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Hydraulic Power with Reversible Pump of Foz do Tua Dam

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Dedication

To my dearest mother,

Whatever I do or say to you, I cannot thank you as I should, your affection covers me, your benevolence guides me and your presence close to me has always been my source of strength to face the different obstacles.

To my dearest father,

You have always been close to me to support and encourage me. May this work reflect my gratitude and affection.

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It is with great pleasure; I dedicate this modest work to you.

Abstract

Hydroelectric power generation is one of many ways in which electricity can be generated. In 2009, the three most heavily used sources for generating electricity were coal, natural gas and oil. These sources not only release emissions that are harmful to the environment, they are resources that are quickly running out. Therefore, different ways of generating power will need to be explored. Hydroelectric power works to harvest the inherent energy of moving water.

Hydropower on a small-scale is one of the most cost-effective energy technologies to be considered for rural electrification in less developed countries. It is also the main prospect for future hydro developments in Europe. Small hydro technology is extremely robust and is also one of the most environmentally benign energy technologies available. The development of hydro-electricity in the 20th century was usually associated with the building of large dams. Hundreds of massive barriers of concrete, rock and earth were placed across river valleys worldwide to create huge artificial lakes.

To this end, this work proposes a case study of a hydroelectric power plant of a dam in Portugal "Foz do tua dam" which is mainly separated in 3 parts. The first part presents the state of the art where we explain the hydroelectric plant. The second part introduces the manual operation of the different types of energy. And the last part is a simulation on CFD software.

Key words: Hydroelectric power, Small hydro power, Large hydro power, Dam, Renewable energy, Environmental effect.

Resumo

A produção de energia hidroeléctrica é uma das muitas formas em que a electricidade pode ser gerada. Em 2009, as três fontes mais utilizadas para gerar electricidade foram o carvão, o gás natural e o petróleo. Estas fontes não só libertam emissões nocivas para o ambiente, como também são recursos que se esgotam rapidamente. Por conseguinte, será necessário explorar diferentes formas de produção de energia. A energia hidroeléctrica trabalha para colher a energia inerente à deslocação da água.

A energia hídrica em pequena escala é uma das tecnologias energéticas mais rentáveis a ser considerada para a electrificação rural nos países menos desenvolvidos. É também a principal perspectiva para o futuro desenvolvimento hidroeléctrico na Europa. A tecnologia das pequenas centrais hidroeléctricas é extremamente robusta e é também uma das tecnologias energéticas mais benignas do ponto de vista ambiental disponíveis. O desenvolvimento da hidroeletricidade no século XX foi geralmente associado à construção de grandes barragens. Centenas de enormes barreiras de betão, rocha e terra foram colocadas através de vales de rios em todo o mundo para criar enormes lagos artificiais.

Para o efeito, este trabalho propõe um estudo de caso de uma central hidroeléctrica de uma barragem em Portugal "Foz do teu barragem" que se encontra principalmente separada em 3 partes. A primeira parte apresenta o estado da arte onde se explica a central hidroeléctrica. A segunda parte introduz o funcionamento manual dos diferentes tipos de energia. E a última parte é uma simulação sobre o software CFD.

Palavras-chave: Energia hidroeléctrica, Pequena energia hidroeléctrica, Grande energia hidroeléctrica, Barragem, Energia renovável, Efeito ambiental

Résumé

La production d'énergie hydroélectrique est l'une des nombreuses façons de produire de l'électricité. En 2009, les trois sources les plus utilisées pour produire de l'électricité étaient le charbon, le gaz naturel et le pétrole. Non seulement ces sources émettent des émissions nocives pour l'environnement, mais elles constituent des ressources qui s'épuisent rapidement. Il faudra donc explorer d'autres moyens de produire de l'électricité. L'énergie hydroélectrique consiste à exploiter l'énergie inhérente à l'eau en mouvement.

L'hydroélectricité à petite échelle est l'une des technologies énergétiques les plus rentables à envisager pour l'électrification rurale dans les pays moins développés. C'est également la principale perspective pour les futurs développements hydroélectriques en Europe. La technologie des petites centrales hydroélectriques est extrêmement robuste et constitue également l'une des technologies énergétiques les plus respectueuses de l'environnement. Au XXe siècle, le développement de l'hydroélectricité était généralement associé à la construction de grands barrages. Des centaines de barrières massives de béton, de roche et de terre ont été placées à travers les vallées fluviales du monde entier pour créer d'énormes lacs artificiels.

Dans ce but, ce travail propose une étude de cas d'une centrale hydroélectrique d'un barrage au Portugal "Foz do tua dam" qui est principalement séparée en 3 parties. La première partie présente l'état de l'art où nous expliquons la centrale hydroélectrique. La deuxième partie introduit le fonctionnement manuel des différents types d'énergie. Et la dernière partie est une simulation sur le logiciel CFD.

Mots clés : Energie hydroélectrique, Petite hydroélectricité, Grande hydroélectricité, Barrage, Energie renouvelable, Effet environnemental.

الملخص

يعد توليد الطاقة الكهرومائية أحد الطرق العديدة التي يمكن من خلالها توليد الكهرباء. في عام 2009 ، كانت المصادر الثلاثة الأكثر استخدامًا لتوليد الكهرباء هي الفحم والغاز الطبيعي والنفط. لا تطلق هذه المصادر انبعاثات ضارة بالبيئة فحسب ، بل إنها موارد تنفد بسرعة. لذلك ، سوف تحتاج إلى استكشاف طرق مختلفة لتوليد الطاقة. تعمل الطاقة الكهرومائية على حصاد الطاقة الكامنة في نقل المياه.

الطاقة الكهرومائية على نطاق صغير هي واحدة من أكثر تقنيات الطاقة فعالية من حيث التكلفة التي يجب مراعاتها لكهربة الريف في البلدان الأقل نمواً. كما أنه يمثل الاحتمال الرئيسي للتطورات المائية المستقبلية في أوروبا. تعتبر تكنولوجيا الطاقة المائية الصغيرة قوية للغاية وهي أيضًا واحدة من أكثر تقنيات الطاقة المتاحة غير الضارة بالبيئة. ارتبط تطوير الطاقة الكهرومائية في القرن العشرين عادة ببناء سدود كبيرة. تم وضع مئات الحواجز الضخمة من الخرسانة والصخور والأرض عبر وديان الأنهار في جميع أنحاء العالم لإنشاء بحيرات صناعية ضخمة.

تحقيقا لهذه الغاية ، يقترح هذا العمل دراسة حالة لمحطة الطاقة الكهرومائية لسد في البرتغال "سد فوز دو توا" والذي تم فصله بشكل أساسي إلى 3 أجزاء. يقدم الجزء الأول أحدث ما توصلت إليه التكنولوجيا حيث نشرح محطة الطاقة الكهرومائية. يقدم الجزء الثاني التشغيل اليدوي لأنواع الطاقة المختلفة. والجزء الأخير هو محاكاة لبرنامج CFD.

الكلمات المفتاحية: الطاقة الكهرومائية ، الطاقة المائية الصغيرة ، الطاقة المائية الكبيرة ، السد ، الطاقة المتجددة ، التأثير البيئي.

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List of abbreviations

IEA: International Energy Agency

CFD: Computational Fluid Dynamics

MMPH: Micro-and-Pico Hydropower

PWTPs: Pumped Water Transfer Stations

MW: Megawatt

PAT: Pimp as Turbine

CFX: Compact from Factor

ANSYS: Analysis system

List of symbols

A Area

B Inlet width

Γv Vortex strength

ΔH The total losses in meter

ΔP The total losses in Pascal

E_k Kinetic energy

E_M Mechanical Energy

E_p Potential energy

H Water head

η Efficiency

Λ Pressure loss coefficient

μ Dynamic fluid viscosity

Ns Turbine specific speed

P Pressure

ρ Fluid density

ν Specific speed

ω Angular speed

D_h Hydraulic diameter

F Force

g Gravitational acceleration

hin Depth of water at the inlet

Q Volumetric flowrate

L Pipe length

P Power

Pm Wetted perimeter

Re Reynolds number

V_θ Tangential velocity

Chapter 1

General Introduction

1.1 Introduction

The considerable increase in population is followed by inflation in demand, human energy consumption can become a large-scale problem, the main trouble is the growing consumption of electrical energy which leads to the rising of electricity cost, also to environmental effects if it continues to be produced only from conventional sources. According to the International Energy Agency (IEA), in 2018 the production of electricity based on fossil fuels (gas and oil) was estimated at 64% of the total electricity production in the world, while the contribution of renewable sources was estimated at only 26% (hydroelectricity 16%, wind 5%, biomass 3%, solar 2%) and 10% of the production was from nuclear power plants (1).

From the Middle Ages to the nineteenth century, hydraulic energy was the first mass-produced mechanical energy, allowing for economic, social, artisanal, and industrial growth. This energy was then used to generate electricity, first decentralized by thousands of small turbines, then centralized by large dams and powerful installations. Hydraulic works provided more than half of the electricity in half of Portugal in the 1960s, but their share has gradually declined to between 10% and 15% of electricity output in Portugal (depending on annual rainfall) and around 9% in the world in recent years (1).

Hydroelectric plants can extend their capacity to generate electricity by re-using the available water resource and pumping back to the reservoir some of the previously turbined water.

The reversible system has also been introduced because of the different electricity prices during the day, allowing net gains in such systems, in this report it is took as a case study the hydroelectric plant of Foz do Tua and selected as the problematic object.

1.2 Objectives

The work presented in this thesis has several objectives mainly:

- Study the dimensions of the dam whose role is to block the natural flow of water, to retain it and to store it.
- Study the water pipes, which are used to direct the water flow artificially to the hydropower plant below the dam
- Study the hydropower plant where the water is directed to a specific point to turn the chosen pump-turbine. Driven by the force of the water, the turbine turned an alternator that produces electricity and the pump that circulates the water from downstream to the upstream.
- Study the calculations of all types of energy in the hydraulic power plant in order to find out the electrical energy produced.
- Design of a dam and simulation in Ansys CFD software of the hydraulic plant
- Discussion of the power plant's simulation results.

1.3 Thesis Structure

The work presented in this thesis is organized into five chapters:
Chapter 1 (Introduction) addressed to show the general idea of the problem, the motivations that led to its treatment, the expected objectives of the thesis and the structure followed in its writing.

Chapter 2 (State of the Art of Hydropower Energy System) aims to describe the position of the world community towards renewable energies and the importance of moving towards hydropower, also gives a description of hydraulics systems and hydroelectric systems with the importance of their implementation, with a characterization of the dam and hydropower plant.

Chapter 3 (Energy management of the experimental case study) is composed of two parts. The first part describes the structure of the dam and the different characteristics of the dam. The second part deals with the calculation of the different types of energy that make up the hydraulic energy with the choice of the pump-turbine.

Chapter 4 (Modelling and simulation) defines on the one hand the chosen dam model and on the other hand ensures the simulation of the mechanical energy of the water pipe flow with discussion of the results.

Chapter 5 (Conclusion) describes the results obtained by implementing the fluid mechanics-based energy management systems for the case study. The results of the two scenario approaches are interpreted and justified in order to calculate the energy produced while respecting the economic criteria. Hydropower generators while respecting the economic and environmental constraints.

Chapter 2

State of The Art of Hydropower Energy

2.1 Introduction

2.1.1 Demand and Supply of Electricity

Electrical energy, commonly known as electricity, is a key component in the progress of a modern world dominated by technology. Being a secondary source of energy, electricity can be obtained through the conversion of primary sources of energy, such as fossil fuels, nuclear energy or green energy. Moreover, it has the great advantage of being flexible, clean as well as easy to control and transmit. However, since the consumers are not located where the electricity is produced, very long transmission lines are used to transmit electrical energy. A complex system, called electrical grid (Figure 2.1), supplies the electrical energy produced in generating stations, such as thermal – coal or nuclear – as well as hydro, wind and solar, in order to reach the demand of domestic and industrial consumers. This request is satisfied through the use of a distribution network, consisting in transmission lines, transformers, transmission towers, electric posts, etc. (2).

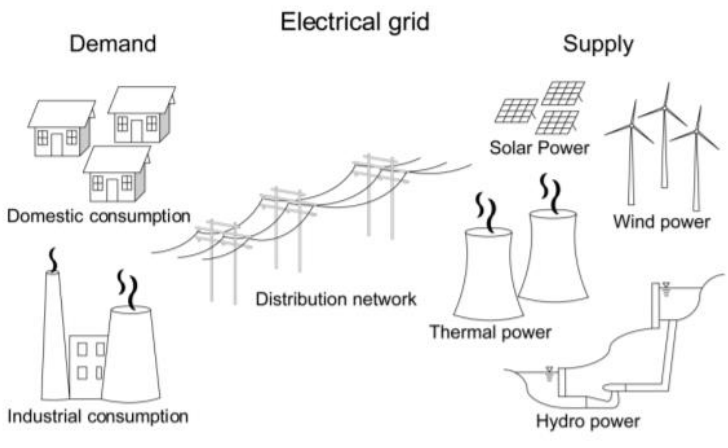

Figure 2. 1: Overview of electrical grid (2)

Both the demographic growth and the socio-economic development that took place during the last century have led to a continuous increase in electricity demand. According to International Energy Agency (IEA), these two events caused an increase of the yearly total world electricity generation in the period 1973-2008, which increased from 6’116 TWh/year to 20’181 TWh/year. As illustrated in Figure 2.2, in 2008, about 81% of the total world electricity was generated from the use of non-renewable fuels, such as coal, oil, gas, and nuclear. In contrast, the rest (about 19%) was produced from renewable sources. More precisely, hydro sources generated the majority of this 19% energy while geothermal, solar, wind, as well as bio fuels and waste created a small part of it (see Figure 2.3) (2).

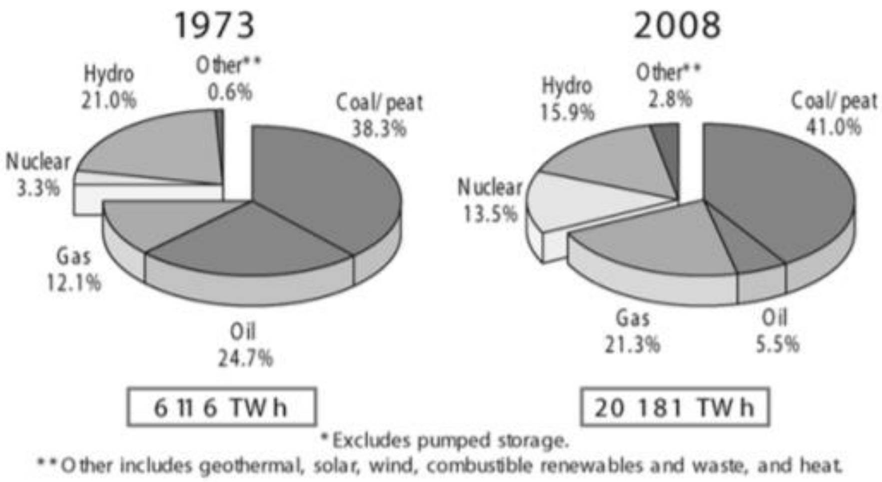

Figure 2. 2: 1973 and 2008 yearly total world electricity generation by fuel *(2)*.

2.1.2 Green Power

Green energy is any energy type that is generated from natural resources, such as sunlight, wind or water. It often comes from renewable energy sources although there are some differences between renewable and green energy. The key with these energy resources is that they don’t harm the environment through factors such as releasing greenhouse gases into the atmosphere.

- **Renewable Sources**

Electricity obtained by renewable energy sources is considered “green” due to the negligible impact on the greenhouse gas emissions. While in the past the interest in green power was driven by the goal of replacing fossil fuels to minimize the dependence on oil, contemporary researchers aim rather at minimizing the CO_2 emissions that results from the burning of fossil fuels, which are the main responsible for the global warming. According to IEA, an annual growth rate of 1.9% was registered in the period 1990-2008 (figure 2.3) despite a slight reduction of renewable energy contribution to yearly total generated energy between 1973 and 2008.

Thanks to the effort to limit global warming and climate change, this contribution is expected to continue growing in the future. The list of economically feasible renewable sources used for electricity production includes hydro, wind, biomass, geothermal, solar and wave/tide energy.

Hydro energy is considered as the most mature renewable source of electricity around the world. Moreover, even if opportunities for new and large hydro projects are very limited in most industrialized countries - the reason being that most economically exploitable sites have already been created - there still exist many potential hydro sites in the developing world.

Wind, which is an indirect form of solar energy, represents the next most popular source of green energy. It provides a variable and environmentally friendly option in an epoch where the long-term sustainability of global economy is threatened by the decreasing of global reserves of fossil fuels.

Biomass is the conversion of plant material into a suitable form of energy, usually as electricity or as fuel for an internal combustion engine. Electricity produced from landfill gas is considered to be a renewable energy source and, as such, it attracts a premium sale value per unit.

Another source of energy that generates electricity cost-competitive with conventional sources is the so-called geothermal energy, which is contained in the Earth's interior in the shape of natural steam or hot water.

Solar energy may be converted in electricity using photovoltaic cells that capture the energy of solar photons. With increasing attention toward carbon-neutral energy production, photovoltaic technology is seen as a potentially widespread approach to sustainable energy production.

The ocean provides a vast source of potential wave and tidal energy. The greatest potential of wave energy is found in the regions with the strongest winds – at the temperate latitudes between 40° and 60° north and south, on the eastern boundaries of oceans. Contrary to solar, wind and wave energy, tidal power has the advantage of being highly predictable. Furthermore, tidal fences and turbines can be installed where tidal flows and topographical constraints create predictable currents of 2 m·s-1 or greater (2).

