 26. Blueprints of the lateral section of Brežice HPP

4. NUMERICAL MODEL

The objective of the numerical model of the Brežice HPP is to create a model that can predict the functioning of the power plant for different case scenario, in which the input is the water flow that goes through the power plant, and the output is the amount of active power that the HPP produces, and the amount of active power that the HPP could produce if it was not for maximum water flow limits. This analysis will give further comprehension to analyse the installing of hydrogen electrolyzers, and the potential use of the Brežice HPP for additional power production.

This chapter will explain the method that has been followed in order to obtain a numerical model of the hydraulic power plant. It goes through the basic presentation of the data obtained by the operators of HESS, the sorting process, the graphic disposal for thorough comprehension, the calculations and consideration to obtain the numerical model, the explanation of the numerical model and graphic disposal of the numerical model.

In order to present the numerical model the following subsystems will be explained:

- **Water head model,** which represents the water head and predicts the value out of height difference before and after the HPP.

- **Water flow model,** which represents water flow and models its behavior over a year.

- **Total power model,** which takes water flow and head as input, and provides a value of power for the total HPP.

- **Individual turbine model,** which takes individual values of water flow and head for each turbine, and provides a value of power for the corresponding turbine.

- **Shell diagram,** which represents together water flow, power and performance.

4.1. Available data for development of the model

4.1.1. Parameters of the HPP

- **Active power**

Active power is presented in Megawatts (MW).

It is the most important parameter of the study. It gives a value for the amount of active (useful) power that the HPP is producing. The active power is the part of the energy produced or used by a system, which can create or use actual work, and defers from the reactive power, which is normally intended to be as closest as zero as possible.

In this analysis the power will be presented for different systems. Values for the general power plant are given, as well as for each of the separate working units (turbines). The aim is to analyse the active power produced by the HPP for any given water flow.

- **Water flow**

Water flow is given in cubic meters per second (m^3/s).

Water flow is among the most important parameters to consider for the calculation of the numerical model, for it is the input to the system. The aim is to obtain an accurate value of active power for every different value of water flow. It is also important to describe the water flow regimes and analyse the water flow of Sava River, and also to learn how the Brežice HPP manages the water intake. In other words, how much water goes through the turbines, how much water goes through bypass, which is the maximum flow capacity of the power plant and which is the amount of flow that could be used for potential improvement or implementation of hydrogen electrolyzers.

The values of water flow given by the HESS operators are given both in a hourly frequency and in a lower resolution including also the bypass flow. Also indirect values were obtained derived from the water head value.

- **Water head**

Water head is presented in meters (m).

This parameter represents the water jump height from one point to the following considered point. In the case of the Brežice HPP the values are taken in points before and after the power plant, which gives the potential base production. Together with the consideration of the water flow and efficiencies the rated power of the HPP can be obtained by means of the general hydroelectric power generation equation.

$$P = Q \cdot \rho \cdot g \cdot h \cdot \eta \tag{4.1}$$

Where "*h*" is the water head of the hydroelectric power plant. In this case the water head has been obtained as a direct value from the HESS operators or as an indirect value as the difference between upper water level and lower water level.

- **Water upper and lower level**

Water level is presented in meters (m).

Water level is the water height in meters above the sea level. For the Brežice HPP two values are given, which represent the water level before and after the power plant. The difference between these two values is the water head of the HPP, which is a very important value to calculate the power generation.

- **Bypass**

Bypass is presented in cubic meters per second (m^3/s).

The bypass is the value of water flow that does not go through the turbines but instead goes through the bypass. This happens when the maximum water flow capacity of the turbines is reached, and water must go by somewhere else. This value is very important in the analysis, for it represents the potential of the power plant to use extra water flow to produce active power. Nonetheless, if the maximum capacity of the turbines is reached, that power shall not be used for active power production, but could be used in the hydrogen electrolyzers.

The parameter is given in a time span of approximately 8 hours. The value is general for the whole power plant and it is combined together with water flow in the 9 hour data set.

4.1.2. Data analysis of the HPP

The first step to develop the numerical model is to gather data of different and various parameters of the HPP, sort them and make them clear for the understanding and treatment, and then use the data to develop the model that can depict the functioning of the power plant. In this case the data was facilitated by the HPP operators of HESS. The data has been treated using the software Microsoft Excel 2010.

The parameters submitted by the company where the following:

Table 9. List of parameters submitted by the HESS operators.

NAME OF DATA	MEANING	UNIT
HEBR_A1_P	Active power of units individually	MW
HEBR_A1_PADEC	Total head of unit	MW
HEBR_A1_PRETOK	Water flow through unit	m3/s
HEBR_HE_PRETOK	Water flow through power plant	m3/s
HEBR_HE_P	Total power of power plant	MW
HEBR_HE_ZG_VODA	Upper level of water	m.n.v.
HEBR_HE_SP_VODA	Lower level of water	m.n.v.
HEBR_HE_dH_PADEC_VODA	Total head (level difference)	m
HEBR_PRT_JEZ	Water flow through bypass	m3/s

They were submitted in “csv” text document files in a list of sequential data, sorted by date and with the codes listed in Table 9. There were three different types of data depending on the resolution and if the data were per unit or for the whole HPP.

“HEBR_HE_PRETOK”, “HEBR_HE_dHPADEC_VODA” and “HEBR_PRT_JEZ” were given every 8 hours 45 minutes and 36 seconds, giving a total number of values of 1000. The values were for the whole HPP, not considering the individual contribution per unit. The period is taken from the 1st of January 2019 to the 31st of December 2019.

“HEBR_A1_P”, “HEBR_A1_PADEC” and “HEBR_A1_PRETOK” were given every half an hour for every day of the year, and for three different units, giving a total number of values of 52 499 (“3 units” · “2 measures an hour” · “8760 hours a year”). These data have independent value for each turbine. The period is taken from the 1st of January 2019 to the 31st of December 2019.

“HEBR_HE_P”, “HEBR_HE_ZG_VODA” and “HEBR_HE_SP_VODA” were given every hour for every day of the year giving a total of 8760 values. The data are given for the whole HPP and do not take into account the separate units. The period in which the measures have been taken is from the 1st of January 2019 to the 31st of December 2019.

All the data came in a format that could not be directly treated as real values, since there was no distinction between the dots to indicate decimals and the dots separating thousands. For this reason all the data had to be checked in order to obtain the real values. For this purpose, the power plant also provided with several graphics associated to each parameter and sets of data, and usually divided in months. This graphics represented the real values that were expected from the HPP. By means of corrective equations and visual comparison, the final and correct data were obtained. An example for some of the data is given below:

“HEBR_HE_P”, “HEBR_HE_ZG_VODA” and “HEBR_HE_SP_VODA”

For total active power, water level before power plant and water level after power plant the data were separated monthly. The data were provided as in Table 10.

Table 10. Power and water level ata provided by HESS

POWER	2019-06-01T00:00:21.000Z	270.226.059	Good	WATER LVL B	2019-06-01T00:00:21.000Z	1.529.709.625
POWER	2019-06-01T01:00:21.000Z	4.860.787.201	Good	WATER LVL B	2019-06-01T01:00:21.000Z	1.529.172.058
POWER	2019-06-01T02:00:21.000Z	4.862.975.311	Good	WATER LVL B	2019-06-01T02:00:21.000Z	1.529.060.059
POWER	2019-06-01T03:00:21.000Z	485.568.161	Good	WATER LVL B	2019-06-01T03:00:21.000Z	1.528.878.632
POWER	2019-06-01T04:00:21.000Z	4.909.289.551	Good	WATER LVL B	2019-06-01T04:00:21.000Z	1.529.329.987
POWER	2019-06-01T05:00:21.000Z	4.901.266.479	Good	WATER LVL B	2019-06-01T05:00:21.000Z	1.529.086.914
POWER	2019-06-01T06:00:21.000Z	4.957.791.519	Good	WATER LVL B	2019-06-01T06:00:21.000Z	1.528.702.698
POWER	2019-06-01T07:00:21.000Z	497.383.728	Good	WATER LVL B	2019-06-01T07:00:21.000Z	152.817.749
POWER	2019-06-01T08:00:21.000Z	4.865.528.107	Good	WATER LVL B	2019-06-01T08:00:21.000Z	1.528.067.474
POWER	2019-06-01T09:00:21.000Z	4.994.258.881	Good	WATER LVL B	2019-06-01T09:00:21.000Z	1.528.216.858
POWER	2019-06-01T10:00:21.000Z	4.956.697.464	Good	WATER LVL B	2019-06-01T10:00:21.000Z	1.528.276.978

The problematic was that the numerical values provided in these csv files were separated by dots indistinctively, and could not be directly translated to functional values. For example, the forth value of power (485.568.161) compared to the third (4.862.975.311) could be understood as 48.5 MW or as 4.85 MW, being 48.5 MW the correct one. In order to correct all these data the following equation was used:

“=IF.ERROR(IF(E2="POWER";VALUE(LEFT(SUBSTITUTE(G2;".";"");
4+1*(LEFT(G2)<"6")))/1000;VALUE(LEFT(SUBSTITUTE(G2;".";"");5))
/100);0)” (4.2)

After filtering the data with Equation (3.2) still the results were not completely accurate, and manual corrections had to be done comparing the graphics provided by the HESS operators with the graphics obtained from the outcome of the csv files. Below two samples are shown, one for the measured values and the other for the calculated ones:

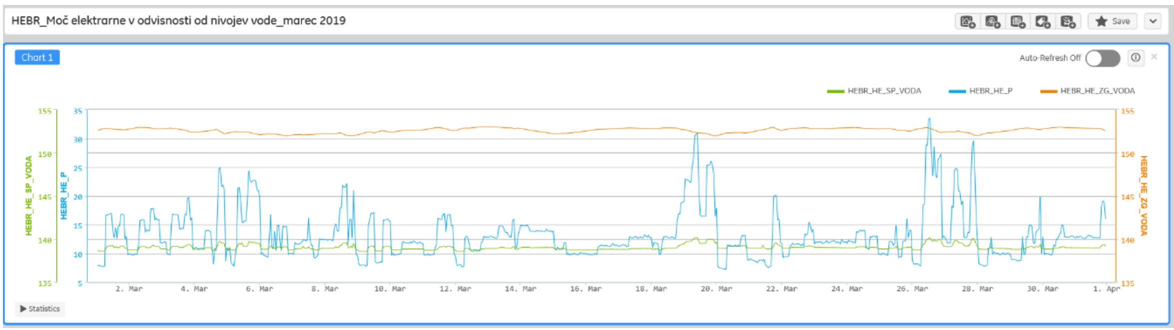

Figure 27. Power and water level for March, HESS provided.

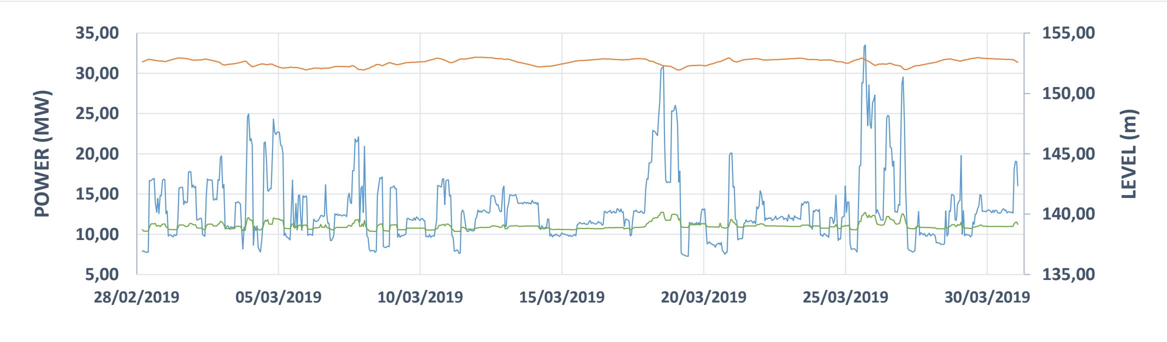

Figure 28. Power and water level for March, crafted from data sets.

Both graphics were compared to change the mismatching data, until the graphics looked exactly alike. The figures shown before are the result after the treatment of the data. As it can be seen, the matching is pretty good.

After the previous corrections the data was sorted as in Table 11, which is an example of the month of May 2019 for the first 13 hours:

Table 11. Sample of sorted data of power, water level, date and hour.

POWER (MW)	WATER LVL B (m)	WATER LVL A (m)	DATE	HOUR
7,82	152,61	138,70	01/03/2019	12:00 AM
7,95	152,65	138,60	01/03/2019	1:00 AM
7,80	152,70	138,58	01/03/2019	2:00 AM
7,75	152,74	138,58	01/03/2019	3:00 AM
7,79	152,78	138,59	01/03/2019	4:00 AM
7,77	152,83	138,58	01/03/2019	5:00 AM
16,65	152,82	138,90	01/03/2019	6:00 AM
16,67	152,81	139,17	01/03/2019	7:00 AM
16,75	152,79	139,19	01/03/2019	8:00 AM
16,90	152,78	139,19	01/03/2019	9:00 AM
16,94	152,76	139,19	01/03/2019	10:00 AM
13,92	152,73	139,23	01/03/2019	11:00 AM
12,75	152,73	138,99	01/03/2019	12:00 PM

“HEBR_A1_P”, “HEBR_A1_PADEC” and “HEBR_A1_PRETOK”

For the data of power, water flow and water head for each of the three different units the data was given every half hour and sorted in column one unit after each other for every month. The data were given as shown below:

Table 12. Sample of power data provided by HESS operators.

Tag Name	Historian Tag Name	TimeStamp	Value
HEBR_A2_P	HEBR_A2_P	2018-12-31T23:31:27.000Z	1.159.674.644
HEBR_A2_P	HEBR_A2_P	2019-01-01T00:01:27.000Z	9.736.889.839
HEBR_A2_P	HEBR_A2_P	2019-01-01T00:31:27.000Z	9.773.358.345
HEBR_A2_P	HEBR_A2_P	2019-01-01T01:01:27.000Z	1.037.507.629
HEBR_A2_P	HEBR_A2_P	2019-01-01T01:31:27.000Z	1.030.214.024
HEBR_A2_P	HEBR_A2_P	2019-01-01T02:01:27.000Z	9.645.719.528
HEBR_A2_P	HEBR_A2_P	2019-01-01T02:31:27.000Z	1.026.567.173
HEBR_A2_P	HEBR_A2_P	2019-01-01T03:01:27.000Z	9.718.655.586
HEBR_A2_P	HEBR_A2_P	2019-01-01T03:31:27.000Z	9.663.953.781
HEBR_A2_P	HEBR_A2_P	2019-01-01T04:01:27.000Z	1.008.333.397
HEBR_A2_P	HEBR_A2_P	2019-01-01T04:31:27.000Z	1.006.509.972

The data had to be corrected as it happened with total power and water level. In order to filter the data the following equation was used:

=VALUE(LEFT(SUBSTITUTE(E2;".";"");4+1*(VALUE(LEFT(SUBSTITUTE(E2;".";"");2))<H1)))/1000 (4.3)

After correcting the data with the equation, the results did not completely match with the expected values, so manual corrections had to be done, comparing the graphic provided by the HESS operators with the graphic obtained from the calculated values. Both graphics are shown below:

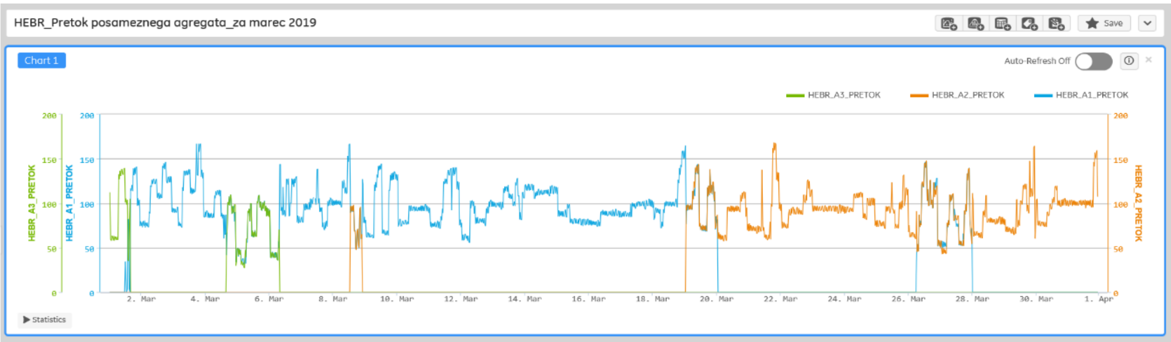

Figure 29. Individual unit water flow for March, HESS provided.

