Training Unit on MiniHydro

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INTRODUCTORY DOCUMENT ON MINIHYDRO ENERGY

MAIN DOCUMENT.TRAINING UNIT ON MINIHYDRO POWER PLANTS

(Part of Deliverable D 4.4)

Rural-RES

PROMOTION OF SMALL-SCALE HYDRO AND WIND SYSTEMS IN MOUNTAIN AND RURAL TERRITORIES

INTELLIGENT ENERGY – EUROPE (IEE)

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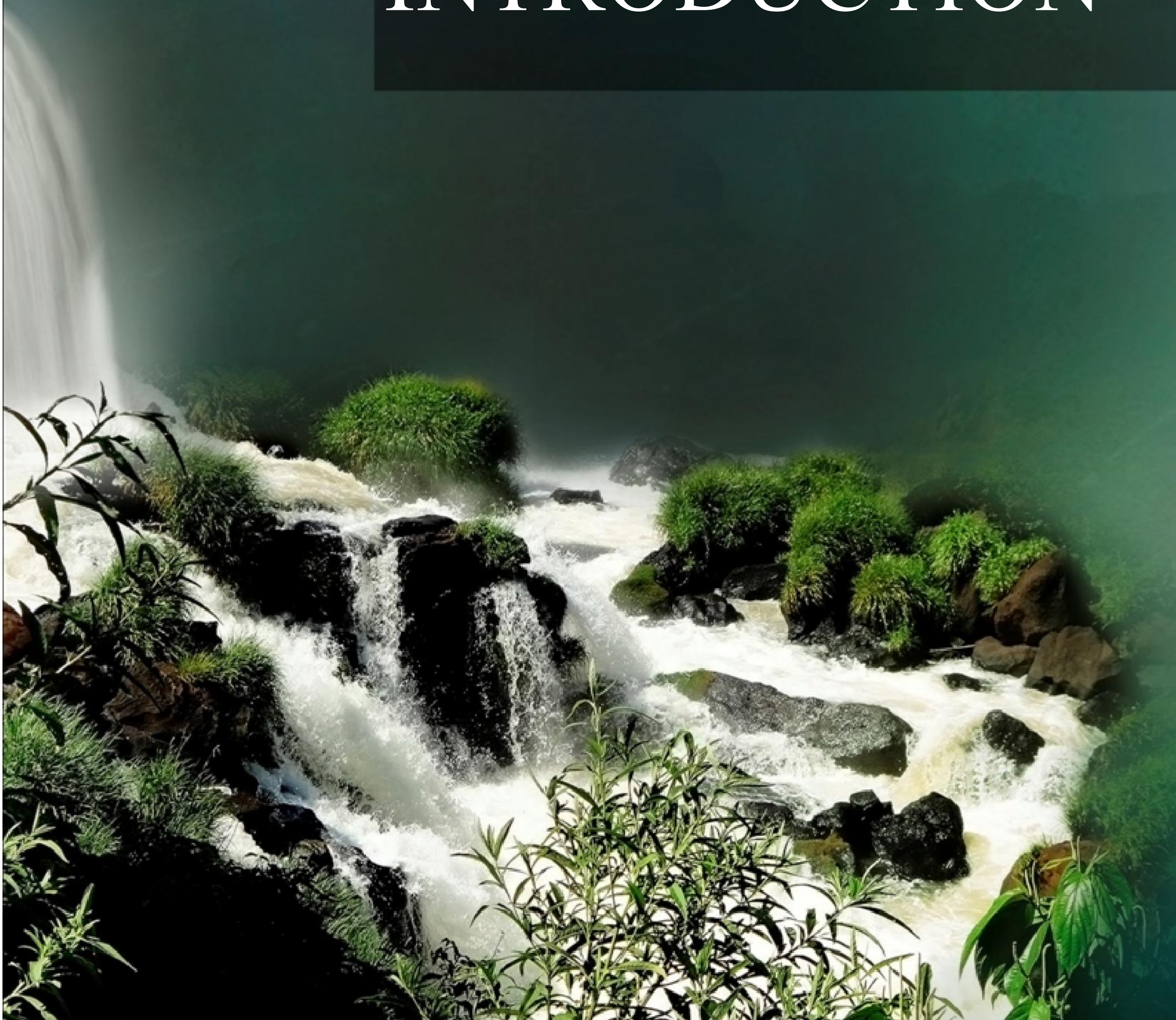
Chapter 1

INTRODUCTION



1. INTRODUCTION

1.1. BACKGROUND

As far back as the ancient Roman and Greek time, Society took advantage of the potential energy stored in water, the most common use being large wheels that were used to grind wheat. However, the possibility of using slaves and livestock delayed hydropower widespread use until the twelfth century. During the Middle Ages, large wooden waterwheels developed with a maximum of 50 HP, but it was the British civil engineer John Smeaton at the beginning of the Industrial Revolution, who first built waterwheels of cast iron.

Picture 1: Doña Aldonza SHP. Úbeda (Jaén)

Hydropower became very important during the Industrial Revolution. It boosted textile and leather industries and mechanical engineering workshops in the early nineteenth century. Although steam engines had already been perfected, coal was scarce and wood was found unsatisfactory as fuel. Hydropower allowed the growth of those new industrial cities that were created in Europe and America until the construction of canals in the mid-nineteenth century, which provided cheap coal.

Since 1973, following the so-called oil crisis, developed countries began a clear movement to contain their strong growth of energy consumption and heavy reliance on oil and this provided a renewed interest in all forms of Renewable Energy.

Dams and canals were needed for the installation of waterwheels with slopes greater than five meters. The construction of large dams was not yet possible, and the low flow of water during the summer and autumn, coupled with frost in winter, forced the replacement of water wheels by steam machinery at the very moment in which coal became available.

The use of systems capable of generating energy in a "clean" and sustainable way has seen a great growth in recent years, due to the impulse received by the acceptance of climate change as a real threat and also due to the shortage of resources that our planet currently faces. These systems are expected to become more and more important, particularly after the decision of the European Community and other countries to accept the obligations outlined in the Kyoto Protocol, aimed at reducing the emissions that cause climate change.

Since the late eighteenth century, water resources have been used to produce electricity. However, it was not until more recently that the environmental benefits for this type of electricity production were appreciated when compared to other types of energy production.

The technology deployed in the field of hydro-electricity has already reached its maturity (in this sector, major technological changes are not expected), and the industrial use of water resources, at least in European countries after almost two centuries of use, has nearly reached its technical potential.

However, the use small-scale hydropower resources for energy production is not widespread. This type of smaller scale installation can appeal to localities, using small turbines (from a few kW, to a few tens of kW) set in mountain or rural streams, for the supply of villages or for irrigation, whilst being easily integrated into the natural environment.

Some hydroelectric plants, especially large ones, with reservoirs of millions of cubic meters of water, have negative impacts on the environment. Currently, there is some negative press for renewable energies, including that coming from environmental groups. These groups are trying to draw attention to the imbalance between the productivity and impact that some technologies have. Unfortunately, more often than not, there is no dialogue between the parties concerned to mitigate the real impact produced in the territory. The lack of communication is likely to hinder the development of renewable sources such as mini-hydro, which in some countries are specifically promoted by environmental organizations.

Public authorities and professionals have an important role in exploiting the opportunities offered by the development of renewable energy sources: Local resource managers responsible for areas of energy, environment and socio-economics, have the opportunity to encourage the establishment of small installations of renewable energy sources through planning instruments, through the facilitation of the licensing procedures and the allocation of funds, and through their adherence to European or National projects and initiatives.

The first hydroelectric plant was built in 1880 in Northumberland, England, and the true revival of hydropower development was thanks to the invention of the electric generator. It was followed by the improvements in hydraulic turbines together with a rising demand of electricity in the early twentieth century. In 1920, hydroelectric power already generated a significant portion of the total electricity production.

The technology of the main facilities remained the same during most of the twentieth century with plants depending on a large reservoir of water contained by a dam, where the water flow is controlled and can be kept almost constant. Water is transported through penstocks that are controlled by turbines and valves to couple the flow of water with the demand of electricity. The water entering the turbine goes out through the drainage channels. The generators are located just above the turbine and connected through vertical trees.

In addition to the powerhouses located in dams, which depend on reservoirs of large amounts of water, there are some plants that rely on natural waterfalls when the flow is uniform, the so-called runoff river powerhouses, such as that of the Niagara Falls (at the border between the U.S.A. and Canada).

In the early nineties, the top hydroelectric power producers were Canada and the U.S.A. Canada obtains 60% of its electricity from hydropower. Worldwide, hydroelectricity accounts for approximately a quarter of the total electricity production, and its importance is growing. The countries in which this is the most important power source include Norway (99%), Zaire (97%) and Brazil (96%). The Itaipú plant, on the Parana River, is located between Brazil and Paraguay, was opened in 1982 and has the largest generating capacity in the world.

In the picture above you can see the Itaipú Dam (a joint project of Brazil and Paraguay on the Parana river) and its power plant, the largest in the world, which provides important energy resources for both countries and the region as a whole. With a height of 196 m and a length of 8 km, it has 14 landfills that act as artificial waterfalls. As a reference, the Grand Coulee Dam in the U.S.A. is

Picture 2: Itaipú Dam.
(Source: http://www.nanduti.com.py/noticias/images/99d4bf_Itaipu.jpg)

about 6,500 MW capacity and is among the largest ones in the world. Some countries have set up small power stations with generating capacities that range between 1 kW and 1 MW. In many regions of China, for example, these small dams are the main source of electricity. Other developing nations are using this system with good results.

Undoubtedly, the use of hydropower would not have been possible without the turbine, but this would have had a very limited use without the conversion of the mechanical energy of the turbine into electric power, which can be transported over long distances. This characteristic of electricity has increased the exploitation rate of hydroelectric energy. Before this, due to the scarce capacity of consumption within a very limited transportation distance, hydroelectric plants did not yield much power. Currently, without these limitations, the tendency is to make large reservoirs that determine the annual river regulation and regulatory deposits, located in appropriate places, with which daily or weekly control is achieved. In general terms, it aims for integral use of a river or an entire watershed (i.e., a river and all its tributaries), through the use of successive waterfalls, built in the most appropriate places (namely, those with greatest slopes, or those where the channel is narrow and high in which the construction of the dam will be more economical, etc.).

1.2. RESOURCES AND POTENTIAL

The gross or theoretical potential of a river is the total potential energy, at a given moment, of the total mass of water contained in the river. It is, therefore, a value that varies over time due to oscillations in river flows. The full description of the potential of a river would require knowledge of the temporal distribution of flow (data that are known for major rivers), being usually expressed as the total average energy available during the period of one year. The theoretical annual water potential of a geographic region can be calculated from the mass of annual rainfall in this region and its height above the sea level.

However, the notion of gross potential has only a scientific interest and is certainly not a factor directly used in practice; what really matters is the technically exploitable potential, which represents a necessarily reduced fraction of the overall potential. The review of this potential is influenced by various agents, not only natural (geological and geographical) but also economic. These factors can be broken down as follows:

- Losses of unavoidable runoffs
- Hydraulic, mechanical and electrical limited yields
- Flow oscillations that exceed the limits of the powerhouse
- Environmental flows and servitude flows required for other uses
- Inability to build power plants in some river sections due to technical or economic reasons

1.3. REGULATORY FRAMEWORK

1.3.1. Policies to support renewable energies

Given the importance that the use of renewable energies has at present, its development is supported by means of several policies. The following ones are key documents, which lay the foundations for achieving sustainable development at European, national and autonomic levels, emphasizing those measures that concern minihydro power plants.

Through the writing of the *Green Paper for a Community Strategy* **[EU Commission, 1996]**[1] by the EU Commission in 1997, the EU took the first step toward the diffusion of the use of renewable energies. To achieve this objective, an increase of the penetration of these energies in the market was intended. It would be obtained by doubling the contribution of renewables to the primary energy consumption of the EU before the year 2010. Renewables would contribute 12% of the gross domestic energy consumption at that date. This document disclosed the great minihydro power potential existing in Europe:

> *"Hydropower is one of the traditional forms of renewable energy and has already been exploited for a long period of time. Large-scale hydropower has been generally more economical than small-scale hydropower energy. Large water supplies have been widely exploited, but there are still small-scale water resources available in many regions of the EU (less than 10 MW per site)".*

The publication of the Green Paper led to a broad public discussion focused on the type and nature of the most urgent actions to be undertaken both at a communitarian level and at the level of the Member States. There were over 70 detailed responses, which came from EU institutions, agencies and the governments of the Member States, and from numerous companies and associations interested in renewable energy sources. All this contributed to the development of the White *Paper for a Community Strategy and Action Plan* for renewables [**European Commission, 1997]**[2]**.**

The so-called *White Paper* aims to define, in a more detailed way, those strategic and action plans needed to achieve the main targets of the *Green Paper*, namely, rising the contribution of renewables up to 12% of the total amount consumed. For the specific case of minihydro power, this book predicted an increase of 4,500 MW in installed

[1] **EU Commission.** *Energy for the Future: Renewable Sources of Energy. Green Paper for a Community Strategy*. COM (96) 576 final, 20 November 1996

[2] **European Commission.** *Energy for the Future: Renewable Sources of Energy, Green Paper for a Community Strategy and Action Plan*. COM (97) 599 final (26/11/1997)

power between 1995 and 2010. This implied reaching a total of 13,800 MW installed. This prediction was realistic, considering the number of projects approved so far and the low environmental impact of this type of power plants.

Directive 2001/77/CE [**Official Journal of the European Communities, 2000]**[3] of the European Parliament and of the Council lays the groundwork for a future Community framework for the promotion of electricity produced from renewable energy sources in the internal electricity market. This policy was oriented to provide renewables with an increasing importance such that by 2010, 12% of European energy would come from them, and such that the percentage of energy generated this way would be 22.1%. The Annex to this document shows the reference values for the national indicative targets of Member States regarding the share of electricity to be produced from renewable energy sources with respect to gross electricity consumption in 2010.

Another text published on March 2007 [**European Commission, 2007]**[4] established the legally-binding share of 20% as target for the year 2020. It also raised a new legislative framework for the development and utilization of renewable energy in the European Union.

The final document published by the European Parliament and the Council of the European Union Renewable Energy is Directive 2009/28/EC [**Official Journal of the European Communities, 2009]**[5], which repealed Directive 2001/77/EC. The global energy share coming from renewables proposed by this Directive amounts to 20% in the European Union. To achieve this goal, each country is assigned a percentage based on its amount of resources and level of development.

1.3.2. Regulation

1.3.2.1. European Union Directives

The existing EU Directives can be classified into two groups: energy directives and electricity directives.

ENERGY

- **Council Decision 25/4/2002**, CE Kyoto Protocol approval.
- **Directive 2003/96/EC**, energy taxation.
- **Directive 2006/32/EC**, end-use energy efficiency and energy services.

[3] **Directive 2001/77/CE**. *On the promotion of electricity produced from renewable energy sources in the internal electricity market.* Brussels. 2001
[4] **European Commission.** *Communication from the commission of the council and of the European Parliament Renewable Energy Road Map Renewable energies in the 21st century: building a more sustainable future*. Brussels. 2007
[5] **Directive 2009/28/CE** *Of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing* Directives 2001/77/EC *and* 2003/30/EC. 2009

- **Renewable Energy Directive 2009/28/EC,** on the promotion of the use of energy from renewable sources

ELECTRICITY

- **Directive 2009/72/CE**, common rules for the internal market in electricity (repealing 2003/54/CE).
- **Directive 2005/89/CE**, concerning measures to safeguard security of electricity supply and infrastructure investment.
- **Directive 2003/54/CE**, concerning common rules for the internal market in electricity and repealing Directive 96/92/EC – Statement made with regard to decommissioning and waste management activities.
- **Directive 96/92/CE**, concerning common rules for the internal market in electricity, repealed on July1, 2004.

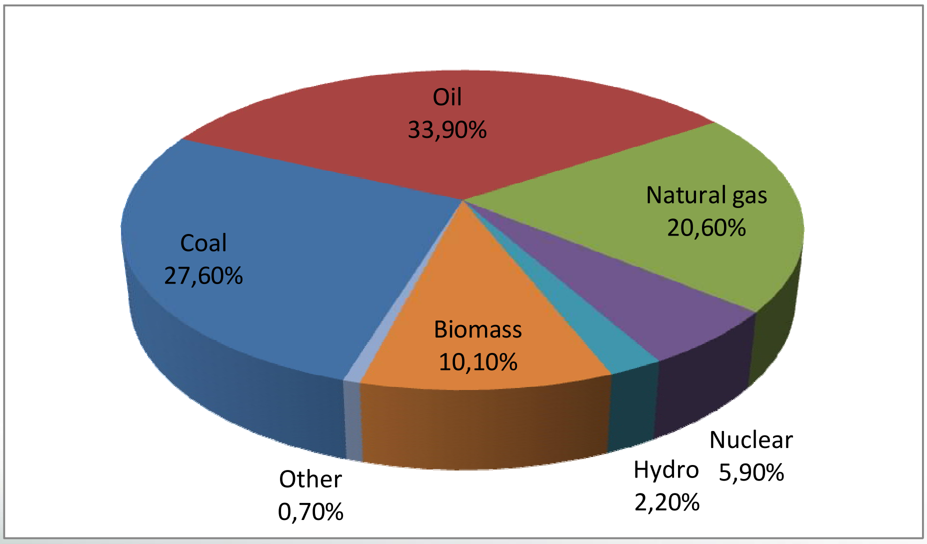
1.3.2.2. National Legislation

For this information please refer to the RuralRES website for your country and the particular training package in your language, and/or the deliverablesD3.2 of the RuralRES project combined potential and feasibility study report. These can be found at: http://ruralres.diphuelva.es/ and by clicking on the “Training” section.

1.4. CURRENT ENERGY SITUATION

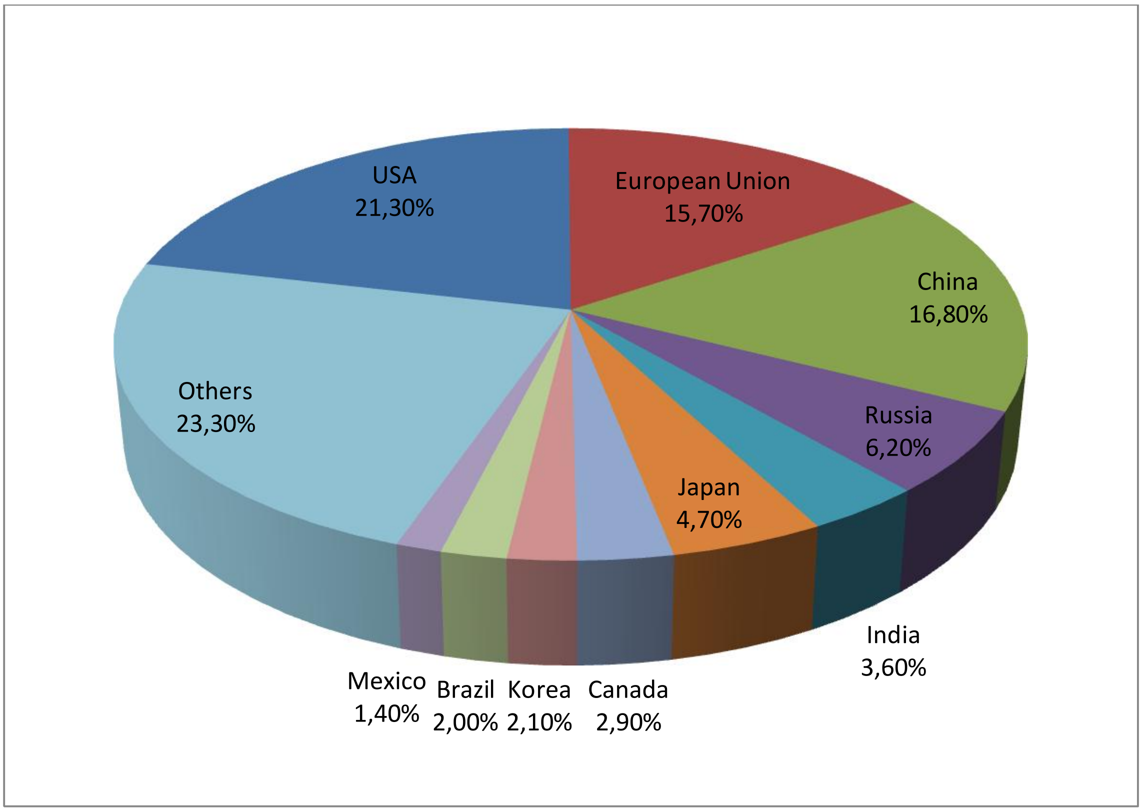
The current energy outlook is based on the following premises:

- Depletion of fossil fuels
- Social and geographic imbalances due to a centralized development model and to the geographical distribution of resources
- Increased energy consumption
- Environmental issues, such as acid rain, greenhouse effect and climate changes



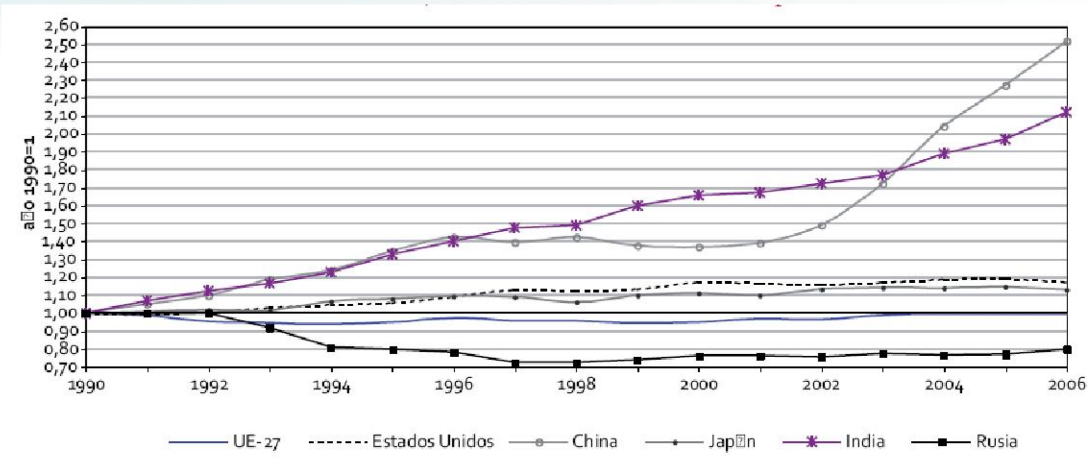
Picture 3: World energy consumption in 2007. Source: European Commission. BP

The figure above shows the primary energy consumption worldwide. As shown, oil represents the highest percentage of consumption. Oil consumption grew by 1.1% in 2007, a figure similar to the average increase over the past 10 years. In the OECD, consumption dropped by 0.9%, registering no growth since 2004. However, in emerging economies, oil consumption increases strongly. The case of China is particularly outstanding. There, the consumption grew by 4.1% in 2007 after figures of 6.7% in 2006, 2.6% in 2005, or the strong increase of 15.8% in 2004. The Asia-Pacific region already consumes 30% of world oil, compared to 28.7% from North America and 17.8% of the EU.



Picture 4: World energy consumption in 2007. Source: BP Statistical Review

Environmental problems are caused largely by the disproportionate increase in CO_2 emissions. Such emissions in 2006 were 33% higher than in 1990. Most of these emissions are derived from the generation of electricity: 35% of the total, compared to 28% in 1980. On the other hand, industry accounted for 17% of the emissions, compared to 26% in 1980.



Picture 5: CO_2 Emissions. Source: European Commission and OECD

1.5. MINIHYDRO POWER APPLICATIONS

The main application of minihydro power is mini-hydro generation; a 'mini' can be connected to the grid (in which case all the energy is transferred to it) or may be an isolated facility (the main function of which is to electrify a building).

Isolated mini-hydropower will provide electricity for constructions and homes such as huts, shelters or off-grid rural hotels to ensure their supply throughout the year.

Microturbines (low power turbines) are used in isolated places since these can take advantage of hydropower from rivers or streams supplying electricity to low power autonomous applications.

Some of the advantages of isolated hydropower are:

- *Continuous production of electricity or energy independence: for example, solar and wind energy are dependent on the weather*
- *Fuel cost savings: after the initial investment, these ensure a free lifetime power supply*
- *No noise or pollution*
- *No batteries are necessary to accumulate electricity*
- *Their power is enough to electrify a cabin or a mountain hut, providing them with enough energy for lighting, radio, television and even a small refrigerator.*
- *They can operate under different conditions (low height or low flow) if the appropriate turbine is placed in the right stream*
- *Installed turbines can generate both 230 V AC and 12/24 V DC*

- *If the flow is constant, it can work as a 230 V generator continuously, without any accumulator required. Thus, the energy yielded can be instantly consumed*

- *When the installation is connected to the grid, all the production generated is transferred to it. This will increase the percentage of renewable (and therefore clean) energies consumed.*

- *In this case, the distributor of the area buys all the electricity produced by the minihydro power plant at a fixed price.*

- *For specific industries (chemical, steel, paper, textiles, cement, etc.) with a high consumption of electricity, it may be useful to have a mini-hydropower, because all the electricity produced can be used in the manufacturing process.*

- *In these cases, the installation of a given industry can be interconnected with the grid. This would not only improve the electrical balance between the supply and the demand of the installation, but would also make possible to sell the energy that is not used during the hours in which a factory is not working.*

1.6. MINIHYDRO POWER PLANTS CLASSIFICATION

The classification of mini-hydro systems is a convention used to reflect different forms of operation.

Minihydro power plants are classified as follows:

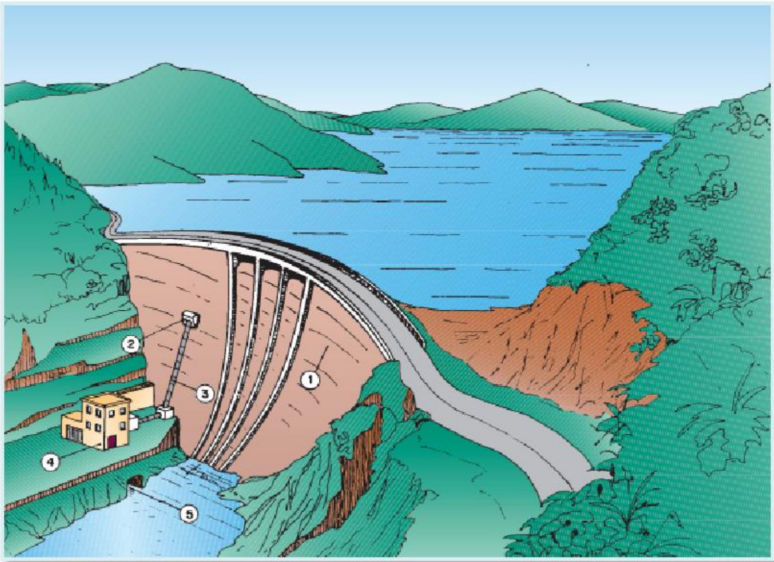
1. Run off River Powerhouses

Also called running water or flowing water. They are built in places where waterpower must be used in the instant it is available, to activate hydraulic turbines. They have virtually no reserves of water and, consequently, the flows which they use, vary. In the rainy seasons, these develop their maximum power, and pass the excess water flow. During the dry season, the power decreases as a function of the flow rate, reaching nearly zero in some rivers in summer. Its construction is done through dams on riverbeds, to maintain a constant drop in the flow of water. In these plants, the turbined water is captured from the riverbed through an intake, and then returned to the river at another point.

Picture 6: Run off river minihydro.

2. Powerhouses Located at the Base of a Dam

In the central reservoirs, an artificial dam is built, where water is collected. According to the needs, it can be transferred and used in the powerhouse. This kind of reservoir is currently achieved through a dam located in appropriate places in the river. The amount of regulation will be connected to the storage capacity of the reservoir.



Picture 7: Powerhouse located at the base of a dam (EVE)

3. Irrigation Channels

In these installations, the equipment is inserted in the same channel used for irrigation. It usually has reduced power due to the fact that its head is not high.

4. Drinking Water Systems

It is also possible to insert a hydroelectric plant into the drinking water network, existing or planned. A first approach should typically contemplate such distribution networks, irrigation and navigation channels as well as wastewater treatment stations. This type of installation takes advantage of the many pre-existing structures. This reduces the cost of the investment, the additional environmental impact is virtually zero, and the bureaucratic procedures for obtaining permits are simplified. Excellent examples of such installations are demonstrated in the Italian Good Practices Guide.

According to the **head** or level difference:

- *High-pressure small-hydropower plants:* Include those plants in which the head is over 200 meters high. The turbined flows are relatively small, 20 m^3/s per machine. Located in high mountain areas, these draw water from streams through very long pipelines. Pelton turbines are generally used as prime movers or, for heads of less height, slow Francis turbines.

- *Medium-pressure small-hydropower plants:* These have head heights between 20 and 200 m. They use flows of 200 m^3 per turbine. Francis, Kaplan and sometimes Pelton turbines for big heads are deployed here.

- *Low-pressure small-hydropower plants:* Their heads are lower than 20 m. Each machine uses a flow rate that could exceed 300 m^3/s. Superfast Francis

Chapter 2

TECHNOLOGY

2. TECHNOLOGY

2.1. STATE OF THE ART: MINIHYDRO POWER AND TURBINES

2.1.1. Hydropower plant concept

Minihydro power, defined by IUNDO (Industrial United Nations Development Organization), refers to hydropower plants below 10 MW. In the field of mini-hydropower, however, it is customary to use the following sub-classification, according to different operating modes and powers.

Micro-hydropower plants.
Mini-hydropower plants.
Small-hydropower plants.

There is no consensus among EU Member States on the definition of small-hydropower: some countries (like Portugal, Spain, Ireland, and now Greece and Belgium) accept 10 MW as the top limit for installed capacity. In Italy, the limit is fixed at 3 MW (plants with larger installed power should sell their electricity at lower prices) while in Sweden, the maximum power is 1.5 MW. In France, the limit has been recently established at 12 MW, not as an explicit limit for small-hydropower plants, but as the maximum value of installed power for which the grid has the obligation to buy electricity from renewable energy sources. In the UK, 20 MW is generally accepted as the threshold for small-hydropower plants. For the purposes of this text, any scheme with an installed capacity of 10 MW or less will be considered as small. [**ESHA,2007**][6]
Five Member States, the ESHA, the European Commission and the UNIPEDE (International Union of Producers and Distributors of Electricity) have accepted the figure of 10 MW.