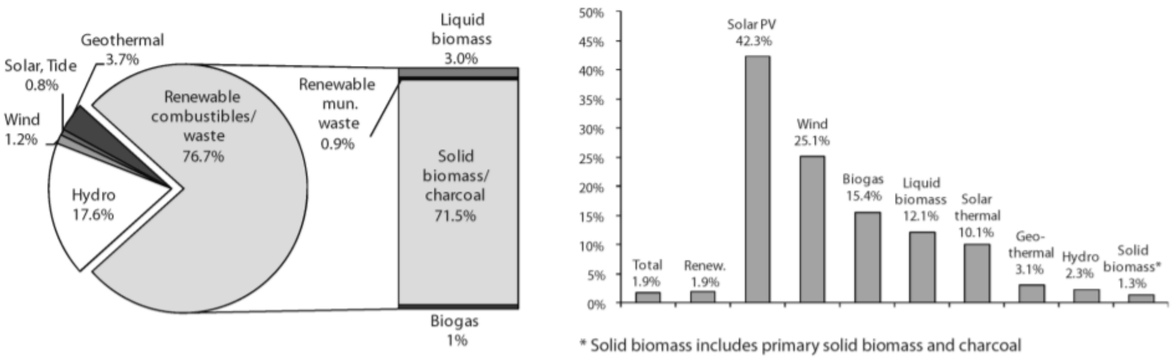

Figure 2. 3: 2008 world renewable energy supply by sources and their world annual growth rates from 1990 to 2008 *(2)*.

- **Hydropower**

Population growth, increasing energy demand and prices, depletion of fossil fuel reserves and increases in carbon emissions are compelling individuals, private and government bodies to consider renewable and sustainable alternatives for electricity production. Hydropower is one of the most commonly used renewable sources of electricity, accounting for about 16.6% of the world's net electricity production with renewable energy contributing to 22.8%. Despite this, hydroelectric energy is still underutilized where exploited-and it could replace a large amount of the contribution of gas and oil to the present energy mix. It is envisaged that by 2060, more than 50% of the world's energy consumption will be from renewable sources which spells significant growth in the hydropower sector.

Hydropower potential can be categorized in terms of pico (< 0.005 MW), micro (< 0.1 MW), mini (< 1 MW), small (< 10 MW) and large (> 10 MW hydropower plants). Out of a global gross theoretical hydropower potential of 52.0 PWh/year spread out over 11.8 million locations, mini-, micro- and pico-hydropower constitute 10% (5.2 PWh/year) covering 91% (10.74 million) locations spread evenly across the globe. Adding to this, off grid electrification in rural areas is one of the primary drivers for the adoption of mini-

, micro- and pico-hydropower (MMPH), particularly in developing countries. As a result, in the past 10 years alone, the market has been flooded with a large suite of novel MMPH technologies where the focus is on higher efficiency, low cost and ease of installation. Furthermore, there has been an increased attraction towards low-head technologies, which generally require a lower capital cost and retain a lower spatial and environmental footprint (2).

2.1.3 Worldwide Hydropower

In the first half of the 20th century, hydropower was the world's largest source of electricity. Today, it is the third most important source of electricity, behind coal and gas.

The situation varies greatly from one country or region to another. Some countries have large power plants, while remote areas develop small hydropower. In developing countries, small, often stand-alone plants prefer action turbines: simpler design allowing on-site manufacture and maintenance, easier access to parts to be replaced, no pressure seal, part-load efficiency, greater tolerance to sand.

Some countries have fully fledged national turbine building industries to meet the demand for building turbines for national demand. Small hydropower plants are expensive compared to the cost of producing electricity, but developing countries use them to have more electricity. (3)

- **The Power Capacity Installed**

Global capacity excluding PWTPs (Pumped Water Transfer Stations) reached 1,100 GW in 2016 (+25 GW in 1 year). Many large dams are regularly commissioned to support the strong economic growth in developing countries, particularly in Africa and Asia. Between 2006 and 2016, capacity in Africa increased by 44% and current projects will triple capacity compared to 2006 (3).

- **Capacity in PWTPs (Pumped Water Transfer Stations)**

The world list includes 400 PWTPs for 150 GW in 2015 (+6.4% in 1 year), allowing to modulate 6% of the world's production, with significant growth. The table 2.1 summarize the capacities of PWTPs in service and under construction in 2014.

Table 2. 1: Capacities of PWTPs in service and under construction in 2014 *(3)*.

Country	PWTP capacity installed in 2014 (GW)	PWTP capacity under construction in 2014 (GW)	Share of PWTPs in the total capacity in 2014 (%)
Japan	24.5	3.3	8.5
China	22.6	11.6	1.8
USA	20.5	0	1.9
Italy	7.1	0	5.7
Spain	6.8	0	6.6
Germany	6.3	0	3.5
France	5.8	0	4.4
Austria	4.8	0.2	21
UK	2.7	0	3
Switzer land	2.5	2.1	12
Portugal	1.1	1.5	6.1

2.2 How Hydropower Works

Hydropower is the use of water to generate electricity to fuel machinery. Water evaporates from lakes and seas, forms clouds, precipitates as rain or snow, and then flows back to the ocean in a massive global cycle. The sun-driven energy of this water cycle can be used to generate electricity or for mechanical tasks such as grain grinding. Hydropower is based on the use of a fue. Water is used as a fuel in hydropower, and it is not reduced or used up in the process. Hydropower is considered a renewable energy source because the water cycle is continuously depleting and recharging its compartments (figure 2.4).

Hydroelectric power, also known as hydropower, is produced when flowing water is captured and converted into electricity. Hydroelectric plants have a variety of types and sizes, but they are all driven by the kinetic energy of moving water as it flows downstream in rivers. Turbines and generators turn the energy into electricity, which is then delivered to households, businesses, and industry through the electrical network (4).

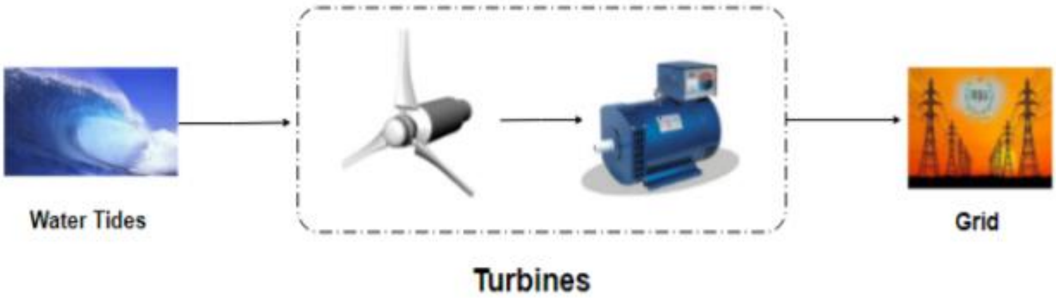

Figure 2. 4: Simplified diagram of hydroelectric power *(4)*.

2.3 The Components of a Hydroelectric Power Plant

This part talks about the layout, basic components and working of a hydroelectric power station (5).

- **Dam and Reservoir:** The dam is constructed on a large river in hilly areas to ensure sufficient water storage at height. The dam forms a large reservoir behind it. The height of water level (called as water head) in the reservoir determines how much of potential energy is stored in it.
- **Control Gate:** Water from the reservoir is allowed to flow through the penstock to the turbine. The amount of water which is to be released in the penstock can be controlled by a control gate. When the control gate is fully opened, maximum amount of water is released through the penstock.
- **Penstock:** A penstock is a huge steel pipe which carries water from the reservoir to the turbine. Potential energy of the water is converted into kinetic energy as it flows down through the penstock due to gravity.
- **Water Turbine:** Water from the penstock is taken into the water turbine. The turbine is mechanically coupled to an electric generator. Kinetic energy of the water drives the turbine and consequently the generator gets driven. There are two main types of water turbine; Impulse turbine and Reaction turbine. Impulse turbines are used for large heads and reaction turbines are used for low and medium heads.
- **Generator:** A generator is mounted in the power house and it is mechanically coupled to the turbine shaft. When the turbine blades are rotated, it drives the generator and electricity is generated which is then stepped up with the help of a transformer for the transmission purpose (5).

2.4 Types of Hydropower Plants

Impoundment, diversion, and pumped storage are the three forms of hydropower plants. Some hydropower plants employ dams, although others do not (6).

Hydropower plants vary in size from small systems for a home or village to massive utility-scale facilities. The table 2.2 lists the dimensions of hydropower plants.

2.4.1 Impoundment

An impoundment facility is the most common form of hydropower plant. A dam is used to store river water in a reservoir at an impoundment facility, which is usually a large hydropower system. Water emitted from the reservoir spins a turbine, which activates a generator, which generates electricity. The water could be released to meet fluctuating energy demands or to keep the system running smoothly.

2.4.2 Diversion

A diversion, sometimes called run-of-river, facility channels a portion of a river through a canal or penstock.

2.4.3 Pumped storage

Pumped storage hydropower is a form of hydropower that functions like a battery, storing electricity produced by other sources such as solar, wind, and nuclear for later use. Pumping water from a lower elevation reservoir uphill to a higher elevation reservoir stores potential energy. Pumped storage facilities store energy by pumping water from a lower reservoir to an upper reservoir when the demand for electricity is minimal. When there is a high demand for power, the water is released into the lower reservoir, where it spins a turbine, which generates electricity (6).

2.4.4 Sizes of Hydroelectric Power Plants

Small and micro plants, operate according to local electricity needs or to sell power to utilities, vary in scale from large power plants that provide many consumers with electricity to large power plants that provide many consumers with electricity (6).

❖ Large Hydropower

Large hydropower is described by the DOE as facilities with a capacity of more than 30 megawatts (MW).

❖ Small Hydropower

While definitions differ, the Department of Energy describes small hydropower as projects with a capacity of 10 megawatts or less.

❖ Micro Hydropower

A micro hydropower plant can produce up to 100 kilowatts of electricity. A house, plantation, ranch, or village will all benefit from a small or micro-hydroelectric power plant.

2.5 Hydro Turbines

Hydro turbines are divided into two types: impulse and reaction. The type of hydro turbine selected for a project is determined by the elevation difference between the standing water level and the outlet of the hydraulic circuit (known as "gross head") and the discharge of the water flowing through the site. Other considerations include the elevation at which the turbine must be installed, reliability, and cost (7).

Table 2. 2: Hydropower turbines types *(7).*

Hydropower Turbine Type	Typical Site Characteristics
Archimedean Screw	Low heads (1.5 - 5 meters)Medium to high flows (1 to 20 m^3/s).For higher floxs multiple screws are used.
Crossflow turbine	Low to medium heads (2 - 40 meters) Low to medium flows (0.1 - 5 m^3/s).
Kaplan turbine	Low to medim heads (1.5 – 20 meters) Medium to high flows (3 m^3/s – 30 m^3/s) For higher flows multiple turbines can be used.
Pelton/Turgo tubine	High heads (greater than 25 meters) Lower flows (0.01 m^3/s – 0.5 m^3/s)
Waterwheels	Low heads (1 – 5 meters) – though turbines often more appropriate for higher heads Medium flows (0.3 – 1.5 m^3/s)
Francis turbine	No longer commonly used except in very large storage hydropower systems, though lots of older, smaller turbines are in existence and can be restored. For older turbine : Low to medium heads (1.5 – 20 meters) Medium flow (0.5 – 4 m^3/s)

2.5.1 Impulse turbine

The runner of an impulse turbine is usually moved by the velocity of the stream, and it discharges to atmospheric pressure. Each bucket on the runner is struck by the water stream. The water spills out the bottom of the turbine housing after touching the runner so there is no suction on the down side of the turbine. An impulse turbine is well suited to applications with high head and low discharge (7).

- Pelton

A Pelton wheel (Figure2.5) has one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Draft tubes are not required for impulse turbine since the runner must be located above the maximum tailwater to permit operation at atmospheric pressure.

A Turgo Wheel is a variant on the Pelton that is only rendered in England by Gilkes. The Turgo runner is a cast wheel that resembles a fan blade on the outside and is closed on the inside. The water stream enters from one side, crosses the blades, and exits from the other.

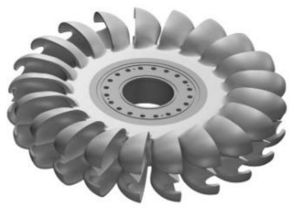

Figure 2. 5: Pelton turbine *(8).*

- Cross-Flow Turbine

The nozzle of a cross-flow turbine (figure2.6) is elongated and rectangular in section, and it is aimed toward curved vanes on a cylindrically shaped runner. It has the appearance of a "squirrel cage" blower. The stream flows twice through the blades of a cross-flow turbine. The first pass occurs as water passes from the outside to the inside of the blades; the second pass occurs when water flows from the inside to the outside. A guide vane at the turbine's entrance guides the flow to a certain area of the runner. Cross-flow turbines are designed to accommodate larger discharges and lower heads as compared to Pelton.

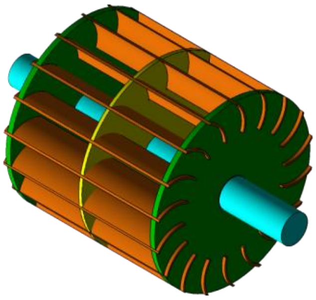

Figure 2. 6: Cross-Flow turbine *(8).*

2.5.2 Reaction Turbine

The combined effects of gravity and pressure changes on motion of flowing water generates electricity in a reaction turbine. Instead of hitting each blade independently, as in the impulse turbines, in the reaction type the runner is positioned in a container subjected to hydrostatic pressure that is part of the water circuit generating turbine rotation. In comparison to impulse turbines, reaction turbines are typically used for locations with lower head and higher discharges (7).

- Propeller

A propeller turbine (figure2.7) usually has a runner of three to six blades, with water actively contacting both of them. Consider a boat propeller in a pipe. The friction is constant through the pipe; otherwise, the runner will be out of control. The blade pitch may be constant or adjustable. A scroll case, wicket gates, and a draft are the main elements, apart from the runner. There are several different types of propeller turbines:

Figure 2. 7: Propeller turbine *(8).*

- Straflo

The generator is directly connected to the turbine's periphery. As it can be seen in Figure2.8.

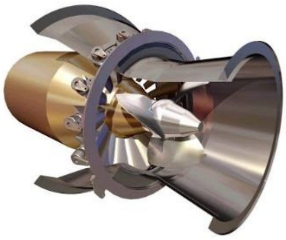

Figure 2. 8: Straflo turbine *(8)*.

- TUBE TURBINE

The penstock bends just before or after the runner, allowing a straight-line connection to the generator. As shown in figure2.9.

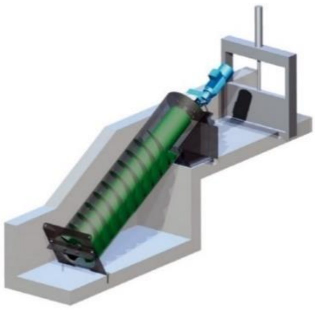

Figure 2. 9: Tube turbine *(8)*.

- KAPLAN

Both the blades and the wicket gates are adjustable, allowing for a wider range of operation. Figure 2.10 represent a Kaplan turbine.

Figure 2. 10: Kaplan turbine *(8)*.

- Francis

A Francis turbine has a runner with fixed buckets (vanes), usually nine or more. Water is introduced just above the runner and all around it and then falls through, causing it to spin. Besides the runner, the other major components are the scroll case, wicket gates, and draft tube, as seen in figure 2.11.

Figure 2. 11: Francis turbine *(8).*

2.5.3 Kinetic Turbine

Kinetic energy generators, also known as free-flow turbines (Figure 2.12), use the kinetic energy in running water to produce power rather than the potential energy from the head. Rivers, man-made channels, flood waters, and ocean tides can all be used for the networks. The normal course of a water stream is used for kinetic systems. They don't need water to be diverted into man-made rivers, riverbeds, or pipelines, but they may be useful in those settings. Kinetic schemes do not necessitate extensive civil works; instead, existing infrastructure such as bridges, tailraces, and channels may be used (7).

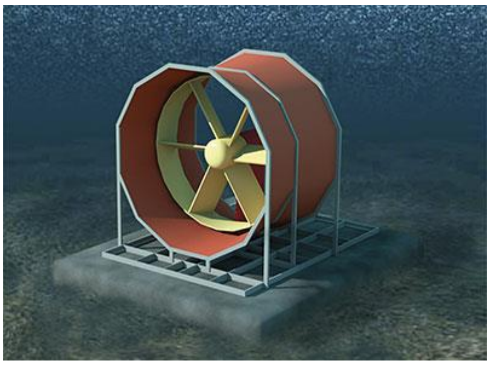

Figure 2. 12: Kinetic turbine *(8).*

2.6 Pumped Storage Plant

2.6.1 Electricity and energy storage

Storing of energy has in recent times become the major concern as reliable renewable energy source has become more widespread. Several developed countries have put up pumped storage systems as added megawatt-scale machineries are being established (9). To be able to store reliable renewable energy to substitute base-load capacity, the demand level should be met by the storage for a longer period not just for hours. The quick intensification of renewable energy resources generating capacity across the globe. Thus, small hydropower and solar have called for a resilient incentive for the development of large-scale electricity storage facilities (9).

The level of the storage facility development will determine the extent of the renewable energy distribution. Although it is not possible to store electricity on any scale, it could be transformed to other energy forms that could be kept and reconverted in future when the need arises or in times of electricity demand. However, these storage facilities are in limited form. It is therefore necessary to construct pump storage facilities to support hydro energy generation. Pump storage facilities comprises pumping water to reservoirs or uphill to be used for hydropower generation; particularly for small, micro and mini hydropower generation when the need arise. The dual process efficiency is around 70%. About 95% of globally large-scale storage of electricity as of 2016 was from pumps. This project can stay for a longer period usually 50 years or more compared to others such as batteries with a maximum of 8 to 25 years (9).