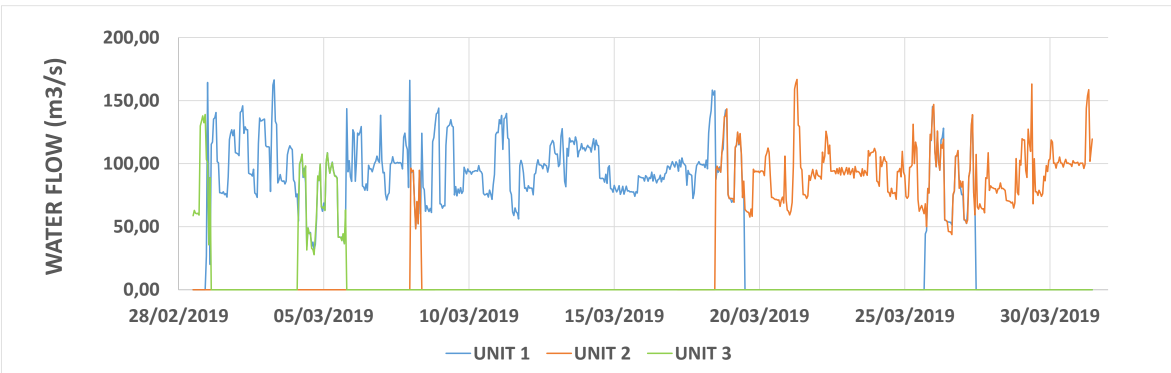

Figure 30. Individual unit water flow for March, crafted from data sets.

After manual corrections and sorting, the data were presented in sets of columns of three, each column of the set for every unit. It is presented as seen in

Table 13:

Table 13. Data sets sorted and separated by turbine units.

POWER (MW)			WATER FLOW (m3/s)			WATER HEAD (m)			DATE	HOUR
UNIT 1	UNIT 2	UNIT 3	UNIT 1	UNIT 2	UNIT 3	UNIT 1	UNIT 2	UNIT 3		
0,00	9,75	0,00	0,00	74,66	0,00	14,17	14,16	14,16	01/01/2019	12:00 AM
0,00	10,34	0,00	0,00	78,99	0,00	14,18	14,18	14,18	01/01/2019	1:00 AM
0,00	9,96	0,00	0,00	76,04	0,00	14,20	14,20	14,20	01/01/2019	2:00 AM
0,00	9,69	0,00	0,00	73,98	0,00	14,21	14,20	14,20	01/01/2019	3:00 AM
0,00	10,07	0,00	0,00	76,81	0,00	14,22	14,22	14,21	01/01/2019	4:00 AM
0,00	9,85	0,00	0,00	75,10	0,00	14,23	14,23	14,22	01/01/2019	5:00 AM
0,00	9,69	0,00	0,00	73,79	0,00	14,24	14,25	14,24	01/01/2019	6:00 AM
0,00	11,73	0,00	0,00	89,54	0,00	14,12	14,11	14,12	01/01/2019	7:00 AM
0,00	12,03	0,00	0,00	92,00	0,00	14,09	14,06	14,08	01/01/2019	8:00 AM
0,00	11,44	0,00	0,00	87,46	0,00	14,12	14,11	14,11	01/01/2019	9:00 AM
0,00	11,25	0,00	0,00	85,98	0,00	14,11	14,09	14,10	01/01/2019	10:00 AM
0,00	11,73	0,00	0,00	89,65	0,00	14,10	14,07	14,10	01/01/2019	11:00 AM
0,00	11,43	0,00	0,00	87,41	0,00	14,10	14,10	14,09	01/01/2019	12:00 PM

HEBR_HE_PRETOK", "HEBR_HE_dHPADEC_VODA" and "HEBR_PRT_JEZ"

For water flow, water head and bypass the time interval was different, and also the values which were given in the database where not in the same format as the ones graphed in the real values set. As explained for previous data sets, the values had to be treated so that they would represent the real expected values. The data were given as shown below:

Table 14. Sample of water head data provided by HESS operators.

Tag Name	Historian Tag Name	TimeStamp	Value
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-01T07:47:02.040Z	1.410.721.779
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-01T16:32:37.080Z	1.401.446.724
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-02T01:18:12.120Z	1.424.822.998
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-02T10:03:47.160Z	1.395.164.967
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-02T18:49:22.200Z	1.397.560.787
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-03T03:34:57.240Z	1.426.181.507
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-03T12:20:32.280Z	141.480.217
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-03T21:06:07.320Z	1.415.634.918
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-04T05:51:42.360Z	1.426.027.966
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-04T14:37:17.400Z	1.426.915.455
HEBR_HE_dH_I	HEBR_HE_dH_PADEC_VODA	2019-01-04T23:22:52.440Z	1.424.261.665

The equation to correct the data for water head is the one presented below, Equation (3.4):

```
=VALUE(LEFT(SUBSTITUTE(E2;".";"");4+1*(VALUE(LEFT(SUBSTITUTE(E2;".";"");2))<$H$1)))/1000
```
(4.4)

After treating the data with Equation (3.4) the data were still not completely matching the expected results, and also in this case, manual corrections had to be done. The procedure was the same as explained for other data sets. Both graphics were compared to correct the remaining wrong data until the results matched almost perfectly. Both graphics are shown below:

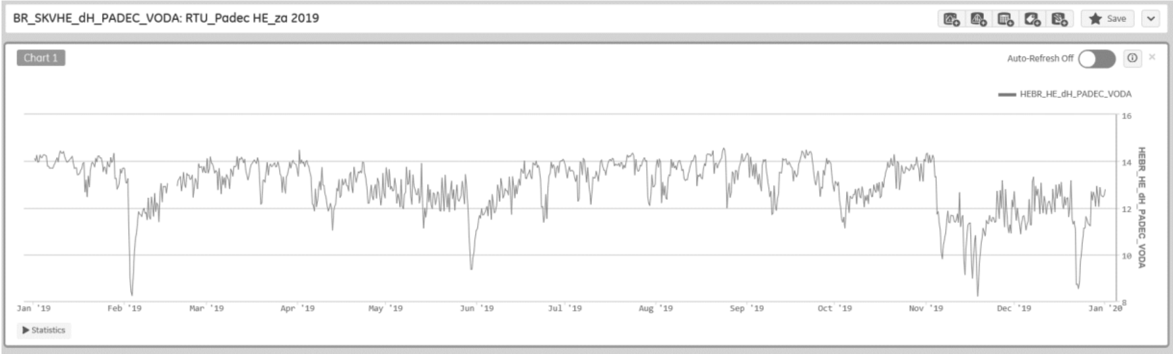

Figure 31. Water head values for the whole 2019, HESS provided.

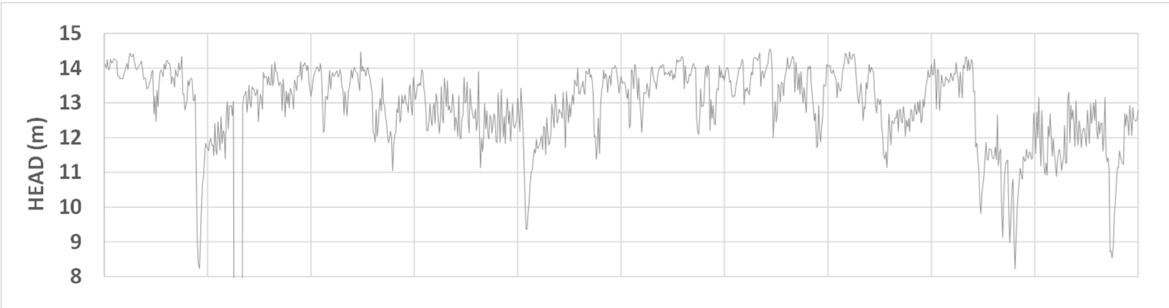

Figure 32. Water head values for the whole 2019, crafted out of data sets.

After correcting the data and sorting it, the result were as shown below:

Table 15. Data sets of water head, flow and bypass corrected and sorted.

FLOW (9H)	HEAD (9H)	BYPASS (9H)	DATE
84,30	14,11	0,00	01/01/2019 07:47 AM
95,70	14,01	0,00	01/01/2019 04:32 PM
83,47	14,25	0,00	02/01/2019 01:18 AM
89,03	13,95	0,00	02/01/2019 10:03 AM
86,37	13,98	0,00	02/01/2019 06:49 PM
80,64	14,26	0,00	03/01/2019 03:34 AM
84,36	14,15	0,00	03/01/2019 12:20 PM
88,34	14,16	0,00	03/01/2019 09:06 PM
70,63	14,26	0,00	04/01/2019 05:51 AM
69,39	14,27	0,00	04/01/2019 02:37 PM
68,34	14,24	0,00	04/01/2019 11:22 PM
67,39	14,22	0,00	05/01/2019 08:08 AM

4.1.3. Descriptive graphics and data of the HPP

In this epigraph some basic results are presented, but which do not present any evaluation or conclusion value, but only clarification and comprehension of the functioning of the HPP and some statistical interpretation of the sorted data. In order to obtain pertinent conclusions and in order to take a good approach to the evaluation of the data, first thorough analysis and comprehension of the power plant is needed. For that purpose the data are shown and represented in a format that helps the understanding of some important parameters.

- **Power average for every month**

The most relevant parameter of the mathematical model of the power plant is the active power. It is the value in which the study is interested in, for the main objective is to use the energy that the power plant could be using and is currently not using.

Power averages for every month is an interesting value to understand and have a magnitude of the size and capacity of the power plant. It is also very important in terms of operation to know which months have the highest power output (and the highest water flow input), and to discern whether there is a relation between the bypass flow and the time of the year. In terms of sorting the data, it is also important to check if there are abnormal deviations from the expected values, and to acquire magnitude concern.
In order to obtain the numerical average value the Microsoft Excel 2020 functions were used:

$$=SUM(P2:P744)/COUNT(W2:W744) \quad (4.5)$$

Equation (3.5) sums every value of power in the column of a month, and then the function COUNT counts how many values there are in the column. The division is the arithmetic average of the set of values. Doing the same for every month and making the graphic the result is the following.

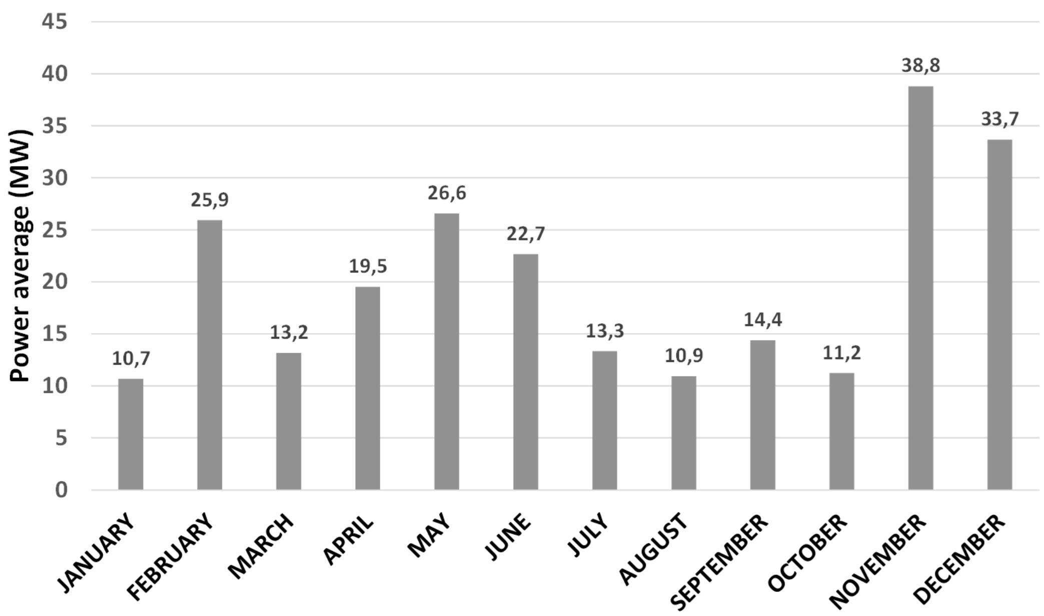

Figure 33. Power average for each month.

Analysing the result the highest average powers are obtained the months in which the water flow is higher, which, expecting a linear correlation, is an expected result. November and December are the only months in which the power output is closer to the HPP rated power capacity (47.4 MW). During the rest of the months the power output is further from the maximum capacity.

- **Annual averages of power, water level and water flow**

It is also very useful to analyze annual data in perspective. It is less useful in terms of getting specific parameters, and in terms of the numerical model it is not the most helpful approach. Nonetheless, broad understanding of the power plant is essential to address the project. To obtain the annual averages of the data the same Excel function as before, Equation (3.5), was used, but with different data sets.

Table 16. Data sets of power water level and water flow.

POWER (MW)	WATER LVL B (m)	WATER LVL A (m)	DATE	HOUR
7,82	152,61	138,70	01/03/2019	12:00 AM
7,95	152,65	138,60	01/03/2019	1:00 AM
7,80	152,70	138,58	01/03/2019	2:00 AM
7,75	152,74	138,58	01/03/2019	3:00 AM
7,79	152,78	138,59	01/03/2019	4:00 AM
7,77	152,83	138,58	01/03/2019	5:00 AM
16,65	152,82	138,90	01/03/2019	6:00 AM
16,67	152,81	139,17	01/03/2019	7:00 AM
16,75	152,79	139,19	01/03/2019	8:00 AM
16,90	152,78	139,19	01/03/2019	9:00 AM
16,94	152,76	139,19	01/03/2019	10:00 AM
13,92	152,73	139,23	01/03/2019	11:00 AM
12,75	152,73	138,99	01/03/2019	12:00 PM

Table 16 is the actual Excel display of how the data sets were disposed and where the values were taken in order to calculate the average values.

POWER (MW)	WATER LVL BEFORE (m)	WATER LVL AFTER (m)	WATER FLOW (m3/s)
19,98	152,47	139,53	166,11

Table 17. Annual average values.

In Table 17 the annual average values for power, water level and water flow are presented. The average power is almost 20 MW, which is almost a 40 % of the HPP rated power capacity. This means that the power plant could deal with scenarios of as much as double of the actual power output most of the time. The water level annual average before and after the power plant have very little dispersion among values, which means that through all the year the values remain almost the same. This means that the average head (the difference between water level before and water level after the power plant) is about 13 meters. The water flow annual average (166.11 m^3/s) is very close to being one third of the maximum water flow capacity of the HPP (500 m^3/s).

- **Box and whiskers diagrams of power and water flow**

Box and whiskers diagrams offer a very complete and clarifying disposal of a set of data. It represents the three quartiles, the maximum and the minimum among those values. For this reason the box and whiskers diagram of power and water flow were done, in order to obtain visual immediate information for every month of the year [26].

The results for power are presented in Figure 34. There is a clear higher power outcome in the months of December and November, where also most of the values are close to the maximum power value of the power plant. Dispersion in the months of December, November, June, May, April and February is considerably higher than in the months of October, September, August, July, March and January. Maximum values for every month remain almost the same, close to 50 MW, except for October, July, March and January. Minimum values also oscillate around 0 to 5 MW.

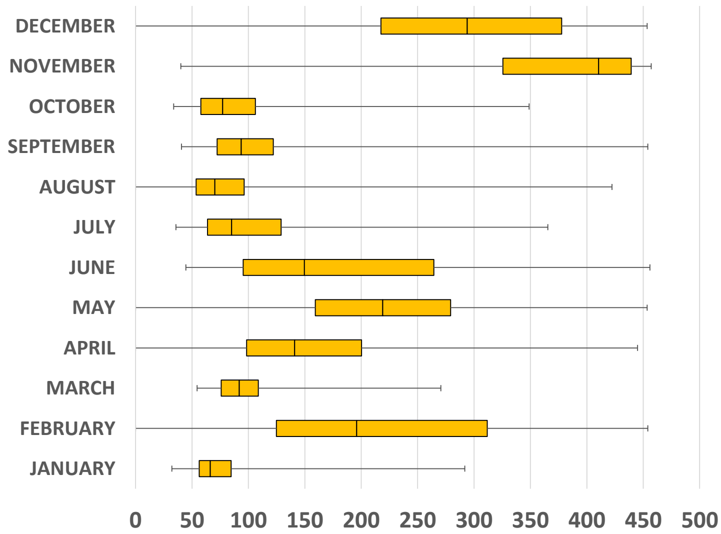

Figure 34. Box and whiskers diagram of water flow.