	Micro (kW)	Mini (kW)	Small (MW)
USA	< 100	100 - 1000	1 - 30
Canada			<25
China	-	< 500	0.5 - 25
Russia	< 100	-	0.1 - 30
France			<12
Italy			<3
Spain			<10
India	< 100	101 - 1000	1 -15
Brazil	< 100	100 - 1000	1 - 30
Norway	< 100	100 - 1000	1 - 10
ESHA	< 100	< 1000	< 10
UNIPEDE	<0.5	<2	<10

Table 1: Small-hydropower plants classification

[6] ***ESHA*** *Guide on how to develop a small hydropower plant. Brussels. 2007 http://www.esha.be/index.php?id=39*

2.1.2. Historical Analysis

For millennia, man has used this source of energy to perform heavy duty tasks(in Mesopotamia, remains of giant water works from the year 3000 BC have been found) and there are references to bucket wheels used for irrigation in Egypt in the times of the Pharaohs (2000 BC).

Likewise, the Greeks used the water wheel (invented by Philo of Byzantium around the year 250 BC) to pump water or grind wheat. However, the possibility of using slaves and beasts of burden delayed its widespread use until the twelfth century. The Roman architect and engineer Vitruvius Pollio Marco described water wheels and their applications extensively in his book *De architectura*.

More recently, in the Middle Ages, the economic prosperity of some large cities built along rivers relied heavily in the use of hydropower, particularly in the use of mills. It is said that the mill of the bridge over the Rhine at Constance had three grain mills, a sawmill, a mill grinding workshop and a forge powered by a water wheel held by thirty-two piles and fed by a intake system with flow control. Both vertical and horizontal systems of water wheel were used in the Middle Ages and the Renaissance, not only in agriculture but also in mining, textile and wood industry as well as in transport.

In Europe, before the creation of the large existing electric network, there were more than ten thousand small hydraulic resources that operated sawmills, tanneries, blacksmith shops, pulp and paper factories, mechanical workshops, etc. Hydraulic machines had to be redesigned after the popularization of hydroelectric energy, which propitiated the construction of new workshops far from rivers.

The hydraulic machines used in these facilities were large and slow water wheels, able to transform hydraulic energy into mechanical by offering very high torques with reduced performances.

Hydropower was very important during the Industrial Revolution. It boosted textile and leather industries and mechanical engineering workshops in the early nineteenth century. Although steam engines had already been perfected, coal was scarce and the use of wood as fuel was considered unsatisfactory. Hydropower helped the growth of the new industrial cities created in Europe and America by that time, until the construction of canals in the mid-nineteenth century, which provided cheap coal.

Dams and canals were needed for the installation of successive waterwheels with slopes higher than five meters. The construction of large dams was not yet possible: the low flow of water during the summer and fall, coupled with frost in winter, forced to replace water wheels by steam engines when coal became available.

The invention of the water turbine in France in 1827 led to the development of modern hydropower. In the 1880's hydropower turbines were used for the first time to generate electricity on a large scale. The world's first reasonable scale hydroelectric plant was installed in Appleton, Wisconsin, in 1882, with a modest power (it was only able to feed 250 incandescent lamps). In Europe, turbines had replaced the water wheel almost completely by the end of the nineteenth century.

The conversion of hydropower into electrical energy, thus enabling the transmission of power through long distances, was a step forward in the use of this energy source. Higher yields were obtained thanks to the development of hydraulic turbines with improved profiles adapted to the utilization characteristics.

From the historical point of view, the hydraulic turbine has a rich and varied history [**National Rural Electric Cooperative Association,80**], [**Gulliver John S. et al, 91**][7], [**Fritz Jack J, 84**][8] and has been developed as a result of a natural process that has evolved from the water wheel. The use of the hydraulic turbine to generate electricity is a relatively recent activity. Much of its development occurred in France, a country that (unlike England) could not dip into the cheap and abundant coal sources that drove the industrial revolution in the eighteenth century. In the nineteenth-century, France found that its most abundant source of energy was water.

In 1826, the Societé de Encouragement por L'Industrie Nationale offered a prize of 6000 francs to anyone who could *"apply on a large scale and in a satisfactory manner, in factories and manufacturing facilities, turbines or water wheels with wheels curves Bellidor*". Bellidor was a hydraulic engineer and eighteenth-century military, which between 1737 and 1753 wrote a monumental four-volume work on water wheels. The water wheels that he described diverged from conventional ones in the sense that the former ones had a vertical axis of rotation and were locked into a long cylindrical chamber of a diameter of one meter. These wheels were fed by large quantities of water coming from a lock placed tangent to their chamber. The water came with a considerable rotation speed. This rotation, along with the weight of water above the wheel, was the driving force. The original wheel provided performances ranging from 15 to 20%.

The development of hydraulic turbines continued from 1750 to 1850. The classic horizontal axis wheel was improved by engineers such as John Smeaton (England, 1724-1792), who also played an important role in the development of windmills, and the French engineer J. V. Poncelet (1788-1867), who increased the performance of water wheels to averages ranging up to 60 and 70%. At the same time, many investigators were considering the use of jet turbines. The great Swiss mathematician, Leonhard Euler (1707-1783) investigated the theory of operation of these devices. In 1807, Mannoury of Ectot (1777-1822) introduced in France a practical application of the concept. His machines were built as radial outflow devices. The theoretical analyses of Burdin (1790-1893), French professor of mine engineering, greatly contributed to deepen into the understanding of the principles of operation of turbines

[7] ***National Rural Electric Cooperative Association.*** *Small Hydroelectric Powerplants National Rural Electric Cooperative Association. Massachusetts. 1980*

[8] ***Fritz Jack J.*** *Small and Mini Hydropower Systems. McGraw-Hill. New York. 1984*

and highlighted the main requirements for inlets and outlets free from collisions at minimum speeds, considered as a fundamental need for high efficiency. A disciple of Burdin, Foureyron Benoit was responsible for implementing the theory of his master. Their work led to the development of high-speed turbines with efficiencies above 80 percent. Foureyron's initial work was applied in several practical devices and he was given in 1983 the 6000 francs prize above mentioned. After nearly a century of development, Bellidor wheels had been officially improved.

Foureyron developed around 100 turbines in France and Europe during the rest of his life. Some turbines even reached the United States, the first one in 1843. Foureyron turbines were designed for different ranges of conditions: heads up to 114 meters and speeds up to 2300 rpm. Turbines were also designed for very small heads.
Despite the success of Foureyron turbines, they lacked flexibility and were effective only in a limited range of operating conditions. This problem was addressed by Hoyd and Borden (1804-1879). Their work evolved toward the concept of a motor inflow due to James B. Francis (1815-1912). The modern Francis turbine is the result of this line of development. In 1849, the first jet turbine was built and tested. Its design surpassed that of most previous forms in which the flow was directed under pressure in centripetal direction, so that any tendency of runaway was partially controlled by a reduction of the flow of water, which was obtained through an increase of the centrifugal force.

During the early development of the European industry between 1800 and 1850, energy requirements increased rapidly. These needs were mainly covered by coal steam engines. On the other hand, France, which had a higher hydroelectric potential, tried to cover its needs intensively by using wheels. However, these did not provide a lot of energy and could not use large heads. Therefore, France decided to develop faster and more efficient systems. The water turbine was rapidly developed in France and, by exploiting this new technology, the country soon became a leading nation in terms of industrial development. Following this, other European countries soon joined the new discovery and the Forneyron turbine evolved into the Francis turbine.

At the same time in which the Francis turbine was being developed, European engineers approached the idea of axial flow machines, which are represented by Kaplan propeller-type turbines. The Czechoslovakian Professor Victor Kaplan created and patented in 1920 a turbine in which the angle of the blades was automatically adjusted to the load, improving the propeller-type and the fixed-blades turbine.

As vertical Belidor wheels evolved in modern Kaplan or Francis reaction turbines, the development of traditional horizontal shaft waterwheels reached its climax with the introduction of the drive or action turbine. Pocelet laid the seeds of development in 1826 with his description of the criteria for an efficient waterwheel. These ideas were promoted by a group of Californian engineers in the late nineteenth century, one of whom was Lester A. Pelton (1829-1908) who in 1899 patented a turbine named after him.

Thus it can be argued that the relatively-high speed Francis and Kaplan turbines have their origins in vertical axis Belidor wheels, while Pelton wheels can be considered the direct evolution of the best known horizontal axis waterwheel.

During the twentieth century, Kaplan turbines suffered major adaptations, which resulted in the system of semi-regulated turbines, the S turbine and the bulb-type turbine. New types of turbines, such as turgo and crossflow, have also been introduced.

Small turbines are increasingly used throughout Europe and North America, the basic technology evolved more slowly. With the expansion and increasing capacity of transmission networks, power generation is concentrated in larger units that benefit from economies of scale. This led to a trend away from minihydroelectric plants between 1930 and 1970.

The oil crisis in 1973 created a new interest in the development of minihydro power resources, leading to a revival of the industry, with the addition of new manufacturers to the market, creating a booming industry, especially in Europe. The interest in the development of hydropower declined slightly again in the 1980's and early 1990’s due to low fuel prices and the subsequent use of other energies.

More recently, the liberalization of the electricity sector, oriented to meet the goals outlined in the Renewable Energy Plan, and the creation of powerstations under special regimes have contributed to the development of hydroelectric power generation and particularly to the recovery of old abandoned power plants.

2.2. MAIN ELEMENTS OF A MINIHYDRO POWER PLANT

A hydroelectric plant consists of channels and hydraulic components (pooling elements, water intake, penstock, return system, etc.) and electromechanical components (turbine, alternator, electrical panels, control systems, etc.).

The water from the supply systems is driven through channels to the forebay, which determines the level of flow depending on the useful head of the plant. From this point, water is channelled through turbines, penstocks, and mobile blades (rotors) that determine its rotation. The spinning rotor shaft is connected to a generator (alternator), the water leaving the turbine is returned thought the return system to its original course.

More specifically, a hydroelectric plant consists of the following components:

- **Water intake systems** whose configuration depends on the type of watercourse intercepted and the topography of the area.
- **Filtration systems** for the removal of suspend solids in the water; their type, including their degree of automation, depends on the flow and the entity arising from the solids carried by water flow.
- **Conduction systems** formed by channels or penstocks depending on the topography and the installation typology, regardless the head.
- Powerhouse, containing **the electromechanical equipment**, the turbine alternators, transformers, electric meters, electrical panels and control systems.
- **Returning water systems** that lead water to its main course.

The power that could be obtained from an installation, with the same head and flow, depends on the performance of the hydroelectric installation, which is the result, at least, of the product of the following five partial performances:

- Hydraulic performance
- Volumetric efficiency of the turbine
- Mechanical efficiency of the turbine-generator
- Electrical performance of the generator
- Transformer performance.

A minihydroelectric plant is made up of various components and equipments that can be classified into three groups

- Civil works
- Electromechanical equipment
- Auxiliary equipment.

2.2.1. Civil Works

Civil engineering encompasses those works and facilities necessary to derive, drive and restore water turbines, and to house and protect the electromechanical equipment. This includes the following elements:

- Weirs and dams
- Intake structures
- Bypass channel
- Forebay
- Penstock
- Powerhouse
- Suction tube

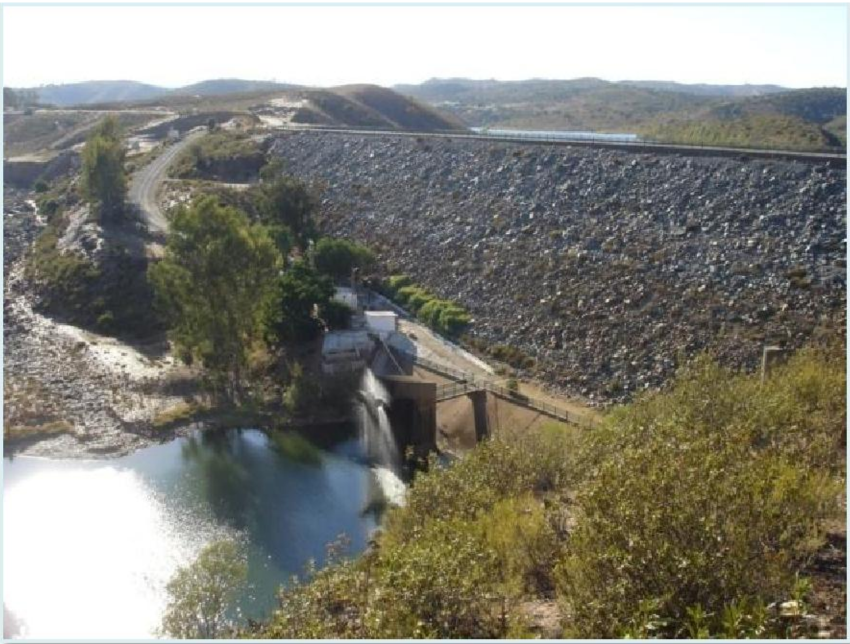
2.2.1.1. Weirs and Dams

These are constructed in the course of the river, crossing it, to pool and derive water to the flow intake that leads to the powerstation.

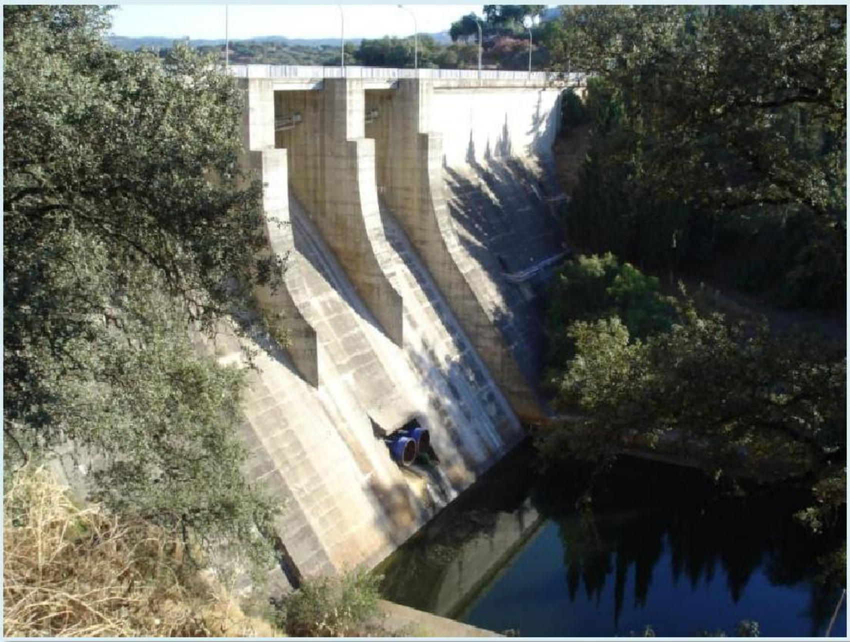
In weirs there is water retention with no significant variation in water level.

In the dams, the wall is built to raise the free surface watercourse creating a reservoir.

The material used in their construction classifies dams. So, we find earth and concrete dams.

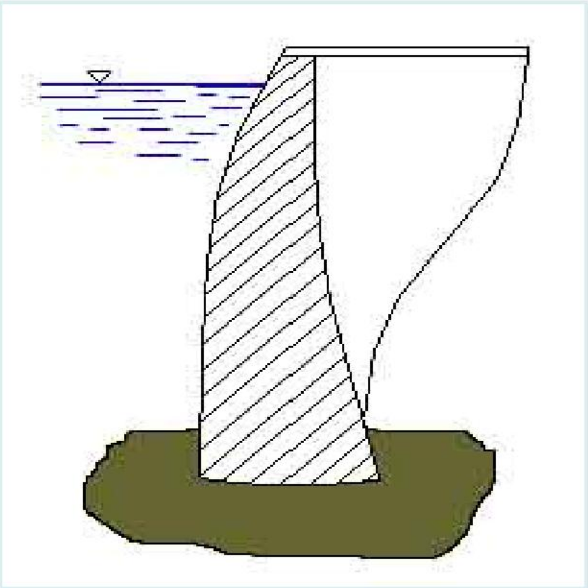


Picture 8: Earth dam. Agrio Dam. Seville.

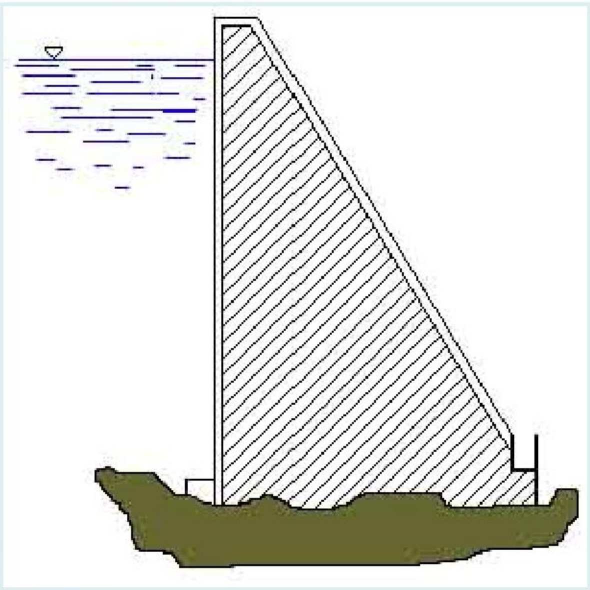


Picture 9: Concrete dam. Retortillo Dam. Seville.

Concrete dams are the most widely used and divided into:



Gravity dams: As shown in the figure, these have an appropriate weight to counteract the overturning force produced by water.



Vault dams: require less material than gravity dams, and are often used in narrow gorges. The pressure created by water is totally transmitted to the slopes thanks to the effect of the arc.

According to the purpose for which they are built, dams are divided into two groups:

1. Diversion dam

Diversion dams are also called landfill. These are arranged, preferably, to raise the level contributing to the head. Their side effect is the fact that they may store water when it is required by consumption needs and not for energy production. Generally, water flows over these through spillways.

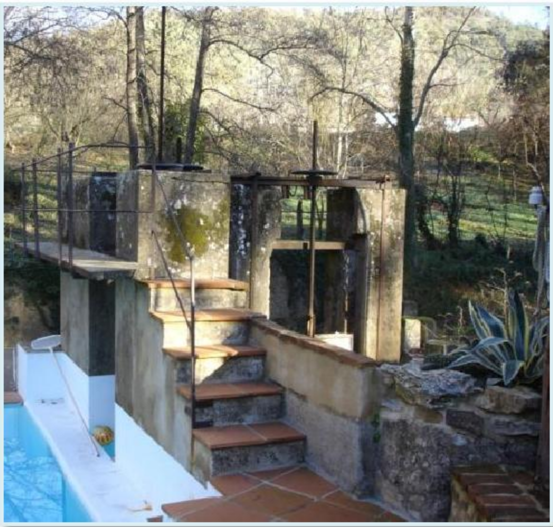
2. Reservoir dam

By contrast, the main objective of ***reservoir dams*** is the pooling of water to regulate the flow of the river, being their side effect the raising of the level of water which is necessary to produce the water head. Generally, water is not allowed to flow over these. It usually flows through side buildings, called surface spillways used to return the exceeding water to the river downstream from the dam, once the reservoir is filled.

In fact, dams almost always have a mixed function. These will be classified as diversion or reservoir dams depending on whether the objective intended is an increase in the level of water for its diversion or a constant flow of water.

2.2.1.2. Intake structures

Intakes gather the drained water and take it to the machines by means of channels or pipes. In the front wall of the dam, in contact with the water reservoir, there are intakes from which several lines directed to the pipes start. These intakes and the few gates that regulate the amount of water reaching the turbines have metal trash racks that prevent objects such as logs, branches, etc. from obstructing or damaging the blades.



Picture 10: Intake. Santa Teresa Small-hydropower plant. La Nava. Huelva

2.2.1.3. Bypass channel

The bypass channel is used to convey water from the diversion dam to the turbines of the plant. When the head is higher than 15 m, water should be driven to the powerhouse by means of penstocks. For this purpose, a pressure chamber becomes necessary at the point in which the channel ends and the pipe begins. In many cases, the diversion channel is eliminated and the penstock is directly connected to the intakes of the dam.

In general, and to prevent leakage in the field, bypass channels are lined with masonry, mass or reinforced concrete. Channels can be done in clearing, that is to say, by excavating the ground, a solution that is the safest for the purposes of stability and for the reduction of leaks. These can also be done in the hillside, or excavating the hillside on one side and having an embankment on the other. There is a third in fill configuration, with masonry on both sides, a solution which is rarely used because it is the most expensive and because, to have the necessary stability conditions, it should be reinforced by buttresses foundations, etc.

Picture 11: Bypass Channel. Huelva

A tunnel channel is sometimes used. This should not be confused with the gallery of pressure, in which the water pipe is under pressure. In channel tunnels, water flows thanks to the inclination of the surface, without hydraulic load.

Once the beginning and end of the channel are known, it is clear that the best solution is a straight line in which the loss of head can be reduced to the minimum. But this ideal solution is rarely possible since the unevenness of the surface must be overcome, and the construction of expensive channels must be avoided. Normally, the channel is adapted to a slope that equals the one chosen for it, and its sides are conveniently moved so that, through clearing, little earthworks become necessary.

2.2.1.4. Forebay

This is a reservoir at the end of the bypass channel that splits the penstock. This chamber is necessary to prevent any air from entering the penstock, which causes overloads.

Picture 12. Forebay. Santa Teresa Small-hydropower plant. La Nava Huelva

2.2.1.5. Penstock

In mini-hydropower plants, pressure pipes or penstocks are intended to convey water from the pressure chamber to the turbine when, because of the height of the head, such a provision is needed to transform the potential energy that water holds in the pressure chamber into potential pressure energy, which is found next to the turbine and at the end of the penstock.

Picture 13. Penstock. Cerrada de Utrero SHP. Jaén.

Regarding the materials used to construct the pipeline, the most commonly used are:

- Steel
- Reinforced polyester pipes with Fibreglass
- PVC
- Polyethylene

2.2.1.5.1. Steel pipes

Steel is the material used in fluid installations that reaches the highest mechanical strength. It is also characterized by a lower coefficient of linear expansion, which consequently diminishes stress and strain problems.

Its melting point is much higher than that of other materials and, so, it can maintain its mechanical properties at temperatures well above those that others would stand.

Steel properties	
Relative density (g/cm^3)	7.85
Tensile stress (MPa)	500
Break elongation (%)	22
Brinell hardness	140
Thermal expansion coefficient (°C^{-1})	11.6 x 10^{-6}
Melting point (°C)	1540

Table 2: Steel properties.

2.2.1.5.2. Reinforced polyester pipes with Fibreglass

The main properties and advantages of polyester reinforced with Fibreglass are:

- Corrosion resistance
- Long life
- It does not need coatings, cathodic protection or other means of protection against corrosion
- Low maintenance costs
- Hydraulic properties remain constant over time
- High mechanical strength
- Resistance to high pressures
- Abrasion resistance
- A lower wave speed than that obtained with pipes of other materials, resulting in cost savings in the design of parts aimed at reducing the effects of possible water hammers.
- Smooth inner surface
- Low friction losses represent less pumping energy requirements and lower operational costs

- Less accumulation of mud helps to reduce cleaning cost
- Lightweight (25% of the weight of cast materials and 10% of the weight of concrete)
- Lower cost of transport
- Lower installation cost
- It does not require expensive handling equipment
- Precision joints
- Fewer joints reduce installation time
- A greater number of lines per vehicle reduces transportation costs
- Tight connection designed to eliminate infiltration and exfiltrations
- A variety of accessories
- A full range of accessories made to complement the GRP pipe
- Possibility of making accessories with specific and particular designs according to different cases.
- Connections with other materials
- There are reliable solutions to join GRP pipes with pipes of other materials for renovations, repairs or replacement of sections in poor condition. Mechanical joints or flanged connections are the most used ones

2.2.1.5.3. PVC Pipes

Polyvinyl chloride is obtained through the polymerization of vinyl chloride.
For the manufacturing of PVC resin, there are different processes, namely:

- Emulsion polymerization.
- Suspension polymerization.
- Bulk polymerization.

Depending on pressure, temperature, additives, etc. and depending too on the manufacturing process, different PVC polymers can be obtained. These variations are derived from the differences in their having longer or shorter chains (higher or lower average molecular weight), different dispersions of molecular weights in relation to mean values, or different particle structures (shape, porosity, etc.).

A number of factors including bulk density, particle size, volatile content and ash will define PVC resins. Particularly relevant is the viscosity index and the K value, which expresses the length of chains.

With increasing molecular weight, the K value increases too, and the mechanical properties are consequently improved. On the down side, this makes forgery more difficult.

Tubes that are manufactured by extrusion do not require as high a flow of plastic material as accessories (elbows, tees, etc.) do, which are manufactured by injection. So, at making pipes, the characteristic required is for PVC to have good mechanical strength and, therefore, a high K value.

To improve the features that polymers have, resins are mixed with a number of additives such as:

- Stabilizers and UV filters to optimize the life of the material
- Lubricant to facilitate manufacturing processes
- Impact modifiers to improve the mechanical strength
- Pigments to give a final colour to the product

The physical properties of rigid polyvinyl chloride (without plasticisers) are shown in the table below:

RIGID PVC PROPERTIES	
MECHANICAL	
Relative density (g/cm^3)	1.38 -1.4
Tensile stress (kg/cm^2)	500 – 550
Break elongation (%)	80
Modulus of elasticity	30,000 - 40,000
Shore hardness	80 – 85
THERMAL	
Specific heat (cal/g °C)	0.25
Thermal expansion coefficient (°C^{-1})	7 x 10^{-5}
Thermal conductivity (kcal/m h °C)	0.13
Vicat Temperature (°C)	80
ELECTRICAL	
Dielectric strength (kv/mm)	30 – 40
Resistivity (Ω cm)	5 x 10^{-15}

Table 3: PVC properties (Source: [Mayol Mallorqui, 1997])

This material has advantages and disadvantages that must be taken into account according to the purpose for which it is used:

Advantages:

The main advantage of this material is that the raw materials from which it is produced are low cost: 56.7% of the PVC molecules are formed by chlorine. This means that neither the price nor the availability of polymer materials depend entirely from oil.

The following positive characteristics can also be taken into consideration:

- Low cost
- High mechanical strength
- Good chemical resistance
- Low water absorption
- High impact resistance
- Notable features of the tubes
- Good weatherability
- Non-combustible
- Good stiffness
- Excellent electrical properties
- Good surface appearance

Disadvantages:

- Difficulties in processing its instability
- Low thermal deflection
- Poor resistance to deformation under static load at high temperatures

2.2.1.5.4. PE Pipes

Polyethylene is a polymer of ethylene, which is obtained by the polymerization of ethylene. Since this entails the polymerization of an olefin, polyethylene belongs to the family of polyolefin.

According to the manufacturing process, crystallinity varies, corresponding the lowest rates to low density polyethylene (LDPE). This is due to the high degree of branching of the molecules.
Commercially, three types of polyethylene are manufactured according to its density:

- Low density polyethylene (LDPE) of 0.925 g/cm^3
- Medium Density Polyethylene (MDPE) from 0.930 to 0.945 g/cm^3
- High Density Polyethylene (HDPE) of 0.955 g/cm^3

In the case of the penstock, HDPE is used. Its properties are shown in the following table:

HIGH DENSITY POLYETHYLENE PROPERTIES	
MECHANICAL	
Relative density (g/cm^3)	0.955
Tensile stress (kg/cm^2)	220 – 250
Break elongation (%)	500 – 800
Modulus of elasticity	9,000
THERMAL	
Specific heat (cal/g °C)	0.55
Thermal expansion coefficient (°C^{-1})	20×10^{-5}
Thermal conductivity (kcal/m h °C)	0.37
ELECTRICAL	
Dielectric strength (kv/mm)	40
Resistivity (Ω cm)	10^{18}

Table 4: High-density polyethylene properties (Source: [Mayol Mallorqui, 1997])

The main advantages and disadvantages of this material are listed below:

Advantages

- Good to prevent the passage of moisture, useful in many packaging applications
- Good stiffness, which is suitable for some structural applications
- Applications support loads when the plastic deformation is handled correctly in the intended use
- Relative chemical inertness
- Good thermal stability in the range of -40 to 316 °C

Disadvantages

- Relatively high rates of gas transfer
- HDPE has a strong tendency to deformation, the load carrying capacity decreases rapidly with increasing temperature
- Some chemicals can cause premature failure of the PE due to breakdown by weathering

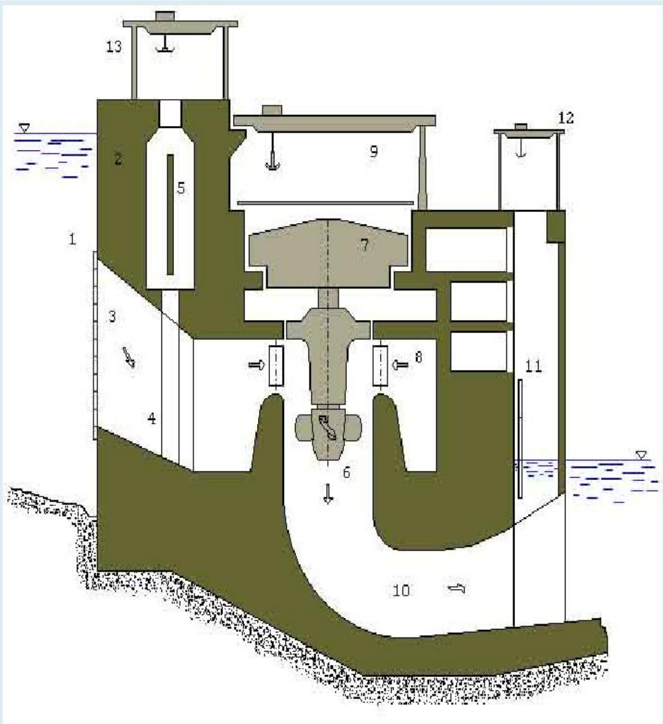
- High temperatures can cause degradation of HDPE; this can be avoided by adding an antioxidant to the resin

2.2.1.6. Powerhouse

In a powerhouse of a small-hydropower plant, electrical groups are mounted to produce electric power and auxiliary machinery is necessary for its operation. Understandably, the arrangements for the powerhouse are extremely diverse and depend on the circumstances and conditions of hydroelectric power.

An example is shown in the figure below, in which there is a section of the building of a central with high flow and low head. The dam is included in its very structure to the powerhouse.

The picture shows that this arrangement is compact and that the water inlet to the turbine is made through a chamber built in the dam. The entry and exit gates are used without water to stop the machinery in case of repair or disassembly.



1. Reservoir
2. Dam
3. Water input to the machines (intake), with trash rack
4. Water inlet pipe
5. Gate
6. Hydraulic turbine
7. Alternator
8. Guide for regulating the turbine inlet
9. Bridge crane of machinery room
10. Water outlet (suction line)
11. Flat out gates
12. Crane to maneuver departure gates.
13. Crane to maneuver entrance gates.

2.2.1.6.1. *Turbine house*

The space of a plant devoted to the accommodation of hydraulic turbines is called turbine house.

The turbine house can be open, if it is communicated with the outside part of the plant, or closed.