2.6.2 Pumped Hydroelectric Storage

Pumped storage is used to balance up day-to-day production load in communities of some countries by pumping water to tall storage dam throughout off-peak seasons with the use of surplus base-load capacity obtained by inexpensive coal otherwise nuclear sources. This water can then be unconfined to be used by hydraulic turbines to reservoir for hydropower generation transforming potential energy to electrical energy throughout the peak demand. Pump as turbine (PAT) can perform in both pump mode and in reverse as turbine. This system can be the best alternative to meet the highest demand attributable to quick ramp-up as well as ramp-down, in addition to cost-ineffectiveness caused by the discrepancy between peak and off-peak wholesale charges (10).

According to the World Energy Outlook 2016 report, about 160 GW pumped storage facilities have been installed globally, which included 27 GW in Japan, 31 GW in USA, 53 GW in both Europe and Scandinavia, as well as China's 23GW facility. These accounted for nearly 95% of global extensive electricity storage. The report also projected an addition of 27 GW capacities by USA, China and Europe in 2040. Italy is far ahead in the EU countries in the installing capacity of small hydropower and annual electricity generation. Italy in 2010 had an installed capacity of 2735 MW small hydropower units, with an annual energy generation reaching 10958 GW; and still expecting the installed capacity of small hydropower to reach a scale of 3900 MW by 2020, compared to the 2010 growth of 42% (10).

2.6.3 Pump as Turbine (PAT)

One of the main problems of utilizing hydro potentials especially in the developing countries is that routine turbines are insufficient or proper turbines are expensive. Use of reverse pumps instead of turbines is a good alternative for reducing capital cost of hydro plants. In the reverse mode, the flow and rotation direction of the pump are changed, and consequently hydraulic behavior of the pump will be similar to a turbine. But of course, efficiency of PATs is lower than conventional turbines. From an economical point of view, use of PATs can be recommended for sites below 500 kW generated power (10).

Pumps are divided into three main groups: centrifugal, mixed and axial pumps that each type can properly operate as turbine in a specific range of operation. The centrifugal pumps can be worked as turbines in head ranges approximately from 15 to 100 m and flow rate ranges from 5 to 50 l/s. These ranges for the mixed flow PATs are about 5e15 m and 50e150 l/s for the head and flow rate, respectively. For head values between 15 and 100 m and flow rates between 50 and 1000 l/s, double suction pumps or multi centrifugal pumps in the parallel arrangement are suitable.

For heads ranged between 1 and 5 m and flow rates between 50 and 1000 l/s, the axial pumps can be used as turbines. Some relationships have been presented to predict performance of the PATs from the pump operation. But the results of these relationships have about 20% deviation from experimental data. So, for determining accurate characteristic curves of each PAT, the pump should be tested in the reverse mode. Although many researches have been done on centrifugal reverse pumps, little work is available about axial PATs (10).

2.6.4 Depth–Discharge Relationship

As discussed previously, the flow and rotational strength in a gravitational water vortex hydropower plant are governed by the circulation parameter Γ which itself is controlled by the approach flow geometry. To demonstrate this, one must determine the tangential velocity V_θ at the inlet of the plant through continuity by $V_\theta = \frac{Q}{bh}$ (11) in where b is the inlet width and hin is the depth of water at the inlet. We arrive at the following expression for the vortex strength (11):

$$\Gamma v = \frac{2 * \pi * rin * Q}{b * hin} \tag{2.1}$$

Thus, it can be seen that the strength is strongly dependent on the geometry parameter rin/b denoted as α. As α increases (rin increases or b decreases), so too the strength and vice versa. The relationships between the governing dimension less parameters were recognized which determined a simple relationship for the discharge in the system by (11):

$$Q = \frac{k\alpha}{\left(\frac{5\alpha d}{h\ in}\right)^{n\alpha}} \sqrt{g d^{\frac{1}{2}}} \tag{2.2}$$

2.6.5 Pressure and Tangential Velocity

As discussed in the previous section, the pressure and tangential velocity field in a free-surface vortex in the absence of an impeller can be determined by assuming the flow to be fully irrotational. As a first approximation, the velocity and pressure up to the air core in the absence of an impeller can be determined for an irrotational assuming a constant circulation. Thus, the ideal tangential velocity equation follows (11):

$$v\theta(r) = \frac{\Gamma v}{2\pi r} \tag{2.3}$$

By substitution of equation 2.3 into the radial momentum equation of the Navier–Stokes equations, one arrives to an equation to describe the pressure or free-surface profile as follows (11):

$$hr = hin - \frac{\rho\Gamma^2}{8\pi^2}\left(\frac{1}{r^2} - \frac{1}{r^2 in}\right) \tag{2.4}$$

2.6.6 Hydraulic Runners Classification

Hydraulic turbomachines convert hydraulic energy in mechanical energy (turbine mode) or vice-versa (pump mode) through the direct interaction between a steady liquid flow and a runner, respectively impeller, fitted with blades and completely submerged in the working liquid. In the design of a hydraulic turbine, nominal characteristic parameters, such as discharge Q, specific energy E and angular speed ω, allow the computation of the so-called specific speed ν (equation 2.5), and consequently, the selection of the runner type, which, in turn, allows to recover the maximum of mechanical power with the highest efficiency (11).

$$v = \frac{\varphi^{\frac{1}{2}}}{\psi^{\frac{3}{4}}} = \omega \frac{(\frac{Q}{\pi})^{\frac{1}{2}}}{(2E)^{\frac{3}{4}}} \tag{2.5}$$

2.6.7 Pump-Turbine Selection

Typical micro hydropower plants convert the falling water-con-tined energy to mechanical energy by turning the pump turbine, which converts the water pressure into mechanical shaft power to drive an electric generator. The power available is proportional to the product of head and volume flow rate as the general formula for hydropower systems shows (12).

$$P = \eta\rho g Q H \tag{2.6}$$

Where P is power output, η hydraulic efficiency, ρ fluid density, g gravitational acceleration, Q volumetric flowrate and H water head. As shown in equation 2.7, the turbine selection process for a MHP of interest, should be based on the head and flowrate available at the site. The power output may also be related to the head to express the turbine specific speed (12).

$$Ns = \frac{nP^{\frac{1}{2}}}{H^{\frac{5}{4}}} \tag{2.7}$$

Where Ns is the turbine specific speed and n is the real rotation speed of turbine. This parameter characterizes the turbine runner, spiral casing, blade shape and other geometric design features, thus doesn't depend on the size but the shape of the machine of concern. For instance, two machines of similar shape and different size may have same specific speed. One of the biggest difficulties in micro hydropower technology is to adapt the equipment to the specificity of the plant (12). For instance, as much the PAT can be having many advantages compared to purpose-made turbines, the main drawback in its usage is generally the difficulty of finding the turbine characteristics that are needed to select the correct pump for a particular site.

The adequate selection of the PAT has been a big challenge in the past decades, where different aspects need a close attention, viz. available head range, capacity range, back pressure at the turbine outlet, desired speed, etc. For the PAT based MHP cost effectiveness goal to be achieved, an optimum operational design, smart selection of the equipment and reduced professional consultation must be implemented to lower the overall cost. Nevertheless, for the optimum PAT selection at a particular site, there is a fundamental need of basic information about the head and discharge available at the site, but most importantly, the expected PAT performance characteristics, which in fact, are two key-factors to the PAT selection validity, as seen in figure2.14.

However, the lack of PAT performance data is always stated as one of the significant challenges in the design of PAT for MHP sites. Different researchers have so far provided head-flowcharts depicting the range of application for different PATs (figure. 2.13). It was generally concluded that multistage radial flow PATs fit sites with high heads-low flow rates, whereas axial flow ones perform well at low head - high flow rates sites. However, the use of single stage end suction centrifugal PATs from low to medium heads, has also been recommended by many of researchers. PAT selection can also be carried out through a head-specific speed chart (12).

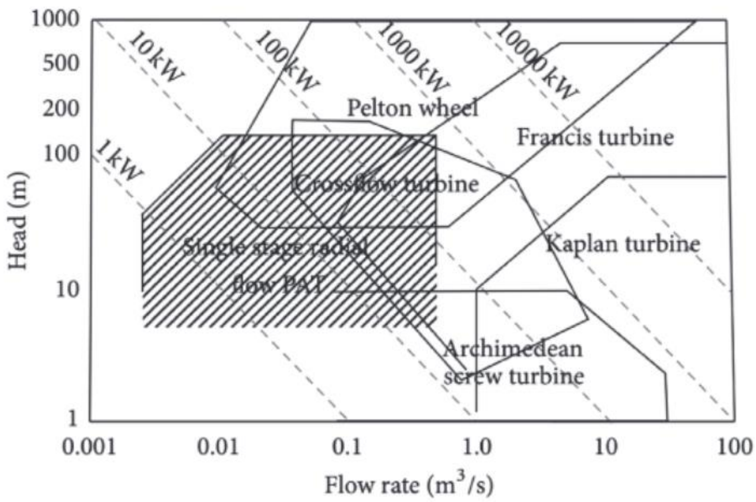

Figure 2. 13: Head flowrate selection chart *(13)*.

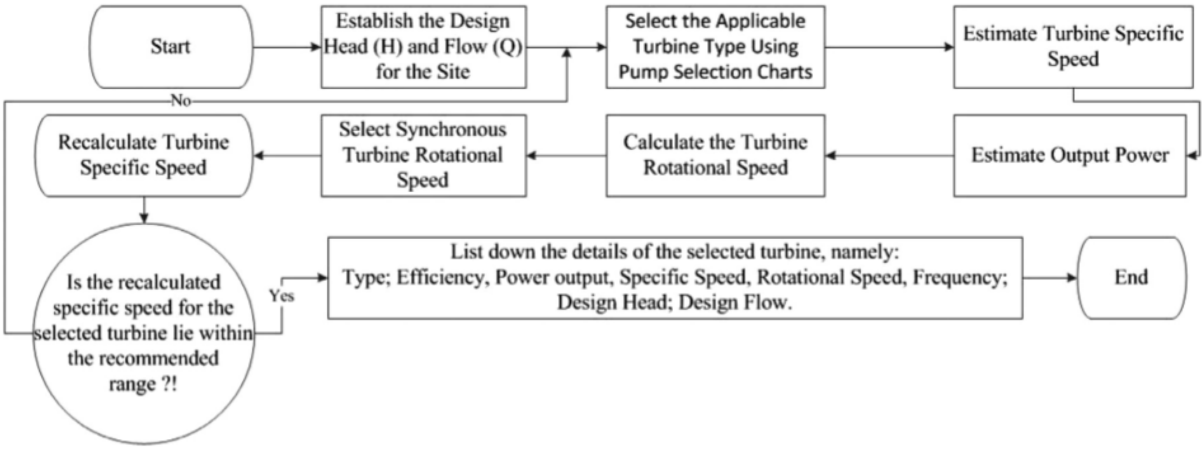

Figure 2. 14: Turbine selection flow chart for hydropower schemes *(13)*.

2.7 Glossary of Hydropower Terms

The glossary of terms defines the components that make up hydro turbines and hydropower plants (14).

Ancillary services: Capacity and energy services delivered by power plants that can adapt quickly, such as hydropower plants, to ensure reliable electricity supply and improved grid stability.

Balancing authority: Responsible organization that integrates resource plans in advance, retains load-interchange-generation equilibrium within a balancing area, and provides real-time support for interconnection frequency.

Black start: The method of reactivating a power plant without the use of an external electric power transmission network.

Cavitation: The noise or disturbance in the water column caused by phase changes caused by pressure changes in a fluid that creates bubbles. Implosion of these bubbles against a firm surface, such as a hydraulic turbine, can cause corrosion and result in capacity and efficiency pressure reductions.

Closed-Loop Pumped Storage Hydropower: The majority of projects consist of two lakes that aren't linked to naturally flowing water bodies.

Control gate: A dam that controls the flow of water from a river to a power plant.

Curtailment: Reduction of output (ramp down or shut down) that is a generation unit's response to a grid operator's request, or to market signals.

Dispatch: The operation of a generating unit within a power system at a designated output level to meet demand for electricity.

Diversion: A canal or penstock that channels a section of a river.

Draft tube: A water pipe that retains a water column between the turbine outlet and the downstream water table, which can be straight or angled depending on the turbine installation.

Efficiency: The real power or energy is divided by the potential power or energy to get a percentage. It indicates how effectively the hydropower plant transforms water's available energy into electrical energy.

Energy arbitrage: When electricity prices are low, purchase (store) energy; when electricity prices are heavy, sale (discharge) energy.

Fish ladder: Around hydropower ventures, a transport structure for secure upstream fish passage.

Flexibility: The power system's ability to adapt to changes in supply and/or demand.

Flow: Volume of water flowing through a point in a given amount of time, expressed in cubic feet or cubic meters per second.

Generator: A device that transforms a turbine's rotational energy into electrical energy.

Head: Between the head (reservoir) and tailwater (downstream) water levels, there is a vertical change in elevation, reflected in feet or meters.

Headwater: The water level above the powerhouse or at the upstream face of a dam.

Hydropower: The harnessing of flowing water—using a dam or other type of diversion structure—to create energy that can be captured via a turbine to generate electricity.

Impoundment: A body of water formed by damming a river or stream, commonly known as a reservoir.

Load: The amount of electrical power delivered or required at any specific point or points on a system.

Load following, Load shifting: Ability of a hydropower plant to adjust its power output as electricity demand changes throughout the day.

Low head: Head of 66 feet or less.

Micro hydro: Hydropower projects that generate up to 100 kilowatts.

Modular: Standardized structures designed so their capacity and function can be scaled by deployment of multiple components that integrate easily.

Nameplate capacity (installed): The maximum rated output of a generator, prime mover, or other electric power production equipment under specific conditions designated by the manufacturer. Installed nameplate capacity is commonly expressed in megawatts (MW) and is usually indicated on a nameplate physically attached to the generator.

Non-powered dams: Dams that do not have any electricity generation equipment installed.

Penstock: A closed conduit or pipe for conducting water to the powerhouse.

Power house: The structure that houses generators and turbines.

Pumped storage: A type of hydropower that works like a battery, pumping water from a lower reservoir to an upper reservoir for storage and later generation.

Ramping capability: Ability of a power station to change its output over time.

Reliable (power generation): Probability that a generating unit will perform when used under stated conditions.

Round trip efficiency: Energy storage typically consumes electricity and saves it in some manner, then hands it back to the grid. Round Trip Efficiency is the ratio of energy stored (per unit of energy) to energy discharged from the storage system (per unit of energy), expressed as a percentage.

Runner: The rotating part of the turbine that converts the energy of falling water into mechanical energy.

Run-of-river: Type of hydropower project in which limited storage capacity is available and water is released at roughly the same rate as the natural flow of the river.

Scroll case: A spiral-shaped steel intake guiding the flow into the wicket gates located just prior to the turbine.

Small hydro: Hydropower projects that generate 10 MW or less of power.

Spillway: A structure used to provide the release of flows from a dam into a downstream area.

Tailrace: The channel that carries water away from a dam.

Tailwater: The water downstream of the powerhouse or dam.

Transformer: Device that takes power from the generator and converts it to higher-voltage current.

Turbine: A machine that produces continuous power in which a wheel or rotor revolves by a fast-moving flow of water.

Ultra-low head: Head of 10 feet or less.

Wicket gates: Adjustable elements that control the flow of water to the turbine (14).

Chapter 3

Experimental Case Study

3.1 Introduction

In this project we have chosen to work on the FOZ-TUA dam to make the study of the PAT hydraulic energy. So, in this chapter we present the characteristics of this dam with the calculation notes using the fluid mechanics and we present the results of this renewable energy.

Tua is a river in northeastern Portugal, flowing by the border of Vila Real District and Bragança District. It is a tributary of the Douro River. The biggest and most important city it flows through is Mirandela.

3.2 Foz Tua dam

The Foz Tua Dam, also known as Tua Dam or Foz-Tua Dam, is a Portuguese dam for hydroelectric use of the Tua River (figure3.1).

The Foz Tua dam is perhaps one of the most controversial dams in Portugal's history, largely because its reservoir forced the closure and submergence of the first 16 kilometers of the Tua railway line, cutting off its connection to the rest of the national railway network and making future use impractical. The construction of the dam was protested by various environmental organizations and civic movements in the Trás-os-Montes region; however, unlike what happened with the equally controversial Foz Côa dam project (in 1994-1995), neither of the two main parties in Portugal opposed the construction of the Tua dam, so the dam was finally built and was completed in 2017 (15).

Figure 3. 1: Dam and reservoir *(15)*.

3.3 Characteristic of FOZ -TUA Dam

3.3.1 Location & Architecture

- Location

The Foz Tua dam is located in the North region of Portugal, in the Tua River, an important tributary of Douro River, close to its confluence into Douro River (figure3.2) (15).