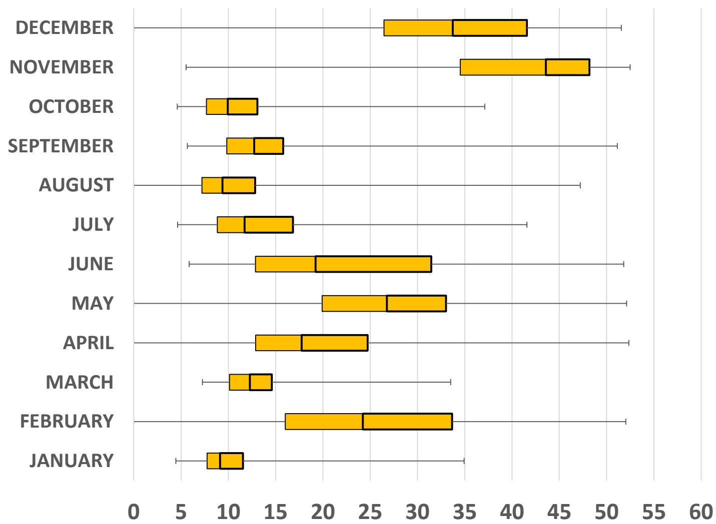

Figure 35. Box and whiskers diagram of power.

When comparing both diagrams of box and whiskers a clear correlation can be seen between both parameters, since the dispersion, width of interquartile range, median value and maximums and minimums are so close (in relative analysis, considering that the magnitude of values is different). Further correlation between these two parameters will be explained and demonstrated in following chapters.

- **Load duration curve for power**

Load duration curve gives a representative disposition of data to understand for how long each power value has been given, and thus to have a visual and qualitative magnitude of the number of hours for each power value. For this purpose the 8760 data (corresponding to the hours of a year) are sorted by decreasing order, and then graphed so that the values can be seen in that corresponding order. In Figure 36 the load duration curve with 8760 values is shown. To make the data more accessible, the time span of a year has been divided into 10 intervals of 876 values (total of 8760 values corresponding to the number of hours of a year), and for every interval the average of that interval has been calculated. This way a representative and immediate impression of the HPP capacity is depicted [27].

The installed plant capacity of 47 MW is reached (considering the average intervals) for 876 hours a year. Also the power plant is at almost more than half of its power capacity (22 MW) for 40 % of the time of the year, that is, 3504 hours.

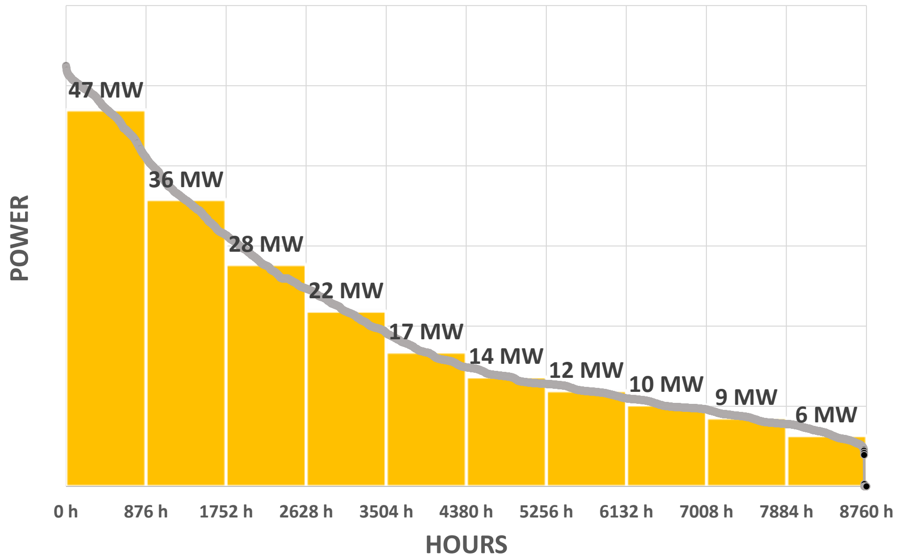

Figure 36. Load duration curve for year 2019.

4.2. Assumptions

In order to develop the numerical model some assumptions or limitations must be defined.

- Operational strategies. The only information available is technical information about the turbines and hydrological parameters such as water flow and water head. There is no information about how the HPP operates, so the model will be limited to technical behavior.

- Data resolution. The data sets taken for the model are given for every hour or for approx. every 9h in some cases. It has been supposed that the values are continuous.

- Data amount. There is only one year data available (year 2019). For this reason statistical approach and hydrological predictions are very limited.

- Some of the data in the data sets are erroneous but impossible to filter with basic filters, so are all the same included in the model and distort the result.

- The parameters that represent total values for the power plant are considered the exact sum of the three individual turbines. So losses in conductions and auxiliary elements might be neglected in some cases.

- The auxiliary power is either not considered in the measured values, or it is negligibly small.

4.3. Numerical models elements

The objective of the numerical model is to obtain an analytic description of the power plant that can predict the functioning of HPP Brezice, providing output values of power for input values of water flow and head.

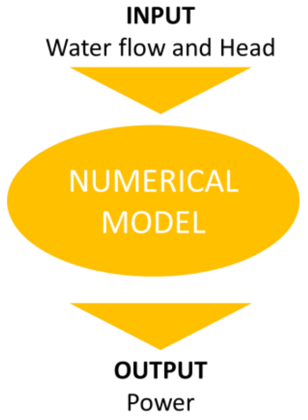

Figure 37. Numerical model simplified scheme.

For this purpose water head, water flow, turbines and power must be evaluated and descripted. Once the descriptive process is finished the mathematical model can be crafted.

First a general description is given, to provide understanding of the general aspects of the HPP and to understand the focus in the different approaches to the mathematical model. This are the steps taken to develop the numerical model:

1. Description of the HPP

2. Water head data are analysed for the year 2019, and maximums, minimums and averages are taken, numerical equation crafted and statistical approach given.

3. Once water head correlation is verified, water flow is thoroughly analysed. Maximums, minimums and averages. Turbine distribution. 2019 data sets graphics.

4. Descriptive mathematical power equations for the general power plant. Water flow and head correlation with power. Parabolic equations and parameters.

5. Descriptive mathematical power equations for individual turbines. Water flow and head correlation with power. Parabolic equations and parameters.

6. Turbine shell diagram.

4.3.1. Description of the HPP

The HPP Brežice is a three turbine hydropower plant. The three turbines are equal to each other. They are Kaplan type. The intake water flow is divided into the three turbines depending on operation considerations. Maximums are depicted in Figure 38. When there is water overflow, the overflowing water is derived by the bypass.

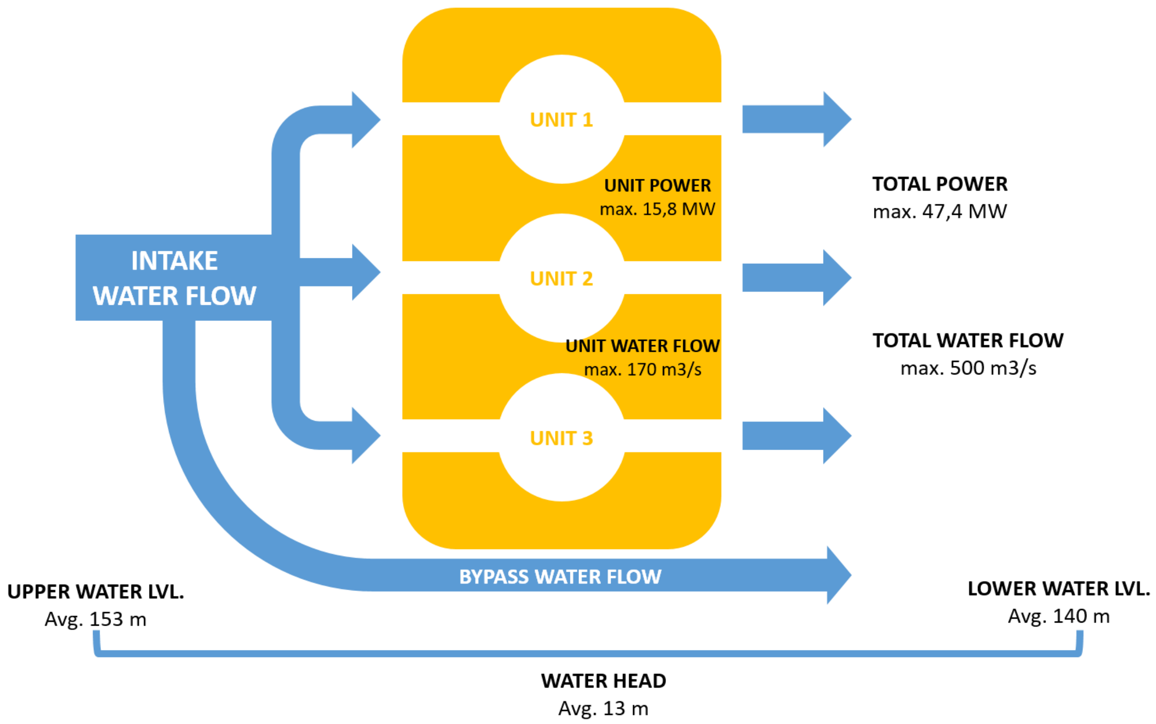

Figure 38. Scheme of the Brežice HPP.

4.3.2. Water head model

Water head is the difference between upper water level, or water level before the power plant and lower water level or water level after the power plant. This height difference comes given by hydrological conditions and it is not controllable without a dam. This means that HPP Brežice has no water level control, and must adapt to the given head discharge.

To comprehend the behaviour of water level in the HPP the data where cleansed and filtered to obtain reasonable values. Once the data was correct, a graphic of the whole year was crafted, where upper water level, lower water level and head are visible. Figure 39 is an example of the mentioned graphic, which takes approximately 500 random values (from 21 March to 20 April). Upper water level is in colour blue, lower level in red and water head in grey. Throughout all the year the values are pretty stable and oscillate around certain average values.

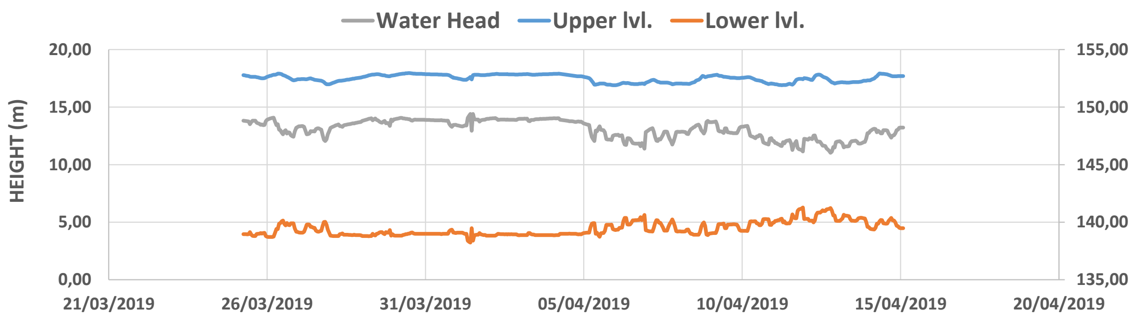

Figure 39. Sample of water level before and after and water head.

Since it is impossible to understand a clear tendency or behaviour analysing chronologically sorted data, the data set of water head was sorted from minimum to maximum, and then graphed together with the corresponding values of water level. Figure 40 shows the results. Darker brown shows the distribution of lower water level, light cream colour belongs to upper water level and the orange line corresponds to water head.

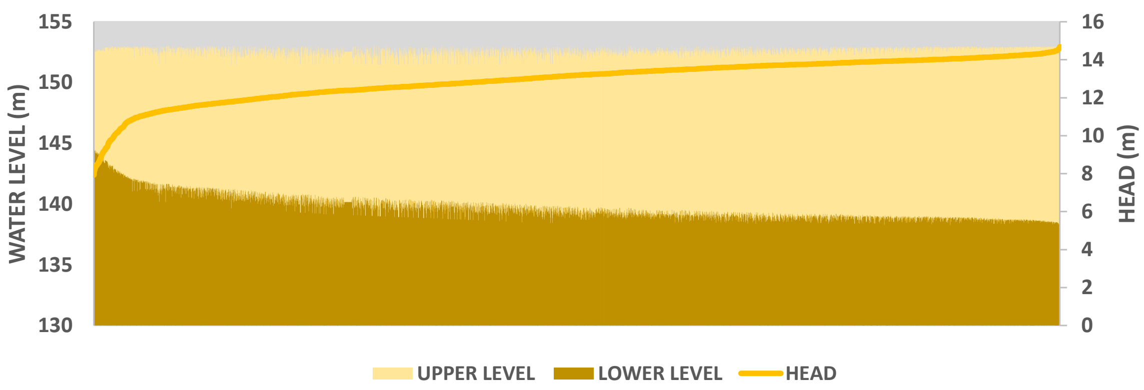

Figure 40. Water head sorted from minimum to maximum.

This graphic provides more clear information about the dependence of water head. It is pretty clear that upper water level remains almost constant and that it has a much lower variability than lower level. The main reason why water head increases is because lower level of water decreases. So there head upper level can be ignored when stablishing a mathematical relation between water head and water level. As we see in Figure 42 upper level has no clear correlation at all (R^2 = 0.0368) while in Figure 41 we see that lower level has a good linear correlation (R^2 = 0.8925)

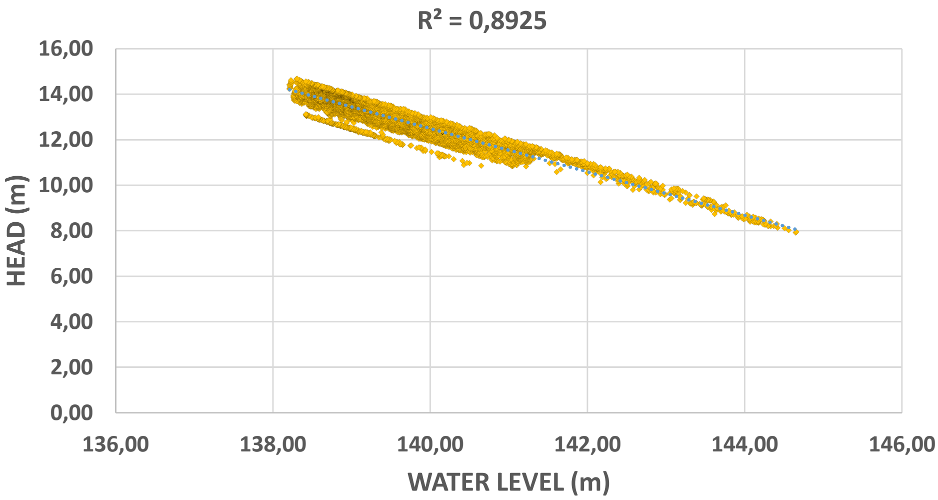

Figure 41. Head correlation with LOWER water level.

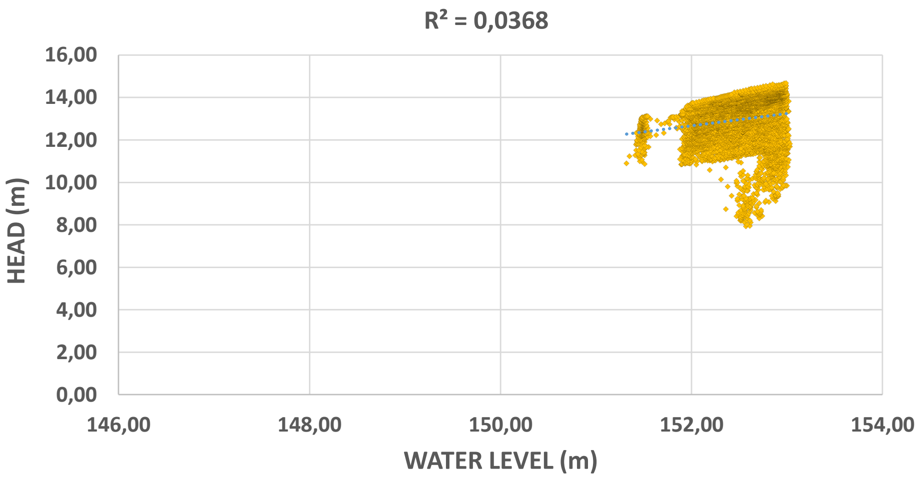

Figure 42. Head correlation with UPPER water level.

The correlation between water head and water level is pretty good with a parabolic correlation, which would be as follows:

$$H = A_1 \cdot {Z_1}^2 + B_1 \cdot Z_1 \qquad (4.6)$$

Where:
H = head, m
A_1 = parabolic correlation constant, m^{-1}
B_1 = parabolic correlation constant
Z_1 = Lower water level, m

Using Excel 2010 tools the parameters of the parabolic correlation can be calculated, the function used was “LINEST”. Using the correct variation of the formula the values can be given in the form of polynomial constants, and are the following [28]:

Table 18. Parameters of the parabolic correlation of head and water lower level.