The open house configuration is only used in heads of small height (up to 15 m) in which is possible to drive water from the diversion channel directly to the distributor of the turbine; in these cases, it sometimes also functions as pressure chamber. In open houses, vertical and horizontal axis turbines are used. In the first case, the house is under the engine room and the upstream level is also under its floor. In the second case, the camera is adjacent to the engine room and the level of water is above the floor of the engine room.

Open houses use vertical axis turbines when the head is small (less than 6 m) and there is not enough height to install horizontal axis turbines (the floor would be very close to the level of the water below and might be flooded); or in shore break, as horizontal axis turbines need more floor space and, therefore, in the mentioned case, their installation is more expensive. In other cases, it is preferable to use horizontal axis turbines.

Currently, the most common arrangement is that of close house turbines, through which the water coming from the penstock flows. This configuration allows the pipe to be placed in the most convenient location, the effects of foundation since the pressure pipe, which connects the pressure chamber with the turbines, can be given the most suitable route and length.

Turbines are installed in vertical sealed chambers when the floor of the machinery room is not free from danger of flooding during the highest floods.

The cost of the work when the plant is to be installed on a steep hillside may also influence the choice, as the vertical arrangement of the turbines is more economical than the horizontal one due to the fact that the installation of vertical axis turbines requires less floor space and, subsequently, less earthworks. Generally, almost all modern facilities with Francis or Kaplan turbines adopt the vertical axis turbines with an electric generator directly coupled to them.

This is a summary of the advantages and disadvantages in both vertical and horizontal configurations:

- ***Vertical axis turbines***

Advantages:

- Possibility to install generators above the level of water, to the most convenient height, irrespective of the size of the head
- Low-priced installation

Disadvantages:

- If the turbine has to operate a generator of horizontal axis, transmission gears are needed
- The vertical loads for the machines have to be born by a support bearing

- ***Horizontal axis turbines:***

Advantages:

- Normal support bearings
- Horizontal axis direct transmission
- Easier to watch because all elements are at the same height

Disadvantages:

- Installation with more surface area, therefore more expensive
- The water has to re-enter in the drainage channel through one or more pipe elbows at 90 degrees; therefore, higher losses

2.2.1.7. Suction tube

The suction tube acts as a link between the turbine and the drain and to exploit further the gap between both. It is constructed of concrete or steel plate and must have a variable section for a maximum recovery of the kinetic energy of water at the outlet of the turbine runner. In this chapter, we have seen different models of vacuum tubes.

In Pelton turbines, the existing energy recovery to the discharge of the wheel is not important and, moreover, between the centre of the wheel and the drain water level there is a distance representing a very small proportion of the total height head. But in other types of turbine (Francis, propeller and Kaplan), the output speed of the runner is high and the performance with free download would be very low. As a consequence, the recovery of the download speed becomes necessary.

The pipe should be as straight as possible, but when this installation is not feasible, pipes bend slightly, draining horizontally, giving a larger output to the horizontal rather than to the vertical light, and they are splayed to decrease gradually residual velocity.

Picture 14: Suction Tube (Source: Saltos del Pirineo SL)

2.2.1.8. Drainage channel

The drainage channel collects the water leaving the turbine to return it back to the river at the appropriate point. After leaving the turbines, water maintains a high velocity and, therefore, enough eroding power. To prevent it, the mouth of water turbines should be carefully coated.

In low heads at which little slope should be lost, the drain must be short. In high heads, and especially in those in which water carries little or no solid material, the drainage channel may be longer.

2.2.2. Electromechanical Equipment

The following equipment is considered paramount:

- Turbine shutters
- Turbine
- Generator
- Regulatory elements
- Transformer
- Switchgear and switchboards
- Power line interconnection

2.2.2.1. Shutter valves

Shutter elements, generally called valves, are used to open and close the passage of water through the penstocks. According to the job they are intended to, these may be:
1.- Switching elements whose mission is to shut off the water toward the turbines, when necessary.
2.- Security elements, which should seal the tube, not only in the case in which the flow exceeds the quantities normally absorbed by the turbine, but also in runaway cases. These valves are equipped, almost always, with automatic closing devices, which come into action when water speed exceeds a maximum value set beforehand.

Switching bodies are often provided with a device for remote closing. The valve actuation may be triggered from any place, although most frequently it is made from a central distribution box in which the current acts on a magnet or small engines that, in turn, act on the main controller of the valve, by means of counters. In addition, there should be the manual closing control near the valve. On the other hand, remote opening of the valve is almost never necessary, so that remote control devices are more often than not used for closure only.

In the hydroelectric facilities there are many types of shutters that also perform very different functions. We will study only the most common ones:

1.- Gate valves
2.- Butterfly valves
3.- Ball valves

Choosing the most appropriate type depends on the size, shape of the section to be filled, the pressure, the need for regulating partial opening, etc.

1.- Gate valves, as their name suggests, are operated as a gate, i.e., by vertical movement of a sliding board through a track. Gate valves are used in open channels, to empty the reservoir bottom, etc.

2.- Butterfly valves are used especially as emergency and safety devices at the start of penstocks of hydropower plants. In mid-height heads, these act as shutoff elements before turbines. Small butterfly valves are driven manually: either by a wheel or by counterweight.
3.- Ball valves have as main drawback the fact that their closure is not fast, which can be critical in emergencies. These are used as isolation and security devices and their operation, as in previous cases, can be manual or activated through a servomotor.

2.2.2.2. Turbines

These machines are able to transform hydraulic energy into mechanical energy in their output shaft. Their coupling to a generator through a shaft finally permits the generation of electricity.

These consist of:

- a fixed **distributor** with the mechanical function of directing and regulating the flow driven to the runner and the hydraulic function of transforming the potential energy of water into kinetic energy.

- a moving part, **runner,** set in motion by the water exiting the distributor, which has the function of communicating mechanical energy to the axis to which it is mounted.

2.2.2.3. Generators

These machines transform, in their terminals, the mechanical rotation energy of turbines into electricity. These can be of two types: synchronous and asynchronous.

Synchronous generators are typically used in grid-connected power plants with more than 1,000 KVA, or small power plants operating in islands (not connected to the grid).

Asynchronous generators, however, must always be connected to the electricity grid, out of which they take the energy needed to produce their magnetization. These are usually used in power plants with less than 500 KVA, always grid-connected.

For power plants between 500 and 2000 VA, the choice of synchronous or asynchronous generators depends on economic concerns, on the operation system, and the technical conditions required by the electrical company.

2.2.2.4. Regulatory elements

These are the ones that govern the moving components of turbines. They can be divided into hydraulic and electronic.

Their mission is to adapt turbines to the existing circumstances at any given time (flow, electricity demand, etc.) so that it is possible to work with the best energetic efficiency in every circumstance.

2.2.2.5. Plant transformers

These machines are designed to convert an input voltage into a different output. The purpose of the transformer is to increase the power generation voltage to minimize transmission losses through the line.

2.2.2.6. Electrical panels

Are usually installed inside the plant and made up of various electrical components for regulation, control, protection and measurement.

2.2.2.7. Transmission powerlines

The voltage obtained is equal to or lower than 20kV. With transformers, it is raised to the proper voltage for transport. In the distribution park, the plant is connected to the grid. Transmission powerlines carry out this transport.

Most plants are interconnected through the transmission system; therefore, they must be synchronized so that their energy inputs are compatible.

2.2.3. Auxiliary equipment

The following equipment is also necessary for the proper functioning of a plant. Among the most common devices we find:

- Gates
- Trash racks and cleaning devices
- Cranes to move machinery
- Fire-extinction equipment
- Lighting
- Flow meter
- Spillways

2.2.3.1. Gates

Gates are used to close water pipes (channels - pipelines) and to regulate the flow of water in these pipes. In hydroelectric plants, gates are located, as we have seen, in the water intakes, at the bottom outlets, in diversion channels, etc. The gates used in all listed sites display the same construction features. It must be born in mind that those gates under great pressure (as in water intakes), will require a more robust building than those others that stand smaller pressures (as in open diversion channels).

Picture 15. Gates. Santa Teresa small-hydropower plant. La Nava. Huelva

In hydroelectric plants, it is frequent to close the water passage openings through rectangular panels that rest on the bottom, above a threshold of stone, wood and iron, which on their sides are supported by vertical slots. These tops are made of wood or laminated steel structures and the set is called a sliding gate. These offer the higher isolation rates. They are more economical for low pressures and moderate sizes, but require more effort in their movement than other types of gates. Because of this last reason, they are not used for large sizes and pressures, as the volume and the cost of their drive mechanisms would be very big. Big gates are arranged on a mobile board, rolling devices that help to reduce the effort required to drive the gate.

2.2.3.1.1. Rising of the gates

Rising a gate requires an effort that must exceed the weight of the gate and the friction caused by hydraulic pressure. The weight of rolling and segment gates is greater than the friction caused by hydraulic pressure. As a consequence, its dead weight is sufficient to close it. In other cases, a drive must also be displayed.

Only small gates can be operated manually. To do this, a lathe with a shaft made of wood or steel is used, driven by two cranks and often fitted with gears. Sometimes an elevator or a vertical spindle screw is used.

For heavier gates, multiple devices are used:

- Racks with one or more wheels; the crank radius is 35 to 40 cm and the axis of rotation is located approximately at 1 m from the ground of the gateway. If the width of the gate is greater than 1.5 m, it uses two zippers and motor effort is applied to the centre of an axis on which the wheels of both gates are mounted
- Rack drive gear and worm.
- Horizontal lathe spindle.

2.2.3.2. Spillways

The spillways are vital elements of the dam that have the mission of releasing the pooled water without its passing through the engine room. These are found on the main wall of the dam and can be bottom or surface-type.

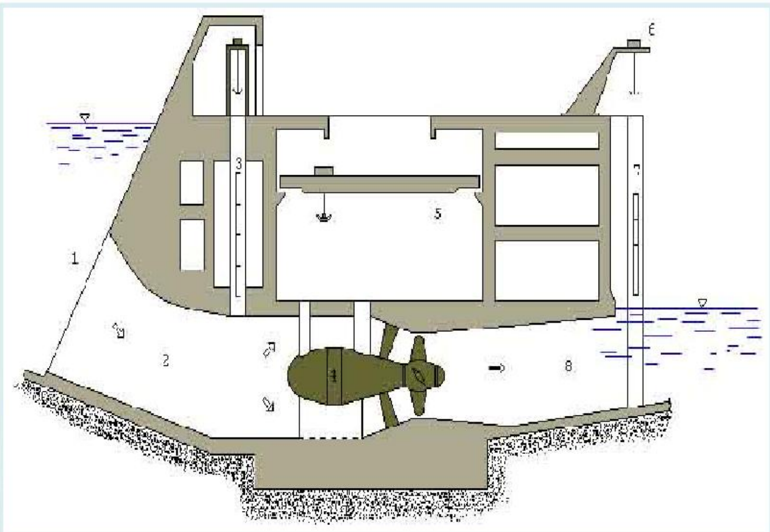
The mission of the spillway is to release, if necessary, large quantities of water or meet irrigation needs. To avoid the damage that water may cause after falling, spillways are designed so that most of the liquid is lost in a basin that is located at the foot of the dam, the so-called buffer. To get the water out through the spillway there are large, steel-made gates that can be opened or closed at will, depending on the situation.

2.2.4. Hydropower plant configurations

There are several configurations, which include:

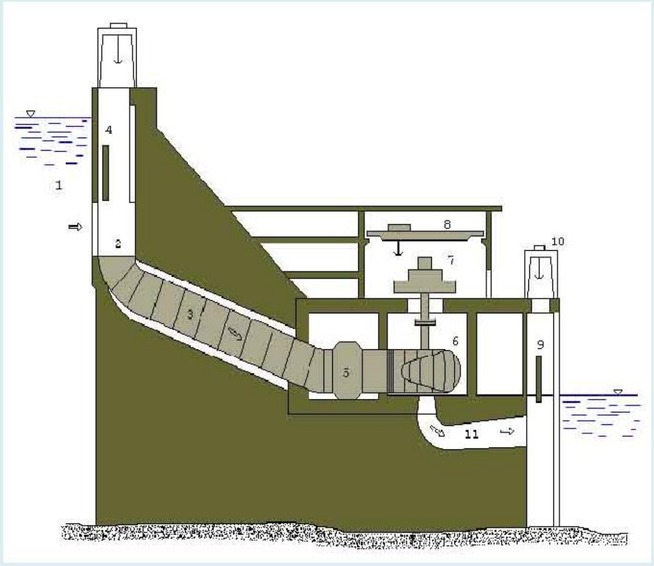
Bulb. The following figure shows the image of a low head plant with high flow and with bulb generators that are totally submerged

1. Reservoir
2. Water inlet pipe
3. Gate
4. Bulb assembly with turbine and generator
5. Crane of the machinery room
6. Gate crane
7. Gate
8. Outtake



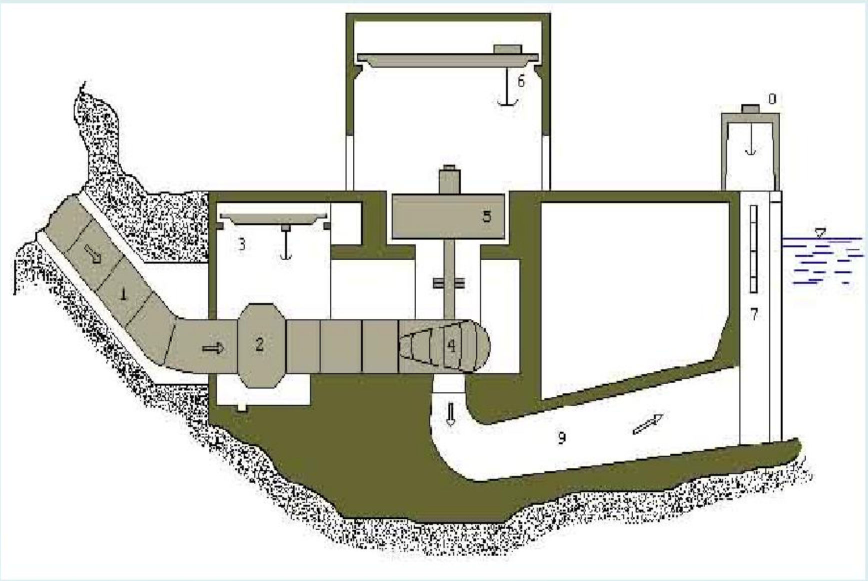
The following figure shows the scheme for medium flow and medium head, with the machinery room at the foot of the dam. Water enters through the intakes performed on the dam and is carried to the turbines through metal conduits embedded in the dam.

1. Reservoir
2. Water intake
3. Metal conduit embedded in the dam
4. Gates
5. Water inlet valve to turbine
6. Turbine
7. Alternator
8. Central bridge crane
9. Gate
10. Crane
11. Outtake



Another configuration is included in the figure below for a plant with high pressure and low flow. This type of machinery room is built away from the dam. The water comes through a pipe under pressure from the outlet, usually away from the plant, and on the way there is usually a surge tank. The high water pressure that occurs in these cases requires a valve to regulate water hammers.

1. Penstock
2. Closing control valve
3. Valves room crane
4. Turbine
5. Alternator
6. Machinery room crane
7. Hoisted exit gates
8. Exit gates crane
9. Outtake. Suction tube



2.3. TURBINES

Turbines are mechanical devices that convert hydraulic energy into mechanical energy through rotation on their axis. These can be classified according to several criteria:

2.3.1. Hydraulic turbines classification

The potential energy of water is converted into energy in the turbine engine, according to two fundamentally different mechanisms:

In the first one, potential energy is converted into kinetic energy by a high velocity stream, which is propelled against a few buckets, fixed on the periphery of a disc. This type of turbine is known as ***impulse turbine***. Since water, after crashing against the cups, falls down with little energy left, the main role of the casing in this sort of turbine is to avoid splashing.

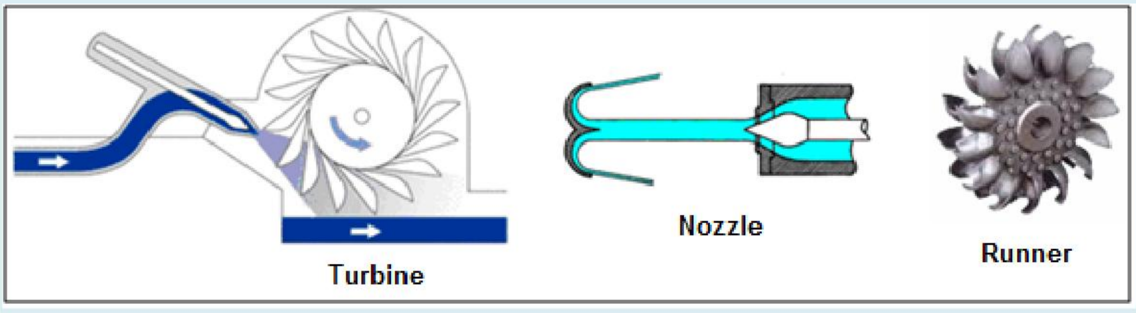
In the second one, the pressure of water acts directly on the blades of the runner, decreasing in value as it progresses through its course. This type of turbine is known as ***reaction turbine***. In this case, runners are completely submerged and suffer the pressure of water. Thus the casing of this sort of turbine must be resistant.

2.3.1.1. Impulse Turbines

- ***Pelton turbines***

They are impulse turbines in which the nozzle or nozzles (a vertical axis turbine can host up to six nozzles, with one or two impellers) convert the energy of the pressure of water into kinetic energy. Each nozzle produces a stream whose flow is regulated by a needle valve. They are usually equipped with a deflector whose role is to divert the stream injected to avoid possible water hammers. They are used in heads between 40 and 1200 m.

The jet axis is always located in the meridian plane of the runner. The water leaves the buckets against which it is injected at a very low speed. Consequently, the casing of these turbines does not have to resist any pressure.



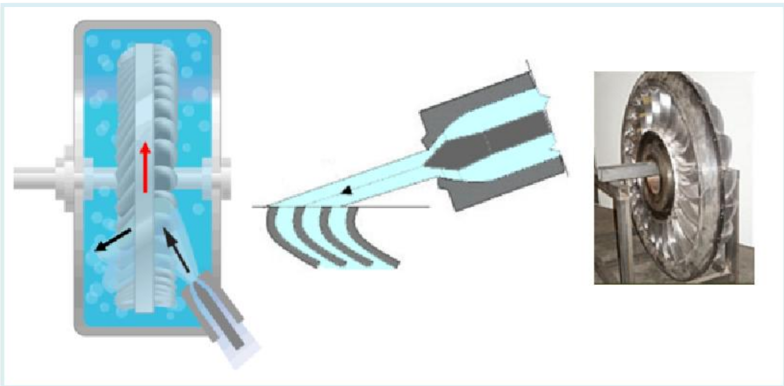
Picture 16: Pelton turbine

The needle valve, with a longitudinal displacement controlled by means of hydraulic oil, allows the regulation of the flow and the sealing of the nozzle.

The deflector, in turn, prevents water hammers and turbine runaways during scheduled or emergency shutdowns.

The runner is a circular solid piece, made of cast steel usually equipped at its periphery with a set of buckets, called blades, on which the running water impinges.

- ***Turgo Turbines***

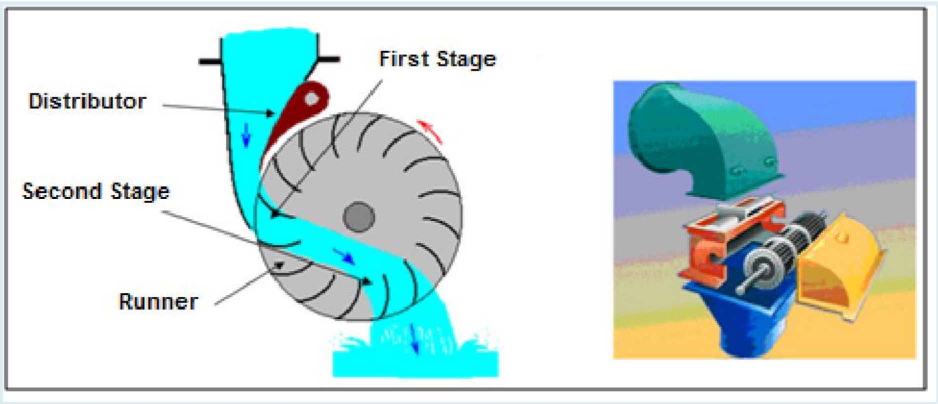


Picture 17: Turgo turbine

Turgo turbines can work on heads with heights ranging from 15 to 300 m. These are similar to Pelton turbines in the fact that both are impulse turbines, and differ from them in the arrangement and shape of their blades. The jet impinges at an angle of 20° on the runner, entering from one side of the disk and exiting through the other (see picture 17). In Turgo turbines, the stream impacts simultaneously on several blades, as in steam turbines. Thanks to their smaller diameter, higher angular speeds are obtained at the same rates of peripheral speed. This facilitates their direct connection to the generator and, by eliminating the gearbox, it also reduces the price of the equipment and increases its reliability.

- ***Crossflow turbines***

This model of turbine is also known as Michell-Banki (after its inventors) and as Ossberger, the company that has been manufacturing them for more than 50 years. They are used in a wide range of flow rates (from 20 l/sec to 10 m^3/sec) and heads (from 1 to 200 m). Their maximum performance is less than 87%, but it remains almost constant when the flow drops to 16% of the nominal flow, and have a technical minimum below 10% of the design flow.



Picture 18: Crossflow turbine.

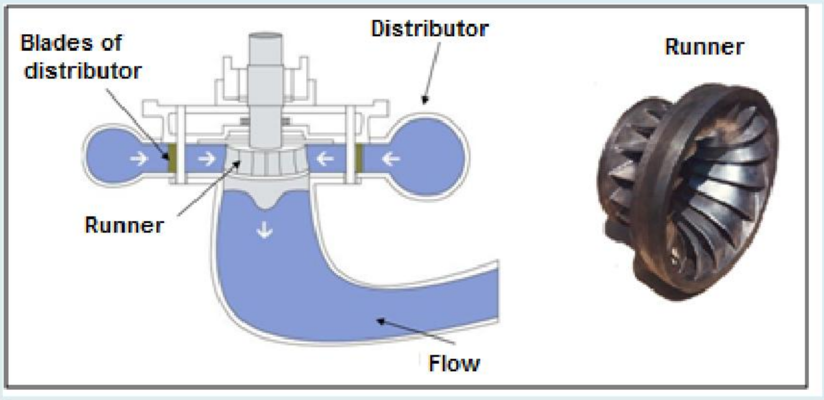
The water enters the turbine through a distributor, and passes through the first stage runner blades, which operate almost completely submerged (even with a degree of reaction). After going through this first stage, the flow changes its direction in the centre of the runner and crosses again in a second stage. This change of direction is not easy and leads to a series of shocks that are the cause of their low performance rating.

Their runner consists of two or more parallel discs between which several curved plates are mounted. These plates act as blades. This sort of runner is suitable for handcrafting in developing countries.

2.3.1.2. Reaction Turbines

- ***Francis turbines***

They are reaction turbines with radial flow widely used in heads of average height, equipped with a distributor of adjustable blades and a runner of fixed blades.



Picture 19: Francis turbine

The admission of fast Francis turbines is radial and their outlet axial. In these turbines water is channelled as in penstocks, going from the fixed distributor to the moving runner without any contact with the atmosphere.

Francis turbines may have ***open flume*** (usually for low altitude heads) or ***spiral flume***. The casing of spiral flume turbines is built, depending on their size, of reinforced concrete, welded steel or cast iron. In this type of turbine, blades are made of cast aluminium and bronze if they are small. If runners are big, blades are made of stainless steel and are welded to the hub and the rim in molten steel.

In reaction turbines, the water at the outlet of the runner passes through a suction tube, a diffuser, before reaching the discharge channel. The mission of this device is to recover part of the kinetic energy contained in the water leaving the runner at high speed.

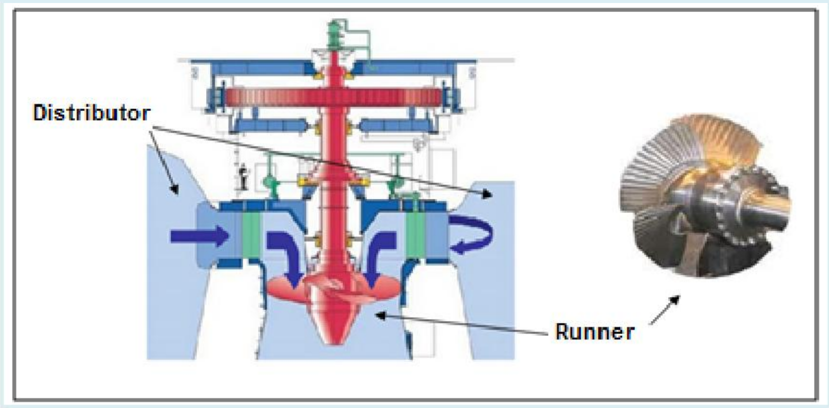
To reduce the rate at which water reaches the discharge channel (the kinetic loss is proportional to the square of the speed), the output section of the diffuser takes a conical configuration. Its role is particularly critical in high specific speed runners. In these, water comes out of the runner at a particularly high speed. In horizontal axis turbines, it is important for the body of the turbine to be anchored with concrete to prevent them from operational limitations derived from vibration.

Francis turbines may be installed to cover flow rates ranging from 0.150 m^3/s to 40 m^3/s and heads from 2 to 250 m.

Their operating range is acceptable, starting at 40% of the capacity of the turbine.

- ***Kaplan and Propeller turbines***

They are reaction turbines with axial flow. The blades of runners in Kaplan turbines are always adjustable, while distributors can be fixed or adjustable. If both are adjustable, it is a true Kaplan turbine; if only the blades of the runner are adjustable, it is a semi-Kaplan.



Picture 20: Kaplan turbine

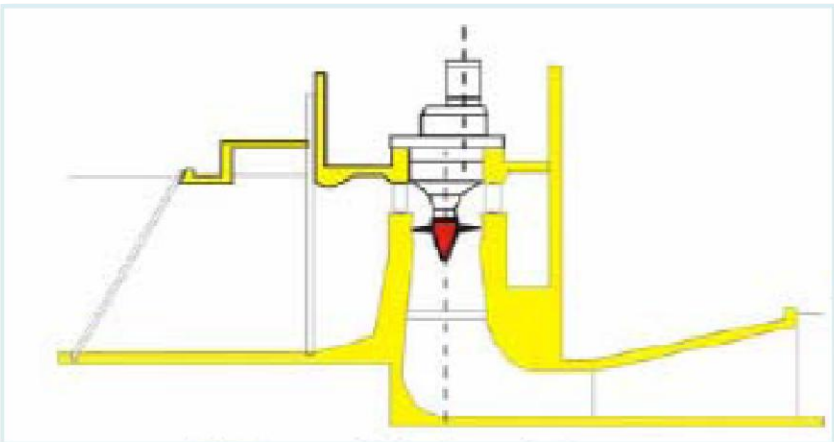
Kaplan turbines have radial admission and semi-Kaplan may be radial or axial. Propeller turbines are characterized by the fact that both the blades of the runner and of the distributor are fixed and, consequently, only used when the flow and the head are practically constant.

Bulb turbines are a derivation of the former ones in which water passes axially through the fixed blades and in which the generator and the gearbox (if any) are contained in a waterproof housing, bulb-shaped, submerged in water.

Kaplan turbines have different configurations, according to their flow (radial or axial), their closure system (gate, distributor or siphon) and the type of leverage (parallel gears, forwarding angle, planetary gears).

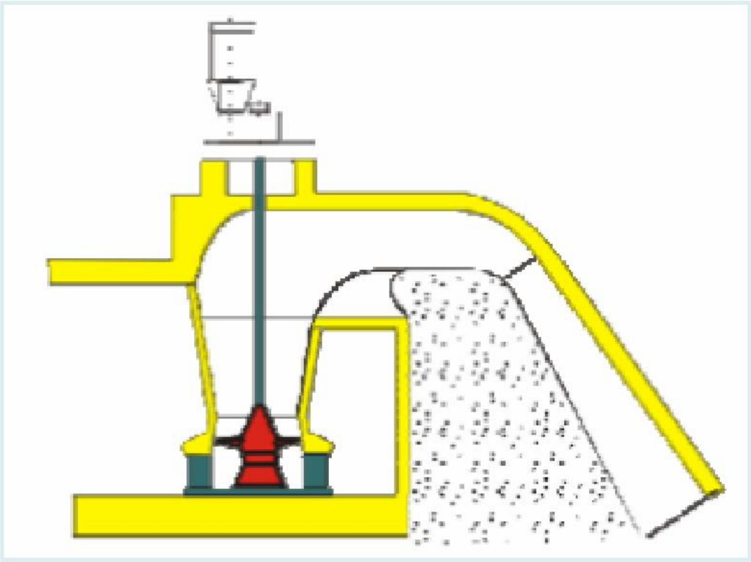
The different types of configurations are:

- Kaplan or semi-Kaplan parallel vertical radial gate.
- Semi-Kaplan vertical radial parallel siphon.



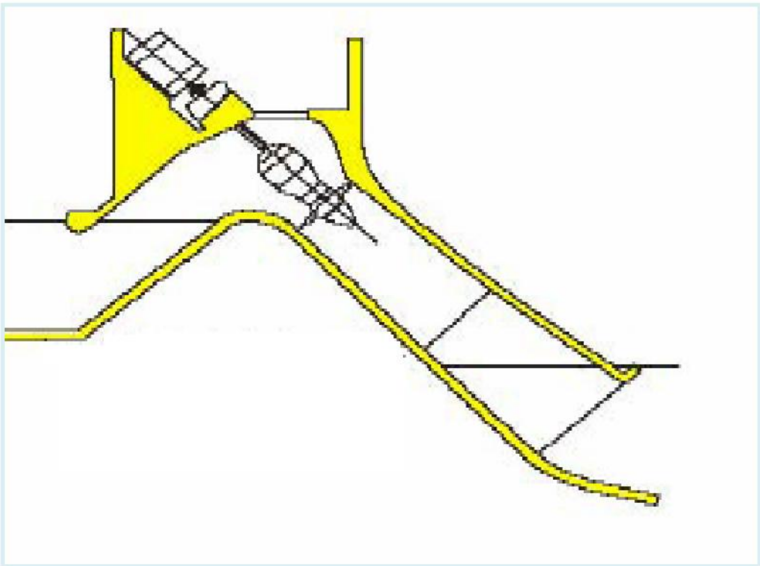
Picture 21: Kaplan or Semi-Kaplan vertical

- Semi-Kaplan reverse radial parallel siphon.