- Location : Bragança, Portugal ; Alijó, Vila Real, Portugal

- Content on : TUA

- Coordinats : 41 ° 13'4.77 "N 7 ° 25'24.31" W

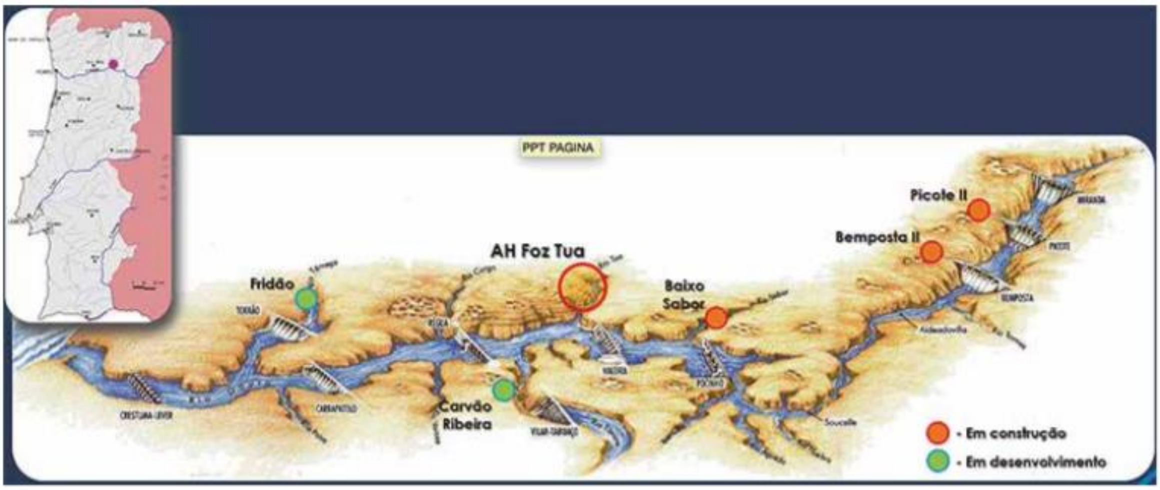

Figure 3. 2: Location of Foz-Tua dam *(15)*.

- Architecture

The planned arch dam is a 108-meter-high structure with a total crest length of 275 meters at elevation 172 and a concrete volume of 317 thousand cubic meters. The valley is relatively small at the dam location, and the rock foundation is solid granite. The valley widens downstream, near the Douro River's confluence, where schist mass rocks can be found (figure 3.3).

The dam's catchment area is 3809 km2, with an average annual precipitation of 940mm and a mean annual runoff of 1421 hm3. The reservoir capacity is 106 million cubic meters at the full storage level, which is at an elevation of 170 meters above sea level. A controlled surface spillway, with four 15.7 m wide spans controlled by radial gates and a downstream plunge pool, is located in the central part of the dam crest, designed for a 5500 m3/s flood (Figures 3.4). The dam also has a bottom outlet with a 200m3/s discharge capacity. The dam will be built in the river bed zone thanks to a diversion tunnel on the left bank and two concrete gravity type cofferdams (15).

The structural and hydraulic calculations were done in accordance with the Portuguese Dam Safety Rules (figure 3.4). The geotechnical characteristics of the site also favor the design of a ground and underground hydraulic circuit in front of the valley. The water intake is directly in front of the dam's abutment.

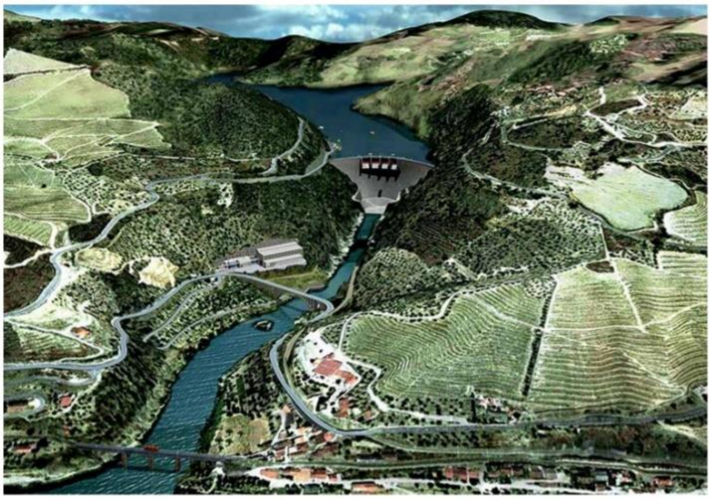

Figure 3. 3: Artist's depiction of the Tua valley after the construction of the dam *(15)*.

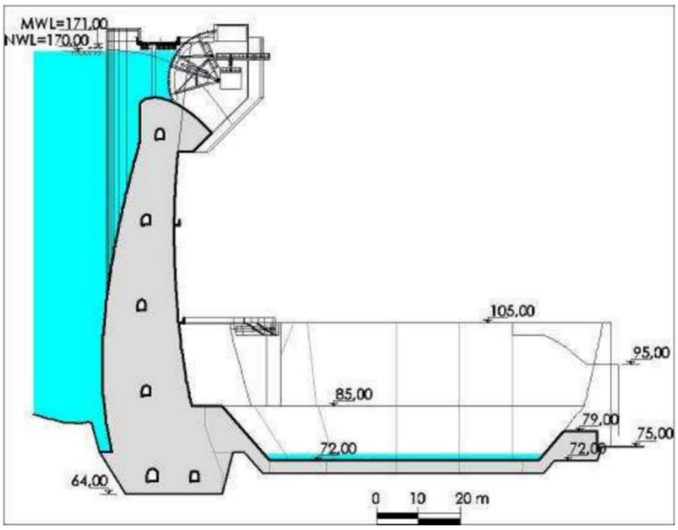

Figure 3. 4: Cross section of the dam in the spillway zone *(15)*.

3.3.2 Dam Characteristics

In this part, we present the different dam characteristics (15).

- Dam Characteristics

Concrete: height of double-curved dome.

Above foundation: 108.00 m.

Capping allowance: 172.00 m.

Crown length: 275 m.

Width of crown: 5 m.

Foundation: granite massif.

Concrete volume: 316,900 m3.

- Flood Discharge

Location: central area of the dam.

Type of control: 4 segment gates.

Type of spillway: free blade.

Weir crest level: 159.00.

Weir development: 4 x 15.70 m.

Maximum discharge: 5600 m3/s.

Energy dissipation: Impact dissipation basin.

- Background Discharge

Location: in line with central pillar.

Type: metal conduct.

Duct section: rectangular 2.10 mx 3.10 m.

Maximum flow rate: 200 m3/s.

Upstream control: with wagon.

Downstream control: includes segment.

3.4 Calculation of Energy Produced

In this part of the project, we present the detailed calculation of the hydraulic energy that is converted into electrical energy through the turbine that we will choose in the next parts. To start the calculation of the hydraulic energy it is necessary to calculate the forces exerted on the Foz Tua dam.

In our project, we present two scenarios a and b for the height of the water in the dam. In the first case we consider that the water level is maximum in the dam H_a=107m and in the second case that the water level is H_b=75m in the dam. In hydropower, we have four types of energy, starting with potential energy, kinetic energy, mechanical energy and finally electrical energy.

According to the university's background in fluid mechanics and physics, we calculate the electrical energy produced using the following procedure.

3.4.1 Pressures and Forces Exerted on the Dam

Dams are subject to many forces and stresses. we have different forces exerting on the dam. the main force is the pressure of the water on the dam. we express this pressure "P" according to the law of hydrostatics in point M (figure 3.5) with (16):

$$P = \rho \times g \times h + Patm \quad (3.1)$$

ρ: Density (1000 kg/m^3).

g: Gravity acceleration (9.81 m/s^2).

h: Height of water above point M.

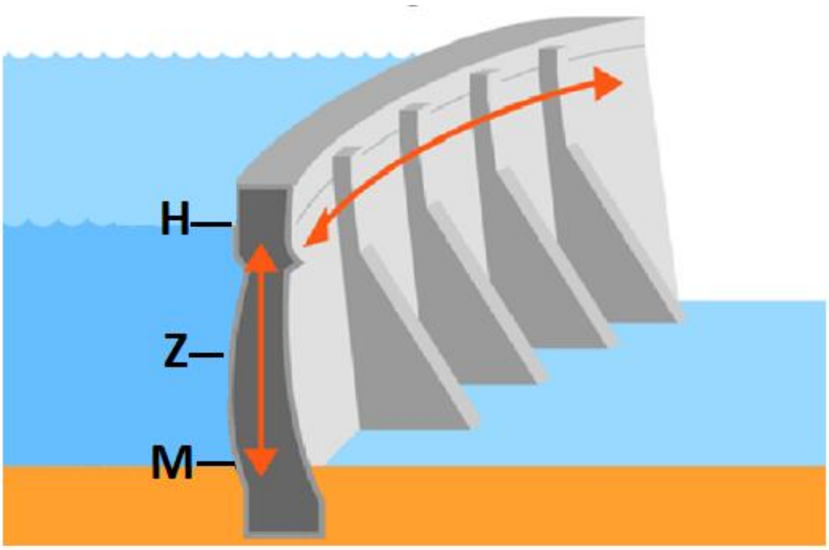

Figure 3. 5: Dam Drawing.

Table 3. 1: Pressure at the depth and middle of the dam.

Height of The Water	H_a=107 m	H_b=75 m
Pressure	11.49 bar	8.35 bar

And in this case, if we move 1m, the pressure increases by 0.1 bar, so for every 10m the pressure increases by 1 bar as it is simplified in the following figure (3.6).

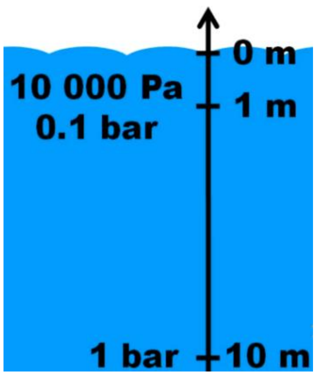

Figure 3. 6: Water Pressures *(16)*.

We have located the point Z the center of circle which is located in the dam wall, where is the beginning of the flow of the water in the pipes which drifts towards the turbine

In our case we have the following equality (16).

$$P = Patm + \rho \times g \times (h - Z) \qquad (3.2)$$

In this section, we calculate the pressure at point Z, which is the center of the hole at the beginning of the water pipe and is located at a height of Z=27m.

Table 3. 2: Pressure at Z-point level.

Height of The Water	H_a=107 m	H_b=75 m
Pressure	8.85 bar	5.71 bar

To express the force from this expression, we must be interested in the force that is exerted on a precise point of the dam.

We take a small area element dS which is the result of the force dF (16).

$$dF = P \times dS \qquad (3.3)$$

$$F = \rho \times g \times \frac{h^2}{2} \qquad (3.4)$$

Table 3. 3: Force at the depth and middle of the dam.

Height of The Water	H_a=107 m	H_b=75 m
Force	56.15 MN	27.59 MN

It can be seen that the force exerted on a dam depends on the height squared, which means that the height of water that counts and not the volume of water in the dam.

3.4.2 Average Velocity Calculation

To begin the calculation of pressure losses it is necessary to calculate the average speed in order to determine the losses from the Bernoulli equation.

In this section we present a simplified diagram of our hydropower installation. In our case, we have the hydropower brings water from the reservoir as it shown in the figure 3.7 from the points 1 and 2 area and in point number 3, we have the turbine.

The diameter intake tube is 1.3 m which is the same diameter in the end which is close to the turbine (16).

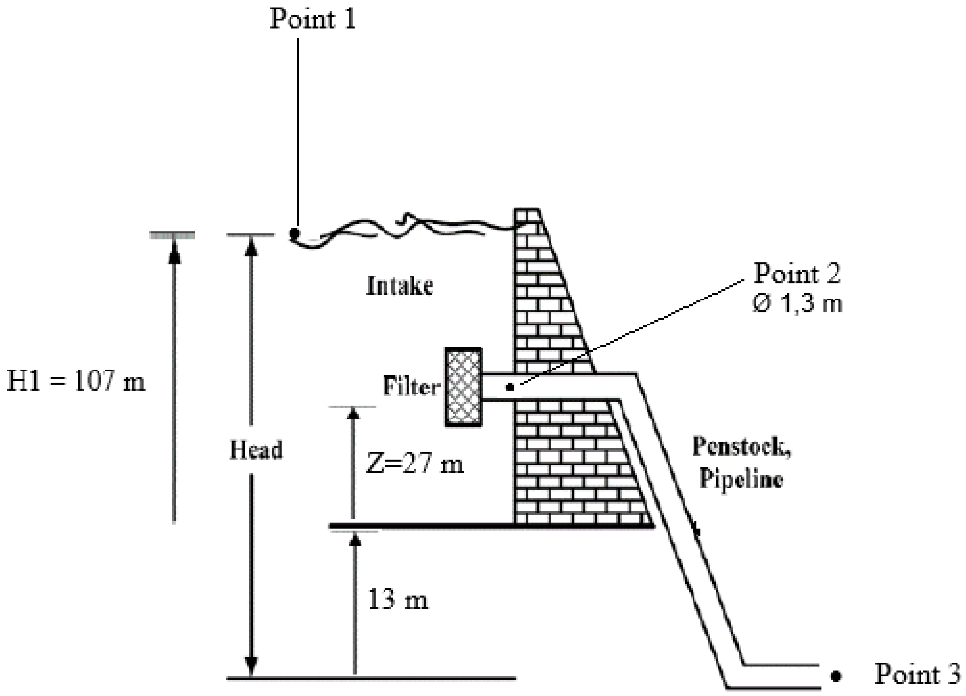

Figure 3. 7: Water Flow Shema.

Figure 3.7 shows the elevation between the dam and turbine level is 13m as notice in real project, also the water elevations between the top of the dam at point 1 and the turbine at point 3, which is noted as Y avec $Y_3 = 0\text{m}$ and $Y_2 = Z + 13 = 40\text{m}$.

Table 3. 4: Height of The Water in the installation.

Height of The Water in the dam	H_a=107 m	H_b=75 m
Height of The Water in the installation	$Y_{1\,a}=H_a+13$ m $Y_{1\,a}$=120 m	$Y_{1\,b}=H_b+13$ m $Y_{1\,b}$=88 m

We assume that points 1 and 3 are in contact with the air. Then the pressure at point 1 and 3 are equal to the atmospheric pressure (Figure 3.7).

$$P1 = P3 = Patm$$

The area at point 1 “A1” is very large so the speed at point 1 is almost 0 m/s.

$$A1 >> A3 \quad \text{Then} \quad V1 << V3$$

Since
$$A1 \cdot V1 = A3 \cdot V3 \tag{3.5}$$

To calculate the average velocity at point 3, we must apply perfect Bernoulli’s theorem (without losses) which is presented by:

$$P_1 + \rho g y_1 + \frac{1}{2}\rho {V_1}^2 = P_3 + \rho g y_3 + \frac{1}{2}\rho {V_3}^2 \quad (3.6)$$

After simplification, we have

$$V_{average} = V_3 = \sqrt{2gy_1} \quad (3.7)$$

Table 3. 5: Velocity average of Water in the installation.

Height of The Water in the dam	$H_a = 107$ m	$H_b = 75$ m
Height of The Water in the installation	$Y_{1\,a}=H_a+13$ m $Y_{1\,a}=120$ m	$Y_{1\,b}=H_b+13$ m $Y_{1\,b}=88$ m
Velocity average at point 3	$V_{average\ a} = 48\ m/s$	$V_{average\ b} = 41\ m/s$

3.4.3 Total losses Calculation

We found the average speed of the pipe; with this speed we calculate the sum of the pressure losses.The pressure loss corresponds to the dissipation, by friction, of the mechanical energy of a moving fluid.

The total losses are expressed in pascal (ΔP), or in meter (ΔH). These two notations are strictly equivalent with the relation (16):

$$\Delta P = \rho g \Delta H \quad (3.8)$$

ΔP : Losses in Pascal.

ΔH : Losses in meters (equivalent fluid column height).

The losses equations distinguish between:

-Regular pressure losses.

-Singular pressure losses.

-Other pressure losses. (It is considered 5% of the total losses).

$$\Delta P_{total} = \Delta P_{regular} + \Delta P_{singular} + \Delta P_{others} \quad (3.9)$$

When friction is present, Bernoulli's theorem no longer applies and the load is no longer constant in the circuit. This is called pressure losses.

For incompressible fluids, we then use the generalized Bernoulli theorem between points 1 and 3, including a pressure losses term, which is written:

$$P_1 + \rho g y_1 + \frac{1}{2}\rho {V_1}^2 = P_3 + \rho g y_3 + \frac{1}{2}\rho {V_3}^2 + \Delta P \qquad (3.10)$$

Which is also:

$$\frac{P_1}{\rho g} + y_1 + \frac{1}{2g}{V_1}^2 = \frac{P_3}{\rho g} + y_3 + \frac{1}{2g}{V_3}^2 + \Delta H \qquad (3.11)$$

- **Regular losses**

Regular pressure losses are generated by the friction of the fluid on the inner wall of the pipe as it passes through (16).

They depend on:

-The length of the pipe (L in meters).

-The relative roughness of the pipe.

-The speed of the fluid flowing in the pipe (V in m/s).

Regular pressure losses are most often calculated from the Darcy-Weisbach equation:

$$\Delta H_{regular} = \Lambda \frac{L}{D_h}\frac{V_{average}^2}{2g} \qquad (3.12)$$

With:

Λ : Pressure loss coefficient (without unit).

$V_{average}$: Average fluid velocity in the pipe (m/s).

L: Pipe length (m).

D_h : Hydraulic diameter (m), defined by $D_h = \frac{4S}{P_m}$. S being the cross-sectional area of the pipe and Pm the wetted perimeter.

As we consider the length of the pipes is L= 32 m and is made up of steel.

The value of the coefficient Λ can be found in specific charts, called the Moody diagram or the Nikuradze Harp, for each pipe configuration. These are usually graphs expressing the value of Λ as a function of the Reynolds number of the flow, for different values of relative roughness.

So, in the first step we calculate Reynolds number by the equation (17):

$$Re = \frac{\rho V d}{\mu} \tag{3.13}$$

Re: Reynolds number.

V: Average velocity (m/s).

D: Tube diameter (m).

μ: Dynamic fluid viscosity (10^{-3} kg/ms).

To determine the regular pressure, we drop coefficient from the Moody diagram (Annex 1), before that we need to calculate the Reynolds number of each scenario a and b because the average velocity is different for both scenarios (table 3.6) and the constant $\frac{\varepsilon}{d}$, using steel is the material of the pipes.