H = A1 · Z1 ^ 2 + B1 · Z1

A	B	C
-7,40E-03	1,12E+00	0

The equation was then verified to check that the obtained values with Equation (4.1) correspond to the real values. To do this lower water level input values were taken and introduced in the equation, and then the resulting values where compared to the real values. Both “Head sets” where graphed together to compare them in a year time span. The results were satisfactory. Figure 43 represents a portion of those values randomly taken:

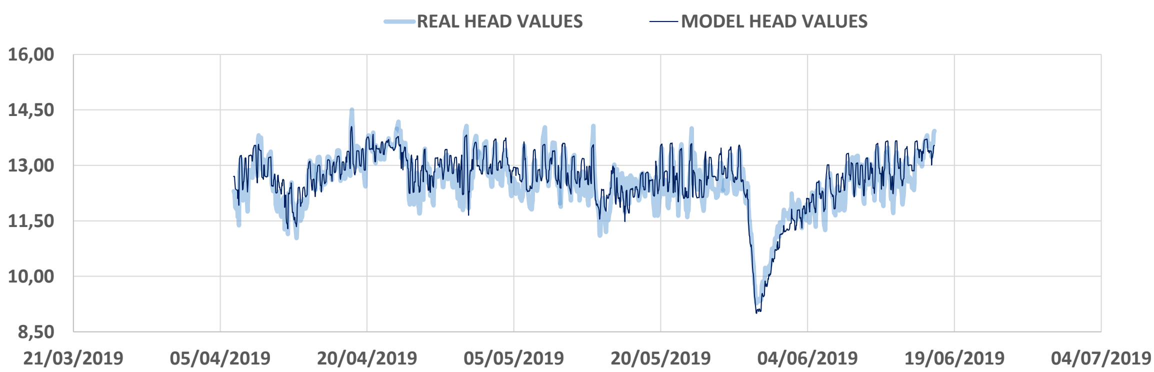

Figure 43. Head model comparison with real head values.

Light blue represents the real values of water head and dark blue represent the values obtained with the equation. There is good resemblance between both series, although for some points there is little deviation. It must be considered that the standard deviation of real values around the average is very little, and so it is for obtained values.

To analyse the distribution of head values a *normal distribution* or *Gauss distribution* was crafted. Values are sorted from smaller to higher and then using the average and the standard deviation the distribution can be constructed. The results are shown below:

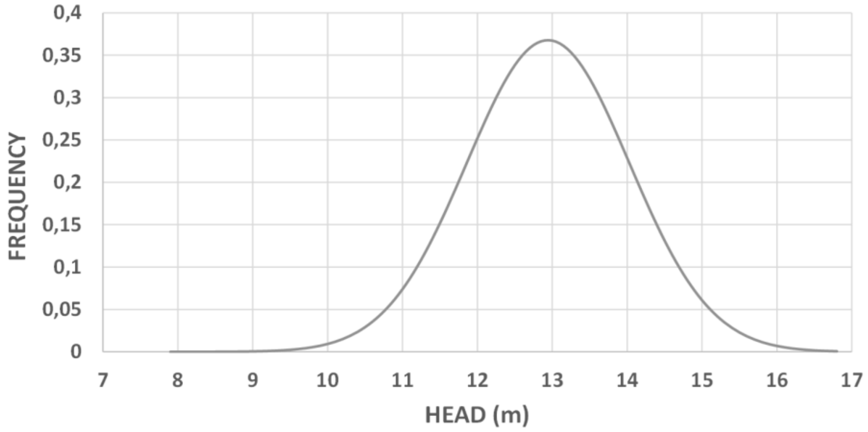

Figure 44. Normal distribution of water head in 2019.

The average obtained, as also calculated before is almost 13 m. The distribution shows great kurtosis, which means that most of the values oscillate close to the average, low standard deviation. The curve is also symmetric, which means that head values below 13m are as likely to happen as values over 13 m.

4.3.3. Water flow model

Water flow is one of the most important parameters to analyse and it is very important to define a descriptive model of water flow in order to craft an accurate numerical model. It is the input value for the main equations that were defined in the power numerical model.

Water flow is presented in two different ways. There are turbine individual water flow data, and water flow values together with bypass flow. The first thing done was to check that the sum of the three separate unit is the total power plant flow values together with bypass but in moments of no bypass water flow, so that calculations could be done with both of them indistinctly. In order to do so accumulated water flows of units were depicted. Figure 45 shows the accumulated water flow of units, that is, water flow of *unit 1*, sum of *unit 1* and *unit 2*’s water flow and sum of *unit 1*, *unit 2* and *unit 3*’s water flow, together with the total water flow of the power plant. Sum of the three units should correspond with the total flow values. The data taken corresponds with arbitrary election of values which comprises time lapses with all one, two and three turbines working at the same time.

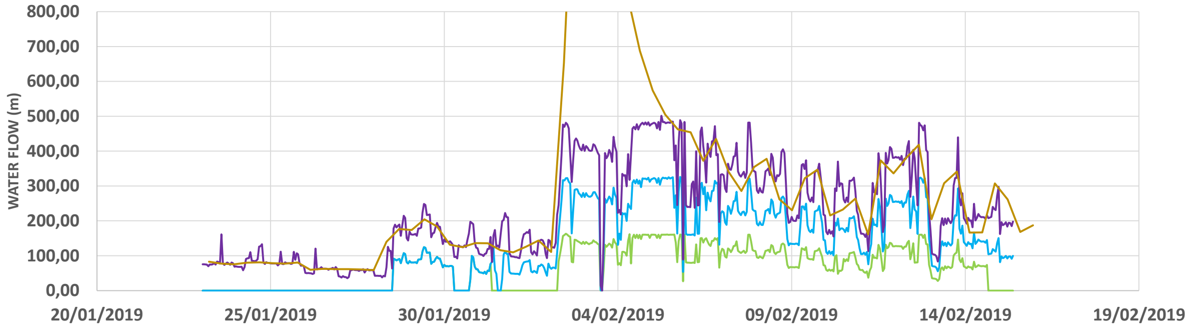

Figure 45. Units water flow comparison to total water flow.

Orange line shows the *total water flow together with bypass* and the other three are respectively the sum of the units. The results showed that both data are not to be used indistinctly. Individual turbine data had higher resolution (the frequency with which they were measured was 9 times higher), and are to be used when general calculations do not involve bypass water flow. In cases when there is need to evaluate bypass water there is only option to use the 9h time values. In the graph there is also a peak of bypass flow represented.

The second step was to analyse the graphics of water flow for the whole year 2019, in order to detect patterns, abnormalities, to analyse bypass water flow scenarios and to decide the water flow numerical model characterization. The whole graphic can be found in the appendix X, and here just a sample is represented. Figure 46 is a sample of the whole year which represents total water flow of the power plant together with bypass water flow. To choose the sample a period of time with bypass peaks was selected.

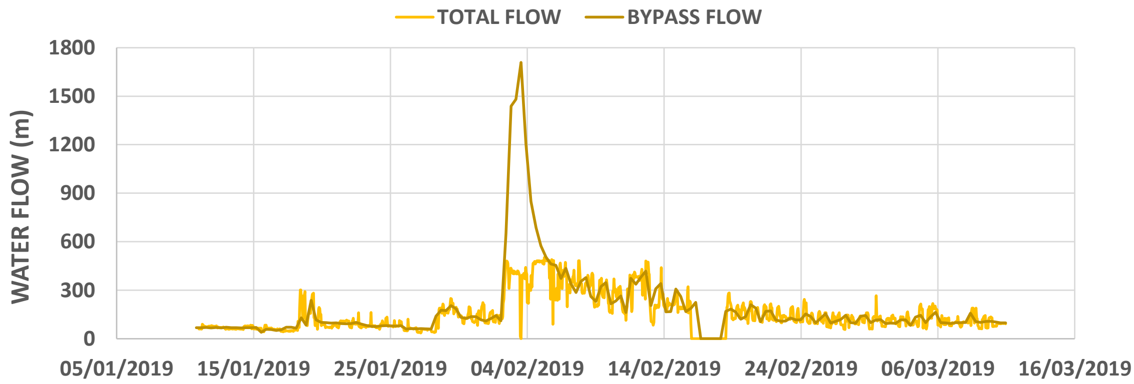

Figure 46. Total and bypass water flow sample.

The sample itself is not enough to extract consistent conclusions, but the whole year was analysed and the following considerations were made. Firstly, the bypass peaks are not many, there is a total of 7 big bypass peaks, but their value is extremely high compared to average water flow. Average value is 175.56 m3/s and peaks almost reach 1800 m3/s. This means that peaks can be almost 10 times bigger than average water flow.

In order to have numerical values of this surplus water flow the following procedure was taken. Firs some important values were added to the already calculated ones. Water flow maximum both for individual turbines and for total water flow of the power plant.

Table 19. Total and turbine individual water flow parameters.

WATER FLOW (m3/s)		
TURBINE MAXIMUM	**TOTAL MAXIMUM**	**TOTAL AVERAGE**
180	500	175.56

Second, once this information was available, it was checked whether the turbines were utilising all the water flow available, that is, if they were working at their maximum when water flow was available. To do this total water flow was compared to water flow plus bypass. The equation used was the following:

$$\text{=IF(“WF + Bypass” > “total maximum (500)” ; “total maximum (500)” ; “WF + Bypass”)} \quad (4.7)$$

Thirdly the surplus water flow was obtained as the difference between this “potential maximum use of water flow” and “water flow + bypass”. The equation used was the following:

$$\text{= “WF + Bypass” – “Maximum potential WF”} \quad (4.8)$$

The results for 2019 are presented below:

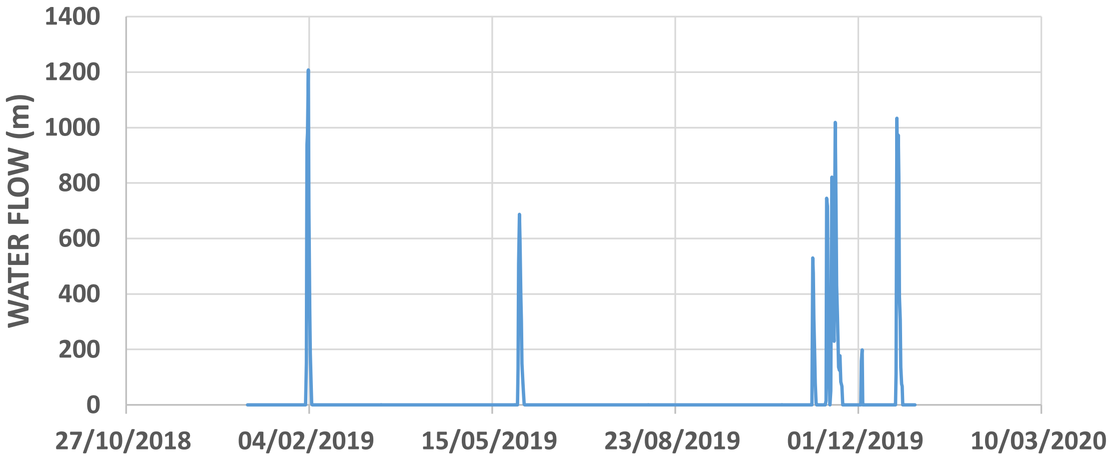

Figure 47. Lost water flow peaks in 2019.

As expected during the bypass peaks there is a considerable amount of water flow lost. In order to get good perception of the amount of water flow that is lost, it is compared in a chart to the total amount of water flow. Figure 48 shows the percentage of each, resulting in 11 % of water losses and 89 % of water flow used in turbine:

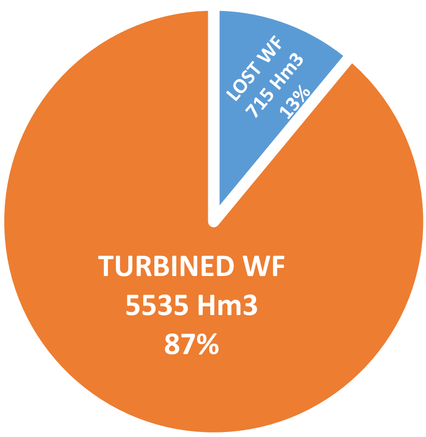

Figure 48. Percentage of lost water flow through bypass.

Finally, in order to also get good perception of the distribution of the data of water flow a *Gauss distribution* was also calculated and graphed. The objective is to analyse not only average values, but to know whether most values are concentrated around the average, or dispersed and with great deviation. This is interesting to analyse the power production potential, since greater negative asymmetry in the *normal distribution* means that there are more “higher values” and that the power outcome will be higher.

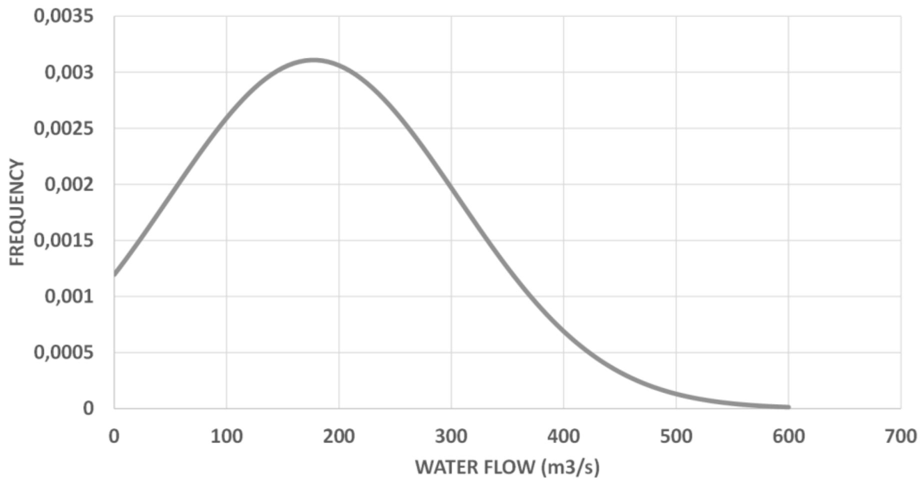

Figure 49. Normal distribution of water flow in 2019

Nonetheless, the results showed the opposite. There is positive asymmetry, which means that water flow data are closer to lower values. Also the kurtosis of the distribution is quite low, which means that values are quite dispersed. Translated into practical terms, this means that the power plant was working pretty much below the rated water flow capacity. It can turbine up to 500 m3/s, but in the normal distribution is easy to see that 500 m3/s have a rather low frequency. The average is 175.76 m3/s, which is almost as if one turbine was always working at its maximum.

4.3.4. Numerical model for total power

In terms of the numerical model power is the most important output. It must be obtained out of head and water flow inputs. Once water flow and head have been characterised it is time to describe and model how the power plant produces power. In this chapter a general approach that analyses the whole power plant will be made, not considering the individual units and its characteristics. The following chapter focuses on the particular aspects of the turbines, the performance and individual unit model, the working regimes, etc.

As it has been done before, the first step is to analyse the annual graphics of power in order to find patterns, anomalies or correlations. For that purpose a sample of 600 values was taken, randomly chosen out of the whole year and presented below:

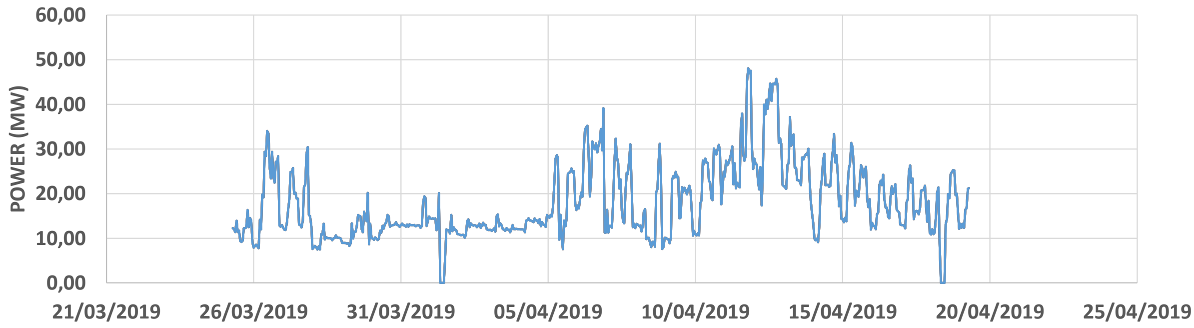

Figure 50. Sample of total power in 2019

The first useful data obtained out of the graphics is the similarities with the graphic of water flow. To better understand the correlation water flow and power are depicted together below:

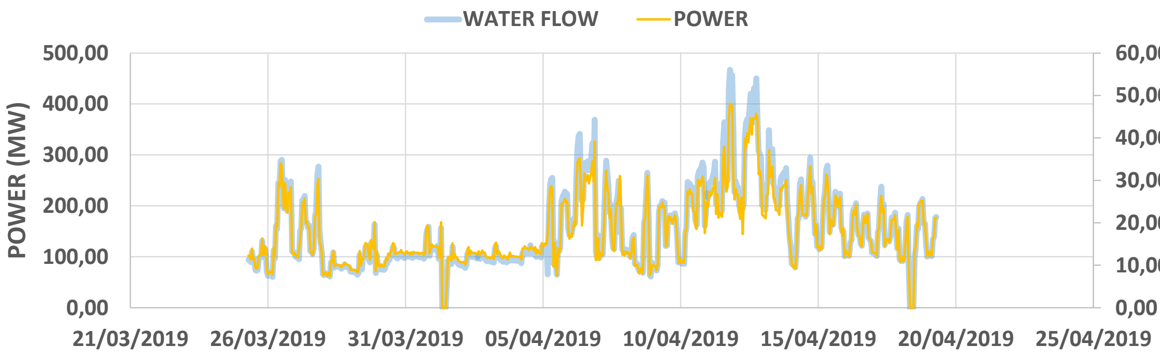

Figure 51. Sample of total power and water flow comparison.