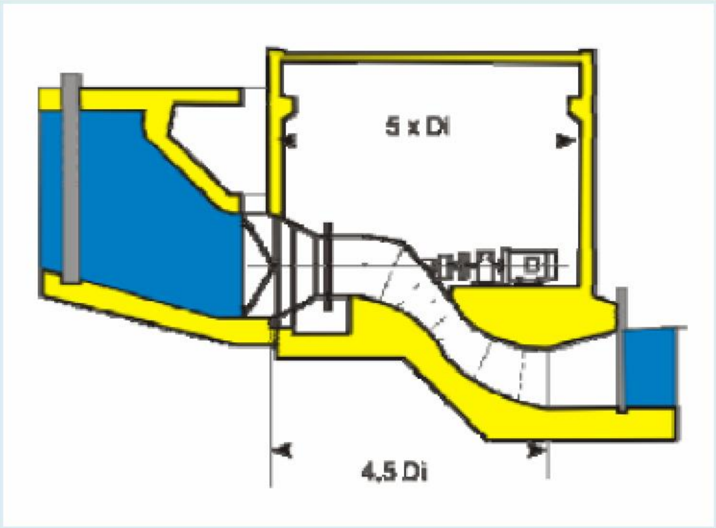
Picture 22: Semi-Kaplan reverse radial parallel siphon.

- Semi-Kaplan tilted axial siphon. Epicyclical siphon.



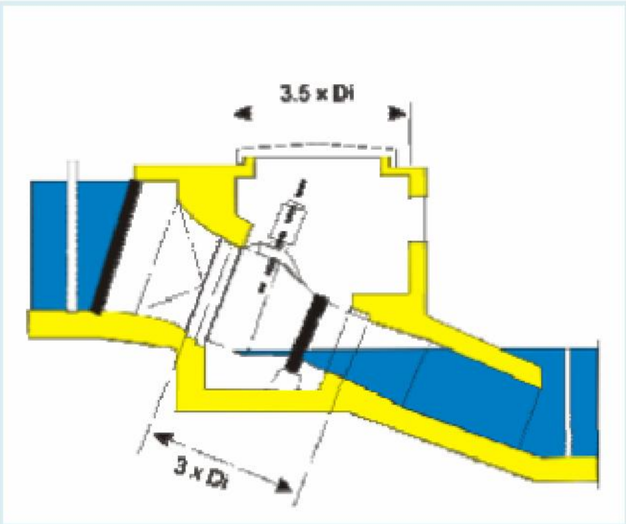
Picture 23: Semi-Kaplan vertical Epicyclic siphon

- S-Kaplan before axial parallel distributor.
- Inverted-S-Kaplan axial parallel distributor.



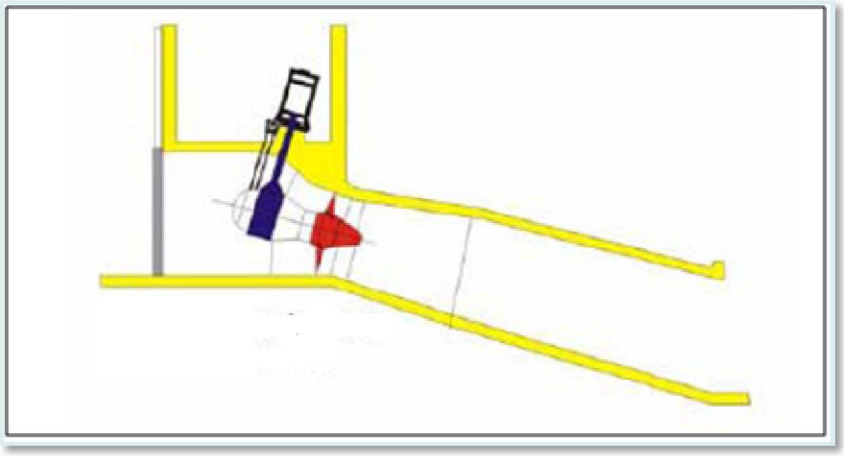
Picture 24: Inverted-S-Kaplan

- Kaplan with 90° axial forward tapered gate.



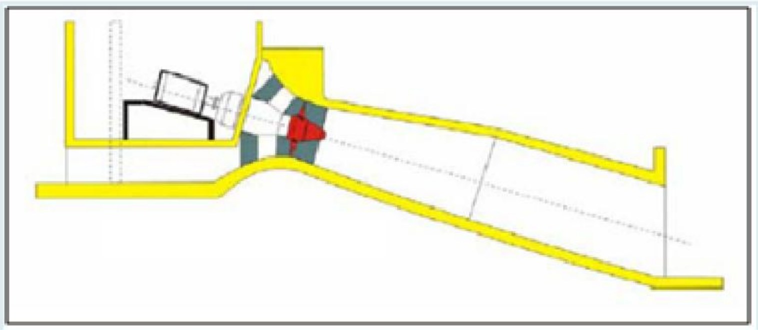
Picture 25: Kaplan with 90º axial forward tapered gate

- Semi-Kaplan with 90° axial forward tapered gate.



Picture 26: Semi-Kaplan with 90º axial forward tapered gate

- Semi-Kaplan pit-axial epicyclical gate.



Picture 27: Kaplan pit-axial epicyclical gate

Siphon closures are reliable, inexpensive and avoid turbine runaway, but they are very noisy too. The ideal solution is a totally or partially underground powerhouse which is only possible with an S-configuration, with a 90° axial forward tapered gate turbine or with well turbines. The second solution allows the use of a 1,500 rpm generator, standard, cheap and not too bulky, with a two-stage gearbox in which the relatively high speed of the axis facilitates the design of the bevel gear. The solution in S is being widely used but has one considerable disadvantage: the turbine shaft has to pass through the outlet pipe (or inlet pipe if the S is inverted) with subsequent losses. A recent study has proved that in a 4 m head with a nominal flow of 24 m3/sec, the 90° configuration yields between 3% and 5% higher performances than the S-configuration. Furthermore, in the former, both excavation and concrete volumes are much lower.

The main advantage of the well configuration is that its main mechanical elements are easily accessible. This facilitates inspection and maintenance procedures, particularly as regards turbines, gearboxes and generators assembly. By having a higher specific discharge (30% more than the vertical axis Kaplan) this turbine is smaller and, likewise, the civil works it requires are smaller.

Since the technical minimum flow is 20% for double regulated turbines and 40% for minimum flow turbines, as long as the minimum flow is below 40%, the double regulated turbine is the best choice.

As turbines can only work with flows between the nominal and the technical rates, a possible solution is to use several small power units instead of a single one, in order to adapt the number of functioning units to the flow available at a given time. This way, all the units (but one) will be working at full load, yielding a significantly higher overall performance. The use of multiple turbines reduces the weight and size of each one and makes transportation and assembly easier. The rotation speed of a turbine is inversely proportional to its diameter. Thus by using several smaller units, the input torque to the gearbox decreases. This will reduce its size too. It will also diminish the ratio of kilos of turbine per cubic meter of flow, but will increase the ratio of equipment cost per cubic meter.

When the number of turbines increases, the diameter of runners decreases. This entails a decrease in the length of the resistive elements of the powerhouse and, therefore, a reduction in their thickness too. In addition, when installing identical devices, the same construction formworks can be used and this will reduce the cost of civil works.

2.3.2. Turbine characteristics

2.3.2.1. Turbine performance

The turbine performance guaranteed by manufacturers is based on the "International code for the field acceptance tests of hydraulic turbines" (IEC Publication-41) or, where applicable, on the "International code for model acceptance tests" (IEC publication-193). Performance is defined as the ratio between the mechanical power transmitted to the turbine axis and the hydraulic power corresponding to nominal flow and nominal head.

It should be noted that in impulse turbines (Pelton and Turgo), the height of the head is measured with respect to the point in which water impacts. To prevent the runner from being submerged during floods, this will always be above the level of water in the discharge channel. As a consequence, there will be a loss of height with respect to reaction turbines, in which the head is measured with respect to the level of water.

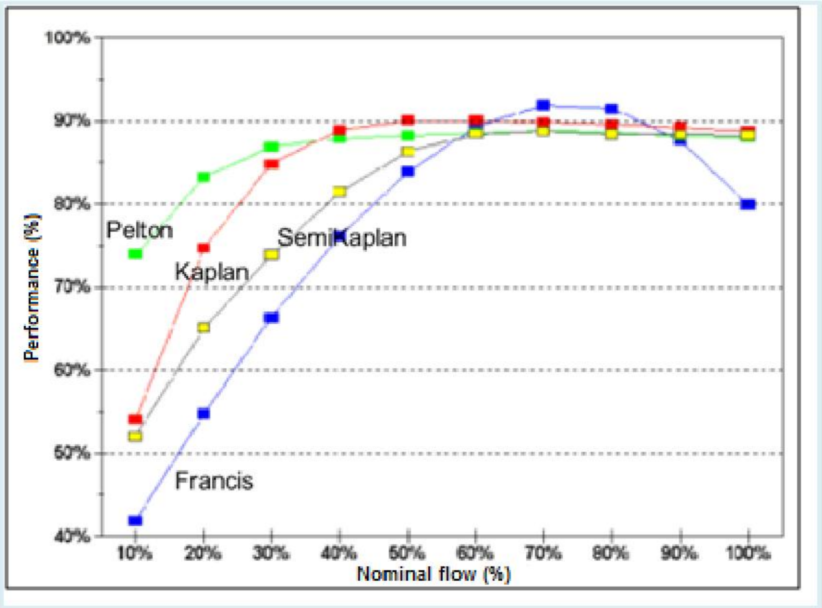
Given the losses that take place in reaction turbines, their runners only use useful heights (Hu), below the values of net head (Hn). These losses are essentially friction losses that occur in the spiral, the directors and the impeller blades, and especially in the suction tube or diffuser. The mission of the diffuser is to recover the largest possible percentage of the loss of kinetic energy corresponding to the rate at which water leaves the runner, and its function is especially critical in high specific speed runners, in which these losses could reach 50% of the head (a figure which is reduced to only 3% or 4% in slow Francis turbines). The water column, which drives the turbine, equals the net head minus the kinetic energy dissipated in the tube, measured by the expression Ve2/2g (where Ve is the average speed at the end of the suction pipe). For this reason, in order to reduce the average speed at the end of the tube, it takes a conic shape in its final increasing the area of the outlet cross section leading to a conical profile. However, if you want to avoid the vein of water off the walls, the taper angle cannot exceed 7 degrees. A well-designed diffuser will install the turbine above the chute without losing practically head height.

Suction tubes may be of different shapes: straight, conic, bent etc. An elbow must follow the suction pipe in horizontal axis Francis turbines. The most extended one is the straight conical diffuser used in vertical configurations. Efficiency decreases if conicity surpasses 7°. To reduce the speed at the end of a pipe with little conicity, pipes must be very long and, consequently, expensive. This is the reason why diffusers often display conicities close to 15°. The water at the outlet of the turbine has certain rotational motion. Within certain limits, this motion improves the performance of the diffuser but can also lead to pressure variations and instability if limits are surpassed.

For all these reasons, the behaviour of the diffuser is so important that it is advisable to have it supplied (or at least designed) by the manufacturer. At the moment, there is no code to define the head height when calculating the performance of a crossflow turbine. So, we must be cautious when comparing solutions that involve turbines of this type. In any case, if the height of the head is measured with the same criteria as in Pelton turbines, their performance rarely exceeds 84%.

MAJOR LOSSES
Friction of water in the distributor
Losses in the rotor caused by the shock of entry and by the sudden change in the speed of the streaks that exit the distributor and collide with the edges of the impeller blades
Friction of water in the suction tube
Distance between the distributor and the rotor, through which some of the water escapes
Passive resistance in the bearings etc.

Table 5: Turbines losses



Picture 28: Turbines performance curves

The figure above shows the performance curves according to the flow for different types of turbine. To calculate the overall performance of the turbo-generator group, multiply the performance of the turbine by that of the gearbox (if any) and the generator. The turbine is designed to work with nominal flow for which, in general, the performance is maximum. As the flow moves away from that value, either up or down, performance goes down, until the flow is below the minimum technical and can no longer function.

Double regulated Kaplan turbines display acceptable performance rates departing from 20% of their nominal flow. Semi-Kaplan turbines only work effectively from 40% of the nominal flow and Francis spiral single camera from 50%. Below 40%, a Francis turbine (depending on its design and the conditions in which it is installed) may experience vibrations. These are likely to make its operating conditions unstable and originate shutdown.

Crossflow turbines have, for the nominal flow, a significantly lower performance than Pelton, Francis and Kaplan turbines. Nevertheless, crossflow turbines can work with this or a similar efficiency levels in a much wider range of flows.

2.3.3. Turbine selection

Depending on the head and available flow, different types of turbines can be installed.

- PELTON: when the head is high and the flow low
- FRANCIS: for mean values of head and flow
- KAPLAN: when the head is small and the flow is big

2.3.3.1. First criterion

The type, geometry and dimensions of the turbine are constrained mainly by the following criteria:

- Net head
- Flow duration ranges
- Rotational speed
- Cavitation problems
- Runaway speed
- Cost

2.3.3.1.1. Head height

In reaction turbines, the gross head is the vertical distance measured from the level of the water surface and the discharge channel. In impulse turbines it is the distance between the water surface and the axis of the pipes. Knowing the gross head, the losses of cargo along the route must be extracted to calculate the net. The following table specifies for each type of turbine, the range of head values in net with which these can operate. Note that there are obvious overlaps, so that for a given height, several types can be used.

Type of turbine	Head (m)
Kaplan and spiral	2 < H < 20
Francis	10 < H < 350
Pelton	50 < H < 1300
Michell-Banki	3 < H < 200
Turgo	50 < H < 250

Table 6: Turbine and head

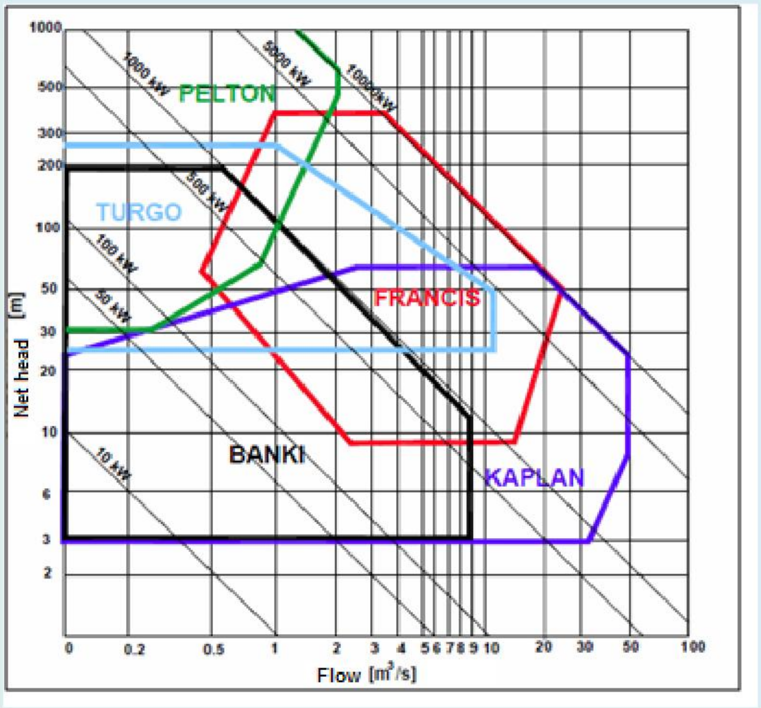
The problem is particularly relevant in the case of low-rise land use. To be profitable, they need large volumes of water. These are cases of heads from 2 to 5 m and flow rates between 10 and 100 m3/s. These use turbines with a rotor diameter of 1.6 m and 3.2 m coupled to an asynchronous generator through a gearbox. The hydraulic lines have dimensions far beyond those required in heads of medium and high elevations. They require major civil works with costs that exceed the cost of turbo-generators.

To reduce the overall cost (civil works and equipment), and in particular to reduce the volume of civil engineering, a number of classic configurations has been devised. All of them make use of one of the two types of turbines used for such heads, semi-Kaplan and Kaplan. The selection criteria are well known:

- Flow range
- Head height
- Type of earth
- Environmental criteria (mainly visual and sound impact)
- Labor cost

2.3.3.1.2. Flow

An isolated flow value has no significance. What matters is the flow regime preferably represented by the flow duration curve (FDC) obtained from the gauging station or from hydrological studies prior to the selection of the turbine. Not all the flows represented in a FDC can be used to produce electricity. First, the environmental flow that has to travel throughout the year must be removed. Second, each type of turbine can only work with flow rates ranging from nominal (in which there is maximum performance) and technical minimum (below which, it is not stable). The flow and the height of the head define a point in the plane that meets the operational ranges of each type of turbine. Any turbine casing that falls within that section may be used in the exploitation in question. The final choice will be the result of an iterative process that balances the annual energy production, the cost of acquisition and maintenance, and reliability. The figure below has been developed by integrating data from several European manufacturers, and displays the operational envelope of the most common types of turbine. The boundaries are not precise, vary from manufacturer to manufacturer, depending on the technology used, and therefore have a purely indicative meaning.



Picture 29: Diagram for choosing the turbine
(Source: ESHA, Guide on how to develop a minihydro power plant)

2.3.3.1.3. Specific speed

The specific speed is an excellent criterion for selection, undoubtedly more accurate than the conventional and well-known operational ranges just mentioned. In a hydraulic turbine, its specific speed stands for the speed at which an exactly homologous turbine would work (i.e., the same type of construction but with smaller size), developing a power of 1 HP, under a head of 1 m), which is given by the expression:

$$n_m = \frac{\sqrt{P_p}}{H_p^{5/4}} n_p \Rightarrow n_{sp} = \frac{\sqrt{P}}{H^{5/4}} n$$

KIND OF TURBINE ACORDING TO THE SPEED		
Specific Speed (rpm)	**Kind of turbine**	**Metres**
Until 18	Pelton 1 nozzle	Until 800
From 18 to 25	Pelton 1 nozzle	From 800 to 400
From 26 to 35	Pelton 1 nozzle	From 400 to 100
From 26 to 35	Pelton 2 nozzle	From 800 to 400
From 36 to 50	Pelton 2 nozzle	From 400 to 100
From 21 to 72	Pelton 4 nozzle	From 400 to 100
From 55 to 70	Francis very low speed Spiral flume	From 400 to 200
From 70 to 120	Francis low speed Spiral flume	From 200 to 100

From 120 to 200	Francis medium speed Spiral flume	From 100 to 50
From 200 to 300	Francis high speed Close flume	From 50 to 25
From 300 to 450	Francis ultra speed Open flume	From 25 to 15
From 400 to 500	Propeller ultra speed	Until 15
From 270 to 500	kaplan low speed	From 50 to 15
From 500 to 800	Kaplan high speed	From 15 to 5
From 800 to 1000	Kaplan ultra speed	Until 5

Table 7: Table for choosing the turbine

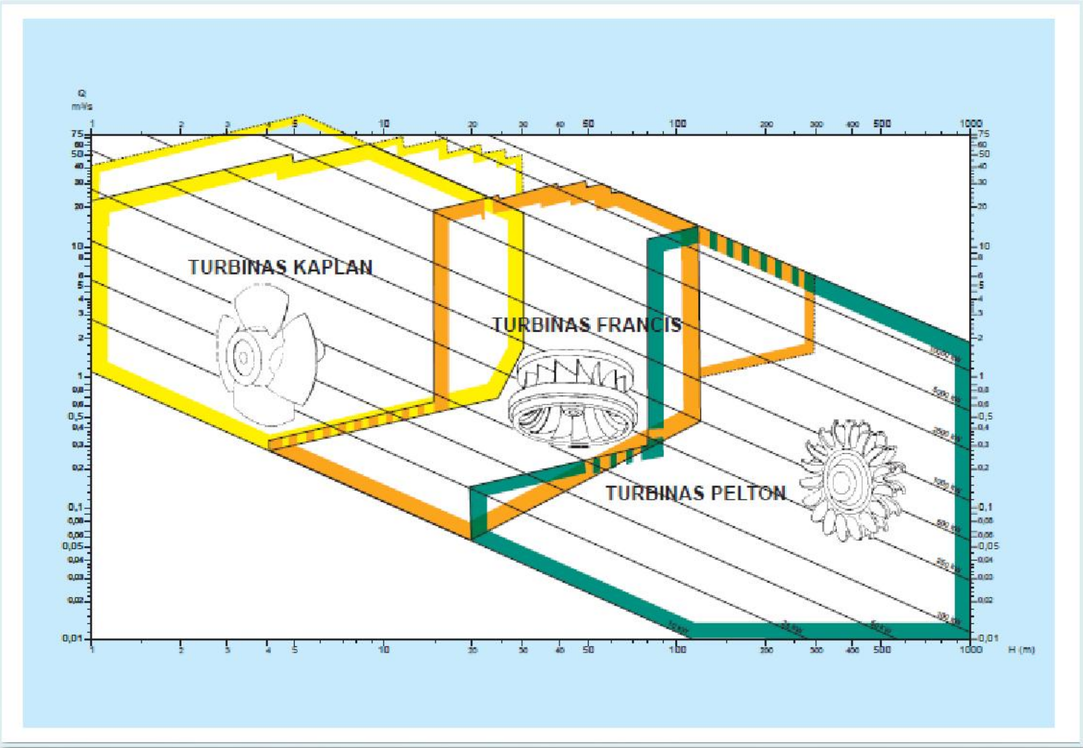
The specific speed is an index to determine in each case, which is the most appropriate type of turbine. According to experimental tests carried out, the turbines have good performance only within certain limits of specific speed. Therefore, this specific rate is to serve as an indication for choosing the most suitable turbine in each case.

Depending on the specific speed, the type of turbine can be selected according to table 7.

2.3.3.2. Second criterion

To pre-select the type of turbine to install in a plant, abaci provided by manufacturers are commonly used. With them, the type of turbine is determined with respect to the head and flow parameters.

As shown in Figure 30, matching the X-axis (height of the head in m) and the Y-axis (water flow m³/s) the most suitable type of turbine installation would be obtained.



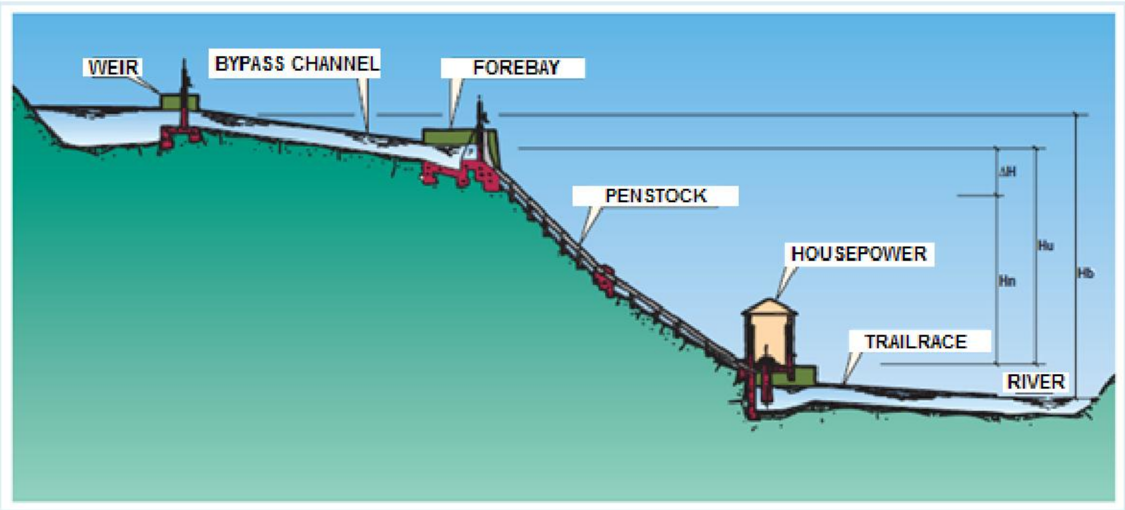
Picture 30: Diagram for choosing the turbine. Source EVE (VOEST-ALPINE)

However, to choose the final turbine to maximize the efficiency of the plant, the flow duration curve should be taken into account (essential to determine the flow of equipment) as well as the use of existing infrastructures.

2.3.4. Determination of the characteristic parameters of the turbine

The electrical power of a plant is directly proportional to two quantities, those of head and flow. Let us briefly recall the two concepts:

The head is the difference in height between the level of water in the dam and the point at which re-enters its natural course (Gross Head [Hb]). Apart from the Hb, other concepts are handled, namely Useful Head (Uh) and Net Head (Hn). The following picture illustrates such concepts.



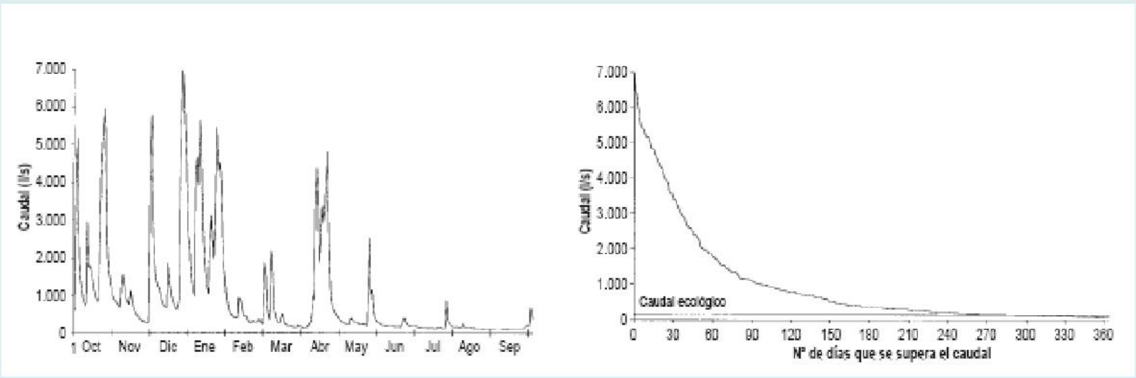
Picture 31: Runoff river small-hydropower plant. Diagram. Source EVE

- ***Useful Head*** (Hu): The difference between the level of water in the forebay and the level of the outtake.
-
- ***Net Head*** (Hn): Is the result of subtracting to the Useful Head (Hu) the losses (DH) created by the passage of water through the mouth of the forebay and penstock and accessories. For the calculation of load losses these are estimated to be between 5% and 10% of the Hb.

To determine the power installed and the energy produced during the year in a plant, it is essential to know the flow rate along the river in the area near the water intake. It is also necessary to obtain flow data relevant to a number of years, broad enough to include dry, normal and wet years.

To characterize years hydrologically from the mentioned data, rainfall information must be collected from nearby weather stations. A correlation between such data and the flows registered must be carried out to determine to which extent the former contribute to the latter.

Once the normal years are determined, the flows corresponding to them are used to calculate the mean daily flows. The flow duration curve is made out of these data. This curve indicates the flow of the river at a given day. The following figure includes a curve of mean daily flow and the flow duration curve derived from it.

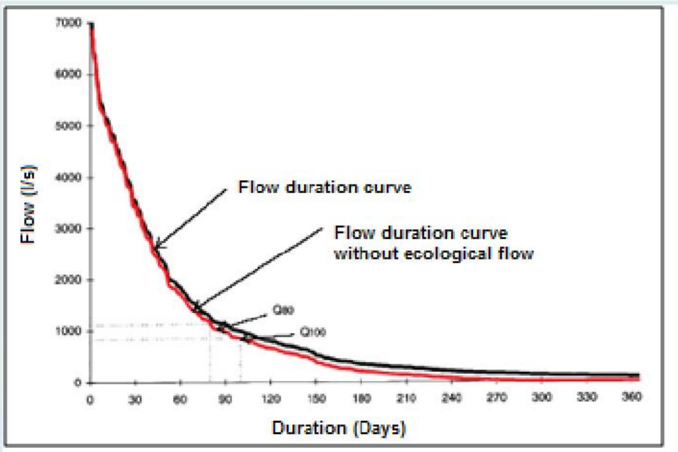


Picture 32: Flows graphics

The ***equipment flow*** of the plant is set from the flow duration curve.
The ecological flow must be extracted from this graph, that is to say, the minimum flow that must circulate through the river all year long.

The corresponding Basin Organization usually indicates the ecological flow. If otherwise, a good estimate is to consider the ecological flow equal to 10% of annual average flow.

Once the ecological flow has been deducted from the flow duration curve, the equipment flow is taken from the range of the curve between Q_{80} and Q_{100}, being Q_{80} the flow through the river 80 days a year and Q_{100} the flow which runs 100 days a year.



Picture 33: Flow duration curve (FDC)

For potential flows within this interval, an estimate of the hours of operation of the plant is carried out, keeping in mind the type of turbine to be installed.

Each type of turbine has an operating range with a maximum and minimum flow below which the turbine would not work with acceptable performance.

This minimum flow is approximately:

- For PELTON turbines: 10% Qequipment
- For KAPLAN turbines: 25% Qequipment
- For FRANCIS turbines: 40% Qequipment

Therefore, once Hn and design flow are calculated, the turbine would be selected with the help of the aforementioned abaci and, after it, estimated productions could be obtained for the equipment flow.

Sometimes, the equipment flow is conditioned by the existing infrastructure in minihydroelectric plants. This is the case of small plants with a channel with capacities smaller than the equipment flow obtained from the flow duration curve. In such cases, the investment required to set the channel could make impossible to build the plant and, as a consequence, the choice would be an equipment flow equal to the maximum flow that the channel can carry.

2.4. WATER RESOURCES AND THEIR POTENTIAL

2.4.1. Introduction

A hydraulic resource needs a certain flow and a certain head to generate electricity. The concept of flow stands for the amount of water that runs through a section of the river during a given time. The slope or gross head is the vertical distance that water must cover to go from the surface of the dam to the point in which the flow returns to its natural course in the river.

The flow from point A to point B, regardless its intermediate course (the course of water, a channel or a penstock) loses potential energy according to the following equation:

$$P = Q \cdot H_n \cdot \eta$$

Where P is the power lost, in kW, Q the flow measured in m^3/s, Hn net head in m, and η the weight of water, which equals its mass multiplied by the acceleration constant of gravity (kg/m^3).

The potential of water will be dissipated in friction and turbulence if water follows the course of the river in its fall. Water can also circulate through a pipe at the end of which a turbine is installed. In the second case, water dispels its power to overcome

friction and to move through the pipe and through the turbine blades. It is this last component of the potential energy that spins the turbine and generates electricity.
To assess the water resource it is necessary to know how the flow evolves throughout the year (one isolated value of flow is not significant) and what is the gross head available. Ideally, water authorities install a gauging station in the stretch of the river where the prospective plant will be set. This will make available a series of temporal flows in which, the longer their history is, the more accurate the values derived from them will be too.

It is not easy though, given the size of rivers on which these plants are constructed, to gather flow records for the section in question. If such data are not available, it will be necessary to look into hydrology, which will give accurate approximations.