Table 3. 6:Determination of Regular losses.

Height of The Water in the installation	$Y_{1\,a} = 120$ m	$Y_{1\,b} = 88$ m
Velocity average at point 3	$V_{average\ a} = 48$ m/s	$V_{average\ b} = 41$ m/s
Reynolds number	$Re_a = 6.2 \times 10^7$	$Re_b = 5.3 \times 10^7$
The constant $\frac{\varepsilon}{d}$	$\frac{\varepsilon}{d} = 1.9 \times 10^{-5}$	$\frac{\varepsilon}{d} = 1.9 \times 10^{-5}$
Pressure loss coefficient	$\Lambda = 0.009$	$\Lambda = 0.049$
Hydraulic diameter	$D_h = 1.29$ m	$D_h = 1.29$ m
Regular pressure losses	$\Delta H_{regular\ a} = 26.21$ m	$\Delta H_{regular\ b} = 19.12$ m

- **Singular losses**

Singular pressure losses are mainly due to pipe accidents, any geometrical modification of the pipe. These include changes in direction (bends, T-joints), changes in cross-section, valves or taps, measuring devices.

Singular pressure drops occur when there is a disturbance to the normal flow, fluid detaches from the walls and vortices form where there is a change in the cross-section or direction of the pipe (16).

The formal used is:

$$\Delta H_{singular} = \Lambda \frac{V_{average}^2}{2g} \quad (3.14)$$

Λ : Pressure loss coefficient (without unit).

In our case of water flow in pipes, we neglect the singular pressure losses because the diameter of the pipe is the same in the whole circuit with negligible bends.

$$\Delta H_{singular} = \Delta H_{singular\ a} = \Delta H_{singular\ b} = 0\ m$$

- **Total losses**

In this section, we present the sum of the head losses (table 3.7) in each scenario with the equation (3.15) and the other pressure losses considered 5% of the total losses.

$$\Delta H_{total} = (\Delta H_{regular} + \Delta H_{singular}) * 1.05 \quad (3.15)$$

Table 3. 7: Determination of Sum of losses.

Height of The Water in the dam	$H_a = 107\ m$	$H_b = 75\ m$
Height of The Water in the installation	$Y_{1\ a} = 120\ m$	$Y_{1\ b} = 88\ m$
Velocity average at point 3	$V_{average\ a} = 48\ m/s$	$V_{average\ b} = 41\ m/s$
Regular pressure losses	$\Delta H_{regular\ a} = 26.21\ m$	$\Delta H_{regular\ b} = 19.12\ m$
Singular pressure losses	$\Delta H_{singular\ a} = 0\ m$	$\Delta H_{singular\ b} = 0\ m$
Total losses	$\Delta H_{total\ a} = 27.42\ m$	$\Delta H_{total\ b} = 20.07\ m$

3.4.4 Velocity Calculation

In the last two parts, we calculated the average velocity to determine the losses.

The next step is the application of Bernoulli's theorem to determine the velocity of the water in point 3 in the presence of losses (17).

$$\frac{P_1}{\rho g} + y_1 + \frac{1}{2g} {V_1}^2 = \frac{P_3}{\rho g} + y_3 + \frac{1}{2g} {V_3}^2 + \Delta H \quad (3.16)$$

After simplification, we have

$$V_3 = \sqrt{2g(y_1 - \Delta H)} \tag{3.17}$$

Table 3. 8: Velocity of Water in the installation.

Height of The Water in the dam	$\mathrm{H}_a = 107$ m	$\mathrm{H}_b = 75$ m
Height of The Water in the installation	$\mathrm{Y}_{1\,\mathrm{a}} = 120$ m	$\mathrm{Y}_{1\,b} = 88$ m
Total losses	$\Delta\mathrm{H}_{\mathrm{total\ a}} = 27.42$ m	$\Delta\mathrm{H}_{\mathrm{total\ b}} = 20.07$ m
Velocity at point 3	$\mathrm{V_a} = \mathrm{V_{3\,a}} = 42.61\ \mathrm{m/s}$	$\mathrm{V}_b = \mathrm{V_{3\,b}} = 36.5\ \mathrm{m/s}$

After calculating the sum of the pressure losses, we calculated the velocities using the Bernoulli equation in the presence of the losses. It is noticed that the velocities in both scenarios a and b decrease after losing energy in the flow.

3.4.5 Pressure Calculation

The pressure at point Z which is the same point 2 changes because the fluid was static and there was no movement. After the construction of the water pipe there is a movement of water at this point. Between points 1 and 2 the pressure losses are negligible because we have no water pipe (Figure 3.7), so the new expression of the pressure is (16):

$$P_1 + \rho g y_1 + \frac{1}{2}\rho {V_1}^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho {V_2}^2 \tag{3.18}$$

Where $\mathrm{A_2\,V_2 = A_3\,V_3}$ (3.19)

And $\mathrm{A_2 = A_3 = \pi\, r_2^2} = 1.32\ m^2$ (3.20)

So $\mathrm{V_2 = V_3}$ (3.21)

After simplification, we have

$$P_2 = P_1 + \rho g(y_1 - y_2) - \frac{1}{2}\rho V_2 \tag{3.22}$$

Table 3. 9: Table 3.8: Velocity of Water in the installation.

Height of The Water in the dam	$\mathrm{H}_a = 107$ m	$\mathrm{H}_b = 75$ m
Height of The Water in the installation	$\mathrm{Y}_{1\,\mathrm{a}} = 120$ m	$\mathrm{Y}_{1\,b} = 88$ m
Velocity at point 2	$\mathrm{V_{2\,a}} = \mathrm{V_{3\,a}} = 42.61\ \mathrm{m/s}$	$\mathrm{V_{2\,a}} = \mathrm{V_{3\,b}} = 36.5\ \mathrm{m/s}$
Pressure at point 2	$\mathrm{P_{2\,a}} = 8.63$ bar	$\mathrm{P_{2\,b}} = 5.52$ bar

After calculating the pressures, it can be seen that the pressures at the z-point (point 2) of the dam decrease with the presence of water movement towards the pipe.

3.4.6 Water Flow

To calculate the flow rate (in m3) multiply the average water velocity (in m/s) by the area of the circle of our water pipe.

$$Q = A \times V \tag{3.24}$$

Q: Water flow (m3/s).

A: Area of the pipes (m2).

V: Velocity (m/s).

Table 3. 10: Water Flow in the installation.

Height of The Water in the dam	$H_a = 107$ m	$H_b = 75$ m
Height of The Water in the installation	$Y_{1\,a} = 120$ m	$Y_{1\,b} = 88$ m
Velocity at point 2 and 3	$V_{2\,a} = 42.61$ m/s	$V_{2\,b} = 36.5$ m/s
Area of pipes at point 2 and 3	$A = \pi r_2^2 = 1.32\ m^2$	$A = \pi r_2^2 = 1.32\ m^2$
Water Flow at point 2	$Q_a = 56.24\ m^3/s$	$Q_b = 48.18\ m^3/s$

The flow rate of the equipment can be variable in relation to the water level, during the year the water level in the dam is variable in relation to the weather. That's why we chose these two scenarios a and b.

For the mechanical energy, a stable water flow is necessary to have a better electricity production.

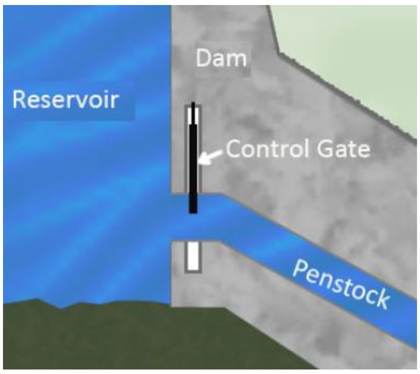

Figure 3. 8: Control Gate *(18).*

In table 3.7 we notice that the two scenarios have different water. So, we fix in point 2 what is called the Control gate (figure 3.8). The Control gate is a flow regulator that enters the water pipe flows. Then, we choose the average of two flows as a flow reference at point 3 (18).

All year round, there are different flow values in the pipe because the water elevation in the dam is variable with respect to the weather, so as we have explained the choice of two scenarios, the maximum elevation H and the minimum elevation H. The dam has a large surface with a very important water elevation so the choice of scenario b is almost impossible to have a lower elevation than scenario b especially with the presence of pumping which we will work on in the following part.

$$Q = Q_{average} = \frac{Q_a + Q_b}{2} \tag{3.25}$$

Water Flow	Q = 52.21 m^3/s

3.4.7 Mechanical Energy

Mechanical Energy "E_M"is the sum of kinetic energy "E_k"and potential energy "E_p" (eq 3.26) (17) . Therefore, Hydraulic energy is in fact kinetic energy linked to the movement of water in pipes and in the side, we have potential energy linked to the gravity, as in our case of the waterfall in the dam.

$$E_M = E_k + E_p \tag{3.26}$$

The flow rate and net head "H_n" are used to calculate the available Kinetic Energy (equation 3.27) and the flow rate and net head are used to calculate the available Potential Energy (equation 3.26).

$$E_k = Q_t \times H_n \times \rho \times g \tag{3.27}$$

- Q_t : Turbined flow (m^3/s).

-H_n : Net drop (m).

$$E_p = \frac{1}{2} \times \rho \times Q_t \times V_t^2 \tag{3.28}$$

-V_t : Turbined Velocity (m/s).

$$V_t = \frac{Q_t}{A} \tag{3.29}$$

-A: Area of pipes.

The Net drop is the height of Hydraulic Energy after the elimination of the losses (equation 3.30)

$$H_n = Y - \Delta H_{total} \tag{3.30}$$

The turbined flow is the water flow that we calculate in previous part, in the next step we calculate the mechanical energy (table 3.11).

Table 3. 11: Determination of Mechanical Energy.

Height of The Water in the installation	$Y_1 = 120$ m
Total losses	$\Delta H_{total} = 27.42$ m
Net drop	$H_n = 92.58$ m
Turbined flow	$Q_t = 52.21 \ m^3/s$
Kinetic Energy	$E_k = 47.41$ MW
Velocity	$V_t = 39.5$ m/s
Potential Energy	$E_p = 40.73$ MW
Mechanical Energy	$E_M = 88.14$ MW

3.4.8 Turbine selection

To choose the type of impeller that best suits the topology of the site, professionals use charts that determine the most suitable type of water turbine based on the head and flow rate. In our case we have a volume flow of 52.21 m^3/s and a maximum waterfall of 120 m.

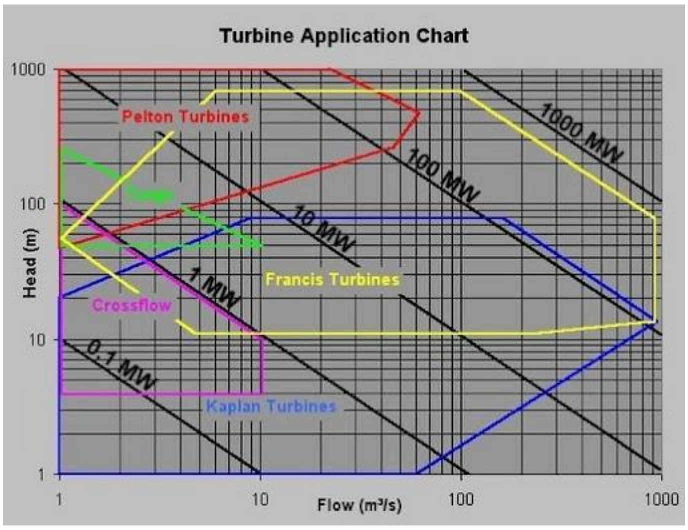

Figure 3. 9: Turbine selection chart based on head and flow rate *(19)*.

According to the figure 3.9, the best choice of turbine for the flow rate and height of our dam is the Francis turbine (figure 3.10) which it is fixed at point 3 (figure 3.7).

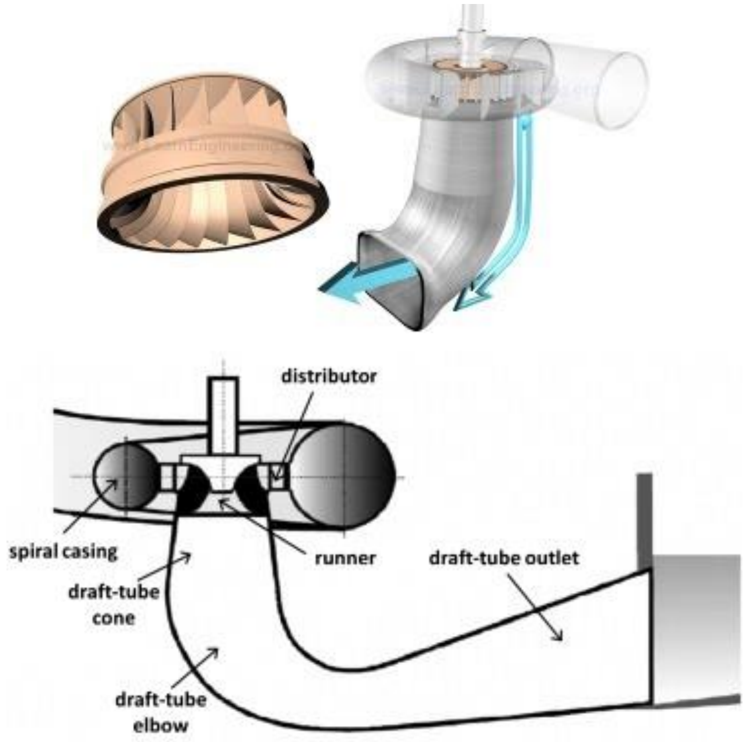

Figure 3. 10: Francis Pompe-Turbine design *(20).*

The stationary part of the turbine consists of the spacer ring that carries the distributor and the bell that supports the main bearing of the machine.

The distributor is used to regulate the flow and to direct the flow optimally to the impeller blades. It consists of a set of guide vanes, the orientation of which is adjusted by means of the connecting rods carried by the valve ring. This ring is operated by the control rod, via two tie rods. At present, it is adjusted manually. It will be necessary to automate it and regulate its opening according to the incoming flows.

The impeller is placed inside the valve. The impeller shaft is supported and guided by the main bearing.

The vertical shaft of a Francis turbine (figure3.10) is supported and guided by the main bearing, which is integral with the bell. This bearing is associated with a second bearing which guides the upper end of the shaft in the vicinity of the idler gear. It is essential to ensure that these bearings are well lubricated.

The transformation of energy depends on all the components of the turbine but to different degrees. The driving wheel is the main element. The study of its blade is centered on the problem of this energy transformation, an operation that must be carried out in the best possible conditions.

- **Turbine inlet pressure**

At the beginning of the study, the turbine inlet pressure P_3 is the atmospheric pressure in order to calculate the hydraulic losses (table 3.12), after fixing the turbine at point 3 (figure 3.7), the pressure changes, so by using the Bernoulli equation we deduce the new pressure P_3(eq 3.31) (21).

$$\frac{P_1}{\rho g} + y_1 + \frac{1}{2g} V_1{}^2 = \frac{P_3}{\rho g} + y_3 + \frac{1}{2g} V_3{}^2 + \Delta H \tag{3.31}$$

After simplification, we have

$$P_3 = P_1 + \rho g y_1 - \frac{1}{2} \rho V_3^2 - \rho g \Delta H \tag{3.32}$$

Table 3. 12: Determination of Turbine inlet Pressure.

Height of The Water in the installation	$Y_1 = 120$ m
Total losses	$\Delta H_{total} = 27.42$ m
Water flow	$Q = 52.21\ m^3/s$
Area of pipes	$A = 1.32 m^2$
Velocity at point 3	$V_3 = 39.48$ m/s
Turbine inlet pressure (point 3)	$P_3 = 2.47$ bar

- **Efficiency**

The knowledge of certain characteristics of the elements adjacent to the impeller, such as the distributor and the diffuser, is however essential. But in our case, we determinate that the efficiency η_T (equation 3.33) (21)of the turbine is equal to 90% with angular synchronous speed $N_S = 400$ rpm which determined from the curve (annex 2) through coefficient of the water flow (m3/s) and the height (m), therefore an angular velocity ω =2513.2 rad/s.

$$\eta_T = \frac{E_a}{E_M} \tag{3.33}$$

E_a : Power recovered by the turbine shaft (W).

Francis vertical axis scroll turbines are primarily designed as compact machines. Modern, reliable, tested, measured and hydraulic designs guarantee the highest performance.

The wheels are milled and manufactured according to different technologies ensuring the highest precision.

The Francis hydraulic turbine is a rotating machine, consisting of 3 parts:

- The distributor with adjustable blades that give the incoming water the appropriate speed to approach the wheel.

- The wheel, which receives the water on its blades, causing it to rotate around its axis (equation 3.34).

- An outlet to discharge the water downstream (22).

$$E_a = \eta_T \times E_M \tag{3.34}$$

Table 3. 13: Determination of Electrical Energy Recovered by the Turbine Shaft.

Height of The Water in the installation	$Y_1 = 120$ m
Mechanical Energy	$E_M = 88.14$ MW
Turbine Efficiency	$\eta_T = 90\%$
Power recovered by the turbine shaft	$E_a = 79.32$ MW
Turbine losses	$\Delta P_{Turbine} = 8.82$ MW

3.4.9 Electrical Energy Produced

The Francis turbine mechanically coupled to a generator drives it in rotation in order to convert to convert mechanical energy into electrical energy.

We use machines called generators to produce electricity. In a generator, a huge electromagnet, or rotor, rotates inside a cylinder, the stator, which contains coils and spools of electrical wire (22).

- **The current generator**

The current generator transforms the mechanical energy available through the rotation of the shaft into electrical energy (equation 3.35) (22). A current generator consists of:

- a fixed part (the stator) surrounded by numerous coils of copper wire.