As expected, there was a very clear correlation between water flow and power. Once the correlation was detected, the next step was to represent that correlation in a dispersion graphic, making power dependent on head and water flow, in order to know which type of equation could describe the relation the better.

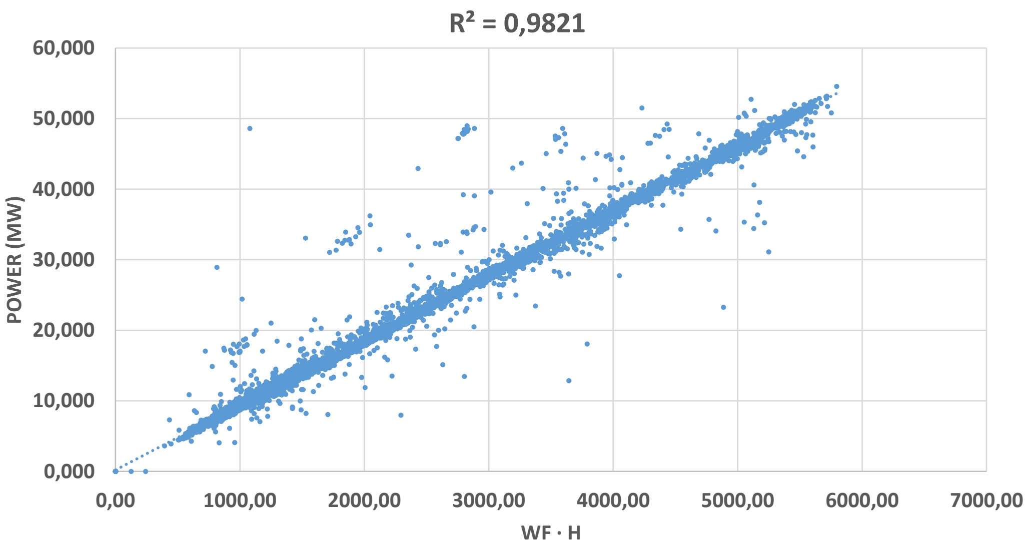

Figure 52. Power and water head and flow correlation.

The correlation comes almost as a straight line, since most of the points are located over it, being the R^2 equal to 0.9821. If the other values are filtered out the correlation could be approximated to a linear correlation, or only slightly better parabolic correlation. In this case the parabolic correlation was chosen to describe the power and water flow head relation. For this purpose the general equation of hydropower was used. The three parameters, power, water head and water flow are related to one another by Equation (4.4):

$$P = Q \cdot \rho \cdot g \cdot H \cdot \eta \tag{4.9}$$

Where:
P = unit power capacity
ρ = mass density of water, kg/m³
g = acceleration of gravity, m/s²
Q = water flow through turbine, m³/s
H = head, m
η = efficiency

Mass density of water, acceleration of gravity and performance can be considered as a single constant value called "A". The equation would be as follows:

$$P = A \cdot Q \cdot H \tag{4.10}$$

This means that the correlation must come in the form of a constant and that the input of the equation must be the product of water head and flow. Since the correlation considered was parabolic, the equation would be as showed below:

$$P_t = A_2 \cdot (Q_t \cdot H)^2 + B_2 \cdot (Q_t \cdot H) \tag{4.11}$$

Where:
P_t = total power output
Q_t = water flow through HPP, m^3/s
H = head for HPP, m

So parameters A_2 and B_2 had to be found. For this purpose Excel 2010 tools were used. Specifically the function LINEST. Out of the data for year 2019 of total power, water head and water flow the following parameters A_2 and B_2 were calculated:

Table 20. Power model parabolic correlation parameters.

P = A·(Q · H)^2 + B·(Q · H)

A	B	C
-4,76911E-08	9,45E-03	0

4.3.5. Numerical model for individual turbine power

The power of individual units defines the total power output of the power plant. Separate data is available for each parameter and they are compared in the diagram below. Blue lines show cumulative power of individual turbines and red line show the total power. The top blue line is not visible since it is covered by the red line which means that separate measurements match very well.

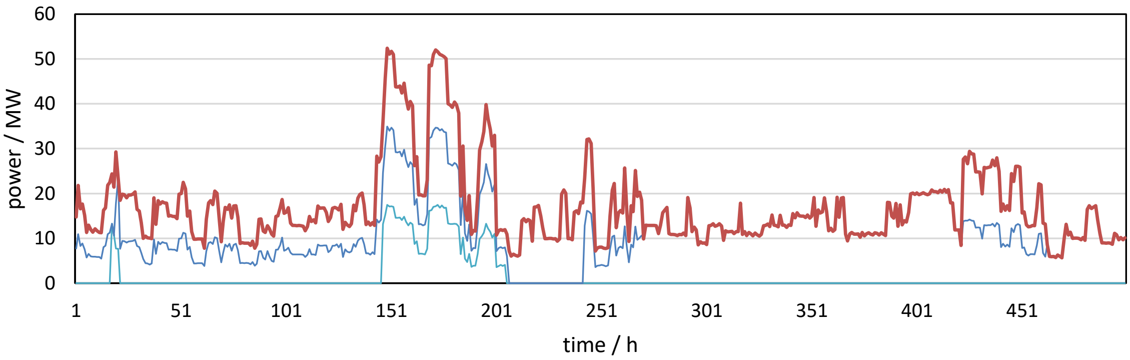

Figure 53. Accumulative power and total power comparison.

In the presented 500 hours interval (randomly selected) of operation different regimes are used - one unit (from 270 to 410), two units (from 30 to 140) or all three units (form 150 to 200) are in operation.

The sum of three individual units is obviously a good representation of the entire output of the power plant. The auxiliary power is either not considered in the measured values, or it is negligibly small.

The correlation with water flow is guaranteed since the analysis in the previous chapter were power and water flow were graphed together must be identical to the individual unit analysis. This is because total power is, as it has been shown in Figure 53, the sum of individual unit power, and total water flow is also the sum of individual turbine water flow. For this reason the graphics of water flow and head correlation with power for individual units are directly presented, and if the previous assumption was false, the validity would be verified in the correlation graphics.

One graphic is presented for each of the turbines. Water head and water flow product are the independent variable of the chart, and power goes in the y axis. The whole year 2010 has been taken in order to do the correlations:

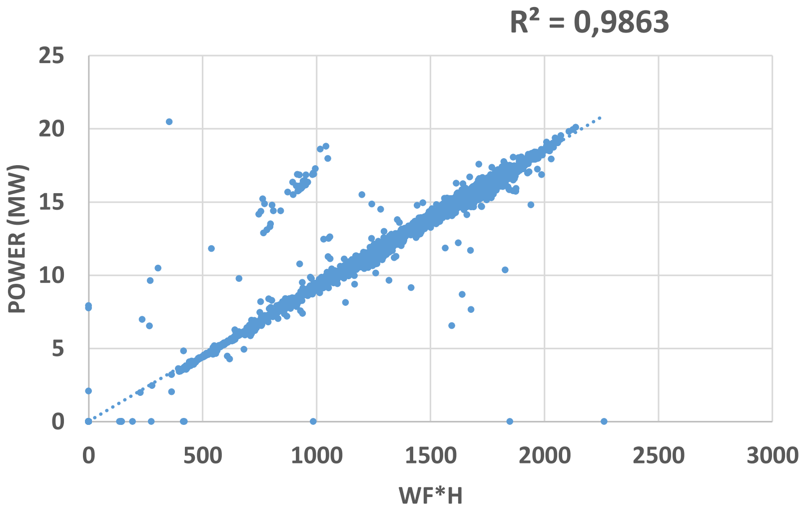

Figure 54. Unit 1 correlation of power and water head and flow.

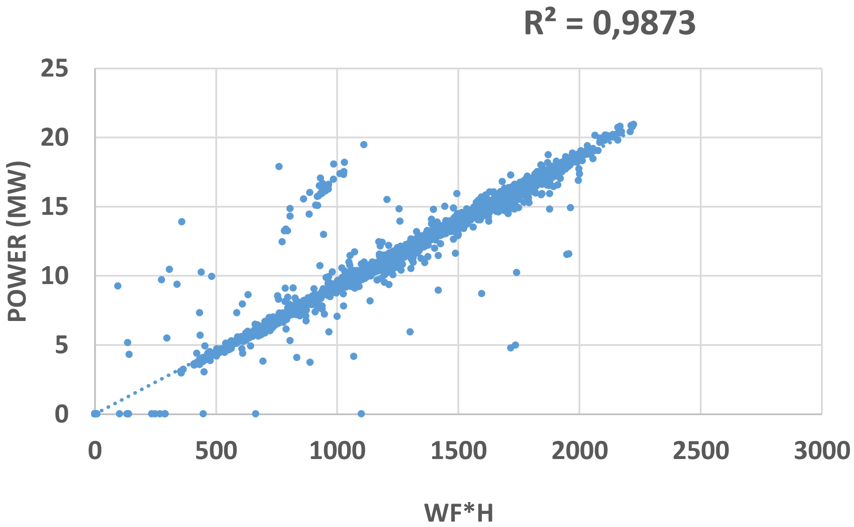

Figure 55. Unit 2 correlation of power and water head and flow.

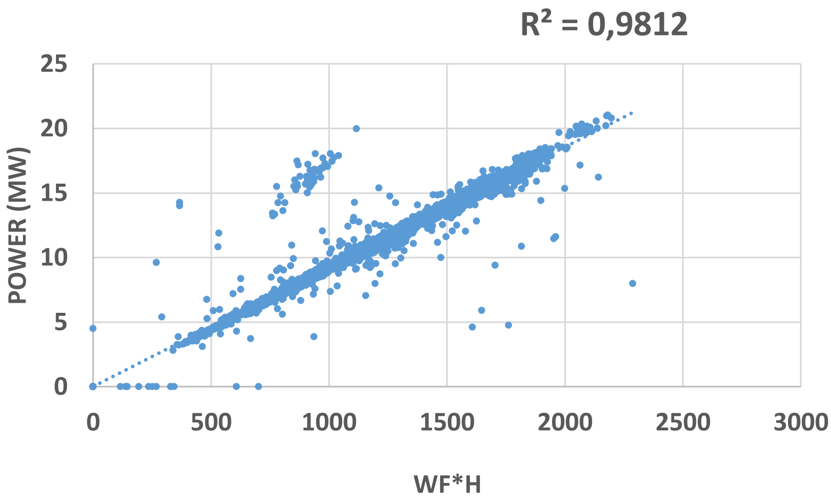

Figure 56. Unit 3 correlation of power and water head and flow.

The correlation between water head, water flow and power was as good as expected. The three unit have approximately an R^2 of 0.98. Linear correlation would have been a good approach, but parabolic correlation was slightly more accurate, and also had been used for the total power model, so a parabolic correlation was determined.

Equations used would be equal to the case of total power, so the purpose was to find parameters A and B for each of the turbines for the equation below:

$$P_i = A_{3i} \cdot (Q_i \cdot H)^2 + B_{3i} \cdot (Q_i \cdot H) \tag{4.12}$$

Where:
P_i = unit "i" power output, MW
Q_i = water flow through unit "i", m^3/s
H = head for the HPP, m

The method to calculate these parameters was the same as the one used for calculating the parameters in total power equation, LINEST. The results obtained are presented below:

Table 21. Individual turbine power mathematical model results.

	P= A·(Q·H)^2 + B·(Q·H)		
	A	**B**	**C**
UNIT 1	-2,78E-07	9,67E-03	0
UNIT 2	-6,27E-08	9,33E-03	0
UNIT 3	-1,28E-07	9,47E-03	0

4.3.6. Turbine shell diagram

Correlation between water flow rate, water head and turbine power is given in turbine's characteristic shell chart. Also the efficiency of the turbines is represented in the shell diagram.

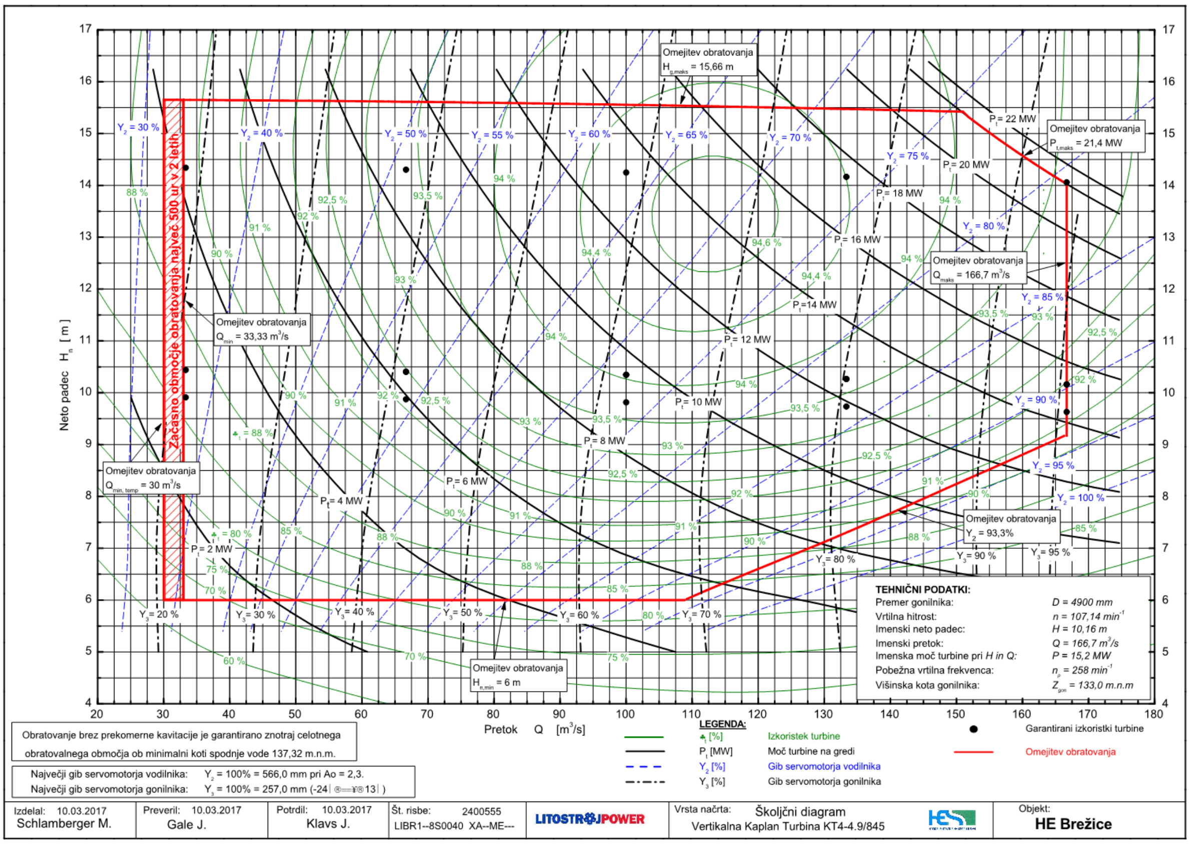

Figure 57. Turbine shell diagram.

5. VALIDATION OF THE MODEL

This chapter will present the results obtained from the numerical model of the Brežice HPP. Once the numerical model was calculated, it had to be verified that it was accurate and valid, and for that purpose one scenario will be presented to check whether the values obtained with the model match those obtained from the operators of the HPP.