The first step to take will be to determine if there are time series of flows for the river under study, for other sections of the river or similar rivers in the area (to reconstruct the flow regime with them). Finally, climate factors to calculate the flows will have to be obtained.

2.4.2. Hydrological data logging

In all countries of the European Union there are organizations specifically dedicated to manage the hydrological and climate data collected in gauging and weather stations.

In the United Nations, there is an organization, the World Meteorological Organization, which has a water information service (INFOHYDRO), dedicated to provide information about:

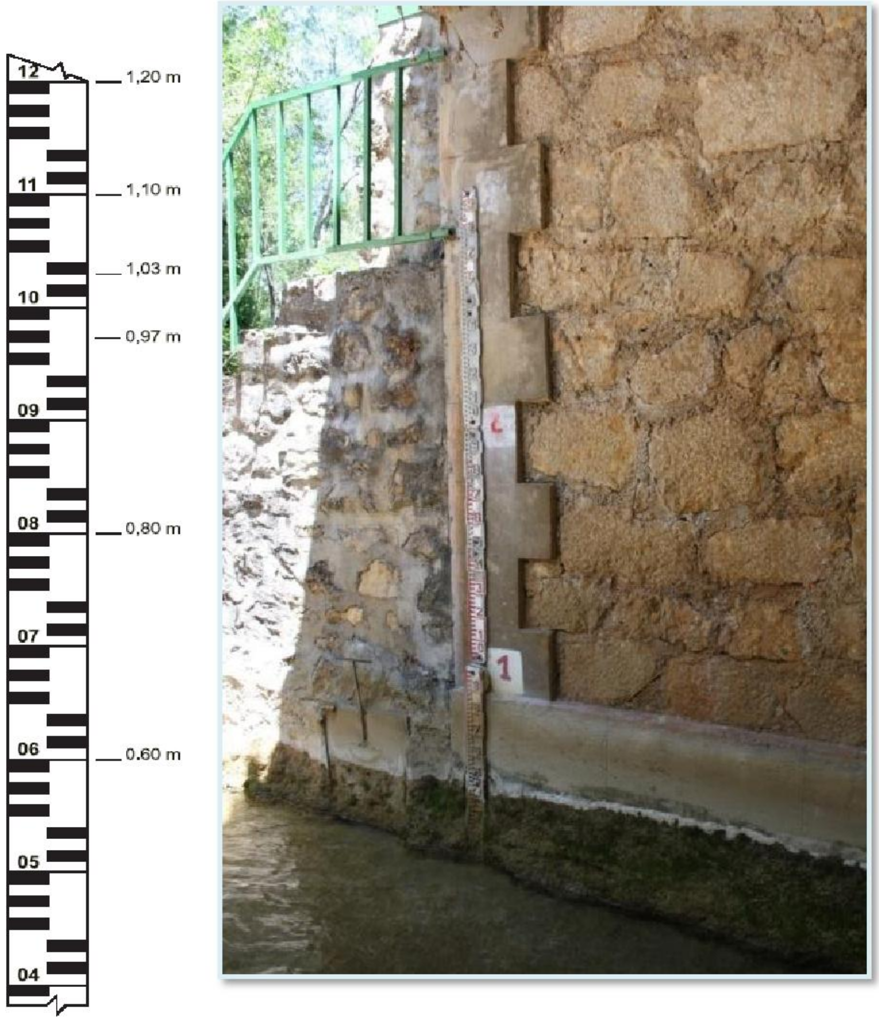
- Organizations, institutions and agencies related to hydrology
- Hydrological activities of such bodies
- Major river basins and lakes in the world
- Networks of hydrological stations of the country, number of stations and length of series
- Hydrological data banks, state of the collection, processing and archiving of data
- International databases related to hydrologic and water resources

2.4.3. Direct channel measurement

If there are no time series available for the river under study, and there is time for this, the flow of the river must be studied during one year (series of isolated measurements have no value). This may be done using several options.

2.4.3.1. Method of measuring cross-sectional area and average speed

A conventional method used in large and medium rivers is to measure the cross-section of the river at a given point, and the average velocity of the water stream flowing through it. This requires having a gauging station downstream of a straight section of reasonable length, in what is known as control section, where a relationship between water levels and flow can be established reliably. See the picture below.



Picture 34: Staff and control section for measuring the flow.

In a gauging station, what is measured and recorded is the level of water over time. For this, in its simplest version it is a measuring staff. In it, the control section and a series of overlapping marks can be seen, high enough so that in any case, water falls below or rises above the marks. In the picture, the staff is embedded in the pile that is the base of the plant. In any case, a stable reference point on the shore should be chosen, to periodically check the levelling of the staff. In modern gauging stations rather than a staff that requires manual data collection, a piezoelectric sensor water level signal is used. It sends data to a computer that registers and gathers them.

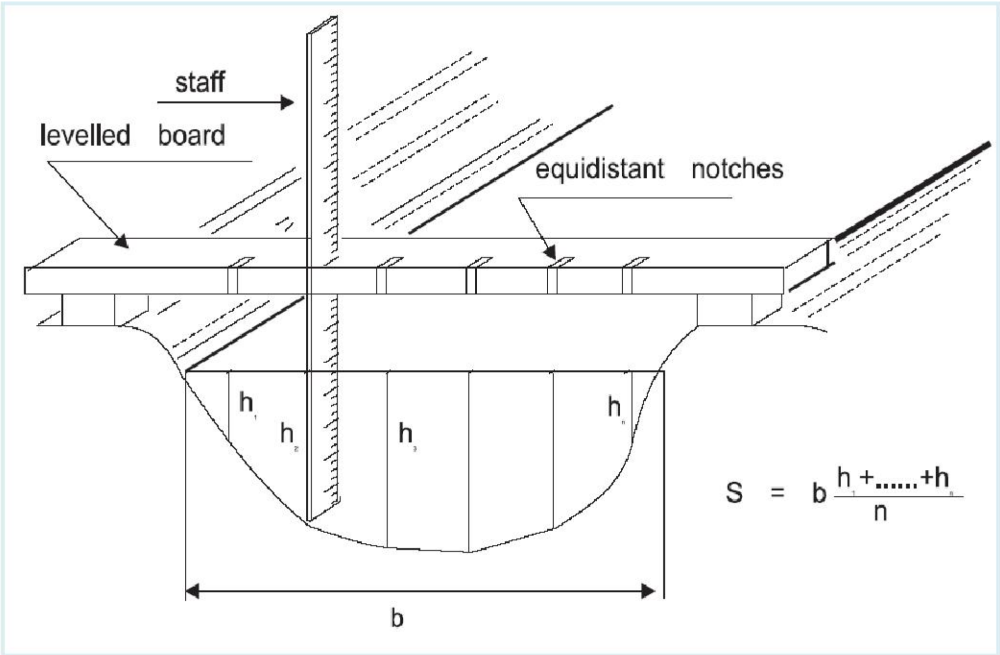
These readings are translated into flow through the output curve of the station, which correlates the level of the water surface with the flow rate. To draw this curve, the level of water and flow must be measured simultaneously through any of the methods depicted in this chapter. It is advisable to start by drawing the section of the curve corresponding to low flows and to take advantage of these measures to start the construction of a curve, which correlates flow and Manning ***n*** coefficient. This may then draw the curve of high flow (very difficult to obtain through direct measurement) by using the method of measurement of the slope of the water surface and estimating the value of the ***n*** coefficient extrapolating it from the correlation curve previously drawn.

There are ISO (*International Organization for Standardization*) recommendations that facilitate the right use of these methodologies.

2.4.3.1.1. Cross-sectional area calculation

To calculate the cross-sectional area, we recommend breaking it down into a series of trapezes, measuring their sides with the aid of a graduated staff, placed as shown in the figure. The area of the wet section of the channel is given by the equation:

$$S = b\frac{h_1 + h_2 + \ldots + h_n}{n}$$



Picture 35: Cross sectional area calculation diagram

2.4.3.1.2. Calculating the average speed in the cross section

To measure the flow speed one of the techniques described below can be used.

Using a float

A not-very-light floating object is placed on the surface of water, for example a wooden plug. Then, the time in seconds (***t***) required for it to cover a certain length in meters (***L***) is measured. This method is not used in channels of irregular shape or very little depth, but gives acceptable results if a relatively straight and uniform section of river is chosen. Superficial speed (m/s) is given by:

$$Vs = \frac{L}{t}$$

It is clear that Vs is not the average speed (***V***) of the section. For Vs, V must be multiplied by a factor that can vary between 0.60 and 0.85, depending on the depth of the channel and the roughness of its bottom and banks (0.75 is a coefficient generally accepted).

Using a rotor

To build a more accurate curve it is necessary to know the average speed in the channel cross-section. For it, the speed of current in a sufficient number of points must be measured.

A rotor may be used to measure the flow speed at a point. In its simplest form, it is a propeller or a buckets wheel mounted on a horizontal axis. The rotor sends in each lap (or predetermined number of laps) of the axis an electrical impulse that is transmitted to a counter. It logs the number of pulses per time unit. Each rotor comes with a curve that correlates the measured number of pulses with the current velocity to be measured.

To measure the flow speed in large and medium rivers, the rotor is hung from a bridge, weighted for it not to be swept away and making it remain in the vertical of the observer. If the bridge is made of several sections, the intermediate piers will lead to a constriction or an expansion of current lines, which can distort the measurements. If there is no bridge in the chosen section of the river, a boat well anchored to the two banks can be used. A lightweight but taut cable will allow knowing with sufficient precision the horizontal position of the point where the speed is being measured. However, knowing the length of the cable and its inclination, the point of measurement can be pinpointed. These rotors offer a good accuracy for current speeds between 0.2 and 5.0 m/s.

There are currently more robust rotors, as the electromagnetic current meter, which has no moving parts and is enclosed in a capsule with its streamlined shape to better withstand the force of the current. It is more compact than the propeller and is suitable for very slow speeds, for which the propeller flowmeters yield very erratic results. It is less vulnerable to jamming by mildew or algae, which makes them very attractive for highly contaminated streams or for those with a lot of scum. To ensure consistency of results, ISO recommendations should be followed.

Knowing the flow speed in an adequate numbers of the cross-section the curves of the same speed or isovels will be drawn on it. Next, with the help of a planimeter the area between two consecutive isovels will be measured. The sum of the products of each one of these areas multiplied by the average value of the isovels that surround it, divided by the total area of the section will give the value of the overall average speed.

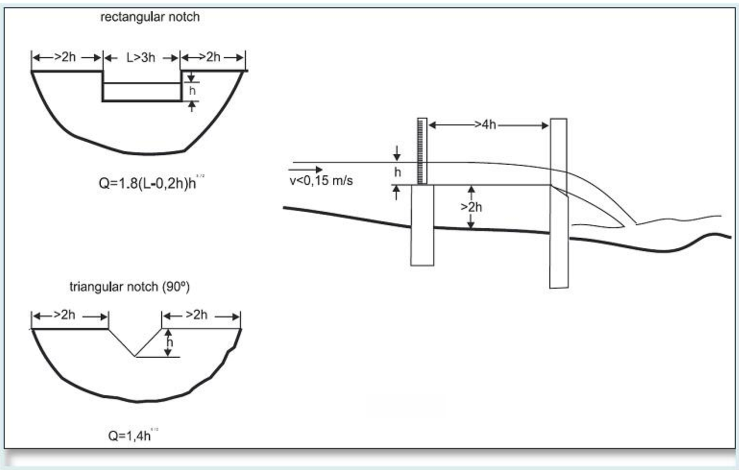
Alternatively, the course can be divided into vertical sections and the average speed in each can be calculated, as shown in the figure above. In this case and to obtain sufficient accuracy, it is recommended that the area of each of the vertical sections does not exceed 10% of the total area.

2.4.3.2. Flow measurement using an overflow

Provided that it does not surpass 4 m^3/s, a flow can be measured by passing it through a dump of a known section, arranged perpendicularly to the stream. Dumps are classified as: V-dumps, rectangular and trapezoidal dumps. Their crest can be wide or thin. Here we will only refer to thin crest dumps.

The experiments conducted in the laboratory can calculate ratios for different types of dumps. It is enough to measure upstream (a distance which equals four times the height) the **h** level, over the dump.

Triangular dumps (V-damps) are more accurate for smaller flows, but rectangular ones can measure a range of much larger flows. The figure below shows the dimensions of two sites, respectively rectangular and triangular, and the formulas used to calculate flow based on h:



Picture 36: Flow measurement using a dump

ISO 3846:1989, 3847:1987, 4359:1983, 4360:1984 and 4362:1992 specify the methods of flow measurement using dumps in different shapes and profiles.

2.4.3.3. Flow measurement by the slope of the water layer

This method, based on Manning's equation is used to measure high flows. A stretch of river from 50 to 300 meters long, straight and with uniform slope and section is screened. The slope of the water depth is measured in the bed sticking a series of stakes, and the cross-section, raising a plane in several sections of the channel and calculating the average of their areas (A) and its hydraulic radius (R) with Q is calculated using the Manning expression

$$Q = \frac{AR^{\frac{2}{3}} \cdot S^{\frac{1}{2}}}{n}$$

The weakness of the method lies in estimating the value of ***n*** (see table). For natural rivers, n is about 0.035. So, an error of 0.001 will result in an deviation of about 3% in the value of the flow.

FLOWS OF WATER	n
Clean streams where the water flows smoothly	0.030
Normal streams and rivers in stable condition	0.035
Shallow meandering rivers and abundant vegetation	0.045
Shallow rivers or streams with branches and stones	0.060

Table 37: Typical values of Manning's n coefficient in natural curses.

2.4.4. Flow regime

To work with a series of flows, this series must be sorted logically.

2.4.4.1. Hydrograph

One way is to group them in chronological order, which will result in a graph known as a hydrograph.

2.4.4.2. Flow duration curve (FDC)

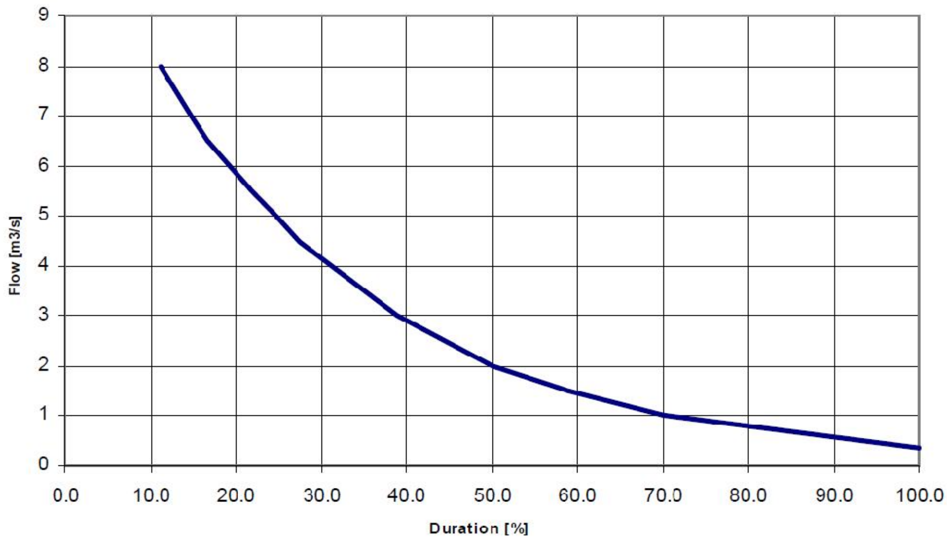
Another way is to sort the data by orders of magnitude rather than chronologically. The call classifieds flows curve (FDC) shows, for the stretch of river in question, the percentage of time is reached or exceeded a certain amount of flow.

	NUMBER OF DAYS	% OF THE YEAR
Flows over 8.0 m³/s	41	11,23
Flows over 7.0 m³/s	54	14,90
Flows over 6.5 m³/s	61	16,80
Flows over 5.5 m³/s	80	21,80
Flows over 5.0 m³/s	90	24,66
Flows over 4.5 m³/s	100	27,40
Flows over 3.0 m³/s	142	39,00
Flows over 2.0 m³/s	183	50,00
Flows over 1.5 m³/s	215	58,90
Flows over 1.0 m³/s	256	70,00
Flows over 0.35 m³/s	365	100,00

Table 8: Flow duration curve data.

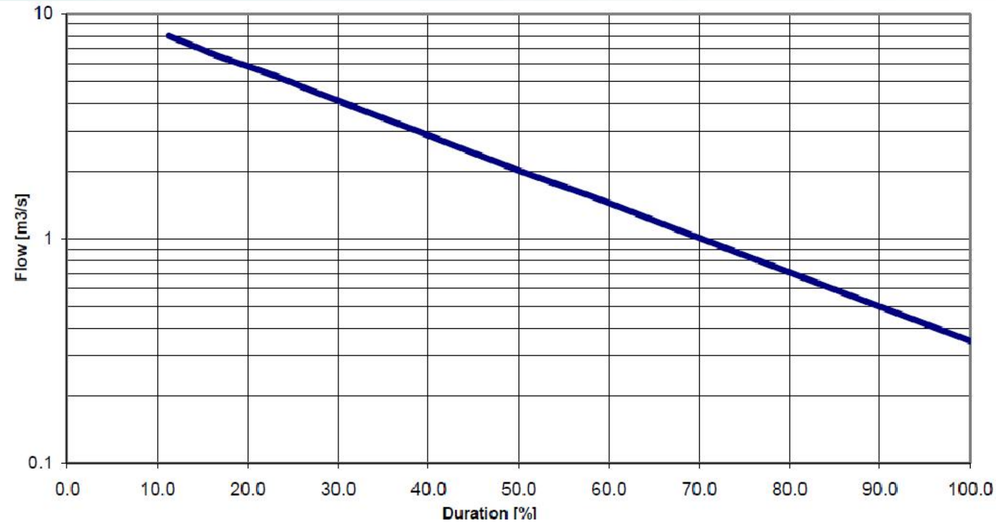
With this table we can draw a chart like the one shown below, the result of grouping the X values of the former figure according to their magnitude and not chronologically. Nowadays, gauging stations log their series, it is advisable to process the chronological list in a spreadsheet, sorted in descending order, and using a simple macro, or hand-sort data in a manner similar to the above table and automatically get the flow duration curve.

When the difference between the maximum and minimum flow rate is two or more orders of magnitude, a flow duration curve should be obtained.



Picture 38: Flow duration curve.

Using a logarithmic scale for the values of Q and a normal scale for frequencies, the figure would be represented as follows:



Picture 39: Classified flow curve (Logarithmic)

2.4.4.3. Standard flow duration curves

To compare the flow duration curves of different rivers, it is useful to divide the values of the flow, first by the pooling surface and then by the annual average rainfall intensity. These curves, where the flows are given m^3/s, per unit area and per annual rainfall pooling unit (typically $m^3/s/km^2/m$) are known as standard flow duration curves.

Picture 43 shows 20 standard flow duration curves, drawn on double logarithmic scale, for different pooling areas.

2.4.5. Water pressure or head

2.4.5.1. Measurement of gross head

Gross head is the vertical distance between the levels of the water measured in the dam and the water outtake.

In the past, the best way to measure gross head was by leveling with a surveyor's level and staff, but this was a slow process. Accurate measurements were made by a tachometer or less accurately by a clinometer or Abney level. Nowadays digital theodolites, electronic digital and laser levels and especially electronic total stations have simplified the task significantly.

Modern electronic digital levels provide an automatic display of height and distance within about 4 seconds with a height measurement accuracy of 0.4 mm, together with an internal memory that can store approximately 2,400 data points. Surveying by

Global Positioning Systems (GSM) is now used widely and a handheld GPS receiver is ideal for field positioning, and rough mapping.

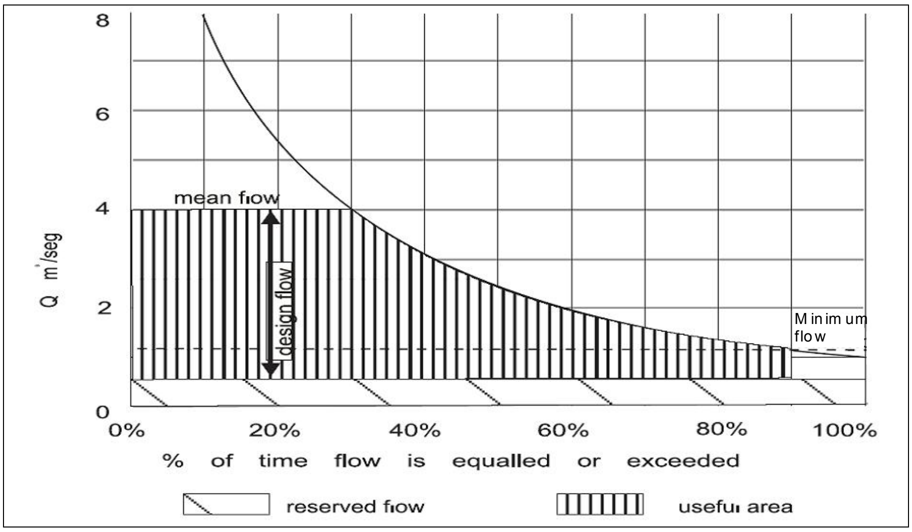
To accurately measure this distance, we recommend using surveyor's levels or electronic theodolites, which are extremely precise and easy to use. For major heads (higher than 100 m), an acceptable value of gross head can be obtained through an topographic altimeter carefully corrected for the local values of temperature and atmospheric pressure. As the power of the head is proportional to $H^{3/2}$, an error of 5% in the measurement of the head will result in a 7.6% deviance in the estimated power plant. For this reason, surveyor's level or electronic surveying equipment is highly recommended.

2.4.5.2. Estimation of net head

Having established the gross head available, it is necessary to make estimates for the losses, from trash racks, pipe friction, bends and valves. In addition to these losses, certain types of turbines need to discharge their water to atmosphere, above the level of the tail water (the lower surface level). The gross head minus the sum of all the losses equals the net head, which is available to drive the turbine.

2.4.6. Installed power and energy generated

The flow duration curve lets you choose the most efficient design flow, and from this, the value of the ecological flow (one of the possible options), and the technical minimum flow from each of the turbines is used to evaluate the power plant and the annual production expected per mean hydraulic year.



Picture 40: Flow duration curve. Design selection flow

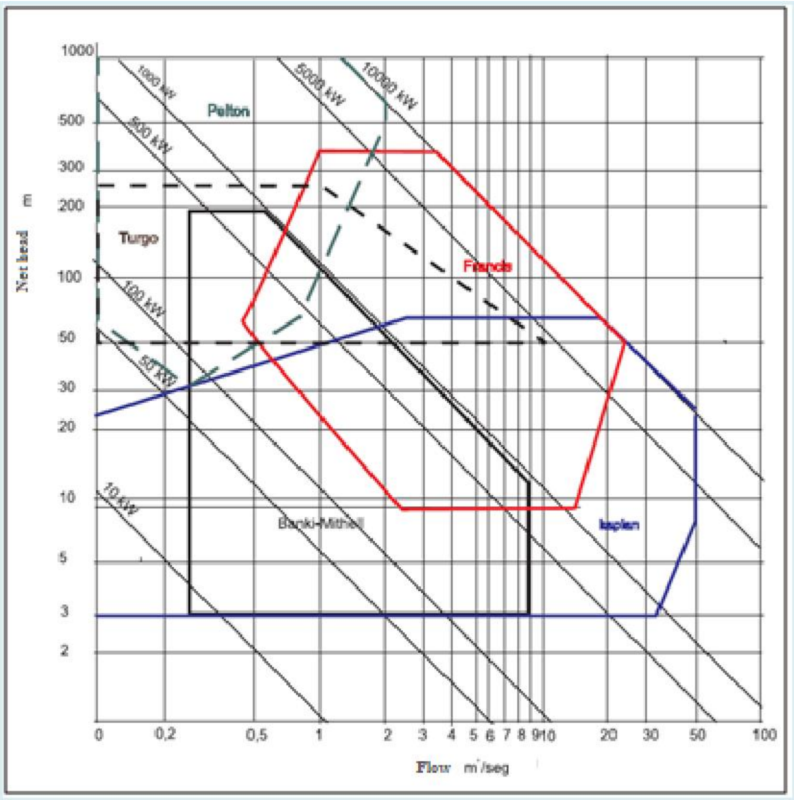
The figure illustrates the flow duration curve for the use to be measured. It is generally taken as the design flow (used to define the type and size of the turbine) the value of the average flow decreased in the value of the ecological flow. In practice it is necessary to work further with other hypotheses to try to improve outcomes. Once the design flow is defined (in this case Q_m - Q_{res}) knowing the net head, the design/flow confluence point will be cast on a graph of turbine operational ranges. All those turbines whose ranges contain one given point will be selected. The power and capacity for each type of prospective turbine must be calculated. For each type of turbine, the minimum technical and performance flow are known.

To calculate the power of each of the selected turbines and the power they generate annually (in an average year) the following steps must be followed:

1. Delimit the range of flow between the average flow ($Q_{average}$), considering the provisional rated flow and the ecological flow ($Q_{ecological}$) required to maintain acceptable environmental conditions in the stretch of river screened

2. Calculate the flow of equipment, or design flow (Q_{design}) that is given by the equation: Q_{design} = ($Q_{average}$) - ($Q_{ecological}$)

3. Measure gross head and calculate the net head



Picture 41: Turbine operational ranges graph

4. Using this figure, we identify the proper turbine types to head (H) and the previously estimated design flow, and determine their income from flow-performance curves for each one of the selected types of turbine and their minimum technical flow. The table below shows the technical minimum flows of turbines used.

Turbine	Qmin (% Qnominal)
Francis (spiral)	30
Francis (Open flume)	30
Semi-Kaplan	30
Kaplan	15
Crossflow	15
Pelton	10
Turgo	10
Helice	65

Table 9: Minimum technical flow in the turbine

5. Calculate the effective part of the flow duration curve, using $Q_{average}$, $Q_{ecological}$ and Q_{min}

6. Calculate the annual energy production and plant power, from the area of usable flow duration curve and taking into account the flow-performance curve, the net head and the gravitational constant.

To calculate the energy generated by each turbine, remove the band corresponding to ecological flow (not passing through the turbines) and divide the usable area of the flow duration curve, from the origin (time = 0), into vertical bands with a width of 5%. The last band Q_{min} intersects the flow duration curve. Average flow is calculated for each band and the corresponding $\eta_{turbine}$ is identified with it for the performance-flow curve of the chosen turbine. The energy contribution (E) of each band was calculated by the formula where:

$$E = W\, Q_{medium}\, H\, \eta_{turbine}\, \eta_{gearbox}\, \eta_{generator}\, \eta_{transforme}\, g\, h$$

Where:

W = width of the band = 0.05 for all but the last one, which will be between 0.05 and 0.005
h = number of hours in a year
g = specific gravity of water (9,81 kNm^{-3})

Gross energy is equal to the sum of the energy contributions of each band.

2.5. Barriers to minihydro power development

The development of small-hydropower plants is limited by a number of barriers that prevent their proper development. These can be classified into technical, administrative, normative constraints, socio-economic and environmental.

The RuralRES project revealed that these barriers vary significantly from country to country. For example, whereas in Czech Republic and Spain the main issues are delays in administrative procedures, in Italy (Province of Teramo) it is the environmental laws are prohibitive. For detailed information for each country, please refer to the D3.2 combined report document for the 6 RuralRES territories, and the rest of the training package for your country located on the RuralRES website: http://ruralres.diphuelva.es/

Chapter 3

PRE-FEASIBILITY STUDY

3. PRE-FEASIBILITY STUDY

3.1. WORK METHODOLOGY

The phases to evaluate the pre-feasibility criteria of small-hydropower plants are:

- ***Phase 1.***

Phase 1 is aimed at the location of the head, search for information on hydrological data, topographic and economic performance of the various administrative procedures. This phase is primarily oriented to gathering information and is governed by the flow diagram described in the following figure. The ultimate goal of this phase will be to determine whether it is convenient to apply for the permits necessary.

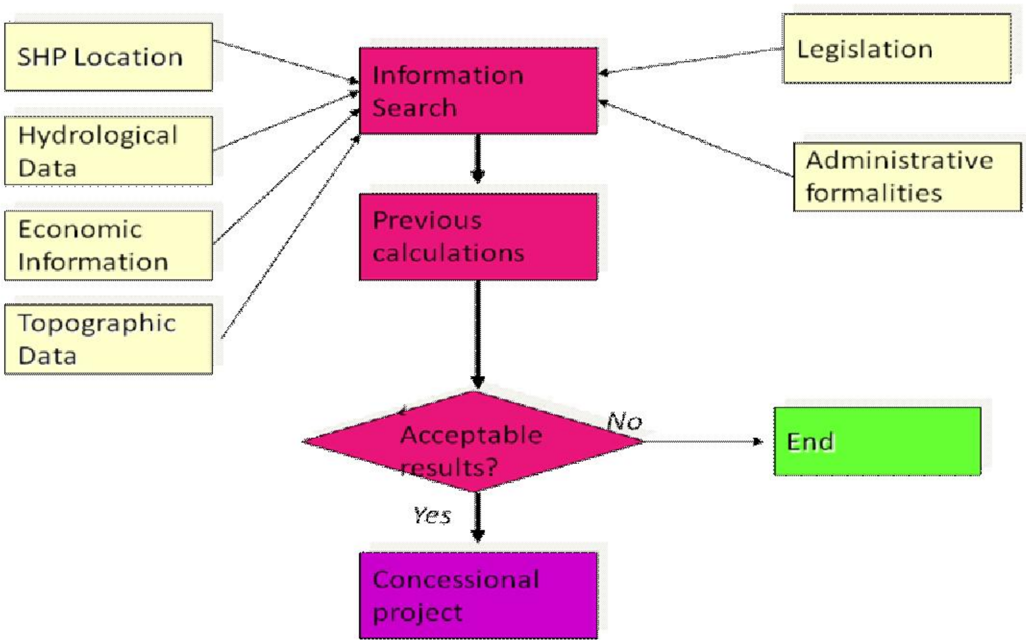


Figure 42: Previous work methodology

The phases above are broken down more specifically as follows:

- *Collection and analysis of existing documentation, analysis and documentation of all the information that is considered relevant*

- *Determination of the hydraulic regime of use and description of the flow duration curve that will define the potential energy wherever possible*

- *Study of the problems arising from concessional status, current uses and possible conditions that can determine viability, and a description of the limitations of various kinds which might involve significant challenges (technical and economical) to build the plant*

- *Visit of the central and emission of a field report describing the dimensions, characteristics and current status of facilities, including:*

- Location
- Dam or water intake
- Bypass channel or pressure gallery
- Forebay and cleaning devices
- Penstock
- Power plant building
- Drainage channel
- Substation, protection and automation items
- Medium voltage lines
- Access

- *The field report should include photos of the various elements existing for each plant*

- ***Phase 2.***

In this phase, the possibility of restoring a plant is analyzed. Consequently, a report that includes the following sections must be carried out:

- Determination of flow equipment
- Analysis of electricity generation
- Budget estimation (investment in civil works or equipment)
- Economic and financial study
- Analysis of profitability

Having verified the viability of the installation, it is time to proceed to the development of the final project, which will present all necessary information on: hydrological data of the area to define the flow of equipment, topographic data to define the head, economic study and applicable law.