- a moving part (the rotor) also surrounded by copper wire coils wire coils, which is driven by the turbine wheel.

The electric current is generated by the rotation of the magnetic field of the rotor of the rotor through the copper coils of the stator with generator efficiency η_g equal to 98% (table 3.14).

$$E_g = \eta_g \times E_a \quad (3.35)$$

E_g : Power recovered by the generator (W).

Table 3. 14: Determination of Electrical Energy Recovered by the Generator.

Power recovered by the turbine shaft	$E_a = 79.32$ MW
Generator efficiency	$\eta_g = 98\%$
Power recovered by the generator	$E_g = 77.73$ MW

- **The transformer**

The current produced "E_f"then passes through a transformer (eq 3.36). This is equipment allowing, depending on the case, to raise or to lower the voltage of the alternating current in order to transport electricity over long distances with transformer efficiency $\eta_{transformer}$ equal to 98% (table 3.15) (22).

$$E_f = \eta_{transformer} \times E_g \quad (3.36)$$

Table 3. 15: Determination of Electrical Energy Recovered by the transformer.

Power recovered by the generator	$E_g = 77.73$ MW
Generator efficiency	$\eta_{transformer} = 98\%$
Power recovered by the generator	$E_f = 76.18$ MW

In order to determine the final electrical energy produced, we calculated the energy produced "E" by the transformer that is transferred through electrical cables to the power plant. In our case, we neglect the load losses of the electrical cables. So, the Electricity Produced is:

$$\boxed{E = E_f = 76.18 \text{ MW}}$$

To determine the total efficiency of our hydropower plant (equation 3.37), we need to calculate the maximum gross power of our hydropower plant.

$$\eta_H = \frac{E}{E_{Max}} \tag{3.37}$$

η_H : Total efficiency.

E: Energy produced (W).

E_{Max} : Maximum gross power of hydropower plant (W).

The maximum gross power is proportional to the gross head, the acceleration of gravity and the water flow rate (equation 3.34)

$$E_{Max} = (g \times \rho \times H \times Q) + (\frac{1}{2} \times \rho \times Q \times V)^2 \tag{3.38}$$

H: Gross height (m).

Q: Turbine flow (m3/s).

V: Turbine velocity (m/s).

Table 3. 16: Determination of Total Efficiency.

Gross height (m)	$H = 120$
Turbine flow (m3/s)	$Q = 62.4$
Turbine velocity (m/s)	$V = 48$
Maximum gross power of hydropower plant (MW)	$E_{Max} = 145.34$
Total efficiency (%)	$\eta_H = 52.4$

3.5 Calculation of Energy Consumption

A head-specific speed chart for Francis-type reversible pump turbines, where the PAT geometric design plays the key role in the classification process. PATs with narrow impeller channels at the runner inlet are characterized by high heads-low specific speeds, while PATs with wider impeller channels at the runner inlet are characterized by low heads-high specific speeds (23) (Fig. 3.11).

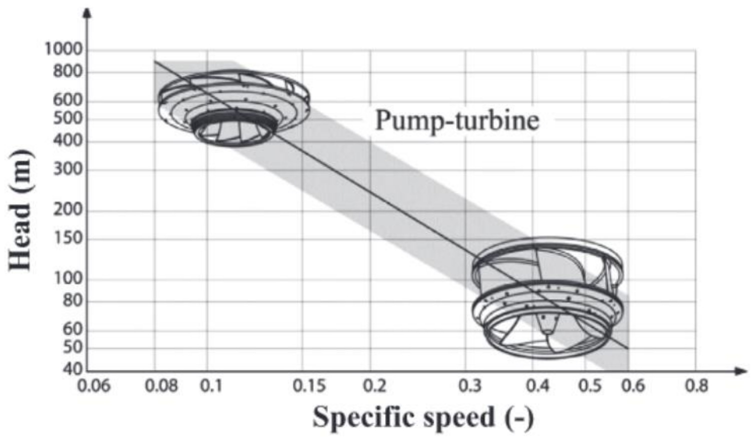

Figure 3. 11: Francis-Type Reversible Pump-Turbine *(19)*.

3.5.1 Total Manometric Height

According to our installation the turbine that will act as a pump has the same downstream elevation, the pressure losses will be the same as calculated for the turbine part because we have the same water pipe with the same pipe length (23) (figure 3.12).

In this part, we calculate the electrical power of the pump starting with the application of Bernoulli's theorem between points 1 and 2 (equation 3.39) to find Pump water flow (24).

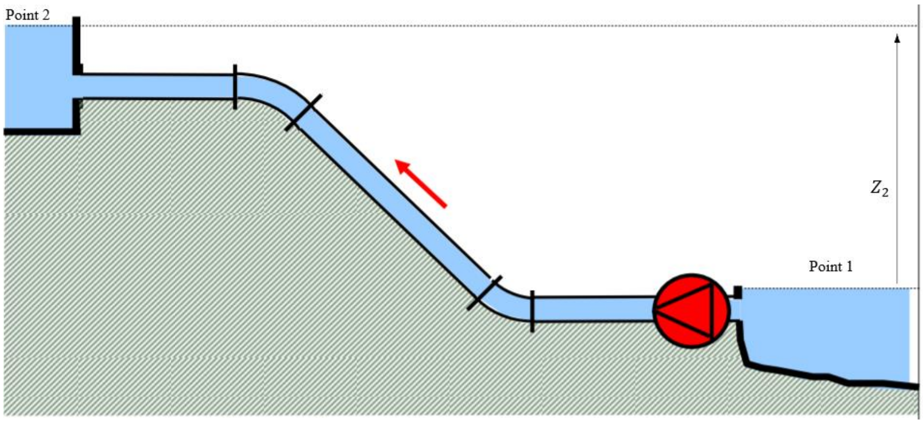

Figure 3. 12: Turbine as Pump Shema.

$$\frac{P_1}{\rho g} + Z_1 + \frac{1}{2g}{V_1}^2 + H_P = \frac{P_2}{\rho g} + Z_2 + \frac{1}{2g}{V_2}^2 + \Delta H_{total} \qquad (3.39)$$

H_P: Total manometric height (m).

ΔH_{total} : Total losses (m).

From our installation we have:

$$P_1 = P_2 = P_{atmospheric} \qquad (3.40)$$

The Downstream surface is large, so the velocity at both points 1 is almost zero.

On the other hand, when the pump is switched on the water level at the dam must be minimal (figure3.13), so we take the height used in scenario b in the previous section (Electrical Energy Generated) in the other side the elevation of water downstream is high 4 m then the pump level (eq 3.41) (24).

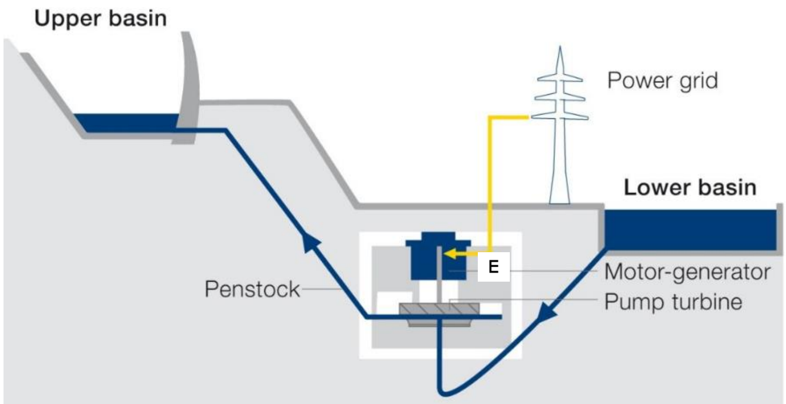

Figure 3. 13: Pump Water Flow Shema.

$$Z_2 - Z_1 = 88 - 4 = 84\text{m} \quad (3.41)$$

After simplifying the Bernoulli equation, we have

$$H_P = (Z_2 - Z_1) + \frac{1}{2g} {V_2}^2 + \Delta H_{total} \quad (3.42)$$

So, if we replace V_2 by $\frac{4 \times Q}{\pi \times d^2}$, we conclude

$$H_P = (Z_2 - Z_1) + \frac{8 \times Q^2}{g \times \pi^2 \times D^4} + \Delta H_{total} \quad (3.43)$$

D: Pipe's diameter (m).

Q: Water flow (m3/s).

After applying the generalized Bernoulli equation, we obtain total manometric

$$\boxed{H_P = 111.42 + 0.28 \times Q^2}$$

In this case we show the total manometric height as a function of flow rate, in annex 3 represent the performance curve of the Francis pump, we have to choose the flow rate of the water randomly in order to draw the curve that corresponds to our pump, then we notice that there is an intersection (annex 3). This point is the operating point of the pump, so we determine from the curve the flow rate Q and the new value of the total manometric height H_P, and the pressure difference the inlet (point E) and outlet of the pump (figure 3.13) (23).

The operating point gives us Q = 9 m3/s, H_P =134.1 m and $\Delta P = 1400\ kpa = 14\ bar$. Generalized Bernoulli relationship between point 1 and point E the pump inlet (equation 3.44).

$$P_E = P_1 + \rho g \times (Z_1 - Z_E) - \frac{V_E^2}{2}\rho \quad (3.44)$$

$$P_E = 0.59 \text{ bar}$$

3.5.2 Power of the pump

To calculate the mechanical power absorbed by the pump (equation 3.45), the efficiency losses must be added to the hydraulic power. The efficiency depends on the pump technology used and the operating pressure as well as the characteristics of the fluid (23).

$$P_h = \Delta P \times Q \quad (3.45)$$

P_h : pump capacity (w).

ΔP : Pressure difference (pa).

Q : Water flow (m3/s).

$$P_h = 12.6 \text{ MW}$$

The overall efficiency η of the powertrain is given by equation (3.46) as the product of the shaft bearing efficiency η_a and the hydraulic efficiency $\eta_h$expressed by

$$\eta = \eta_a\ \eta_h = \begin{cases} \frac{P}{P_h} \text{ Turbine Mode} \\ \frac{P_h}{P} \text{ Pump Mode} \end{cases} \quad (3.46)$$

Table 3. 17: Determination of Electrical Power of the Pump.

Gross height (m)	$Z = 84$
Turbine flow (m3/s)	$Q = 9$
Turbine velocity (m/s)	$V = 1.6$
Total efficiency	$\eta_H = 52.4\%$
Electrical power of the pump (MW)	$P_{Pump} = 24.23$

3.6 Results and Discussions

3.6.1 Results

In order to highlight the results, the electrical power produced by the turbine and the electrical power consumed by the pump were calculated. From these, it is possible to determine the net annual electrical power produced and the project revenue for one year.

During the year it is assumed that the water level in the dam is higher than the minimum during the winter period. During the winter the metrological conditions are rainy in the location of the dam in Portugal. But during the summer there is not much water coming from the rain.

So, it is assumed that the turbine will be in operation half a day for 9 months of the year (winter) and on the other hand the pump will be in operation half a day for 3 months of the year (summer).

- **Electrical Power Net Obtained per year**

In the first step we calculate the energy produced by the turbine during 9 months (equation 3.47), and the energy consumed by the pump during 3 months (equation 3.48) and then we determine the net annual energy produced in our hydroelectric installation (equation 3.49).

$$E_{f\ (9\ months)} = E_f \times 12 \times 30 \times 9 \tag{3.47}$$

$$P_{Pump\ (3\ months)} = P_{Pump} \times 12 \times 30 \times 3 \tag{3.48}$$

$$E_{net\ annual} = E_{f\ (9\ months)} - P_{Pump\ (3\ months)} \tag{3.49}$$

Table 3. 18: Determination of Net Electrical Energy Produced in the Installation.

Electrical Energy recovered by the Generator	E_f = 76.18 MW
Energy Produced by the Turbine during 9 Months	$E_{f\ (9\ months)}$ = 246.82 GWh
Electrical Energy Consumed by the Pump	$P_{Pump\ (3\ months)}$ = 24.23 MW
Energy Consumed by the Pump during 3 Months	P_{Pump} = 26.16 GWh
Net Electrical Energy Produced in the Installation	$E_{net\ annual}$ = 220.66 GWh

- **Recipes**

This table 3.19 shows the revenues obtained from our project and the price of 1 KWh is 0.229 € in 2020 (25).

Table 3. 19: Determination of the Revenues obtained from our project.

Energy Produced by the Turbine during 9 Months	$E_{f\ (9\ months)}$ = 246.82 GWh
Energy Consumed by the Pump during 3 Months	$P_{Pump\ (3\ months)}$ = 26.16 GWh
Net Electrical Energy Produced in the Installation	$E_{net\ annual}$ = 220.66 GWh
Price of 1 KWh	0.229 €
The Revenues Obtained from our project	50 531 140 €

3.6.2 Discussions

In theory, if we consider that the consumption of the coming years remains identical 220.66 GWh, we can hope to cover a large part of the needs. On the other hand, if we consider the most optimistic case and that the latter comes close to an average consumption, we will be able to ensure energy autonomy.

energy autonomy. It should be noted that not all the electricity will be directly consumed (the consumption of the pump) and that some of it will have to be sent back to the grid.

In this respect, at present, installations with an installed power of less than 10 kW benefit from the compensation mechanism: "reverse meter". We can therefore send our production back when it is not needed. Moreover, connection to the grid is free of charge and there is no tax for people who have a hydroelectric installation and who send part of their unconsumed electricity back to the grid. If this sector develops, it is therefore If this sector develops, it is therefore possible that a tax will be introduced, as will soon be the case for the photovoltaic sector. This would inevitably play a role in the return on investment of the installation.

In the event that the reality is closer to the favorable case, the project will be profitable. Indeed, even after a few years of operation and assuming that the assumptions made are almost correct, the investment would be amortized.

The return times are quite high compared to conventional projects. It is mainly influenced by the civil engineering implemented. Nevertheless, the project remains interesting from an energy saving point of view. It allows the production of a certain amount of delocalised electricity. In the future, other more efficient technologies will probably be developed and will allow this type of site to be operated at lower cost.

It should be remembered that there are still many sites that can be rehabilitated throughout Europe.

Chapter 4

CFD Numerical Simulation

4.1 Introduction

After having given an overview of the concept of a dam hydropower system with a reversible turbine and described the different approaches to calculate the net electrical energy produced that can be used, it is now necessary to carry out a numerical simulation, especially at the level of the turbine that we choose the Ansys CFD.

In a first step, we constitute the hydraulic system of the dam, we start by the well detailed structure with the real measurements and dimensions and choose the sources that compose the system.

In the first part of the chapter, we will first define the modelling for the Francis turbine with specific characteristics and choose an architecture that can suit the system to manage it in the most optimal way.

The second part of the chapter will deal with the mathematical formulation of the turbine power with pumping system.

In the last part, we present the results together with the discussion

4.2 ANSYS-Fluent Software

4.2.1 Presentation

There are a number of industrial codes, some of the best performing, allowing the prediction of fluid flows (FLUENT, CFX, PHOENICS, FEMLAB, CFD-ACE, FLOTRAN, CFDS-FLOW3D ...).

To carry out our simulations, we choose the ANSYS-Fluent calculation code, which we present in this presented in this section (26).

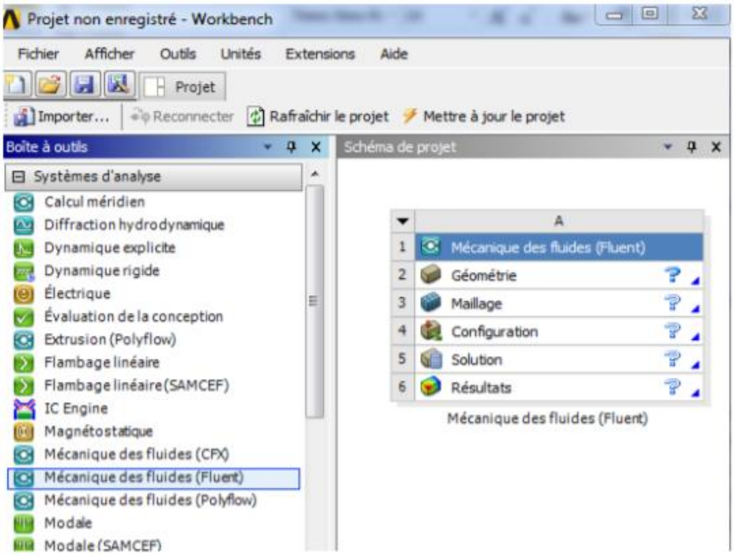

Figure 4. 1: ANSYS-Fluent software.

4.2.2 Software Architecture

The "Fluent" calculation code is marketed by the ANSYS group. This group is currently

group is currently one of the most important centers of competence in numerical fluid mechanics. It develops and markets a complete solution in the form of general-purpose CFD (Computational Fluid Dynamics) software which simulates all fluid flows, compressible or incompressible, involving involving complex physical phenomena, such as turbulence, heat transfer turbulence, heat transfer, chemical reactions, multiphase flows for the entire multiphase flows for the entire industry.

The products and services offered by the ANSYS group help researchers to increase their yields, optimize their designs and reduce their testing time. This code is widely used in the aerospace, automotive and hydraulic industries and offers a sophisticated interface for ease of use. The ANSYS-Fluent" software uses the finite volume method to model a wide range of flows in flows in more or less complex configurations. It is like all CFD software, consists of three key elements: the preprocessor pre-processor, the solver and the post-processor. These three elements are illustrated (26).

4.2.3 Design Modeler& ANSYS Meshing preprocessor

The definition of the problem to be solved is carried out using the Design Modeler preprocessor. It allows to represent the geometry of the system and to specify the type of material (fluid or solid). Using ANSYS-Meshing, we can define the domain boundaries, and also provide several meshing algorithms to discretize the domain algorithms to discretize the domain according to the geometry used (26).