Secondly, once the model was verified, it was used to make an analysis of the power lost by the bypass water flow that was not used in turbine, and that could be used to produce more power, or combine it with the hydrogen electrolyzers that are being researched.

In order to validate the numerical model some scenario must be calculated in which the real results are already known, so that when the virtual results of the model are obtained, they can be compared to the real values. As the data set gathered from the HPP operators had all the power values (output values), the scenario evaluated was to introduce water flow and water head inputs of year 2019, and obtain the corresponding values of power (virtual power) using the numerical model. Then this virtual power values were compared to the real power values. This was done both for the total power of the power plant and for the numerical model of individual turbines power.

5.1. Total power numerical model validation

To validate total power the data used was taken out of the set of data for the whole power plant. The methodology was very simple. First the product of water flow and water head for the whole power plant and for year 2019 (8760 values) was calculated. This product is the input for the model which uses parameters already presented in Table 20. These obtained values must be close to the real values given by the HPP operators (and that have already been checked and verified).

To analyse how far these virtual power values are from the real power values the error of the model was calculated with the following equation:

$$e_t = \left| \frac{P_{rt} - P_{vt}}{P_{rt}} \right| \cdot 100 \tag{5.1}$$

Where:
e_t = error of the total power values, %
P_{rt} = total real power value, MW
P_{vt} = total virtual power value, MW

Error bigger than 10 % were filtered out since the vast majority were errors caused by the desynchronization between the water flow and head product and the corresponding real power value, and were not real miscalculations of the model. After filtering the errors they were presented as shown in Table 22, together with real and virtual power.

Table 22. Sample of the error of the model for power.

POWER TURBINES (MW)	POWER (MODEL) (MW)	ERROR OF THE MODEL (%)
9,75	9,94	1,89
10,34	10,53	1,82
9,96	10,15	1,93
9,69	9,88	1,91
10,07	10,26	1,88
9,85	10,04	1,92
9,69	9,88	1,97
11,73	11,87	1,16
12,03	12,16	1,04
11,44	11,59	1,31
11,25	11,39	1,23

To get some visual understanding of the results the measured power and the calculated power were graphed together for random 500 values. Measured power was put in grey shadow so that calculated power, the one obtained by the model, could fit in in case the model results were correct. As shown in Figure 58, the results match perfectly for almost every value, and although numerical information had to be obtained of the deviation of the numerical model from the measured values, clear correlation was already seen.

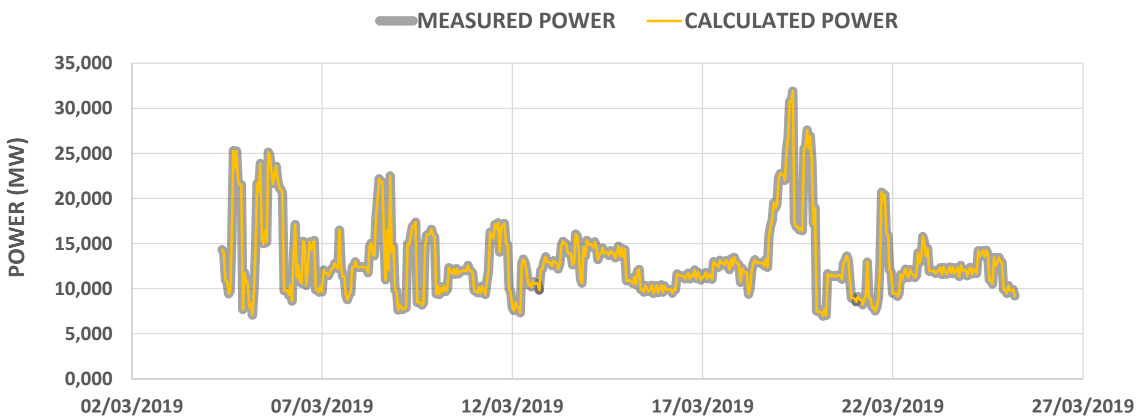

Figure 58. Comparison of mathematical model result of power with measured power.

Once visual correlation was settled more specific numerical results were obtained to measure the accuracy of the model. Out of the error results the average and standard deviation were calculated using Excel 2010 functions AVERAGE and STDEV. The results are given below in percentage:

Table 23. Average error of the total numerical model for power.

ERROR	
AVERAGE (%)	**STANDARD DEVIATION**
2,37	1,95

The average error of the numerical model is 2.37 %. Considering that there is still some deviation caused not because of the inaccuracy of the model but because the time mismatch of power and water flow data, the results are very promising, and good correlation between real power and virtual power can be guaranteed by the numerical model. Standard deviation values together with the average were used to create a normal distribution of the error of the numerical model, not only to know the average, but also to know where most of error values were concentrated.

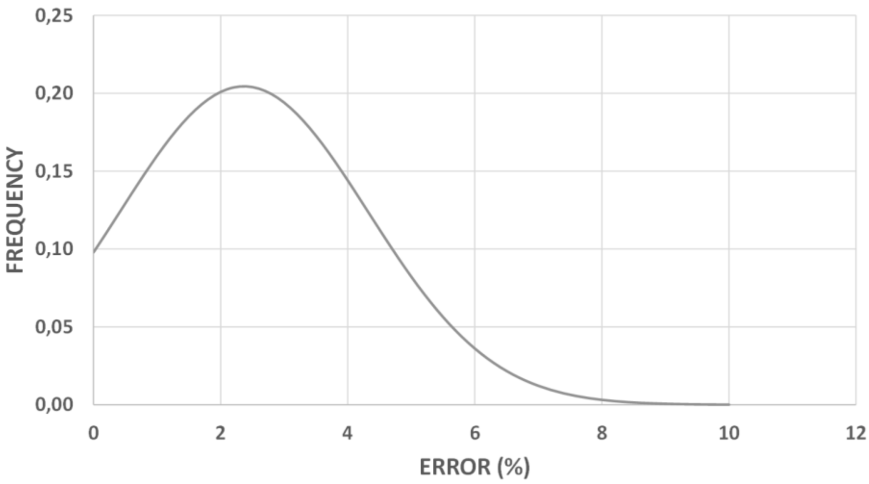

Figure 59. Normal distribution of the error of the numerical model of power.

The results were very promising, since the normal distribution had considerably great kurtosis around the average value, meaning that most of the error values are fairly close to the average of 2.37 %. Also the gauss bell had positive asymmetry, which means that more error values fall on the left side of the average, that is, lower error values, that is, more accuracy of the numerical model.

5.2. Individual power numerical model validation

The methodology to validate the numerical model of individual turbines was very similar to the methodology followed for the whole power plant. In this case, instead of using the total values, the individual values for each of the turbines were used separately.

The data used as an input for the model were water flow and water head values of 2019 for each of the turbines. As for total power numerical model validation, the product of water head and water flow was calculated in order to introduce it in the numerical models equations (shown in Table 21). Using these equations the calculated power values were obtained for each of the three turbines, and sorted in column together with the measured power values.

The next step was to calculate the deviation of the numerical model, by calculating the error of each of the obtained calculated power values. To do so the same equation as in the total power numerical model evaluation was used, but adapted for individual turbines:

$$e_i = \left|\frac{P_{ri} - P_{vi}}{P_{ri}}\right| \cdot 100 \qquad i = 1,2,3 \tag{5.2}$$

Where:
i = number of the turbine unit
e_i = error of the individual power values, %
P_{ri} = individual real power value, MW
P_{vi} = individual virtual power value, MW

Using this equation the errors were calculated and sorted in the following way. Numbers 1, 2 and 3 stand respectively for turbine 1, turbine 2 and turbine 3. As done in the previous total power validation, values above 10 % were filtered out.

Table 24. Sample of the error of the individual turbine numerical model for power.

	MODEL POWER 1 (MW)	MODEL POWER 2 (MW)	MODEL POWER 3 (MW)	ERROR 1 (%)	ERROR 2 (%)	ERROR 3 (%)
01/01/2019	0,0	9,8	0,0	0,00	0,39	0,00
01/01/2019	0,0	10,4	0,0	0,00	0,35	0,00
01/01/2019	0,0	10,0	0,0	0,00	0,45	0,00
01/01/2019	0,0	9,7	0,0	0,00	0,42	0,00
01/01/2019	0,0	10,1	0,0	0,00	0,41	0,00
01/01/2019	0,0	9,9	0,0	0,00	0,48	0,00
01/01/2019	0,0	9,7	0,0	0,00	0,52	0,00
01/01/2019	0,0	11,7	0,0	0,00	0,36	0,00
01/01/2019	0,0	12,0	0,0	0,00	0,56	0,00
01/01/2019	0,0	11,4	0,0	0,00	0,21	0,00
01/01/2019	0,0	11,2	0,0	0,00	0,32	0,00

In order to check the results, the next step was to analyse the visual correlation, graphing together measured power and calculated power. Measured power was presented in shadow grey so that calculated power could fit in in the shape, providing that there was correlation. Samples of the result are presented in Figure 60,Figure 61 and Figure 62. This was done for each of the turbines taking 500 random values out of the year 2019 8760 values.

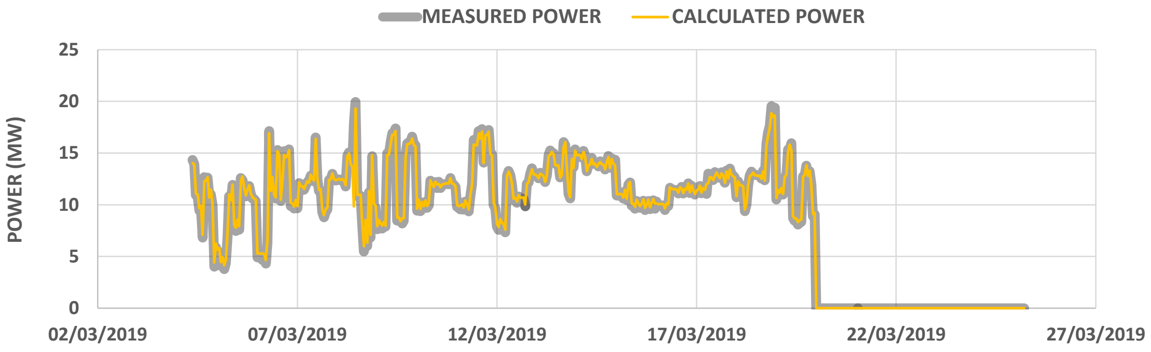

Figure 60. Model validation sample for Unit 1

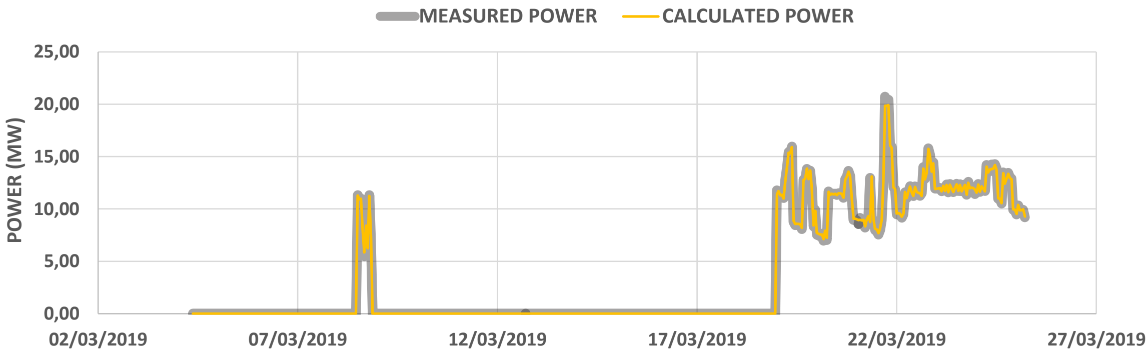

Figure 61. Model validation sample for Unit 2

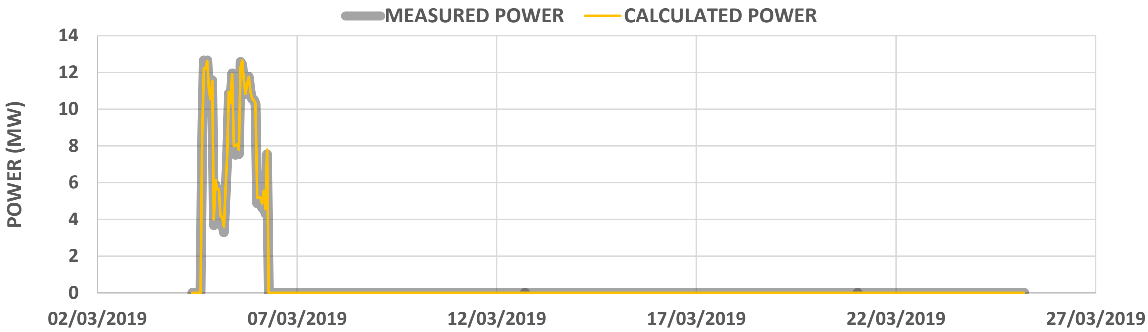

Figure 62. Model validation sample for Unit 3

All three graphics showed a very good result, as it can partially be seen in the result samples. Both lines, in the three graphics matched perfectly for almost every value. After validating the visual comparison, some more precise and numerical results of the accuracy of the numerical model were calculated. As it had been done for the total power model validation, the average of the error was calculated for each of the turbines.

Table 25. Average error of individual turbine numerical model for power.

	AVERAGE (%)	STANDARD DEVIATION
UNIT 1	0,96	1,77
UNIT 2	0,91	1,43
UNIT 3	2,16	1,93

The results were very promising. Average showed quite low values of error, being unit 3 the highest with 2.16 % of error, and unit 2 the lowest with 0.91 % of error. That means that the average of the units together was approximately 1.3 %. In order to provide with normal distributions of the error of each units, the standard deviation was also calculated using the Excel 2010 function STDEV. This was done in order to provide more descriptive information about the distribution of the error data, and to verify with greater perspective the accuracy of the model. The results of the normal distribution are presented below:

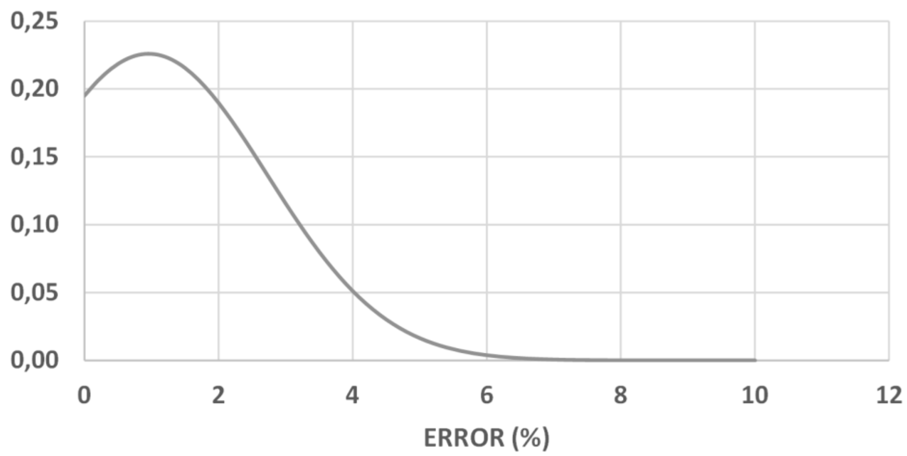

Figure 63. Unit 1 normal distribution of error.

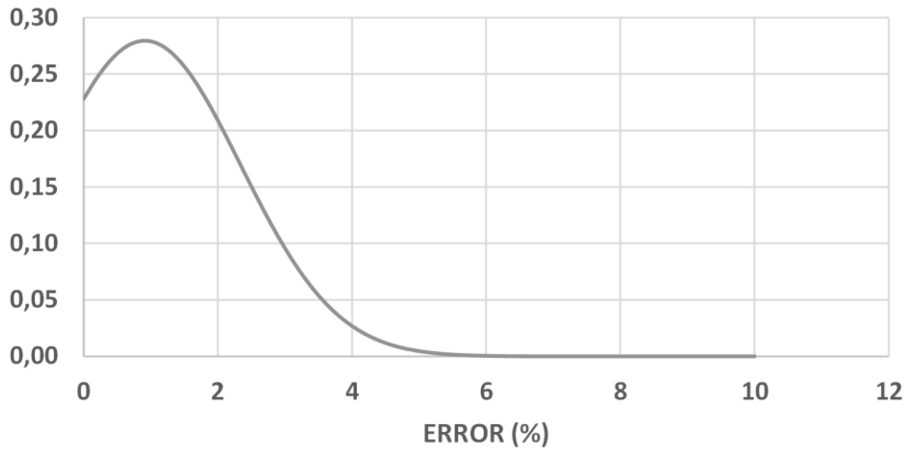

Figure 64. Unit 2 normal distribution of error.