This study must define general characteristics of development, such as collection point, channel length, useful head, drainage channel, possible grid-connection points to evacuate power, etc.

- ***Phase 3.***

Once the concession is granted, electric and hydraulic engineering works will be detailed during the third phase.

- ***Phase 4.***

This involves implementation of the work, which contains common stages associated to this type of facilities:

- Supplies of equipment and facilities
- Execution of works and installation of equipment
- Performance acceptance tests and start-up
- Operation and maintenance of the plant

3.2. FINANCIAL ANALYSIS

3.2.1. Cost analysis: Initial investment

3.2.1.1. Introduction

This section proposes a series of techniques and tools for the determination of the various elements involved in a small plant from two perspectives: dimensioning and cost analysis. The different parts that constitute a plant have been grouped for this analysis, namely civil works, electromechanical equipment, protection, regulation and control and connection to the grid. Finally, we have developed a feasibility-study methodology to determine the financial potential of recovering a plant or installing a new one.

3.2.1.2. Civil works

To calculate the cost of the different elements involved in civil works, a series of equations will be used. Their expressions are defined in terms of unitary prices (Ci) to make the formulae easily adaptable to possible fluctuations in prices and also to allow their use in countries with different prices.

In the case of plant refurbishment, the costs of these elements will be affected by a repair rate (Tk) whose value will depend on its previous state. For certain items (gates, trash rack, forebay, line, or any other considered relevant) it is advisable to use rates from 0 to 100% to indicate whether these are in perfect shape (0%) or need to be replaced (100%), in order to obtain an optimum performance of the installation. For elements with repair rates over 60%, a percentage of 100% will be used.

The following paragraphs analyze the different elements to consider in the study of civil works costs.

3.2.1.2.1. Dam

The dam is the element installed on the riverbed to pool the water that will be diverted later on. Dams do not change the level of water or cause significant water regulation capacity. This is normally found in good conditions if compared to other pre-existing elements. The main problem is usually the deterioration caused by water and solids erosion, especially in the body of the dam and spillway. It is usually repaired with concrete.

The most common action in repairing the dam is clearing vegetation, rocks and mud along the dam. This usually amounts for 5% of the total cost.

Figure 43: Dam of Casas Nuevas plant. Marmolejo. Jaén

From the volume of the various elements that make up the dam, dam shell, screen, wall brackets and abutments, and taking into account the unit prices of different types of concrete, its cost will be determined as follows:

For the dam shell and abutments

$$CO_{pe} = (HCP + HET) \times c_{Hla} \times T_1$$

Where:

CO_{pe} = Cost of dam shell and abutments
HCP = Volume of concrete in dam shell (m^3)
HET = Volume of concrete in abutments (m^3)
c_{Hla} = Price of a m^3 of slightly reinforced concrete
T_1 = % to repair in dam shell and abutments

For the shield:

$$CO_{pan} = (c_{Ha} + 1.5 \times M \times c_{eg}) \times HPT \times T_2$$

Where:
CO_{pan} = Cost of shield
HPT = Concrete in shield (m^3)
c_{eg} = Price of the screen excavation in granite
M = Parameter that indicates the type of material that needs to be excavated: 1 for granite, 0.75 for softer materials and 1.25 for harder materials
c_{Ha} = Price of a m3 of slightly reinforced concrete

T_2 = % to repair in shield

And for the external walls:

$$CO_{mc} = HMC \times c_{Hma} \times T_3$$

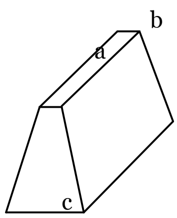
Where:

CO_{mc} = Cost of the external walls
HMC = Volume of concrete in external walls (m^3)
c_{Hma} = Price of a m^3 of highly reinforced concrete
T_3 = % to repair in external walls.

The total cost of the dam (CO_{azud}) is calculated by adding the above equations:

$$CO_{azud} = CO_{pe} + CO_{pan} + CO_{mc}$$

A rough way of determining the volume of concrete in HCP, PTH, TSH and HMC, will be to use the following expression, based on the size of the figure:



$$v = a \times c \times (b + 0,4 \times c)$$

3.2.1.2.2. Intake

This is the point where water is captured and then derived to the channel. The elements to consider are the concrete structure, the trash rack and control gates. Normally, in the intake, the concrete structure is the best-preserved part. On the contrary, the trash rack and the gates will have to be substituted due to the fact that these are frequently made of wood, iron and steel. A complete replacement of them is advisable.

The cost of intake structures can be calculated using the following expression:

$$CO_{etm} = HTM \times c_{Hla} \times T_4$$

Where:
CO_{etm} = Cost of the intake concrete
HTM = Intake concrete (m^3)
c_{Hla} = Price of a m^3 of slightly reinforced concrete
T_4 = % to repair in the intake structure.

If the volume of the intake cannot be determined from values a, b and c, the following approximate formula will be applied:

$$HTM = a \times b \times c - [(b-0.6) \times (c-0.6)]$$

The cost of the trash rack is determined by the expression

$$CO_{re} = SRE \times c_{rj} \times T_5$$

Where:
CO_{re} = Cost of the trash rack
SRE = Trash rack surface (m^2)
c_{rj} = Price of a m^2 of trash rack
T_5 = % of the trash rack to repair

To calculate the cost of the gate:

$$CO_{cp} = SCP \times c_{cpt} \times T_6$$

Where:
CO_{cp}= Cost of the gate
SCP = Gate surface (m^2)
c_{cpt} = Price of the gate per m^2
T_6 = % of the gate to repair

The total cost of the intake will be the sum of all these values. Thus:

$$CO_{toma} = CO_{etm} + CO_{re} + CO_{cp}$$

3.2.1.2.3. Pipeline

The resulting flow must be driven to the forebay. This process can be performed through an open flume, a closed flume or a penstock.

Currently, the trend in the design of small-hydropower plants is the use of closed flume penstocks to lower installation costs and to reduce maintenance costs (cleaning and possible landslides). In the refurbishment of small-hydropower plants, a penstock is usually installed inside the original flume.

3.2.1.2.3.1. Channel

In general, the pipeline is made open-pit following contour lines and with a slight slope (between 0.3 and 0.5 ‰). Normally, the material used is concrete. The cost is calculated by determining the necessary concrete from the wet section of the channel and taking into account a factor of accessibility.

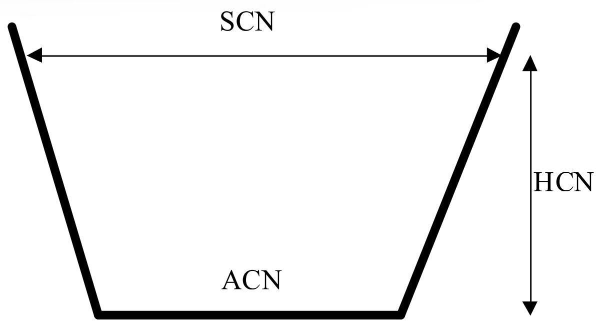
Figure 44: Pinos Puente's channel. Granada

In small mountains, only lined channels are used or, more often than not, channels built in reinforced concrete. Given the environmental requirements that make compulsory to cover them, these are built of rectangular cross section, to dim the light of the slabs that covers them.

The cost of the channel is given by the following expression:

$$CO_{can} = 0.2 \times \left[2\sqrt{\frac{(SCN - ACN)^2}{4 + HCN^2}} + ACN \right] \times (c_{Hla} + c_{pc}) \times K_a \times LCN \times T_7$$

Where:



CO_{can} = Cost of the channel
HCN = Height of the channel
ACN = Width of the channel in its base
SCN = Width of the channel in its surface
c_{pc} = Price of a linear meter of channel or tunnel preparation
K_a = Accessibility parameter: 1 for easily accessible areas, 1.5 for channels of medium difficulty and 2 for channels difficult to access
T_7= % of the channel to repair

If the parameter value ACN cannot be measured, an approximate calculation will be obtained through the formula:

$$ACN = SCN - 2.4 \times HCN$$

3.2.1.2.3.2. Tunnel

The cost of the tunnel will be similar to that of an open channel including the cost of its top arch.

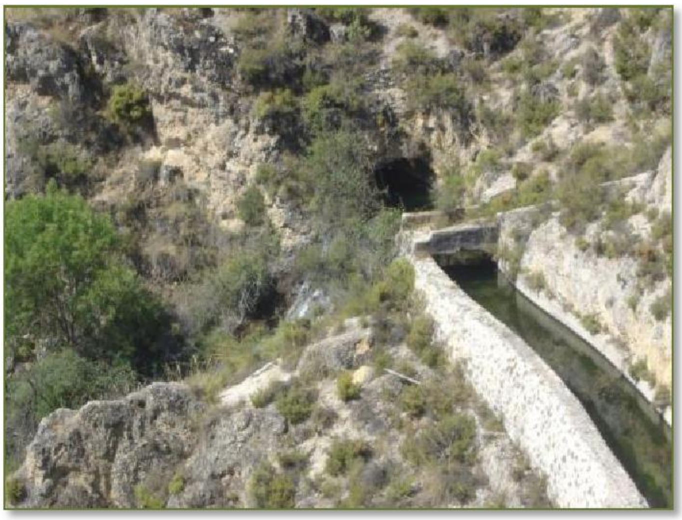
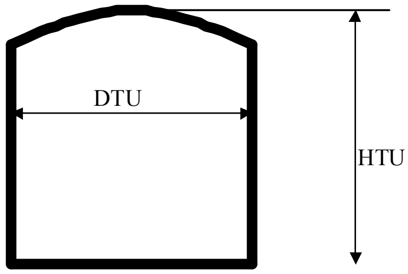


Figure 45: Channel-tunnel. Central Potril II. Granada

$$CO_{tu} = 0,25 \times (1,57 \times DTU + 2 \times HTU) \times (c_{Hla} + c_{pt}) \times LTU \times T_8$$

Where:

CO_{tu}= Cost of the tunnel
LTU = Length of the tunnel (m)
DTU = Diameter of the arch of the tunnel
HTU = Total height of the tunnel
c_{pt} = Price per meter of tunnel to be repaired
T_8= % of the tunnel to be repaired



3.2.1.2.3.3. Pipeline

In case that the reconstruction cost is too high, as well as to protect it from possible rock sliding, a pipeline can be installed. This is normally made of PVC, covered with earth.

$$CO_{CF} = (0.110113 + 0.000221259 \times DCF + 0.000331585 \times DCF^2) \times LCF \times T_9$$

Where:
CO_{pi}= Cost of the pipeline
LCF = Length of the pipeline (m)
DCF = Diameter of the pipeline (m)

The pipeline diameter can be determined using the following equation:

$$DCF = 1.478 \times Q^{0,375}$$

3.2.1.2.4. Forebay

The design of the forebay is difficult to establish because of the topography and geology of the site, both as regards its general form and as regards the provision of spillway and other elements. However, a design and a budget estimate of the work to be done can be obtained by assimilating it to a parallelepiped whose size and dimensions are determined on the basis of design flow and conduction properties.

Figure 46: Forebay. Central Potril II. Granada

Given the flowing characteristics of these conduction systems, the role of the forebay will not be that of regulating. Its main function will be to absorb temporally little mismatches between the flow contributed by the channel and that required by the turbines.

With the dimensions of the forebay: LCC, ACC and HCC, the cost of the structure itself can be determined by the expression:

$$CO_{ecc} = [(ACC + 0.6) \times (HCC + 0.3) \times (LCC + 0.6) - (ACC \times LCC \times HCC)] c_{Hma} \times T_{10}$$

Where:

CO_{ecc} = Cost of the structure of the forebay
ACC = Interior width of the forebay (m)
LCC = Interior length of the forebay (m)
HCC = Interior height of the forebay (m)
c_{Hma} = Price of heavily armed concrete
T_{10} = % of the forebay to repair

If the structure of the forebay is made of concrete, the unitary price C_{Hma} will be used. If it is made of bricks, C_{fl} will be used.

Besides the cost of civil works in the forebay, other elements such as the trash rack, cleaners and flow/drainage control gates will have to be considered:

- *For trashrack:*

$$CO_{rej} = SERT \times c_{rj} \times T_{11}$$

Where:

CO_{rej} = Cost of the trash rack of the forebay
SRET = Surface of the trash rack (m^2)
c_{rj} = trash rack cost per m^2
T_{11} = % of the trash rack to repair

- *For the trash rack cleaner:*

$$CO_{lrj} = SERT \times CLR \times c_{lrj} \times T_{12}$$

Where:

CO_{lrej} = Cost of the trash rack cleaner of the forebay
CRL = Coefficient depending on the transmission system of the trash rack cleaner: 1 if it is rotating and 1.8 if it is hydraulic
c_{lrj} = Trash rack cleaner cost per m^2
T_{12} = % of the trash rack cleaner to repair

- For the gates:

$$CO_{cpt} = SCPT \times c_{cpt} \times T_{13}$$

Where:

CO_{gtf} = Cost of the gates of the forebay
SGTF = Surface of the gates (m^2)
c_{cpt} = Gate cost per m^2
T_{13} = of the gate to repair

The total cost of the forebay (CO_{cc}) will be:

$$CO_{cc} = CO_{ecc} + CO_{rej} + CO_{lrj} + CO_{cpt} \qquad (€)$$

3.2.1.2.5. Penstock

Its mission is to carry water from the forebay to the turbine. It must be prepared to withstand the pressure produced by the water column and by water hammers in an emergency stop of the plant.

The pipeline is an element that must be replaced if it is not in good condition (the percentage of repair must be 100% or 0% only). It is recommended that this replacement be always done in steel pipe-reinforced polyester or fiberglass.

Figure 47: Penstock. Central Alhori I. Granada

3.2.1.2.5.1. Steel pipe

The cost per meter of penstock depends on its diameter and thickness values, which are logically linked to the equipment flow and the head.

For the calculation of the pipeline, the following procedure will be used:

1) Calculate the minimum thickness from the design values of gross head and flow

$$e = 2.21864 \times H^{6/7} \times Q^{6/14}$$

Where:

H = Gross head (m)
Q = Maximum design flow (m^3/s)

To prevent from damage in transport and during assembly, a minimum thickness of 6 mm will be taken, increasing at rates of 1 mm to compensate for corrosion and in accordance with the recommendations of ESHA and ASME [**ESHA,2004a**][9]

[9] **ESHA.** *Guide on how to develop a small hydro site*. ESHA. Brussels. 2004

2) Determine the optimum diameter of the pipe from the thickness using the equation

$$D_{op} = 0.1347 \times \frac{Q^{1/2}}{e^{1/6}}$$

3) Calculate the initial investment made in steel penstock. It shall include the following items:

- ***Cost of the steel in the pipe, including additional costs (€/kg)***

Pipe installation costs (C_{INS}). For this, the expression developed by the Engineering Group Thematic Network on Minihydro power will be used [**Andaroodi Mohammadreza et al,2005**][10], which takes into account the slope of the pipe to determine the costs

Pipe installation costs (per lineal meter) (C_{ins}) (€/m)	
Slope ≤ 10%	**Slope >10%**
200 + 140·D	400 + 140·D

Table 10: Pipe installation cost. D(m). (Source: Andaroodi Mohammadreza et al, 2005)

$$CTAC = (3.185 \times 10^4 \times c_t \times e \times D_{op} + C_{ins}) \times L \times T_{14} \quad (€)$$

Where:

CTAC = Total cost of the steel pipe (€)
c_t = Cost of the steel of the pipe (€/kg)
e = Thickness (m)
D_{op} = Optimum diameter (m)
C_{ins} = Cost of pipe installation (€/m)
L = Length of penstock (m)
T_{14} = % of the steel penstock to repair

[10] **Andaroodi Mohammadreza, Schleiss Anton, Boillat Jean-Luis, yBollaert Erik** *Standardization and Design Rules for Civil Enginenering Works on SHP* European Project FP5. Thematic Network on Small Hydropower . Engineering Work Group. Ecole Polytechnique Fédérale de Laussane (EPFL). Laussane (CH). 2005 http://www.esha.be/index.php?id=29

Reinforced polyester pipe with Fiberglass

According to this study, the value of the diameter of polyester reinforced with glass fiber will be (D_{pol}):

$$D_{pol} = 0.83 \times D_a \qquad (m)$$

Where:

D_a = Calculated diameter for the steel pipe (m)
The value of the thickness of the polyester pipe (e_{pol}) is calculated using the expression:

$$e_{pol} = 2.17 \times 10^{-4} \times H \times D_{pol} \qquad (m)$$

The total cost of the polyester pipe will be:

$$CTPO = (-174.11 + 474.41 \times D_{pol} + 3948.44 \times e_{pol} + C_{ins}) \times L \times T_{15} \qquad (€)$$

Where:

CTPO= Total cost polyester pipe (€)
e_{pol} = Thickness of the polyester (m)
D_{pol} = Diameter of the polyester (m)
C_{ins} = Cost of pipe installation (€/m)
L = Length of penstock (m)
T_{15} = % of the polyester penstock to repair

3.2.1.2.6. Access

The cost of upgrading pre-existing accesses or constructing new ones will vary a lot, of course, depending on the terrain and its length. Moreover, the type of materials used in its finishing (earth, gravel or tar) also be of influence. The cost and the impossibility of construction of an access can obstruct significantly the possibility of construction or refurbishing mini-hydropower plants.

Two types of accesses will be distinguished: access to the building of the plant and access to the pooling area. Although they tend to be similar, they can be constructed differently.

The cost of access can be calculated with the expression CO_{ACC} (€)

$$CO_{ACC} = N_1 \times N_2 \times N_3 \times LCA \times c_{ca} \times T_{16}$$

Where:

c_{ca} = Cost per meter of access path
LCA = Length of access path to the power plant (m)

N_1 = Indicator for difficulties in the terrain in which accesses have to be constructed. Take the value of 1 for flat surfaces and 1.5 for uneven ones
N_2 = Indicator of the status of the access path. Take 1 if it is new or 0.3 if it is rebuilt
N_3 = Parameter indicating the type of path, 1 for land, 1.1 for gravel and 1.3 for tar
T_{16} = % of access path

3.2.1.2.7. Powerhouse

To determine the cost of building the plant, two typologies must be identified, namely:

- Refurbishment of an already existing powerhouse
- Construction of a new power plant

3.2.1.2.7.1. Refurbishment

Figure 48: Powerhouse for refurbishment. Marmolejo. Jaén

To determine the cost of refurbishment, the module base (MB) for this type of facility will be used. The price of this module will be affected in the various items that make up a building of such characteristics. As a consequence, its price will be determined by the following factors:

	PARTICIPATION RATE	% TO EXECUTE
DEMOLITION	7.00%	T_{DE}
EARTHMOVING	5.00%	T_{MT}
FOUNDATION	10.00%	T_{CI}
STRUCTURE	22.00%	T_{ES}
MASONRY	21.00%	T_{AL}
ROOF (COVER)	15.00%	T_{CU}
COATING	10.00%	T_{RE}
CARPENTRY	5.00%	T_{CA}
FACILITIES	5.00%	T_{IN}
	100.00%	

Table 11: Participation coefficient in refurbishment

FE stands for factor of state, so that:

$$FE = (0.07T_{DE} + 0.05T_{MT} + 0.1T_{CI} + 0.22T_{ES} + 0.21T_{AL} + 0.15T_{CU} + 0.1T_{RE} + 0.05T_{CA} + 0.05T_{IN}) = \sum_{i=1}^{i=9} C_i \cdot T_i$$

The construction price of the module (M) should be weighted by factors that directly affect the construction. All these will be included within the building known factor (FC). They are:

$$FC = F_A \times F_T \times F_C \times F_R \times F_{CH} \times F_{OC}$$

Accessibility factors (F_A): determined by access easiness to the different buildings of the hydropower plant. Most facilities are placed in rural areas with a great difficulty for the transport of materials, working procedures, etc. It takes the following values:

	F_A	DESCRIPTION
Good	1	Easy access
Average	1.5	Limited difficulty
Bad	1.75	Access problems
Very bad	2	Great access difficulty

Table 12: Accessibility factors

Typology factor (F_T): Each type of turbine will condition the refurbishment of the powerhouse due to its own construction characteristics:

	F_T	DESCRIPTION
Pelton	1	Horizontal-vertical
Francis	1.25	Open flume-spiral
Kaplan	1,75	Kaplan/Semi-Kaplan

Table 13: Typology factor

Quality factor (F_Q): The quality of its finish and the construction system of each building will yield the following values:

	F_C	DESCRIPTION
Normal	1	Masonry. Adobe. Metallic-fiber cement roof
High	1.10	Load-bearing wall. Carpentry. Ceramic-tile roof
Excellent	1.30	Reinforced concrete. High quality enclosures

Table 14: Quality factor

Refurbishment factor (FR): The construction difficulty of refurbishing an already constructed building is higher than that of constructing a completely new one. This difficulty is due to the use of materials and techniques aimed at conserving the previous building, which entails an extra difficulty.

	F_R	DESCRIPTION
Normal	1	It does not show great refurbishment problems
High	1.30	There are extra problems in its refurbishment
Top	1.60	Building or refurbishment constraints are quite high

Table 15: Refurbishment factor

Historic cataloguing factor (FHC): The different administrative authorities (central, autonomous and local) are creating a catalogue of the different real estates existing in their territories for their subsequent protection. This entails that a building catalogued as historical good of interest will have extra costs for its refurbishment.

	F_{CH}	DESCRIPTION
Is not catalogued	1	It is not included
It is catalogued	1.5	It is included within the catalogue of historical goods of interest

Table 16: Coefficients of factor of historical documentation (Source: Author)

Complementary construction factor (FCC): the existence of accessory elements in the building (such as spillways, drainage channels, multiple accesses, etc.) increases costs.

	F_{CC}	DESCRIPTION
A	1	There are no complementary constructions
B	1.30	There are small auxiliary constructions
C	1.5	The number of elements or their size is high
D	2	There is a great quantity of elements that increase construction prices (spillways, channels, etc.)

Table 17: Complementary construction factor

The operating budget includes the construction material price in accordance with the scales established and according to various factors. Nevertheless, it does not include council tax costs, project fees, corrective actions, general and industrial profits. It equals to:

$$CO_{edf} = FE \times FC \times S \times C_{ce}$$

Where:

C_{ce} = Building construction price (€/m^2)
S = Useful built area of the building (m^2)

3.2.1.2.7.2. New Construction Costs

To assess the cost of new buildings, the same methodology as for refurbishment will be used. The only difference being that in new constructions, all percentages will be at 100%.

3.2.1.3. Protection, regulation and control

The costs corresponding to the protection of alternators, turbines and transformers, regulation systems of the hydropower plant, as well as their automation include the following concepts:

- Generation panel: it includes automatic switch, intensity and voltage transformers, as well as circuit breakers
- Control and protections: programmable controller, graphic panel, protection unit, analyzer of electric parameters, field components and synchronism unit
- Wiring, start-up and exploitation test
- Tele-management

As they share similar characteristics, they have been gathered into four power ranges, producing a cost distribution for each range, according to the following graph:

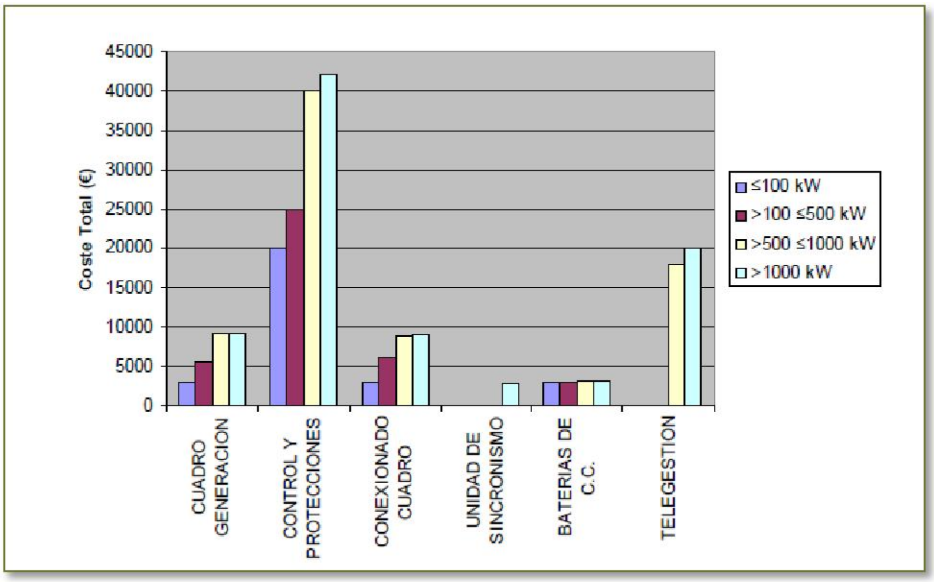


Figure 49: Protection, regulation and control total cost

Therefore, for each section of power, the following costs of protection, regulation and control are considered:

POWER	Costs of protection, regulation and control (€)
≤ 100 kW	29,000
>100 and ≤ 500 kW	40,000
>500 kW and ≤1.000 kW	80,000
>1,000 kW	86,000

Table 18: Protection, regulation and control total cost

3.2.1.4. Connection to the electric grid

To determine the costs of the transformation centre and of the protections of grid connections, two groups will be established:

a) Fixed costs that will only depend on the rated voltage of the grid. These costs will include:

- Customized equipment
- Cubicle of high voltage
- Network protection units
- Transformer protection system

b) Variable costs will be those depending on the power of the plant; that is, those corresponding to the power transformer and the bank of capacitors.

Fixed costs:

Power ≤100 kW

Automatic Interrupter
High sensitivity differential toroidal transformer
Voltage-Current transformers
Measuring equipment

Table 19: Fixed costs of the processing and grid protections. Power ≤100 kW

Power >100 kW

M.T. cells
Network protection unit
Table of metering and billing
Assembly and installation

Table 20: Fixed costs of the processing and grid protections. Power >100 kW (Source: Author)

- ***Variable costs:***

These costs may be determined by the following equation:

Power transformer cost (€)	$COST = 4043{,}2 \times \ln(S) - 15794$
Capacitor cost (€)	$COST = 0{,}0121 \times P^2 + 22{,}911 \times P + 343{,}64$

Table 21: Variable costs for grid connection

Where S is the power transformer and P the power generator.

- ***Total costs:***

Therefore, grid-connection costs are defined by the following expression:
Power ≤100 kW

	COST (€)
Vn = 400	$4500 + (0.0121 * P^2 + 22.911 * P + 343.64)$

Table 22: Grid-connection cost. Power >100 kW

Power >100 kW and ≤1,000 kW

	COST (€)
Vn = 24kV	$49887 + (0.0121 * P^2 + 22.911 * P + 343.64) + (4043.2 * l\,\imath(S) - 15794)$
Vn = 36kV	$62549 + (0.0121 * P^2 + 22.911 * P + 343.64) + (4043.2 * l\,\imath(S) - 15794)$

Table 23: Grid-connection cost. Power >100 kW and ≤1000 kW

Power >1,000 kW

	COST (€)
Vn = 24kV	$49887 + (\mathbf{4043.2} * \mathbf{l\,\imath}(S) - \mathbf{157\,94})$
Vn = 36kV	$62549 + (\mathbf{4043.2} * \mathbf{l\,\imath}(S) - \mathbf{157\,94})$

Tabla 24: Grid-connection cost. Power >1000 kW

3.2.1.4.1. Cost of transmission line

It is necessary to carry out energy distribution in high voltage to consumption points or distribution network. The length of the line will have an important influence over the viability of the project.

Depending on the power will use two types of lines:

- ***LV Line***

Used at power levels below 100 kW. The voltage of transport will be in LV, so that the line will consist of copper or aluminum conductors with 0.6/1 kV insulations.

The cost will depend on the section of the conductor and the type of installation (ground or air). These costs are those shown in the following tables:

LT Air lines	50 mm²	95 mm²	150 mm²
Km on the facade	7.560	8.873	10.500

Burried LT lines	50 mm²	95 mm²	150 mm²	240 mm²
Km 1 circuit	81.029	81.984	84.063	86.478
Km 2 circuit	85.628	87.528	91.718	96.527
Km 3 circuit	90.227	93.083	99.330	106.575
Km 4 circuit	94.831	98.627	106.964	116.624

Table 25: Cost of LV line

- ***HV Line***

Powers above 100 kW must be transported in MT. In this case, the conductor will be LA-56, with a simple circuit configuration.

The cost of the line (civil works and equipment) will be based on a cost per km (CLKM) including share of supports, conductors, insulators and other necessities. This cost has been obtained based on the scales provided by Endesa and the different bases of existing public and private prices. This cost has been set for the year 2008 at 14.658 €/km.

$$COSTE \quad LINEA = CLKM \times FA \times FT \times LL \times T_{17}$$

The cost of the line will be affected by three factors:

- Line length (LL)
- The accessibility factor for installation (FA), that will take a value of 1 for easily accessible lines and 1.25 for others with accessibility problems
- The factor of ground unevenness (FT) depends on how irregular the terrain for the construction of the power line is. A value of 1 will be taken for flat surfaces and 1.3 for rough terrains
- This cost shall include the supply and transportation of different elements.

3.2.2. Profitability Analysis

A hydroelectric project requires a few payments, spread over its life cycle, and provides incomes also distributed in the same period of time. The payments include the initial cost of investment, spread over time through external funding mechanisms, and some quantities with a fixed part (other than insurance and taxes payable on profits) and a variable (operation and maintenance costs). Revenues come from the electricity sold. At the end of the project (whose life is in general limited by the duration of the administrative approval) there will be a residual value that is always theoretically positive. The economic analysis aims to compare incomes and expenses for each of the possible alternatives to decide which of them is to be put up, or whether to give the project an end.

3.2.2.1. Financial mathematics

As the projects under study have, in general, income and expenditure programs that vary in time, it is necessary to convert these cash flows, whether negative or positive, to a common base. A certain amount of money spent or received at any given time has a different value if it is spent or received at another time. The cash can be invested over a given time interval, with the guarantee of a profit. Money and time are thus related. The term *present value* describes the value of a monetary amount at a time different from that in which it has been paid or received.

Assuming that the interest of money or *opportunity cost* is *r*, the amount spent *Ci* (and the benefit *Bi*), paid or received in the year *i*, is updated to year zero by the equation

$$Co = \left(\frac{1}{(1+r)^i}\right)\cdot C_i$$

The portion enclosed in brackets is known as update factor and there are tables showing the values of this factor for periods of time and opportunity costs.