4.2.4 Post-processor "CFD-Post"

The post-processor is the element that allows us to visualize the geometry and the mesh of the domain, but above all to display the results obtained. It offers us the possibility to visualize the velocity vector fields, the pressure fields, the turbulence fields, as well as all the other quantities calculated on a segment, a section of the domain or on the whole volume (26).

In addition, it allows the possibility to draw curves and to visualize streamlines or the trajectory of particles.

4.2.5 Definition of the resolution method

The ANSYS-Fluent calculation code uses an adaptation of a finite volume approach, which consists of discretizing the domain into cells called control volumes and then integrating the evolution equation on each of these volumes.

Each partial differential equation is integrated within a control volume or computational mesh, in order to obtain a discrete equation that relates the value of the variable at the center to the neighboring variables (26).

The computational mesh is a volume whose characteristic length is the spatial discretization step. A Once the mathematical formulation of the problem has been carried out, this discretization step is set in such a way as to ensure the accuracy of the calculations and takes into account, in the numerical stability conditions imposed by the value of the gradients.

4.3 Dam Structure

In this part, we made the design of the dam structure (figure 4.2), the water pipe and the turbine (figure 4.3). The dimensions of the dam are according to the project in reality.

In this part, we can't simulate the whole plant because of technical problems (computer performance) so we will simulate the turbine part only.

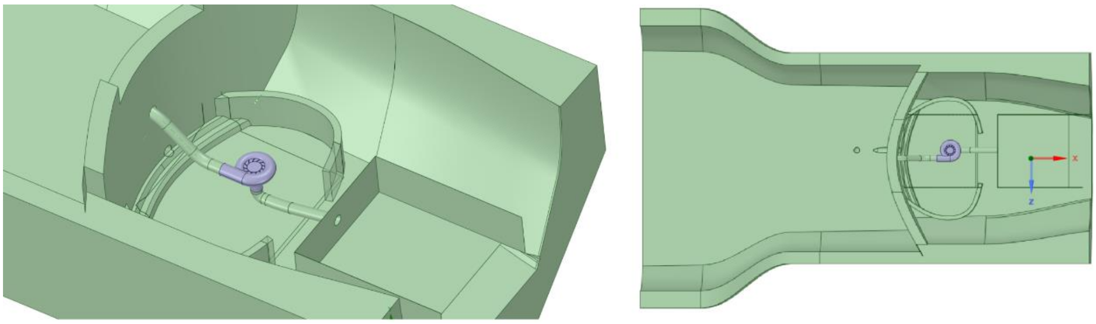

Figure 4. 2: Dam structure.

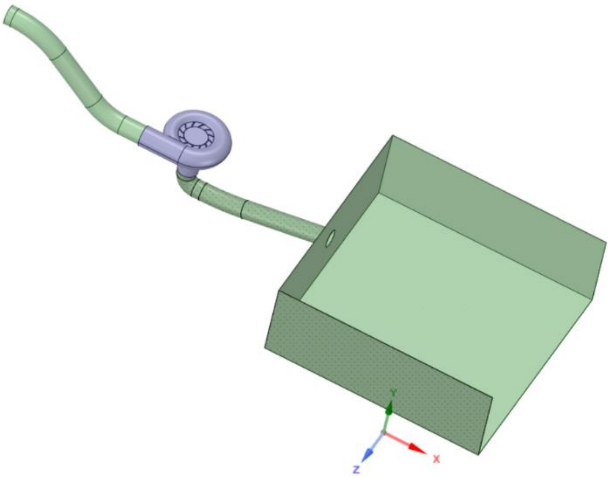

Figure 4. 3: Pipes and turbine structure.

4.4 Francis Turbine Flow Simulation

Generally, the flow field in Francis turbines is quite complicated due to its three-dimensional nature and the curvature of the passages between runner blades. The complexity of the problem requires the application of numerical approaches which are capable of producing accurate results for flow velocity field and pressure distributions on the runner. The application of CFD is an efficient way for the analysis of fluid flow through hydraulic turbines presented an application of CFD to compute the loads caused by water pressure on a blade of the Francis turbine runner. There is a satisfactory agreement between numerical simulations and experimental measurements (26).

And as we did in chapter 3, we will use the manual calculation for the inlet pressure to the turbine, also we take the same diameter of the water pipe as input in the software. Other characteristics that must be entered in our turbine in the software is the type of regime, which in our case is a turbulent regime because the Reynolds number is greater than 4×10^4 and finally the net input speed to the turbine.

4.4.1 Flow Simulations

The flow simulation of the Francis turbine runner is quite complicated and can be calculated only by using numerical methods. CFD simulation of the Francis turbine runner was performed to obtain pressure distribution and flow velocity through the turbine runner.

4.1.2 Geometrical Model

The first step of flow simulation is building the geometrical model of the flow domain. According to the provided specifications from the results of our hydropower station a three-dimensional geometrical model has been created, as shown in Figure 4.4. The geometry of the fluid domain has been created on ANSYS software.

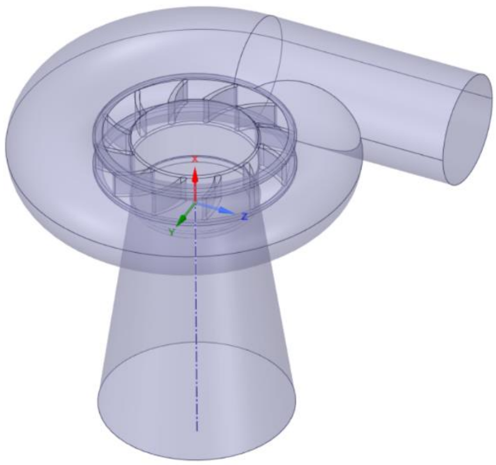

Figure 4. 4: Flow domain and structured model.

As shown in the figure, the entire fluid passageway between the inlet from the Spiral Case side and the outlet from the draft tube side for the turbine is considered.

The flow in the runner was computed in the rotating frame of reference, while the flow in the stationary components was calculated in chapter 3. Figure 4.4 shows the detail of the connection between flow domains used for CFD simulations and Francis turbine runner model.

4.1.3 Mesh Model

In this study, three-dimensional discretization has been used with the finite volume method provided by the ANSYS CFX software. For the computational domain, unstructured 3D tetrahedral meshing has been employed, due to its flexibility when solving complex geometries, as shown in figure 4.5.

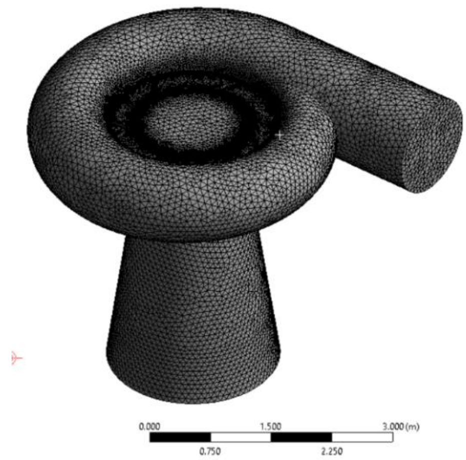

Figure 4. 5: 3D structured grids of the computational domain.

We need to investigate the comportment of the fluid to understand the principal keys in order to enhances the performance of our turbine, to do that we need to pay attention to the phenom called boundary layer which can determine the nature of profile of our fluid (figure 4.6) that's why we applied inflation property around the turbine.

Boundary layer, in fluid mechanics, thin layer of a flowing gas or liquid in contact with a surface such as that of an airplane wing or of the inside of a pipe. The fluid in the boundary layer is subjected to shearing forces. A range of velocities exists across the boundary layer from maximum to zero, provided the fluid is in contact with the surface. Boundary layers are thinner at the leading edge of an aircraft wing and thicker toward the trailing edge. The flow in such boundary layers is generally laminar at the leading or upstream portion and turbulent in the trailing or downstream portion. See also laminar flow; turbulent flow (27).

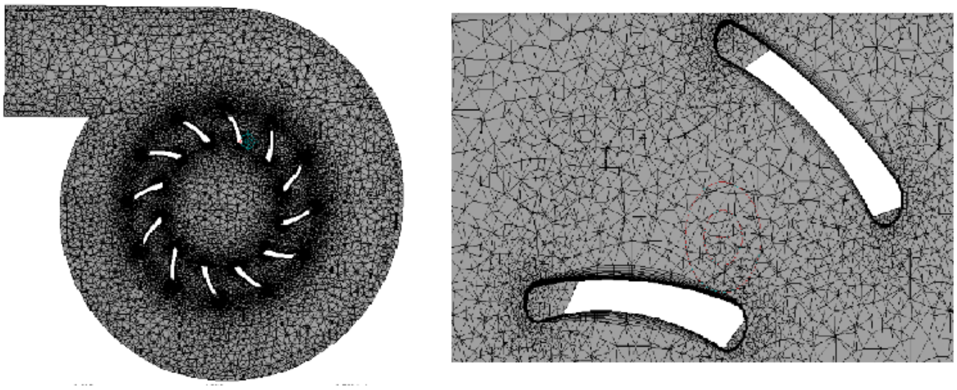

Figure 4. 6: Tetrahedral Mesh with inflation around the turbine.

4.1.4 Numerical modelling of turbulent fluid flow

The flow is considered to be viscous, incompressible and turbulent. The present paper focuses on 3-D Navier-Stokes simulations using the commercial code ANSYS CFX. The continuity equation and Reynolds-averaged Navier-Stokes equation for incompressible flow have been used as governing equations (28):

$$\frac{\partial U_i}{\partial X_i} = 0 \tag{4.1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial X_j} + \frac{1}{\rho}\frac{\partial P}{\partial X_i} - \frac{\partial}{\partial X_j}\left(v\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right) - \tau_{ij}\right) = 0 \tag{4.2}$$

where U, p, υ and ρ are velocity, pressure, kinematic viscosity and density, respectively, and ij are the components of the viscous stress tensor, also called the Reynolds Stress Tensor. The turbulent effects on the flow field are taken into account through the Reynolds Stresses ij, those are calculated from the k-ε turbulence model, which is frequently used for modelling turbulent flow.

4.5 Results and Discussions

Three-dimensional analyses of fluid flow through the Spiral Case, Stay and guide Vanes and then through the turbine blades channel have been carried out. The distributions of pressure and water velocity within the computational domain are illustrated in the form of contour and streamlines that are generated with the ANSYS CFX postprocessor.

The variation of pressure distributions and tangential velocity in the computational domain obtained from the CFD analysis for specific operating conditions are plotted in a plane which is passing through the center of Spiral Case and across the axis's of rotation as shown in figure 4.7 (A and B).The symmetrical inflow to the runner in circumferential direction can be observed, which results in symmetrical distribution pressure from the uniform flow distribution of the runner inlet, as shown in figure 4.7 B. The tangential velocity increase has been detected at the lower ring, which is due to the smaller area at the distributor region, as evident in figure 4.7 A.

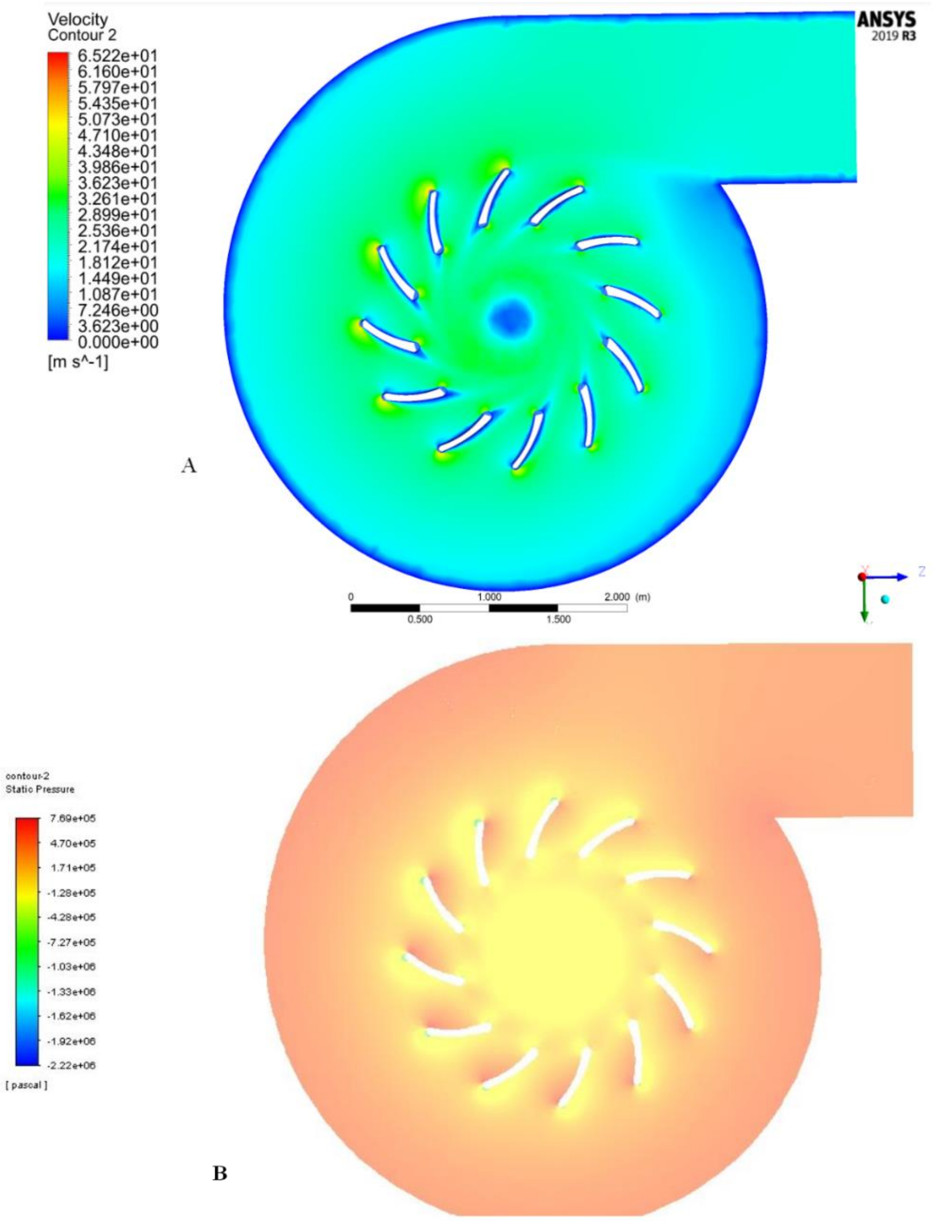

Figure 4. 7(A and B): (A) Variation of tangential velocity (ms-1) and (B) pressure distributions (Pa) in the computational domain.

Figure 4.8 (A and B), show the streamlines of the tangential velocity and the runner surface pressure distributions in the plane passing through the center of Spiral Case and parallel to the axes of rotation. The tangential velocity component decreases on the blade at the leading edge, which is due to the sharp. Bend of the flow in the stagnation regions near the blades, as observed in figure A. From Figure B, reduction from high pressure in the runner inlet to low pressure at the runner outlet is clearly observed.

High magnitudes of water pressure are observed at the leading edge of the runner due to stagnation pressure on the blades, which results from the rapid decrease in the magnitude of the tangential velocity close to the bend of the flow.

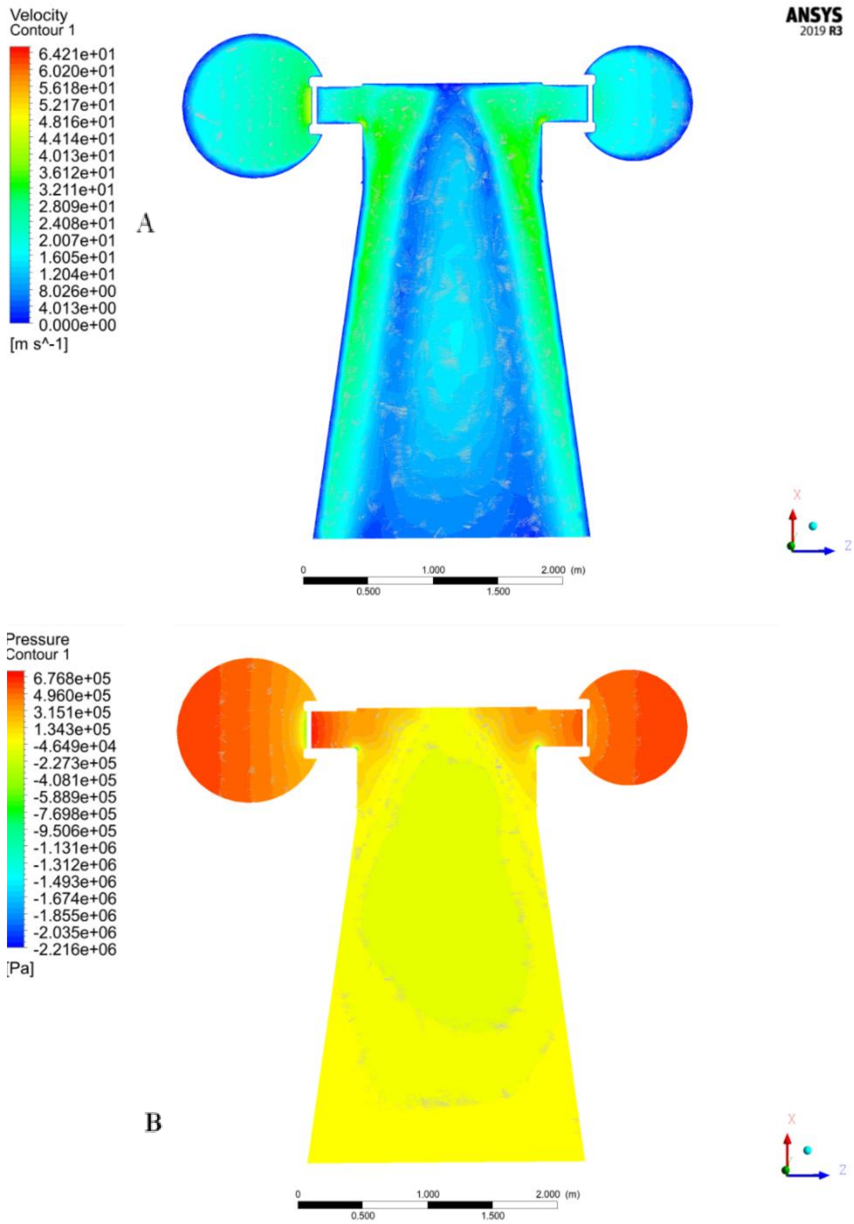

Figure 4. 8(A and B): (A) Tangential velocity (ms-1) and (B) the distribution of pressure (Pa) in the turbine.