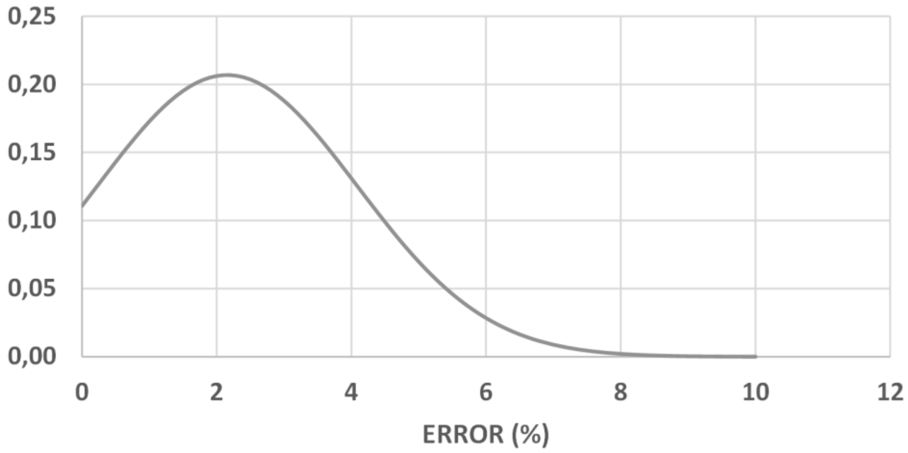

Figure 65. Unit 3 normal distribution of error.

The results were very positive. The three graphics show quite high kurtosis, being clearly unit 2 the highest. This means that most of the values are concentrated around the average and that there is not great dispersion of values. Also the graphics so positive asymmetry which means that most of the values are concentrated at the left side of the average, that is, at lower values of error. In this case also unit 2 had the most positive results, and unit 1 the worst.

Comparing the results of individual turbines with the results of total power analysis, it is clear that the model is more accurate when using the individual power equations rather than the total one. The average error is lower and most of the values are also lower.

5.2. Turbine performance validation

In order to validate the turbine specifications the shell diagram provided by the HESS operators was compared with the power lines obtained from the model calculations. For the comparison over 14 000 measured points were chosen from the total of 3·8760 = 26 280 points for all three turbines. Only points that deviate by less than 10 % from the modelled line are taken into account for further analyses. Other points might be caused by measuring errors or misinterpretation of recorded values.

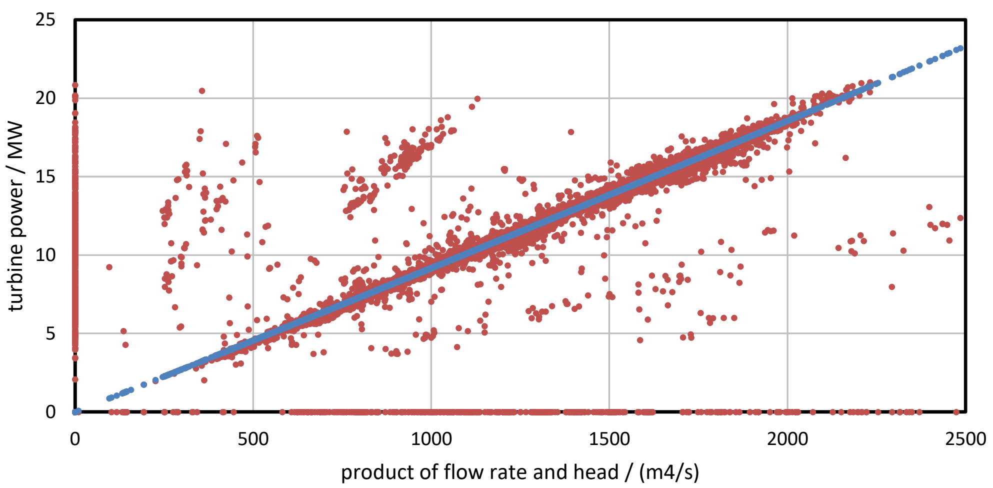

Figure 66. Considered points for the calculation of the shell diagram.

Of the 14 000 points 1780 are shown below. These are the points that deviate by less than 0.1 MW from the constant power lines on the diagram (4 MW, 6 MW etc.). We see that actual points lie very close to theoretical lines (deviation is only notable at large loads). This means that the model of the turbine is very close to the real behaviour of the turbines, and that the model is valid.

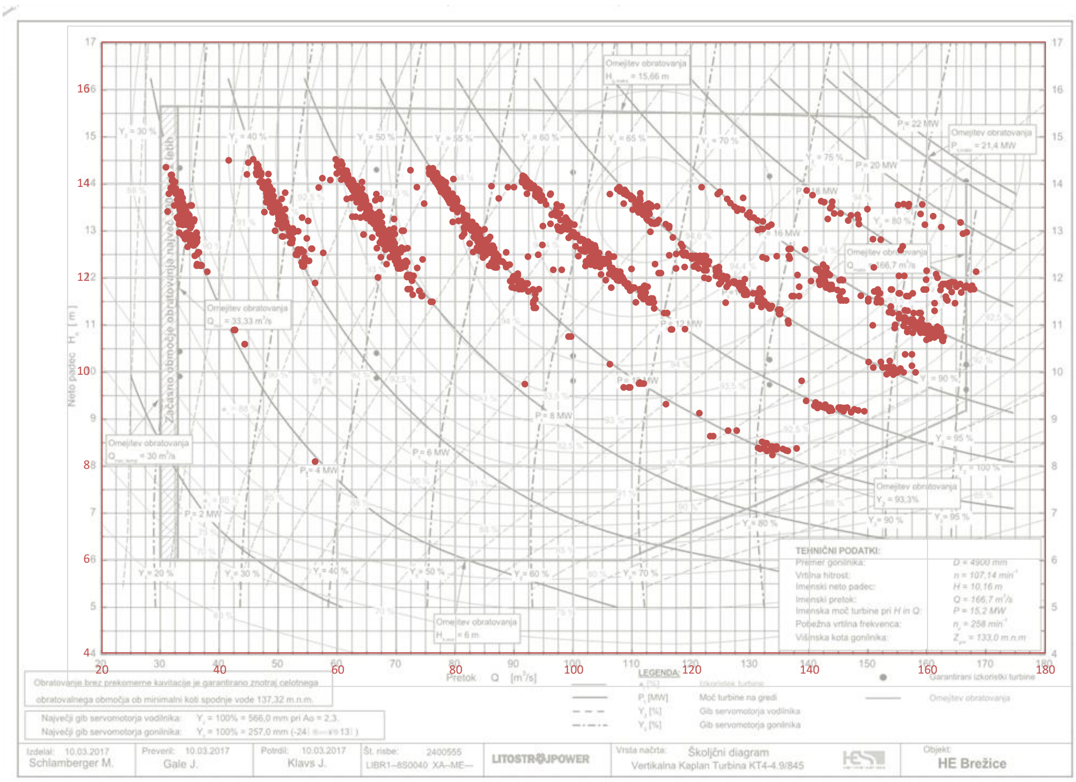

Figure 67. Model results compared in the shell diagram.

6. RESULTS

This chapter will present the results obtained out of the numerical model. Since the model had been validated, it was coherent to use it for obtaining results out of the data sets of the power plant. The main expected results were to measure the potential of the power plant to produce more power, and how this surplus power could be used to install the hydrogen electrolyzers. The results are also discussed as they are presented.

6.1. Introduction

The aim of the project in which this bachelor thesis is involved is to evaluate the possibility of installing hydrogen electrolyzers into the HPP. Although it is not the scope of this project to evaluate the operation of the hydrogen electrolyzers, the first steps of the hydrogen analyse are comprised in the bypass water flow and lost power analysis of this chapter.

The aim of this chapter is to analyse the water flow that is deviated through bypass, that is, that it is not being used to produce power by the turbines. The main reason for water flow to be derived through bypass is that the HPP turbines maximum water flow capacity is reached. This water flow that could give extra power will be analysed.

There are two levels of improvement:

1. The first one, that would be cost cero, is to utilise the turbines until their maximum all the time that there is surplus water flow. There are some times when water flow is being derived through bypass and turbines are not working at maximum. This could happen because of economical strategies in the energy market or some different operation strategy. Nevertheless, this potential was analysed. The power was calculated with the numerical model.

2. The second one analyses the power that could be produced in the hypothetic case that all the water that goes through bypass was used in turbine. The HPP has not actual capacity to turbinate that much water flow, but nonetheless, the potential of that increased power was measured using the numerical model.

6.2. Bypass water flow analysis

Part of this study was already done in chapter 4.4.3. The obtained results showed that approximately 11 % of the water flow was not being used in turbine and was derived through the bypass. The total sum of deviated water flow was 715 Hm^3, which was demonstrated that supposes a great percentage of the total water flow of the HPP.

In order to make the results understandable, the following parameters were defined:

Water flow plus Bypass: It is the total water flow of the power plant, considering both the water flow through turbines and the water flow through bypass.

Usable water flow: It is the water flow that can be used until the maximum of the turbines is reached. Corresponds to the “Improvement 1” mentioned in the introduction of chapter 5.2.

Lost bypass water flow: It is the difference between “water flow plus bypass” and “usable water flow”. It corresponds to the power that would be lost even if the turbines were working at maximum flow.

Usable power: It is the power (calculated with the numerical model) that would be obtained if the turbines reached their maximum capacity of water flow. It is related to the “Improvement 1” from the introduction of chapter 5.2.

Lost power: It is the power (calculated with the numerical model) that would be obtained out of the “lost water flow” that goes through bypass. It corresponds to the “Improvement 2” from the introduction of chapter 5.2.

Virtual power: It is the sum of “usable power” and “lost power”, and is the total power that the HPP would produce if the whole water flow was used in turbine.

The first step to evaluate the bypass water flow was to graphically present the expected results of “virtual power”. In points where there is no bypass water flow peaks “virtual power” should match the real power values. Since the model had already been validated, these correlation was given for granted. The focus of this graphics was set on the points where there is bypass water flow peaks. For that reason the last points of the year 2019 were chosen to present the sample, where the peaks of bypass water flow are more frequent.

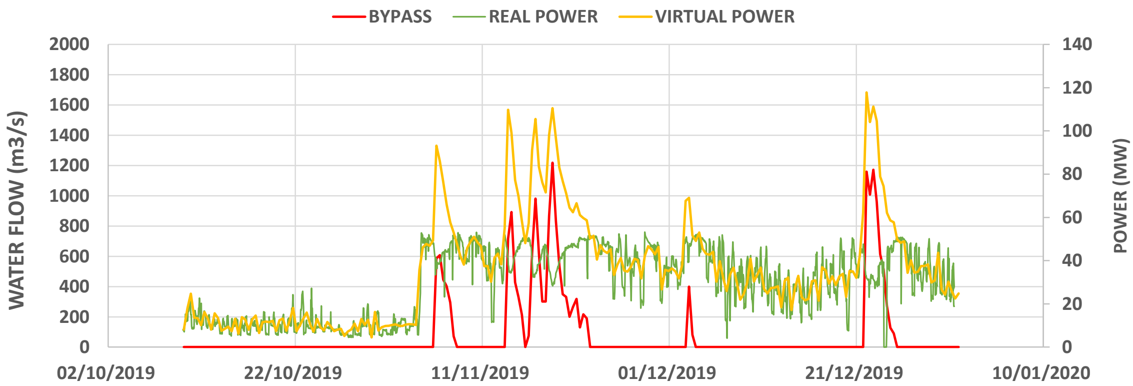

Figure 68. Bypass, real power and virtual power comparison.

In Figure 68 “virtual power” is presented in orange. Green line correspond to the real power. Bypass water flow is shown in red. There was a close match between real power and virtual power in points where there were no bypass water flow peaks (as expected). On the contrary, in points where there were bypass water flow peaks the results were quite different. Virtual power in this cases was much bigger, even double at some points. This showed that the potential increase of the produced power is fairly high.

A sample of the numerical results, calculated with the numerical model are presented below in Table 26. The first values in columns of lost water flow and lost power are cero because those are points where there are no bypass water flow peaks.

Table 26. Sample of the numerical results calculated with the numerical model.

USABLE WF WITH BYPASS (9H) (m3/s)	LOST BYPASS WF (9H) (m3/s)	LOST POWER (9H) (MW)	USABLE POWER (9H) (MW)	VIRTUAL POWER (BP) (MW)
84,3	0,00	0,00	11,17	11,21
95,7	0,00	0,00	12,59	12,63
83,5	0,00	0,00	11,17	11,21
89,0	0,00	0,00	11,67	11,70
86,4	0,00	0,00	11,34	11,37
80,6	0,00	0,00	10,81	10,84
84,4	0,00	0,00	11,21	11,25
88,3	0,00	0,00	11,75	11,78
70,6	0,00	0,00	9,47	9,50
69,4	0,00	0,00	9,31	9,34
68,3	0,00	0,00	9,16	9,18
67,4	0,00	0,00	9,01	9,04
68,6	0,00	0,00	8,90	8,92

Once the graphical representations where analysed, the total values were calculated. In order to get a representative value, total energy was calculated. To calculate energy in the hourly data sets power values for each hour were summed together and given in MWh. In the case of 9 hour (8 and three quarters) the power values of each interval were multiplied by the length (in hours) of that interval, to obtain MWh as well. The results are shown below:

Table 27. Results of the energy analysis.

REAL ENERGY	174.205,50	MWh
USABLE ENERGY	182.301,28	MWh
LOST ENERGY	17.329,95	MWh
VIRTUAL ENERGY	199.031,84	MWh

Real energy: it is the total energy for year 2019 out of the real values provided by the HPP operators.

Usable energy: it is the energy that could be obtained if the turbines were working until their maximum when water flow was available.

Lost energy: it is the sum of all the energy corresponding to the water flow that is derived through bypass considering that turbines are working at the maximum water flow. It is the sum of lost power by the corresponding time lapses.

Virtual energy: it is the sum of usable energy and lost energy and corresponds to all the energy that would be obtained if the turbines had no water flow or power limit.

The percentage of energy that is lost was calculated using "real energy" and "lost energy", dividing one by the other. The results are shown in below:

Table 28. Percentage of energy lost in bypass water flow.

ENERGY LOSS PERCENTAGE
9,948%

Also Figure 69 is provided to have more graphical and visual representation of the results:

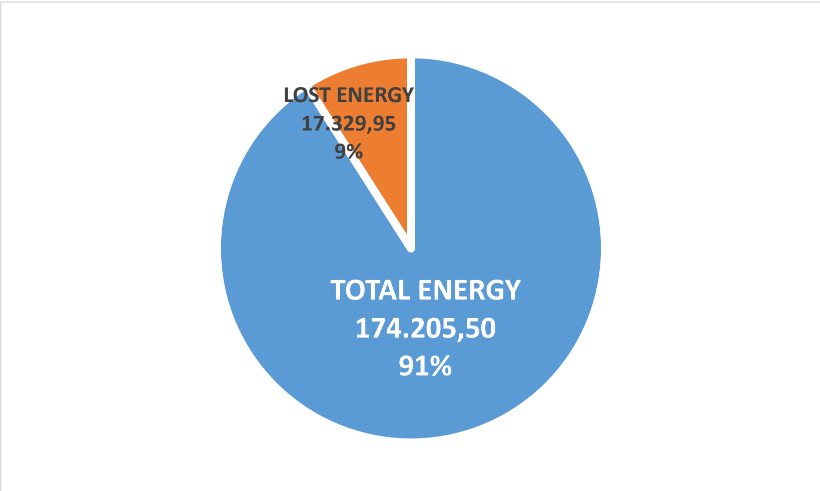

Figure 69. Pie chart of the percentage of lost power.

6.3. Study of hydrogen electrolyzers potential

The previous results showed a quantitative representation of the exceeding power, but were not focus in the hydrogen production purpose of the project. For that reason the “approach 1” explained in chapter 5.2. was followed, where the water flow available to reach the maximum of the turbines was analysed.

In order to make the comparison with the rest of the data easier, the available data for every approximately 8 hours and 46 minutes (1000 points) was rearranged in hourly values.