To know the current value of a certain amount, to receive or pay within i periods of time (years, months or weeks), simply apply the above formula multiplied by the factor or equivalent course, called opportunity cost r and the value of i.

To facilitate the economic analysis, another mathematical concept is used too: the present value of an annuity. Annuity stands for a series of equal payments over a certain period of time. The present value of an annuity in n years, with an annual payment C, starting at the end of the first year will be the result of multiplying the payment C by the factor an, current value of a uniform series, equal to the sum of current values:

$$a_n = v^1 + v^2 + v^3 + \ldots + v^n$$

The following can be demonstrated:

$$a_n = \frac{1-v^n}{r} = \frac{\left((1+r)^n - 1\right)}{r\cdot(1+r)^n} = \frac{1-\left(1+r\right)^{-n}}{r}$$

3.2.2.2. Evaluation cost and Revenues

3.2.2.2.1. Revenues

There are two principal types of incomes:

Subsidies

Subsidies are defined as transfers of cash or goods between various government agents, and from these to other public or private entities and individuals, directed to an end, purpose or specific project activity with an obligation on the part of the recipient to comply with the conditions and requirements that have been established or otherwise, to proceed with its reimbursement.

Sales of energy

3.2.2.2.2. Cost

Costs have been detailed in previous sections.

3.2.2.3. Cash flows and their estimation

The net cash flow of a given time **t** is the difference between the fees generated by an investment at time **t** and the payments that it requires at the same time:

A = Initial investment

Q_t = Net cash flow in year t

$$Q_t = C_T - P_T$$

Net cash flows and its forecast in most investment projects is complex, however, there are certain rules to be fulfilled:

1. Difference between net cash flow and profits

In the majority of new projects, it is usually estimated that the total income of each period will coincide with the charges of that period and that all expenses except amortizations will coincide with the payments of the same period. Amortizations are yearly expenses that are not paid during this very year. When making an investment, they are not considered as costs of the year in which implantation takes place. On the contrary, they are divided into a depreciation rate to be discounted over successive financial years. However, when budgeting investments, it must be noted that the amortizations correspond entirely to the period where the disbursement is made. Therefore, the net cash flow of period t is equal to the benefit of t plus the amortization of t.

2. The moment in which net cash flows are generated

The net cash flow is generated at end of the exercise.

In an investment, the only payments and collections to be considered are those arising from the project.

- ***Considerations of cash flows***

- These can be positive or negative

Normally, receipts and payments occur during the year and not only at its end. For the sake of simplification, a single cash flow at the end of the year is considered

3.2.2.4. Economic evaluation methods

The simplest method of evaluating different projects is to compare the investment ratio to total power (or energy output). Clearly, this method cannot give an accurate indication of profitability since it does not directly include incomes. It is, however, a suitable early evaluation criterion.

3.2.2.4.1. <u>Static methods</u> (do not take into account the opportunity cost)

1. Payback method

The payback method determines the number of years required for the invested capital to be offset by resulting benefits. The required number of years is termed the payback, asset recovery, or break-even period. The calculation is as follows:

$$\text{Payback period} = \frac{\text{investment cost}}{\text{net annual revenue}}$$

The opportunity cost of capital is the return that could be earned by using resources for an alternative investment purpose rather than for the purpose at hand. Investment costs are usually defined as first costs (civil works, electrical and hydromechanical equipment) and benefits are the resulting net yearly revenues expected from selling the electricity produced, after deducting the operation and maintenance costs, at a constant value of money. ESHA estimated that an investment is interesting if the payback period does not exceed 6 or 7 years. However, the IDAE provides a range between 8 and 12. For practical purposes, IDAE figures will be used.

Nevertheless, the payback does not allow the selection among different technical solutions for the same installation neither does it allow choice among several projects that may be developed by the same promoter. In fact, it does not consider cash flows beyond the payback period and thus does not measure the efficiency of the investment over its entire life.

- <u>Disadvantages</u>**:**

- Ignores subsequent flows
- Does not take into account interest rates
- Does not consider the periods well

- ***Advantages:***

- Very simple
- Great utility for risk decisions
- It gives an idea of profitability

2. Return on investment method

The return on investment (ROI) calculates average annual benefits, net of yearly costs, such as depreciation, as a percentage of the original book value of the investment. The calculation is as follows:

$$ROI = \frac{net\ \ annual\ \ revenue - depreciation}{investment\ \ \cos t} \times 100$$

For this formula, depreciation is calculated very simply by using the straight-line method:

$$Depreciation = \frac{\cos t - salvage\ value}{operational\ life}$$

Using ROI can yield a quick estimate of the project's net profits, and can provide a basis to compare several different projects. Under this method of analysis, returns for the entire useful life of the project are considered (unlike the payback period method, which considers only the period that it takes to recoup the original investment). However, the ROI method uses income data rather than cash flow and it completely ignores the changing value of money. To get around this problem, the net present value of the project, as well as its internal rate of return should be considered.

- ***Energy Ratio (ER)***

This is the cost of producing a kWh. Usually, plants with an energy index of 0.30 c€/kWh are considered profitable.

$$ER = \frac{\text{Investment (€)}}{\text{Generated Energy (kWh)}}$$

The IDAE recommended an ER between 0.4 and 0.7€/kWh. This energy index increases with decreasing installed power.

- ***Power Ratio (PR)***

Is the cost of an installed kW.

$$PR = \frac{\text{Investment (€)}}{\text{Installed Power (kW)}}$$

According to data supplied by IDAE, **[IDAE, 2007]**[11] the mean value for mini-hydropower plants must be between 1,500 and 2,000 €/kW. However, this value corresponds to higher powered plants. When there are small amounts of power installed, the power rating increases when the total power of the plant diminishes. This is because the cost of equipment and the necessary works do not decrease at the same rate, as does the total power.

- ***Equivalents hours (EH)***

Its value is given by the ratio of delivered energy and power, so:

$$EH = \frac{Energy(kWh)}{Installed \quad Power(kWh)}$$

It is considered that mini-hydropower plants must have a number of hours equivalent or higher than 3,100 to ensure their profitability.

3.2.2.4.2. Dynamic methods

Dynamic methods take into account all incomes and expenditures over the life of the project and the time they occur.

1. Net present value method (NPV)

The expected benefits of an investment in a certain time and retained throughout its life are based on the prospective benefits flow. The difference between incomes and costs (discounted both) at year zero (in which the developer begins the investment) is known as net present value (NPV).

The equation for calculating NPV being:

$$NPV = -A + \frac{Q_1}{(1+k_1)} + \frac{Q_2}{(1+k_1)(1+k_2)} + \dots + \frac{Q_n}{(1+k_1)(1+k_2)\dots(1+k_n)}$$

[11] **IDAE** *Minicentrales Hidroeléctricas.* IDAE. Madrid. 2007

Where:

$k_1, k_2, \ldots, k_n$ = Discount rates or discounts applicable to each of the n-year project
A = Initial investment or investment size
Q_j = Net cash flow of year j

If k is constant:

$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \frac{Q_3}{(1+k)^3} + \ldots + \frac{Q_n}{(1+k)^n}$$

The calculation is usually done for a period of thirty years, because due to the discounting techniques used in this method, both revenues and expenses become insignificant after a larger number of years.

Different projects may be classified in order of decreasing NPV. Projects where NPV is negative will be rejected, since that means that their discounted benefits during the lifetime of the project are insufficient to make up for the initial costs. Among projects with positive NPV, the best ones will be those with greater NPV.

The NPV results are quite sensitive to the discount rate, and failing to select the appropriate rate may alter or even reverse the efficiency ranking of projects. Since changing the discount rate can change the outcome of the evaluation, the rate used should be considered carefully. For a private developer, the discount rate must be higher than the one that could be obtained from savings being kept in a bank. This discount rate, depending on the inflation rate, usually ranges between 5% and 12%.

- ***CRITERIA OF DECISION***

- Only those investments with positive NPV will be carried out. When the choice is between several projects with positive NPV, the one with a superior NPV will be chosen.

There are 3 possibilities:

- If the NPV is positive, this indicates that the implementation of the proposed investment will make up for the money spent, will meet all payments and will yield net gains equal to the amount expressed by the NPV
- If the NPV is negative or zero, the investment project should not take place because the wealth of the investor would be reduced through a loss equal to the amount indicated by the NPV

- ***Cost-Benefit ratio***

The benefit-cost ratio method compares the present value of the expected benefits against the present value of costs, according to the equation:

$$R_{b/c} = \frac{\sum_{0}^{n} \frac{R_n}{(1+r)^n}}{\sum_{0}^{n} \frac{(I_n + M_n + O_n)}{(1+r)^n}}$$

Projects with a ratio below 1 are automatically rejected.

- ***Internal Rate of Return method (IRR)***

The internal rate of return (IRR) method of analyzing a major project allows considering the temporal value of money. Essentially, it determines the interest rate that is equivalent to the Euro returns expected from the project. Once the rate is known, it can be compared to the rates that could be earned by investing the money in other projects.

If the internal rate of return is less than the cost of borrowing used to fund the project, it will be clearly a money-loser. However, to consider it profitable, a developer will claim that a project must yield IRR ratios at least several percentage points higher than the cost of the money borrowed. This is to compensate for the risk, time, and trouble associated with the project.

The IRR is that discount rate that equals the capital value to zero, therefore, it will be the value of r that makes the NPV zero. The NPV determines the absolute performance, while the IRR determines the relative profitability.

$$NPV = -A + \frac{Q_1}{(1+r)} + \frac{Q_2}{(1+r)^2} + \ldots + \frac{Q_n}{(1+r)^n} = 0$$

Only those investments where $r > k$ are of interest.

- ***CRITERIA OF DECISION***

In some cases $r > k \rightarrow R_n = r - k > 0 \rightarrow$ therefore, accept the project

In some cases $r = k \rightarrow R_n = r - k = 0 \rightarrow$ therefore, reject the project

In some cases $r < k \rightarrow R_n = r - k < 0 \rightarrow$ therefore reject the project.

Only those projects in which r surpasses the cost of capital are interesting.

If there are several investment options that comply with this, those whose return on net investment is positive will be given priority.

If several investment projects meet this condition, the largest one will be chosen.

3.2.2.5. Sensitivity analysis

Generally, there is an element of uncertainty associated with the alternatives studied. It is precisely this lack of certainty about the future that makes the economic decision-making one of the most difficult tasks to be performed.

The sensitivity study should be done with the most uncertain parameter. In such cases, it is desirable to determine how sensitive the IRR or the NPV are to changes of the unit-selling price. In other words, for this type of situation it is highly recommended to determine the unit-selling price at which the proposal would be economically attractive. The evaluation of a proposal may come across uncertainty in the costs of the life of the project. In these cases it is also possible to determine a curve showing the sensitivity of the IRR or the NPV to changes in costs or to changes in the life of the proposal.

Simultaneous changes are not usually carried out in different parameters, as it is very difficult to graphically display the results. Moreover, when most of the parameters of a proposed investment are uncertain, the sensitivity analysis technique is not recommended.

3.2.2.6. Conclusions

The economic study is a tool that facilitates decision-making on issues related to the environment as well as technological and social aspects, also contributing optimal methods for implementation of investment projects.

After studying the various parameters and their characteristics, we can draw the following conclusions:

The projects that should be accepted are:

- Highest NPV (always positive)
- Highest IRR (if they are greater than the social discount rate)
- Highest ratio Income/Cost (whenever more than one)
- The lowest payback period of investment (whenever recoverable)

And in our case we can also add:

- ***Profitable exploitations often include:***

- High heads in rivers with steep slopes, for fully new works
- Totally new heads in regulated rivers with headwaters reservoir
- Existing heads with civil works in good condition or requiring minor repairs
- Plants in which there is a possibility of repair of turbines and control equipment
- Plants in which most of the energy produced is used by the owner

- ***Exploitation is often questionable in:***

- Low heads in rivers with medium or low slope, for completely new work
- Totally new heads in non regulated rivers with headwaters reservoir
- Existing heads with poor civil works and very long channels
- Cases in which new turbines and automation equipment must be installed
- Cases in which the owner uses little of the energy that it produces

In any case, if it is decided to carry out the refurbishment or construction of a plant, a thorough economic and financial study is paramount.

3.3. ENVIRONMENTAL IMPACT STUDY[12]

The Environment is a set of physical, biological, economic, social, cultural and aesthetic elements that interact with other individuals and with the community in which they live, determining its shape, character, behavior and survival.

According to the European Union in Directive 85/337, environment would be the system including:

- Man, wildlife and flora
- Soil, water, climate and landscape
- The interactions between those factors
- Material assets and cultural heritage

It is said that there is an environmental impact when an action or activity produces a favorable or unfavorable change in any component of the environment. Therefore, the impact that a project has on the environment is defined *as the difference between the evolution of the environment without project and with project.*

[12] *Guide on How to Develop a Small Hydro Site. ESHA 2004*

3.3.1. Global impacts

Following the recommendations of the UN Conference in Rio on Environment and Development, in 2000, the European Union pledged to stabilize the emissions of carbon dioxide back to the levels of 1990. It is clear that to achieve this ambitious goal, Europe needs to improve its energy efficiency and a better use of renewable resources.

The original ALTENER programme targeted an increase of the contribution of renewables to total energy demand in the EU, from the current 4% in 1991 to 10% in 2007 and to duplicate, in the same horizon, the electric power generation from renewable resources. Regarding small-hydropower plants, this goal entails for the EU to increase annual average production from 30 TWh to 60 TWh. Achieving this goal would mean, in 2007, reductions of fossil fuel consumption by 10% thereby creating a reduced, 180-million-ton emission of CO_2.

However, considering what has been achieved in recent years, that goal has been missed and will continue to be unless administrative authorizations for new uses are unlocked, mostly due to problems related to the environment.

Some environmental authorities justify this blockage of licenses arguing the low power of small plants. This is unjustified in global terms if it is taken into account that it is possible to more than double capacity by refurbishing old plants, that is increase by more than 9,000 MW (equivalent to 9 nuclear power plants) current installed capacity in Europe. This is also inconsistent with those who claim to be supporters of renewable energy, and seem to forget the decentralized nature of renewable.

It is also true that, although from the standpoint of the global impact of electricity generation in mini-hydropower plants these have indisputable advantages, the fact remains that, being generally located in areas of high environmental sensitivity, they may produce, at the same time, considerable local impacts.

The advantage of mini-hydropower plants in the field of global impacts should not be precluded, without identifying impacts and introducing the necessary corrective measures.

A thermal power plant poses some environmental problems (the emission of carbon dioxide for example) that have no practical solution in the current state of technology. Howeve, given its economic importance, its authorization is passed at high administrative levels. A mini-hydroelectric plant, whose impact can be always mitigated, is authorized at lower administrative levels, where the influence of lobbyists is felt with greater intensity.

3.3.2. Identifying the impacts on small plants

It is essential to identify the impacts on the exploitation site and the technological solution chosen. Technologically speaking, the regulation of a reservoir has impacts, both quantitatively and qualitatively different from those generated by flowing water.

The next tables are an exhaustive description of possible impacts, based on European studies dealing with externalities, and made by groups of experts that perform Environmental Impact Assessments. However, it is not certain that all or most of this will be applicable to a specific project. The list identifies the event, persons or things affected, impact and priority at local and national levels.

EVENTS DURING CONSTRUCTION	PERSONS OR THINGS AFFECTED	IMPACT	PRIORITY
Geological Surveys	Wildlife	Noise	Low
Existing Vegetation Cutting	Forestry	Alteration of habitat	Medium
Enlargement of Existing Roads	General public	Creation of opportunities, alteration of habitat	Medium
Earth Moving	Site geology	Slope stability	Low
Tunnels Excavation	Site hydro-geology	Alteration of groundwater circulation	Low
Permanent Filling Material on Slopes	Site geology	Slope stability	Low
Embankment Realization	Aquatic life, site hydro-morphology	Alteration of river hydraulic	Medium
Creation of Temporary Earth Accumulations	Site geology	Slope stability	Low
Temporary Displacement of Persons, Roads, Electric Lines	General public		Negligible
Realization of Roads and Sheds for the Yard	Wildlife, general public	Visual intrusion, wildlife disturbance	Low
Water Courses Dredging	Aquatic ecosystem	Alteration of habitat	Medium
Temporary Diversion of Rivers	Aquatic ecosystem	Alteration of habitat	High
Use of Excavators, Trucks, Helicopters, Cars for the Personnel	Wildlife, general public	Noise	High
Human Presence During the Works on Site	Wildlife, general public	Noise	Low

EVENTS DURING OPERATION	PERSONS OR THINGS AFFECTED	IMPACT	PRIORITY
Renewable Energy Production	General public	Reduction of Pollutants	High
Watercourses Damming	Aquatic ecosystem	Modification of habitat	High
Permanent Works in the Riverbed	Aquatic ecosystem	Modification of habitat	High
Diversion of Watercourses	Aquatic ecosystem	Modification of habitat	High
Penstocks	Wildlife	Visual intrusion	Medium
New Electric Lines	General public, wildlife	Visual intrusion	Low
Ripraps	Aquatic ecosystem, general public	Modification of habitat, visual intrusion	Low
Levees	Aquatic ecosystem, general public	Modification of habitat, visual intrusion	Low
Flow Rate modification	Fish	Modification of habitat	High
	Plants	Modification of habitat	Medium
	General public	Modification of recreational activities	
Noise from electromechanical equipment	General public	Alteration of life quality	Low
Removal of material from streambed	Aquatic life, General public	Improvement of water quality	High

3.3.3. The construction phase impacts

Schemes of the diversion type, multipurpose reservoirs, inserted on an irrigation canal or built into a water supply system produce very different impacts from one another, from both a quantitative and qualitative viewpoint. A scheme making use of a multipurpose dam has practically no unfavorable impacts, since it is understood that when the dam was built the necessary mitigating measures were already incorporated. The location of the powerhouse will be at the base and shall not alter the ecological system.

Schemes integrated in an irrigation channel or in a water supply pipe system will not introduce new impacts over those generated when the canal and the pipe system were developed. On the other hand, diversion schemes present particular aspects that need to be analyzed.

3.3.3.1. Reservoirs

The impacts generated by the construction of a dam and the creation of the adjoining reservoir include, in addition to the loss of ground, the construction and opening of construction roads, working platforms, excavation works, blasting and even (depending on the dam size) concrete manufacturing plants. Other non-negligible impacts are the barrier effect and the alteration of flow to a river regulation that did not exist before. It has to be underlined that reservoirs are in fact not typical for small-hydropower plants. The majority of small-hydropower plants belongs to the run-off type without any big, dam-like construction work.

However, the impacts generated by the construction of a dam do not differ from those induced by any large-scale infrastructure development, whose effects and mitigating measures are well known.

3.3.3.2. Water intakes, Canals, penstocks, discharge channel

The impacts generated by the construction of these structures e.g. noise affecting the life of animals, danger of erosion due to the loss of vegetation through excavation work, turbidity of the water and downstream sediment deposition, etc. To mitigate such impacts it is strongly recommended that the excavation work be undertaken in the low water season and the disturbed ground restored as soon as possible. In any case these impacts are always transitory and do not constitute a serious obstacle to the administrative authorization procedure.

In view of its protective role against riverine erosion it is wise to restore and reinforce the riverbank vegetation that may have been damaged during the construction of the hydraulic structures. It should be noted that the ground should be repopulated with indigenous species, best adapted to the local conditions.

The impact assessment study should account for the effects of dispersing excavated material in the stream and the unfavorable consequences of construction workers living in a usually uninhabited area during the construction period. This impact, which may be negative if the scheme is located in a natural park, would be positive in a non-sensitive area by increasing the level of its activity. Vehicle emissions, excavation dust, the high noise level and other minor burdens contribute to damaging the environment when the scheme is located in sensitive areas. To mitigate the above impacts the traffic operation must be carefully planned to eliminate unnecessary movements and to keep all traffic to a minimum.

On the positive side, it should be noted that the increase in the level of activity in an area, by using local manpower and small local subcontractors during the construction phase is to be welcomed.

3.3.4. The operation phase impacts

3.3.4.1. Sonic impact

The allowable level of noise depends on the local population or isolated houses near the powerhouse. The noise comes mainly from the turbines and, when used, from the speed increasers. Nowadays, noise inside the powerhouse can be reduced, if necessary, to levels in the range of 70 dBA, almost imperceptible when outside.

Concerning sonic impact, the Fiskeby power plant in Norrköping, Sweden, is an example to be followed. In the scheme, the owner wanted a maximum internal sound level of 80 dBA at full operation. The maximum allowed external sound level, at night, was set at 40 dBA in the surroundings of some houses located about 100 meters away.

To reach these levels of noise it was decided that all the components (turbines, speed increasers, and asynchronous generators) would be bought in one package from one well-known supplier. The purchase contract specified the level of noise to be attained in full operation leaving the necessary measures to fulfill the demands from the part of the manufacturer. The supplier adopted the following measures: very small tolerances in the gear manufacturing; sound insulating blankets over the turbine casing; water cooling instead of air cooling of the generator and a careful design of ancillary components. As well as the usual thermal insulation, the building was provided with acoustic insulation. Consequently, the attained level of noise varied between 66 dBA and 74 dBA, some 20 dBA lower than the average Swedish powerhouses. Having a single supplier, the issue of responsibility was eliminated.

3.3.4.2. Landscape impact

There was a tendency to reject any change, even if small, in the landscape that surrounds us. Most towns would reject a new development in neighborhoods or an artificial beach with sand from an underwater site, although in many aspects, including landscaping, these changes improve environmental conditions. The problem is particularly acute in those hydraulic installations located in a mountain area, middle or high, environmentally sensitive, or in an urban area of historic character. There is no doubt that each of the components that make up the utilization has the potential to produce changes in the landscape. The design and unfortunate location of only one of them can decisively affect the acceptance of the project by the public. It is true that progress has been made, from the times in which small-hydropower plants proudly displayed the mass of penstocks, to the recently constructed ones in environmentally sensitive places, where it is difficult to identify a single component. It is important to be aware of the problem and to seek, from the pre-project level, those solutions that lead to the smallest possibility of rejection.

Although voluminous, most of the components can be hidden from sight, if topography and vegetation are used appropriately. The use of non-reflective paint with colors that fade into the landscape, the construction of dams on the basis of rocks simulating rapid appearance, the design of a power plant that is closer to a fisherman's cabin than to an industrial building, etc. can take a project that faced strong local opposition to be accepted with pleasure. When the place is particularly sensitive and the economic potential of the use is supported, amazing solutions can be found, and a substantial use of power can be located, without dishonor, in a national park.

3.3.4.3. Biological impacts

3.3.4.3.1. In the reservoir

Reservoir projects are very unusual in small-hydropower plants although there are some schemes that store enough water to operate the turbine only during the periods of maximum electrical demand. Such operation is referred to as peaking or peak-lopping. In integral low head schemes, peaking can result in unsatisfactory conditions for fish downstream because the flow decreases when the generation is reduced. The lower flow can result in stranding newly deposited fish eggs in spawning areas. The eggs apparently can survive periods of de-watering greater than those occurring in normal peaking operations, but small fish can be stranded particularly if the level fall is rapid.

3.3.4.3.2. In the streambed

A substantial proportion of minihydro plants use the diversion configuration, in which water is diverted from a stream or a lake into a hydroelectric plant, perhaps kilometers away from the diversion point, to take advantage of the gain in head. The reduction in flow in the streambed between the point of diversion and the tailrace downstream of the powerhouse may affect spawning, incubation, rearing, and the passage of fish and of living space for adult fish.

Concerning peak operations (not typical for small-hydropower plants) significant and frequent changes of discharge can ruin aquatic life because certain areas of the riverbed are flooded and then dried up again periodically.

There is here a clear conflict of interest. The developer will maintain that the generation of electricity with renewable resources is a very valuable contribution to mankind, by replacing other conversion processes emitting greenhouse gases. The environmentalists will say, on the contrary, that the water diversion in the stream represents a violation of the public domain.

3.3.4.3.2.1. Ecological flow

Institutionally, this conflict is regulated by the Administration, which uses the existing legislation to set a permanent level of water to be preserved in the section. This is known as reserved or ecological flow. All methodologies for environmental flow determination in Europe and the USA can be classified into two groups:

Hydrological methods are based on the analysis of historical data of flows and generalized empirical formulas embodied in easy and quick applications or obtained by direct application of flat rates.

- Using a percentage (10%, 15%, etc.) of the *module* (this concept will be described later on)
- Using Matthey's formula (based in the Q_{347} and the Q_{330}, representing the flow exceeded 347 and 330 days per year respectively), which inspires the Swiss and Austrian laws and regulations of the Principality of Asturias and Navarra Autonomous Community in Spain.
- The method of Tennant (1976), which was developed for the rivers of Montana, Wyoming and Nebraska (USA), proposed minimum flows for different percentages of the module that varied with the time of year.

Hydro-biological methods are those based on field data collections for each river in particular, considering both hydraulic and biotic parameters.

- The habitat assessment method
- The wetted perimeter method (Randolph and White, 1984)
- Incremental analysis
- The method of microhabitat of Boveeand Milhous (1978; Stalnaker, 1980)
- The method for the conservation of habitats of Nehring, all precursors to a greater or lesser amount of the methodology PHABSIM (Physical HABitat SIMulation; Bovee and Cochnauer, 1976; Bovee, 1986)
- The methods MDDDR (Méthodes différentielles de détermination du débit réservé) and DRB (Débit de Réference Biologique) based on the works of Cacas, Dumont and Souchon from the CEMAGREF (Francia), well proven in streams of high mountains (Hautes Alpes)
- The method DGB (Débit de Garantie Biologique), developed by HydroM (Toulouse Francia1989)
- The method of Weighted Usable Width (APU) (Garcia de Jalon, Spain)

Most of these methodologies are based on the knowledge of the physical structure of the channel to study a variable or set of variables of the runoff, knowing its flow at any time. To this end, channels are characterized as independent from the flow regime, a simplification that becomes necessary to address the problem.
Once the channel structure is known, we study the modification of variables involved in the runoff (depth, speed, longitudinal slope, roughness) based on a process of

sustained torque hydraulic simulation methodology IFIM (Instream Flow Incremental Methodology).

Hydrological methods are easy to apply but do not obey any scientific basis and are therefore arbitrary. They can lead to excessively high minimum values in rivers with accused droughts and to low values in rivers with moderate droughts.

Habitat simulation methods require long sampling efforts, cannot be extrapolated to other rivers and sometimes use criteria that are subjective (and thus lose their scientific character and are as arbitrary as the others). In most countries, UE legislation at national levels considers ecological flow a percentage of the annual average flow or *module*. In France, Act 84-512 (Law on freshwater fishing) of 29.06.1984 requires a minimum flow of 10% of the module in rivers with an annual average flow under 80 m^3/s. In streams with more than 80 m^3/s of average flow, the environmental flow is set at 5% of the module (Art. 232-6 du Code Rural). These are the minimal values to respect but every local authority, if necessary, may impose a greater ecological flow.

In Ireland, the minimum value equals to 1% of the module, but in the west of the country, where most salmon rivers require higher values (broadly equivalent to the flow through the river 30% of the year or Q_{110}). In Portugal, based on the hydrological and biological characteristics, INAG value determines the time of grant approval. In Austria, the rule is based on the Q_{347}, the flow that exceeds 347 days a year. In Spain, the value varies greatly depending on the region: in Navarra it is 10% of the module for cyprinids and Q_{330} for salmon farming areas; in Asturias it has the largest values, obtained by applying the following formulas: a) $0,35Q_{347}$, b) $15Q_{347}/(LnQ_{347})^2$, c) $0,25Q_{347} + 75$, for all rivers in general, and this value plus 4 $l/s/Km^2$ for salmon farming rivers.

Once the ecological flow is set, adjustments in hydraulic devices must be perform to comply with the requirements.

It should be emphasized that if any of the hydrobiological procedures above is used in determining the environmental flow, at the level of project implementation, a series of measures that will lead to a decrease in the flow can be developed: planting trees on the banks to increase the shadow effect, throwing gravel at the bottom to improve the substrate, enhancing streamside vegetation to combat erosion, etc.

So, the voids and interstices of the substrate (holes between the blocks and gravel) must be taken into account, as well as submerged ledges or caves on the banks and the existence of submerged rooted stumps which consist of a refuge. Riparian vegetation is also favorable if it is near the water surface because it provides fish of any size with shade to defend itself against heat or from land predators. All these elements help to define what the APU method calls the coefficient of refuge ***Ir***. As this coefficient increases, the minimum flow required for biological survival decreases.

This gives for the first time the possibility to act positively on the shorted section to reduce the value of the ecological flow, improving profitability of its use, without damaging the fish habitat.

3.3.4.3.2.2. Fish passes (upstream fish)

Anadromous fish are those that spawn in fresh water but spend most of their lives in the ocean. Catadromous fish are those that spawn in the ocean, reach adulthood in fresh water and require passages at dams and weirs. A great variety of fish pass designs are available, depending on the species of fish involved. Otherwise, freshwater fish will have restricted movements.

The upstream passage can be provided through several means: fish ladders, lifts (elevators or locks), pumps and transportation operations. Pumps are a very controversial method. Transportation is used in high dams. These highly technical approaches are rather unusual in minihydro power schemes. A great variety of constructions and design of fish bypass systems is the main approach in small-hydropower plants. Site and species-specific criteria as well as economic concerns will determine which solution is most appropriate.

Fish bypass systems (natural-like creek without steps, pool and weir, Denil-passes, vertical slots, hybrid etc.) can be designed to accommodate fish that are bottom swimmers, surface swimmers or orifice swimmers. However, not all kinds of fish will use ladders. Fish elevators and locks are favored for fish that do not use ladders

The most common fish pass is the weir and pool fish pass, a series of pools with water flowing from pool to pool over rectangular weirs. The pools then play a double role: provide rest areas and dissipate the energy of the water descending through the ladder. The size and height of the pools must be designed as a function of the fish to be handled. The pools can be supported by:

- Baffles provided with slots, so that both fish and bedload, pass through them
- Baffles provided with bottom orifices large enough to allow fish to pass
- Baffles provided both with vertical slots and bottom orifices

Pools separated by baffles with bottom orifices only do not have practical interest because they are limited to bottom fish swimmers. Salmons do not need them because they can jump over the baffle itself, and shads, for instance, are not bottom swimmers. The system of rectangular weirs (figure 50) is the oldest one, but presents the inconvenience that when the headwater fluctuates, the fish pass flow increases or decreases, resulting in a fish pass with too much or too little flow.