As illustrated in figure 4.9, the flow is coming out from the spiral inlet to the upper part of the draft tube at the outlet. The flow is streamlined up to the runner outlet and recirculation is established in the draft tube. This is due to the change in the direction of the flow in the draft tube.

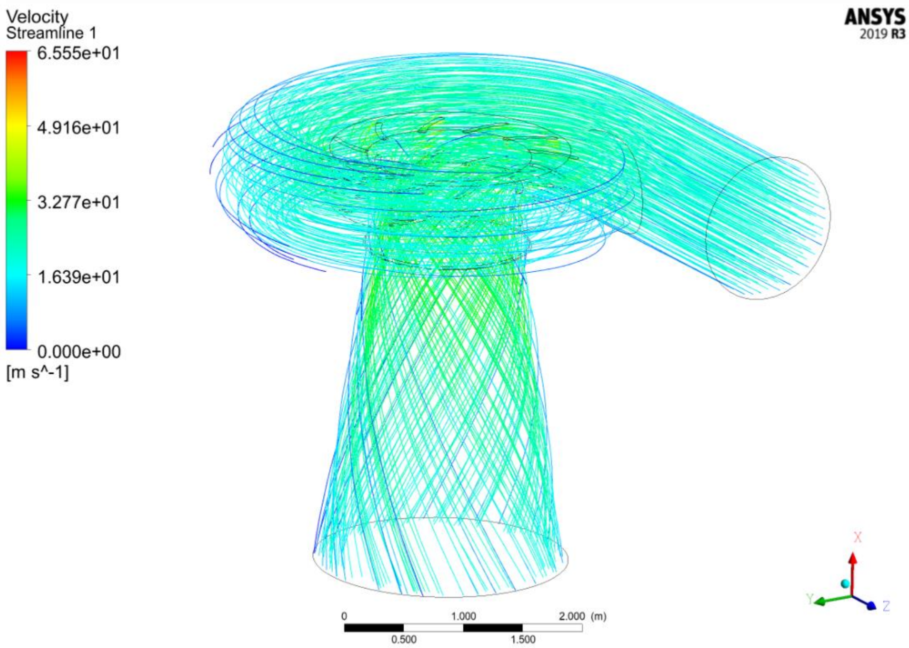

Figure 4. 9: Tangential velocity (ms-1) of the computational domain.

As observed in figure 4.9, the flow direction is almost radial at the outlet region of the runner and it is nearly axial at the center. While the recirculation region varies with the inlet boundary conditions, it increases gradually by decreasing velocity at the inlet. There is a sharp increase in the magnitude of velocity close to the trailing edge of the blade near the ring, due to the reduction of the area between the blade and the ring.

4.6 Pressure and Velocity Distribution Analysis of Pump as Turbine (PAT)

As in the third chapter, the turbine used in our installation is also pumping, so in this part we present a pump-turbine simulation.

Numerical simulations were carried out using a specific centrifugal pump model be made of impeller with 6 blades, volute, front and back chambers, with an Impeller Inlet Diameter of 104 mm, Impeller Outlet Diameter 160 mm, operating at nominal head of 16 m and flow rate of 12.5m3/h at an efficiency of 56% and rotational speed 2900 rpm.

A k- turbulence model to solve a (3D) equations in pump as turbine modes was selected for the study. Figure 4.10 below shows the absolute pressure distributions in a centrifugal PAT with 6 blades. The results revealed that absolute pressure increase with increase in rotational speed. However, at lower rotational speeds such as 1000 rpm, the pressure along the suction side of the impeller is very low comparable to other rotational speeds with the highest pressure located at the inlet pipe. Maximum pressure is located at the trailing edge at all rotational speeds with n=1500 (rpm) having the highest pressure. This shows that this type of pump has higher efficiency, which makes it more applicable to be selected for PAT in energy generation.

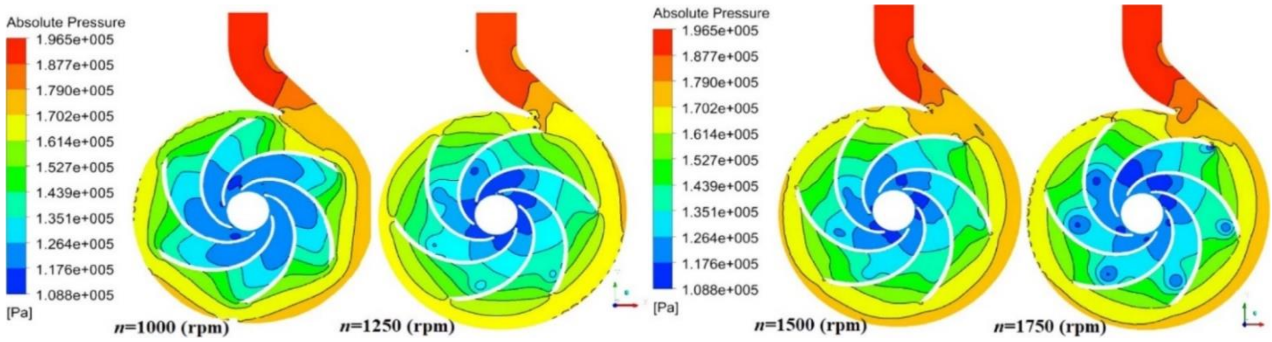

Figure 4. 10: Absolute pressure distributions of pump as turbine at different rotational speed.

Figure 4.11 shows the velocity in the PAT of an impeller with six blades colored by relative velocity distribution. The flow then moves smoothly in the volute region at lower rotational speed and slows down after striking the trailing edge of the impeller blade, after which the relative velocity of the fluid begins to once again increase to some extent. Also, velocity increases along the inlet pipe of the PAT as rotational speed increase till it reached n=1500 rpm after which it begun to decrease. It can therefore be concluded that rotational speed has influence on velocity distribution in PAT.

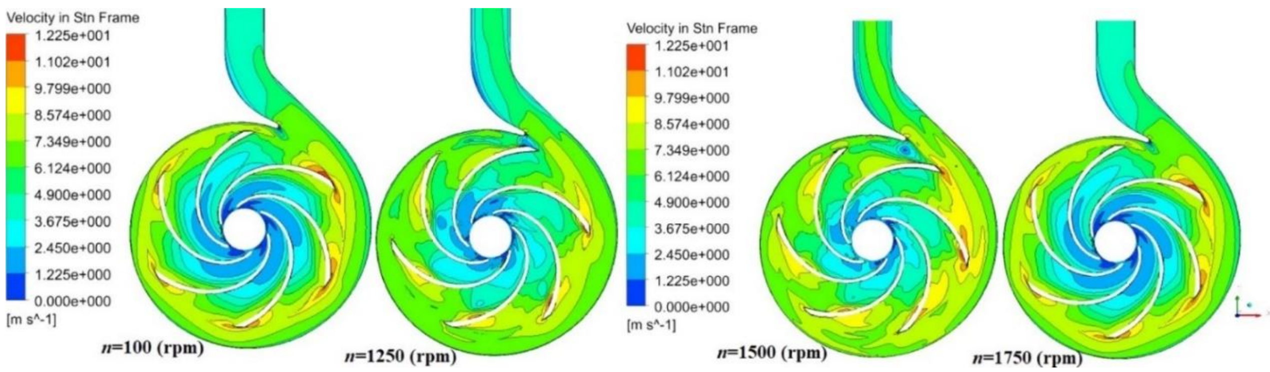

Figure 4. 11: Relative velocity distributions of pump as turbine at different rotational speed.

4.7 Conclusion

The simulation of the 3D steady-state fluid flow with moving reference frame in the entire Francis turbine from spiral case through stay vanes, wicket gates, and runner down to the draft tube is presented. The flow field simulation needs to include the entire flow passage to accurately model the runner surface pressure distributions and the streamlines of tangential velocity. Both these characteristics have been examined for a specific operation condition. Numerical simulation of the entire Francis turbine flow shows clearly the influence of the operation condition on the variation of pressure distributions and tangential velocity in the computational domain.

In this chapter the efficiency of the turbine is 84.5%. The results show good agreement with the previous studies when we supposed 90% for the efficiency of the turbine.

Chapter 5

Conclusion and Future Work

5.1 General Conclusion

Doing this work allowed us to deepen our knowledge of dams and the issues related to their use. The collective elaboration of the final production allowed us to learn how to organize ourselves in order to share the tasks efficiently.

The work presented in this thesis focused on a hydraulic-based generation system for a medium-head dam. The work aimed to use manual calculation notes to find the net electrical energy produced and then a numerical simulation to verify the efficiency of the turbine used.

In the first place, we have given a brief situation of hydroelectric energy with the basic elements to be used in the different types of hydroelectric power plants and more particularly the hydraulic power plant with pumping system. The statistics of hydroelectricity in the world, in Europe and particularly in Portugal, highlighting the different turbines to be used.

In the third chapter, we carried out a case study of a dam located in Portugal in order to calculate the different energies to find the net energy produced with a manual calculation. This study led us to the structure of the Foz do Tua dam which is a medium head dam. The starting point was the use of real hydrological and morphological data to determine the state of the river. Indeed, the characterization of the basin shape and its morphology also allows to know "the dimensions" concerning the constraints to be applied to a basin and the water pipe.

The fourth chapter was devoted to the presentation of a fluid mechanics simulation software in order to simulate the most important element in a hydropower plant "The turbine". In order to be able to do this simulation we need to build the structure of our hydraulic installation, entering the necessary data for the turbine (speed, pressure, type of water regime, diameter of the pipe, etc.) in order to find the results, we want to present from our installation.

5.2 Future Work

The perspectives of the research work of this thesis are open. In the short term, they can be aimed at studying the behavior of the hydraulic power plant, the development of much more complex models of the hill of the hydraulic turbine yields in order to better represent the phenomena related to hydraulics (water hammer, inertia of the water column, losses...) in order to be able to study the behavior of the hydraulic power plant. In the short term, they can be aimed at the study of the hydraulic power plant, the elaboration of much more complex models of the hydraulic turbine efficiency hill in order to better represent the phenomena related to hydraulics (water hammer, inertia of the water column, losses...) in order to be more precise on the efficiency of the turbine.

On the other hand, we also propose to make the simulation of the calculation note on the hardware "MATLAB".

In our project, we have presented the income from the electrical energy produced, so it is necessary to do the whole calculation of the investment to determine the payback time of this project.

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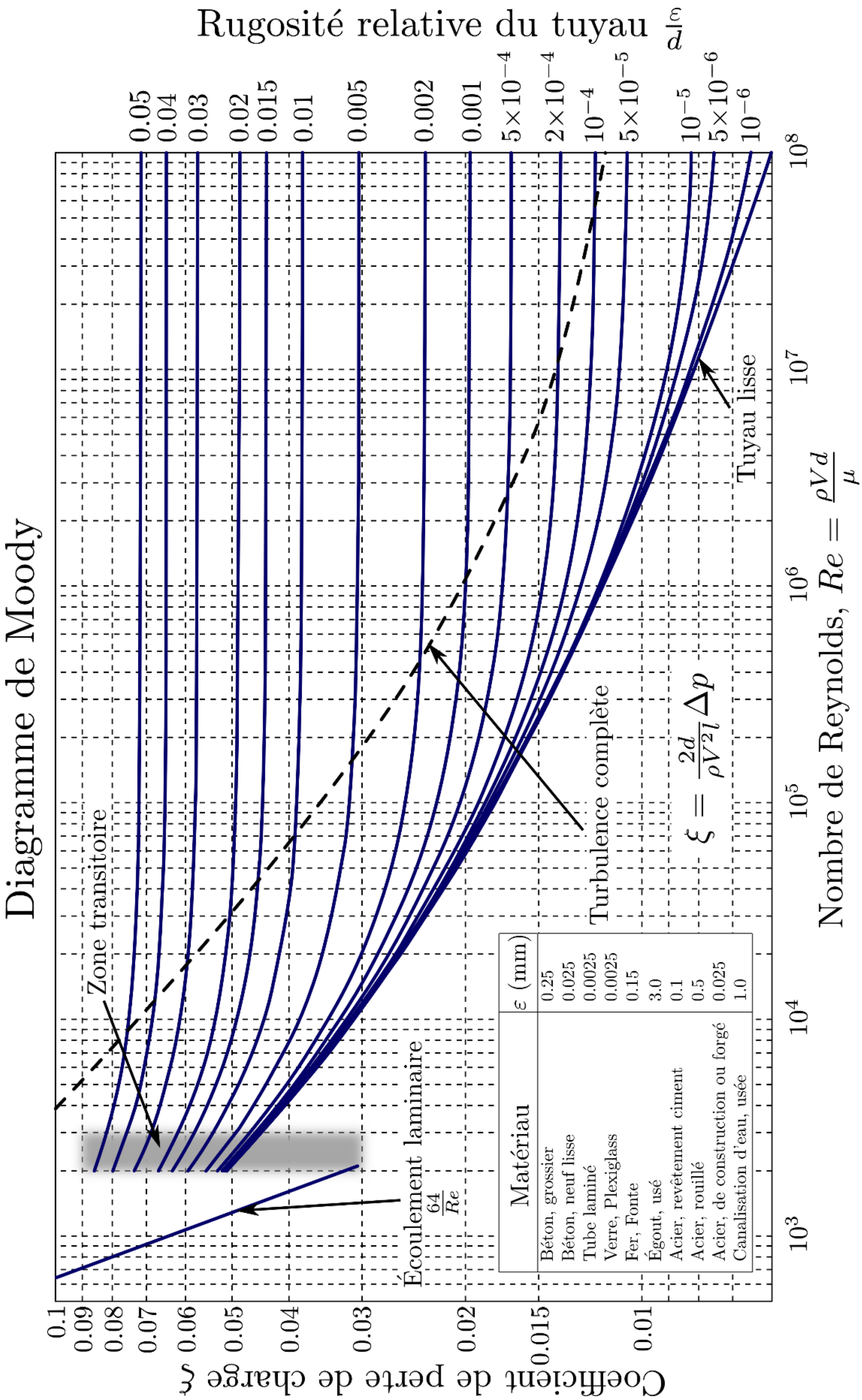
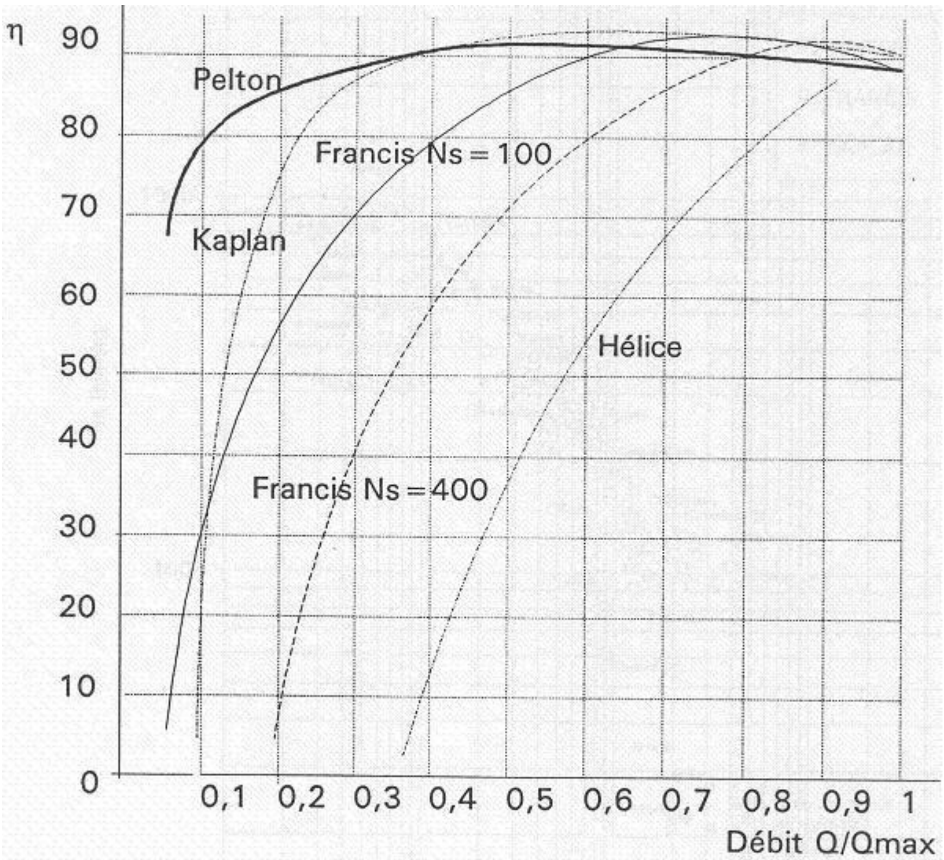
Appendices

Annex 1: Moody Diagram **(29)**.



Annex 2 : Efficiency curves for various turbines **(29)**.



Annex 3 : Pump performance curve **(29)**.