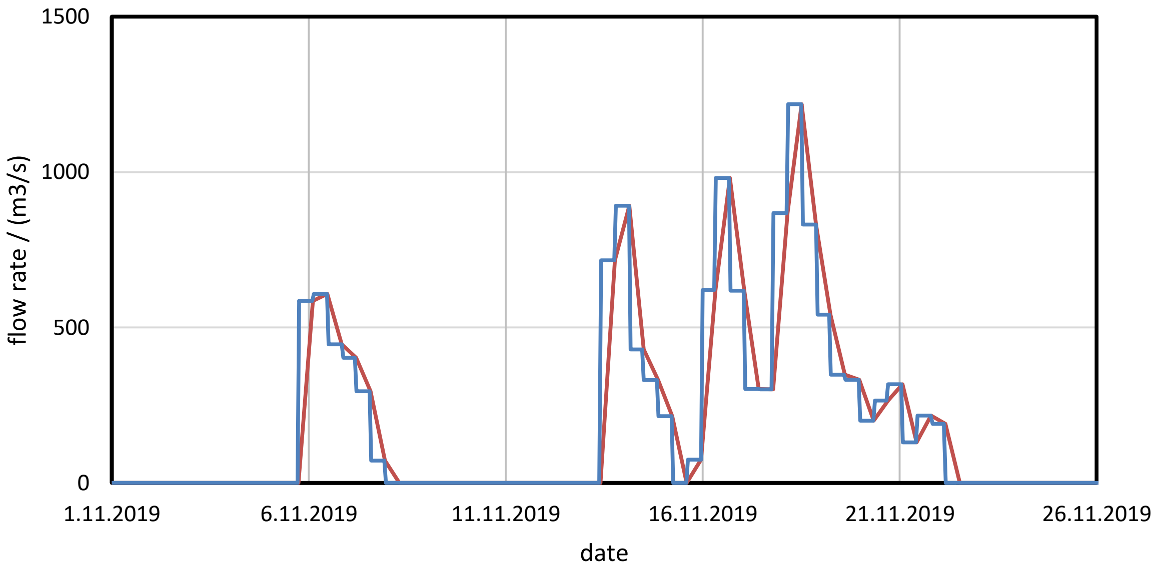

Figure 70. Bypass water flow sample after rearrangement.

In order to check whether there was exceeding water that could be used in the turbines when there was bypass water flow, the bypass flow rate was compared to the available capacity of the turbines. Each turbine has a maximum flow rate of 167 m^3/s which sums up to 500 m^3/s for the total power plant. As in moments of bypass there is already water flow going by the turbines, only limited quantity can be additionally derived though bypass.

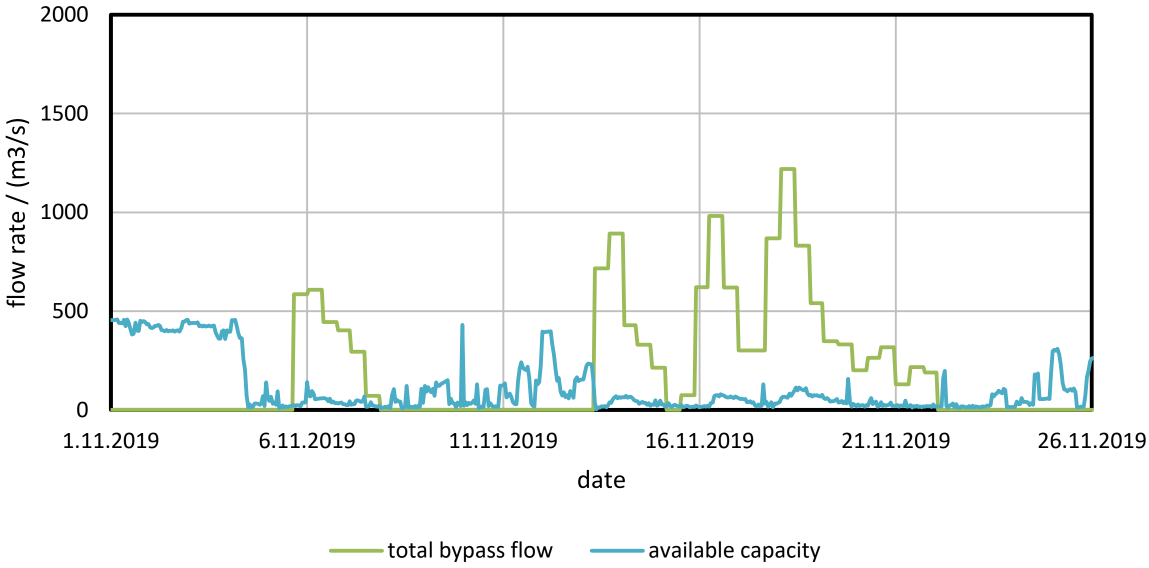

Figure 71. Available capacity of water flow out of bypass.

Once the available additional bypass water flow was checked, it was noticed that the capacity of these additional water flow was quite low, because turbines were already working close to their maximum capacity. For this reason only a limited amount of water flow could produce additional power.

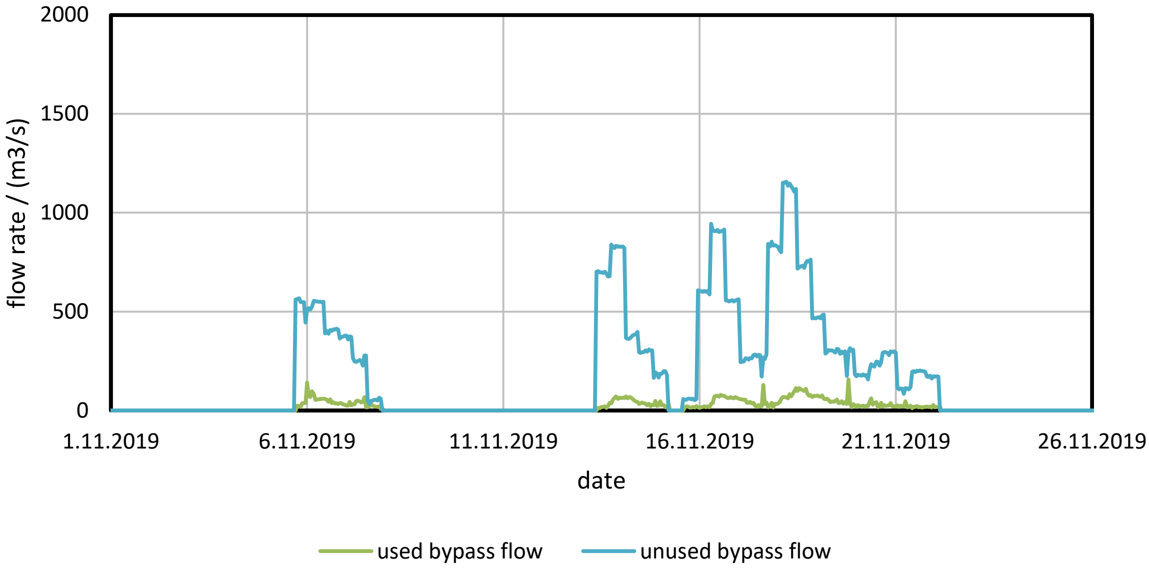

Figure 72. Usable amount of water flow from bypass.

By means of the numerical model the additional water flow was translated to terms of power. The additional power ranged from 0 to 40 MW (for all the 1 hour intervals). Nonetheless, the distribution of the power values was not uniform, and a frequency chart was crafted to analyse the number of hours in which each value of power was given (e.g. during 60 hours the additional power available was between 3 MW and 4 MW).

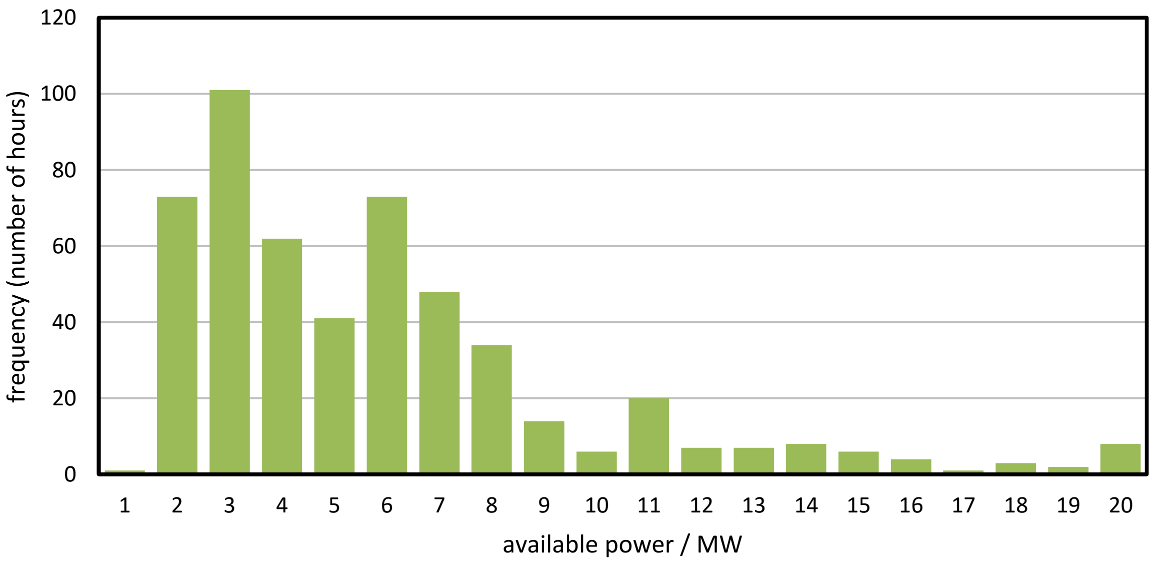

Figure 73. Available working hours for power production.

The load factor that the hydrogen electrolyzers would have is very small, for only 6 % of the time of the year would be working. The rest of the time, 94 %, there is either no additional water flow or the turbines have already reached their maximum capacity.

Total time available with excess power is 545 h, 50 % of those have power below 5 MW, 80 % is below 8 MW. Total energy that could be produced with bypass flow is 3500 MWh. Approximately 2600 MWh could be produced if the electrolyzer operating range is limited to 1 to 8 MW. If load factor is that low, high environmental impacts can be expected from the produced hydrogen.

In order to dimension the Proton Exchange Membrane (PEM), i.e. the hydrogen electrolyzer, the optimal rated power of the device had to be decided. For this purpose, out of the total energy that could be obtained (3500 MWh), the percentage of energy that would be used for each of the rated power was calculated. Figure 74 depicts the percentage that was obtained for each of the rated powers.

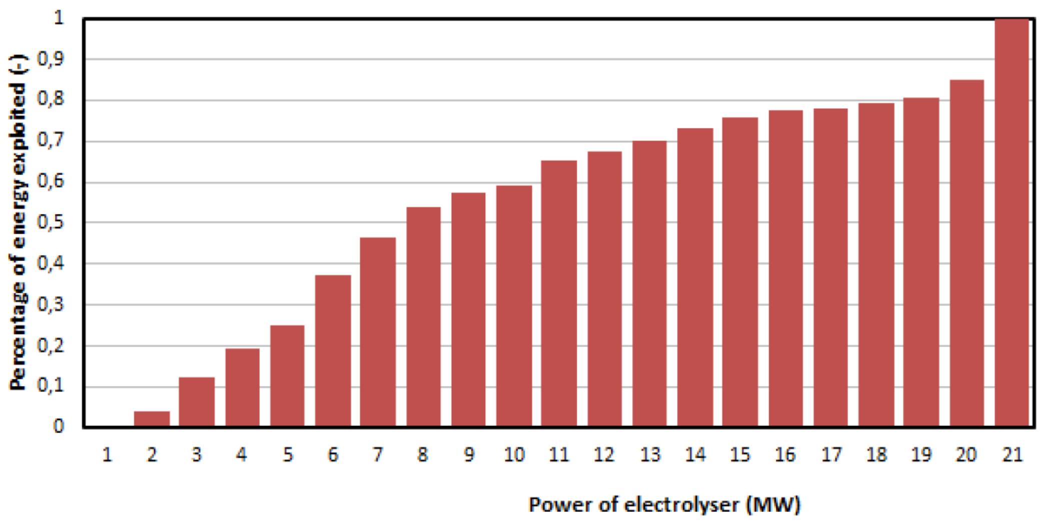

Figure 74. Percentage of energy used as a function of the size of the PEM device [30].

8 MW and 11 MW were the most appropriate values to discuss. 8 MW comprises most of the hours of surplus water flow (80 %), and at 11 MW there is a peak of surplus hours. As it can be marked out of Figure 74, an 8 MW device would use 54 % of the energy, while an 11 MW would use a 65 % of the energy. When this results are compared with power instead of energy values the difference is quite smaller. This is because the amount of hours that 11 MW could be produced are few, but the 3 MW difference between the two options is quite reasonable.

In order to decide the most appropriate rated power to install, a model of the PEMs was developed, to compare the amount of hydrogen that each of the variants would produce. The electrolyzer that was modelled was the *Siemens Silyzer 200.*

Table 29. Technical characteristics of Siemens Silyzer 200 (Siemens Co.)[29].

Electrolysis Type	**PEM**
Rated stack power	1.25 MW
AC input power	1.9 MVA
Start-up time (from standby)	< 10 s
Operating temperature	60–80°C
Operating pressure	Up to 35 bar
H_2 purity (depends on operation)	99.5%–99.9%
H_2 quality	5.0 (deoxo-dryer option)
H_2 rated production	20.3 kg•h^{-1}; 225 Nm^3•h^{-1}
O_2 rated production	162.4 kg•h^{-1}; 112.5 Nm^3•h^{-1}
Design lifetime	> 80,000 h
Dimension skid	6.3 × 3.1 × 3.0 m^3
Skid weight	17 ton
CE conformity	Yes
Tap water requirement	1.5 L•Nm$^3{}_{H2}{}^{-1}$

The model was validated using the data provided by the manufacturers of the PEM, and the results were accurate enough to prove the model valid.

The equation of the model that defines the PEM system is the following:

$$\mathrm{H}_2 = -22{,}5 \cdot Q_{pem}^2 + 216{,}7 \cdot Q_{pem} \tag{6.1}$$

Where:
H_2 = hydrogen produced volume, Nm^3
Q_{pem} = Additional water flow to produce hydrogen, m^3/s

Using this equation the amount of hydrogen that would be produced with each of the rated powers could be calculated. Before this calculations were done, the number of electrolyzers that would be required was calculated.

- **8 MW rated power**

The 8 MW rated power would use 6 electrolyzers of 1.25 MW rated power, which sums 7.5 MW of total rated power. However the devices can work between 0.25 and 1.5 MW, which means that together they can reach without problems the desired 8 MW. With this configuration the volume of hydrogen that would be obtained is **328 610 Nm3**.

- **11 MW rated power**

The 11 MW choice would use 9 electrolyzers. The rated power would be 11.25 MW, so the desired 11 MW would be met without problems. With this configuration the volume of produced hydrogen would be **401 570 Nm3**.

In conclusion, the 73 000 Nm3 difference between one configuration and the other is unlikely to be worthy. The 11 MW configuration would produce more hydrogen, but the load factor would be very small, and consequently the payback time considerably higher. Therefore, the 8 MW configuration was regarded to be the better of the two [30].

7. CONCLUSIONS

This Bachelor Thesis has focused in the analysis of the Brežice HPP in order to develop a numerical model that can predict the functioning of the power plant, in order to help future lines of research to analyse the potential of installing hydrogen electrolyzers. The resulting findings are listed below:

- We performed bibliographic research in hydropower technology and physic fundamentals and presented the findings in a successful way.
- We observed that water flow through bypass was very high, more than double than average water flow, but that the frequency of these bypass water flow peaks was very low.
- We observed and calculated that the correlation between water head and water flow with power was very good, and that it could be modelled with linear correlation or slightly better parabolic correlation.
- We designed a numerical model that takes water flow and water head as an input and gives power values as an output, both for individual turbines and for the whole power plant.
- We demonstrated that the numerical model is valid, that the accuracy is high and the error small enough by presenting a hypothetical scenario where water flow and head of year 2019 are inputs.
- We measured the error of the power model, and found that the model of individual turbines is more accurate than the model of the whole power plant. 2.37 % and 1.30 % for individual turbines and total HPP respectively.
- We observed that the water flow that is not used in turbine goes through bypass, and that the power that could be obtained out of this lost water flow was very high, approximately a 10 % of the total produced in 2019 in terms of energy.
- Load factor of electrolyzers was estimated using the results of the power numerical model and found that the load factor using bypass water flow until turbines reach their maximum would be very small.
- We compared two different configurations of rated powers for hydrogen electrolyzers and found that 6 PEMs of 1.25 MW (working until 8 MW) was the most appropriate choice.

Recommendations for future research

Based on the results of this Bachelor Thesis, we recommend that future research about installing hydrogen electrolyzers considers not only using surplus bypass water flow, but also the operating strategies of the energy market that could make the load factor of the electrolyzers higher. Developing a model of the HPP that could also predict these operational behaviours could be helpful to optimize the PEMs.

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