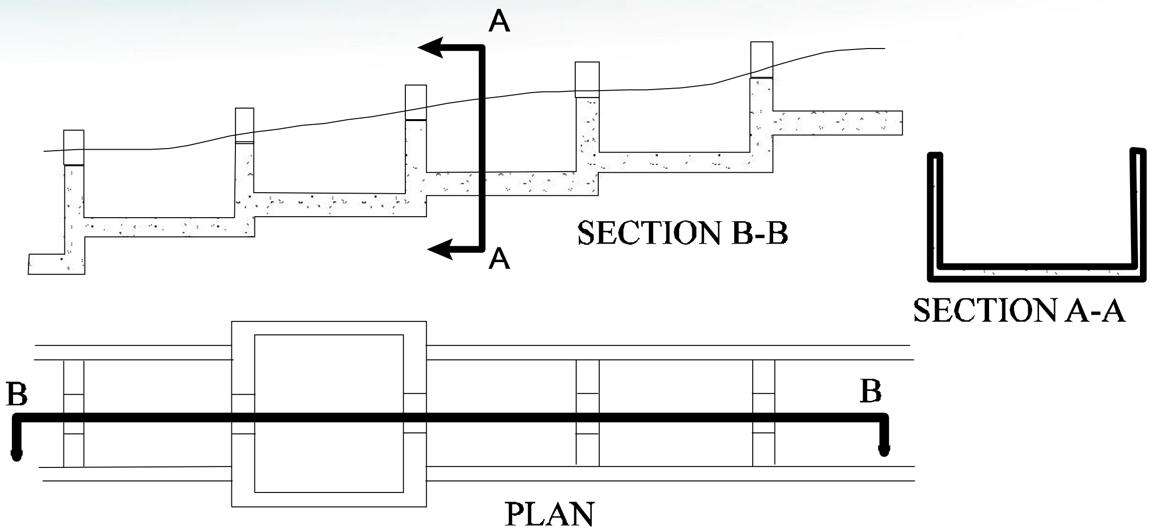


Figure 50: System of rectangular dams (Source: ESHA)

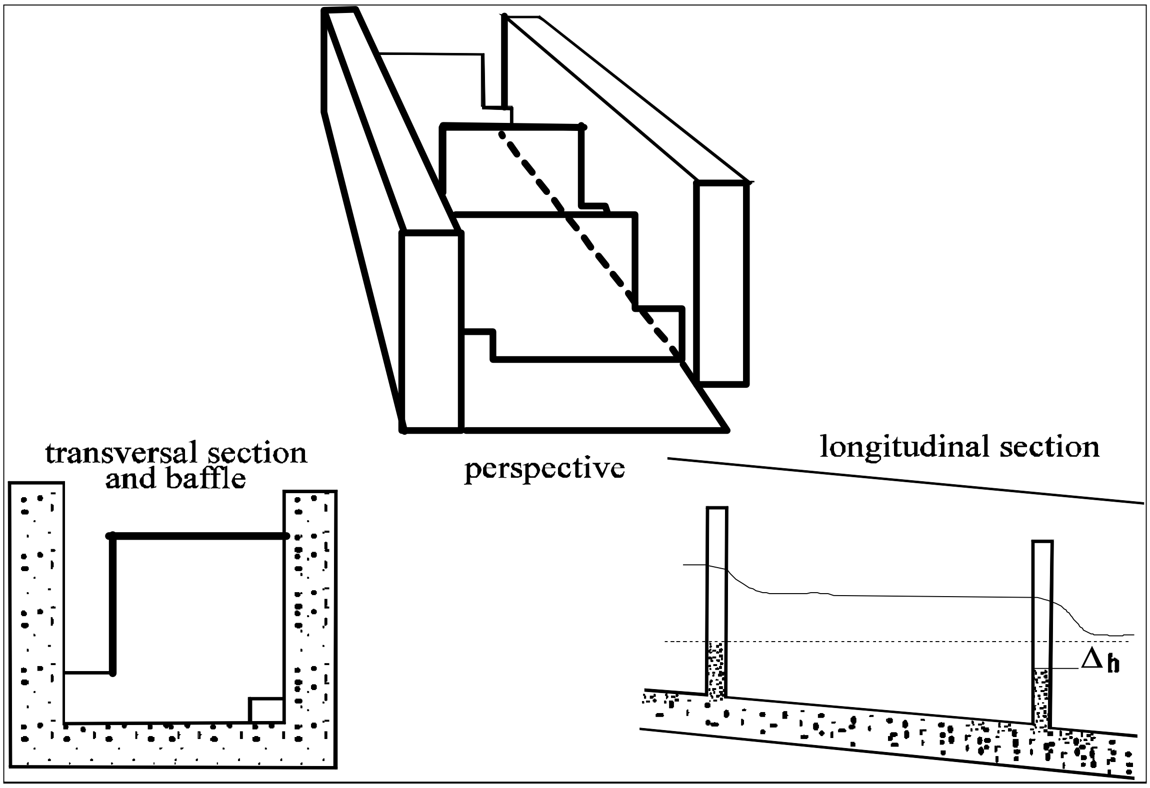


Figure 51: Fishpass baffles in section (Source: ESHA)

The figures to the right show a large population Asturian river trout and a truly rustic ladder with a similar configuration, located in a counting device of salmon in the Esla (Asturias). The width of the pond varies between 1.20 m and 2.40 m for distances between 1.80 and 3.00 m and the gap between successive ponds is about 25 to 40 cm. For the shad, for example, the gap should not exceed 25 cm. Salmons do not require critical parameters. There are computer programs that facilitate the hydraulic calculation of these steps and are used to optimize widths, lengths, hydraulic loading, slopes and dimensions of slots and holes.

Figure 52: Fishpass with vertical slots (Source: ESHA)

Figure 53: Rustic fish ladder for salmon (Source: ESHA)

The fish pass retardant was designed by and Lachadende Denil, and consists of a straight channel, with slopes up to 1:5, a width between 60 cm and 100 cm, and equipped with diaphragms arranged regularly as shown in the figure below. These diaphragms are dedicated to slowing down the flow so that fish can be traced through the indentations performed on the diaphragms. Fish must cross over one time and if the gap is very strong (> 2 m), intermediate nursing ponds must be provided. The steps with flame retardants are generally very selective and are only suitable for large migratory movements.

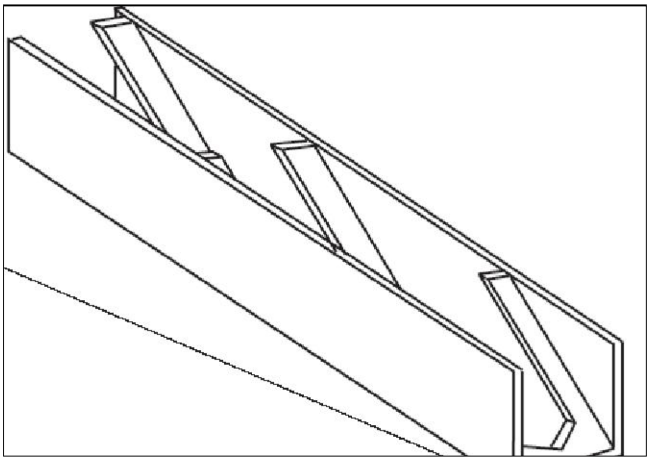


Figure 54: Fish pass retardant. (Source: ESHA)

The *Borland* lock is a static and relatively inexpensive solution for fish to pass over high dams. It operates on a principle similar to the navigation lock, fish come from a fish ladder into a chamber where they are trapped. At one point, the entrance to the chamber is closed and the tunnel that links it with the top of the dam is filled with water. After filling the tunnel, the fish, attracted by the current, rise up to the upper chamber from where they go out swimming.

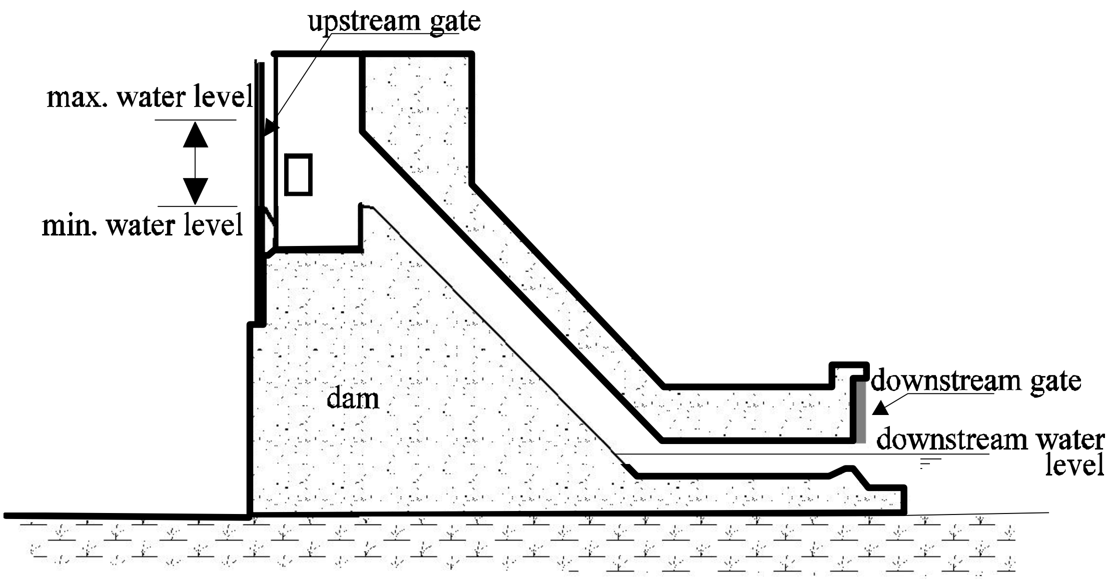


Figure 55: Borland lock (Source: ESHA)

In dams with more height it is necessary to deploy capture and transport devices. In these, fish are trapped in a bucket to be transported upstream, either by water (e.g. by a navigation lock), by lift or funicular, or more simply by truck. In France, EDF has developed very simple steps whose results have been spectacular. The Golfech elevator, for example, in 1989 allowed to lift up one hundred and twenty tons of alewives (about 66,000 individuals), which until their installation were blocked at the foot of the dam.

For a step to fulfill its mission, fish must be attracted to its entrance. Its correct location and the suitable hydrodynamic conditions of the environment (flow, speed, power lines, etc.) condition the success or failure of the device. The further from the entrance to capture the fish, the greater its chance of attraction. In the case of salmonids, the current output of the scale, should be between 1 m/s and 2 m/s, although the steps are fed with very cold water or hot (less than 8 °C or more than 22 °C), we must reduce the speed, as fish become lazy and do not jump. If the flow has to be prevented from circulating around the step, water can be injected at its entrance (see the figure below).

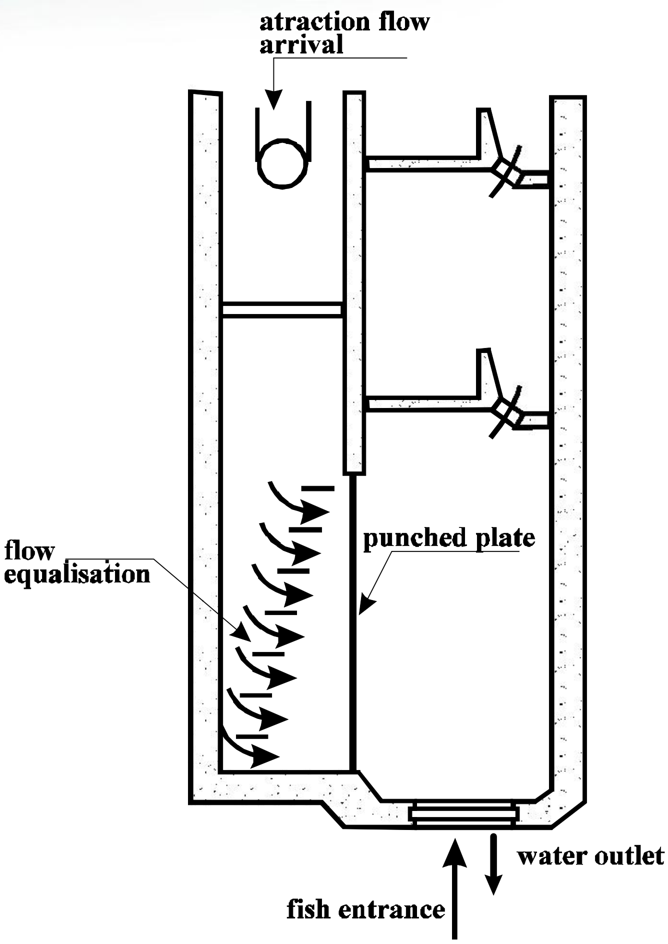


Figure 56: Water attraction facility (Source: ESHA)

It is recommended to set the entrance near the dam due to the fact that salmonids tend to look along the barriers. In low-lying plants without derivation, the entry should be located in the margin next to the powerhouse, as shown schematically in the figure. If the fish ladder is on the opposite bank, there may be a danger for fish to be swept downstream by the current spillway, returning to the initial position.

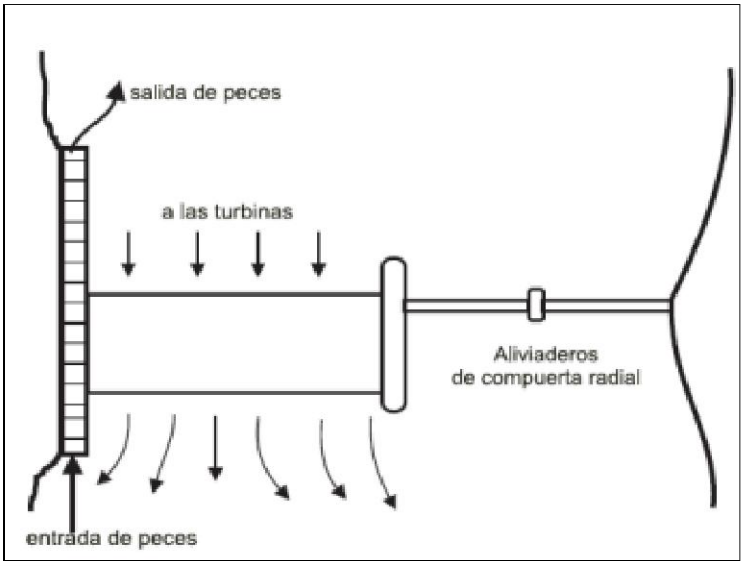


Figure 57: Fish ladder located in the margin next to the house (Source: ESHA)

The behavior of migratory fish is not the only factor to consider when choosing the location of a ladder. Its access in times of floods as well as its protection against floating bodies and its accessibility from the ground to guarantee its monitoring, control and maintenance are paramount too. A fish passage requires careful maintenance or, otherwise, it will not play its role properly.

The **way out** should be in an area of deep water: at least one meter, so that fish can reach with no extra effort a resting place before continuing their migration. No way out will be placed either in a fast flowing, stagnant water or recirculation areas in which the fish could become trapped. These must be protected from poachers and so, it is recommended to fence the area, protecting it with a door locked or even covering it with a grid.

In the outlet channel, the output of the turbines should have a grid of fixed bars, preferably hinged, to allow the exit of foreign bodies but totally prevent the entry of fish upstream.

Some steps to slow down can also be used as steps for canoes if their width (never below 1.40 m) allows doing so.

3.3.4.3.2.3. Fish passes (downstream fish)

Turbines may wash away a large proportion of migrating fish on their journey downstream as well as many resident ones if the proper precautions are not taken. In the past, mortality was low with slow turbines. But by increasing the speed of turbines, the mortality rate rises up to 35% when the rotor speed exceeds 30 m/s. Unfortunately for fish, rapid turbines are more and more frequent in small plants.
The mortality rate in bulb or Kaplan turbines does not exceed 6%, and recent studies seem to show that, by altering the design of the blades in their area of contact with the cube, this percentage can be reduced. The higher the performance of a turbine is, the lower its mortality rate. This is the reason why a turbine, when operating at partial load, produces more mortality than at full load. Alden Research Laboratories have designed a new model of 2-blade Kaplan turbines that move all kinds of fish with less than 10% mortality.

The mortality rate is much higher in action turbines and increases with head height, with the height of the runner over the water level in the outflow channel, with the peripheral speed of the impeller and with the number of blades.

Scottish screening regulations from 1994 (in theory, the most demanding in the world given the richness of salmon in their rivers) require all plants to install, from January 1988, a grid system with an aperture of 12.5 mm x 12.5 mm or less than 12.5 x 25 mm, to prevent the passage of juvenile salmon of 11 cm in length, almost the smallest size of salmon during their migration. Yet, it allows the use of alternative techniques if they are proven effective.

To prevent fish from passing through the turbine, a wide range of excluder devices is available nowadays, which can be grouped into three basic categories:

- Physical barrier systems
- Behavioral guidance systems
- Collection and release systems

Usually, these systems are installed at the entrance of the water intake. When it cannot be installed in its own water supply, an additional device must return the fish to the river. Migratory fish and, to a greater extent resident fish, move downstream with the current flow. When designing a device of exclusion, this behavior must be taken into account and it must be configured so that the fish receive a positive hydraulic stimulation.

- ***Physical barrier systems***

There are on the market large numbers of physical barrier systems: fixed screens, vertical or inclined, vertical continuous tapes, drums and rotating horizontal cylindrical screens. All these use a device with openings small enough so that targeted fish cannot pass through them. The screen itself may be a mesh, woven wire or galvanized steel or synthetic monofilament, a plate of steel or aluminum perforated or a grid built with stainless steel profiles. The most common one is the perforated plate (typically 2 mm thick) with holes of 4 mm in diameter and spaced 5 mm, which is cheap and is easily cleaned with mechanical brushes. The monofilament mesh is too flexible for the mechanical brushes but can be cleaned by reversing the flow of water or through compressed air jets. The woven mesh steel wire is very tough but the brush tends to get adhered to its surface. The speed of the flow must allow fish to swim away without actually hitting it. Its value depends on the type and size of fish and, of course, an evenly distributed flow, less than 1.4 m/s (measured 10 cm upstream). This requires the use of large-area barriers, when dealing with important flows.

The screens are installed at an acute angle with the direction of the flow and placing the bypass device at its lower extremity. This angle should not exceed 45 degrees, so that the speed that drives the fish parallel to the screen is always greater than the dragging force. The current distribution must be uniform because, otherwise, at those points where the approaching speed exceeds the average, the fish will collide against the screen while in those others in which it is lower they will be delayed and exposed to predators.

Regardless the system chosen, it is necessary to have a cleaning mechanism to avoid the accumulation of brush. The brush attached to the screen can harm fish and cause structural damage. Fixed screens are generally cleaned with mechanical brushes, but a compressed air stream can also be used as well as inverted water flow.

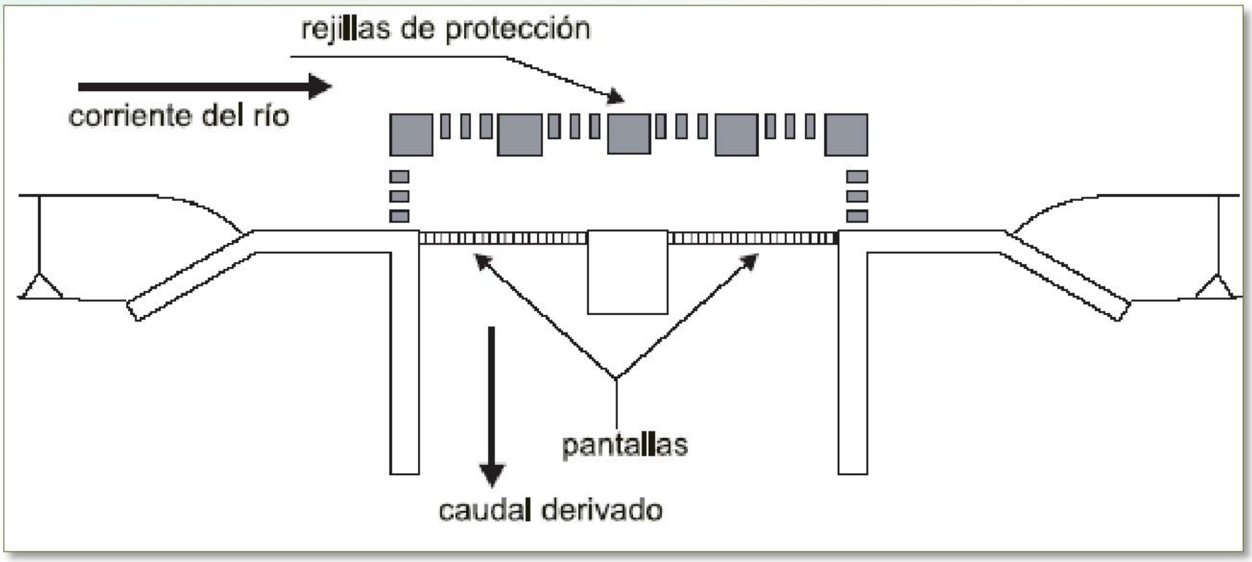


Figure 58: Classical water intakes (Source: ESHA)

When the diverted flow exceeds 3 m^3/s, fixed screens are difficult to install due to their large surface area. The tapes are powered from the mechanical point of view, more complicated than tumblers, but they require less space for installation.

The self-cleaning Eicher screen can be found among the less conventional solutions. This is installed inside the penstock in angle with the flow. This screen allows much higher speeds than those allowed by conventional screens. As shown in the figure, fish move across the screen until a channel through which they are forwarded to the discharge channel. Periodically, and for a very short time, the screen is rotated around a horizontal axis to present a different face to the current flow so that water drags the brush attached. In the two facilities that we know of, the speed of water in the pipe is about 2.4 m/s. As in this screen fish slide over it, it must be smooth. The results obtained so far allow for a mortality rate equivalent to that of conventional displays with greater area. Another type of plant that tolerates higher current velocities is being developed under the sponsorship of EPRI, known as Modular Inclined Screen (MIS). This is a standard modular design, easily adaptable to any use. The MIS module consists of an entrance protected by a grill cleaner, a mesh of stainless steel sections, angles between 10 and 20 degrees with respect to the current, and a bypass to divert the fish into a return conduit. This screen (as in the case of Eicher) is mounted on a pivoting axis in order to turn it to be washed upstream. The length of the module, completely closed, must not exceed 15 m. Depending on the angle of each module, these can stand between 14 and 28 m^3/s, not exceeding an approach speed of 3.5 m/s. If more flow is needed, more modules can be attached. Practice has confirmed that, by its design, an even distribution of passing current is obtained, although the water enters the module at an angle of 45 degrees. As a result, fish are diverted without being damaged by using current velocities much higher than those used in conventional fixed screens.

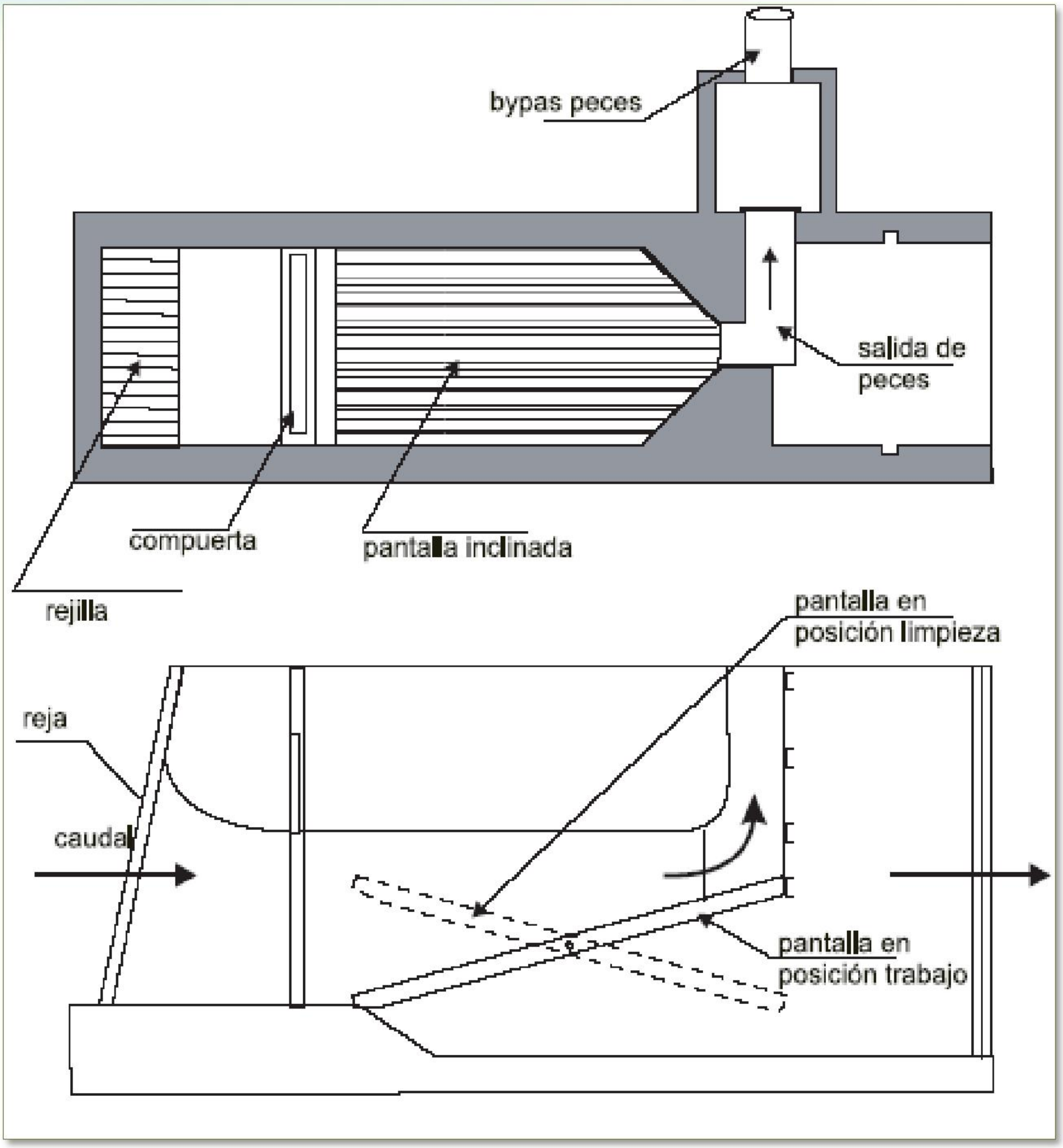


Figure 59: MIS module (Source: ESHA)

In acceptance tests of the prototype, using current rates over 2 m/s, the survival rate was 99%. The photograph below, courtesy of DULAS Ltd., shows another innovative self-cleaning screen. Known as the Coanda (that takes advantage of the *coanda* effect widely used in mineral concentration). This screen is actually a dam faced downstream which is formed by a curved screen constructed of stainless steel cross sections.

Figure 60: Self-cleaning screen (Source: ESHA)

As shown in the figure below, water passes through the profiles and is collected in a channel located below the screen. Fish, scum and 90% of particles with diameters over 0.5 mm make their way downstream. Thus fish are not damaged after slipping on the screen surface that must be very smooth. Fish cannot be dry. So, it is necessary that a certain quantity of water (which could be the ecological flow) flows permanently on the screen.

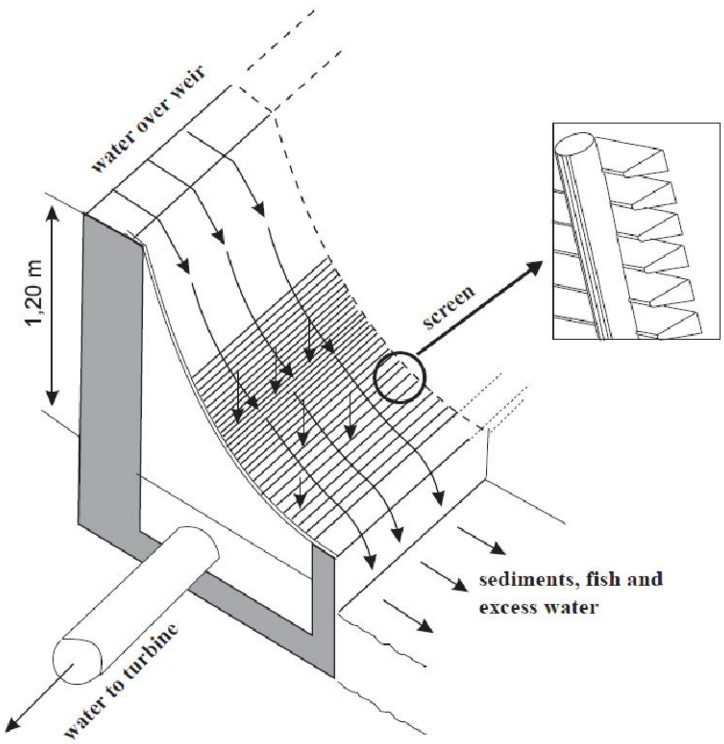


Figure 61: Coanda screen diagram (Source: ESHA)

This flow also drags the brush that may be left at the bottom of the screen and the debris that would endanger the survival of the fish held in the area. The head loss caused by this type of display is high, between 1.20 and 1.60 m. Therefore, it is not recommended for low-altitude heads. The screen can filter up to 140 l/s per linear meter.

- ***Behavioral guidance systems***

Behavioural guidance systems and a variety of alternative technologies to divert or attract downstream migrants have been the object of studies carried out recently by the Electric Power Research Institute (EPRI). These technologies include strobe lights for repelling fish, mercury lights for attracting fish, a sound generating device known as *hammer* for repelling fish as well as a number of electrical guidance systems. It has not yet been demonstrated that these responses can be directed reliably. Behavioral guidance techniques are site and species specific and it appears unlikely that behavioral methods will perform as well as fixed screens over a wide range of hydraulic conditions.

Behavioral screens operate by using the natural response of fish to a stimulus to deflect the fish away from the stimulus. A number of behavioral systems have been tested and acoustic systems have been found to be the most effective ones. For fish to be repelled by a sound, the level of the sound must be high enough to elicit a reaction, taking account of background noise. The background noise issue is important, especially where acoustic systems are deployed next to underwater machinery such as pumps and turbines. The most effective signal types in all applications are based on artificially generated waveforms that rapidly cycle in amplitude and frequency content, thus reducing habituation. A human equivalent would be standing near a wailing police or ambulance siren. It simply gets uncomfortable, so you move away! Deflection is usually the best course of action, as fish are moved swiftly from the source of danger (e.g. water intake) into a safe flow. The BAFF (Bio Acoustic Fish Fence) system produces a "wall of underwater sound" by using compressed air to generate a continuous bubble curtain into which low frequency sound (varying between 50 and 500 Hz) is injected and entrapped. Although well-defined lines of high level sound (at least 160 dB) are generated within the bubble curtain, the noise levels are negligible a few meters away from it. By restricting the sound curtain to a small area, the system allows fish to act normally throughout the remainder of the reservoir or river. The figure below illustrates the disposition of a system of underwater acoustic transducers, which transmit their sound into a rising bubble curtain to create a wall of sound to guide fish out of the turbine passage.

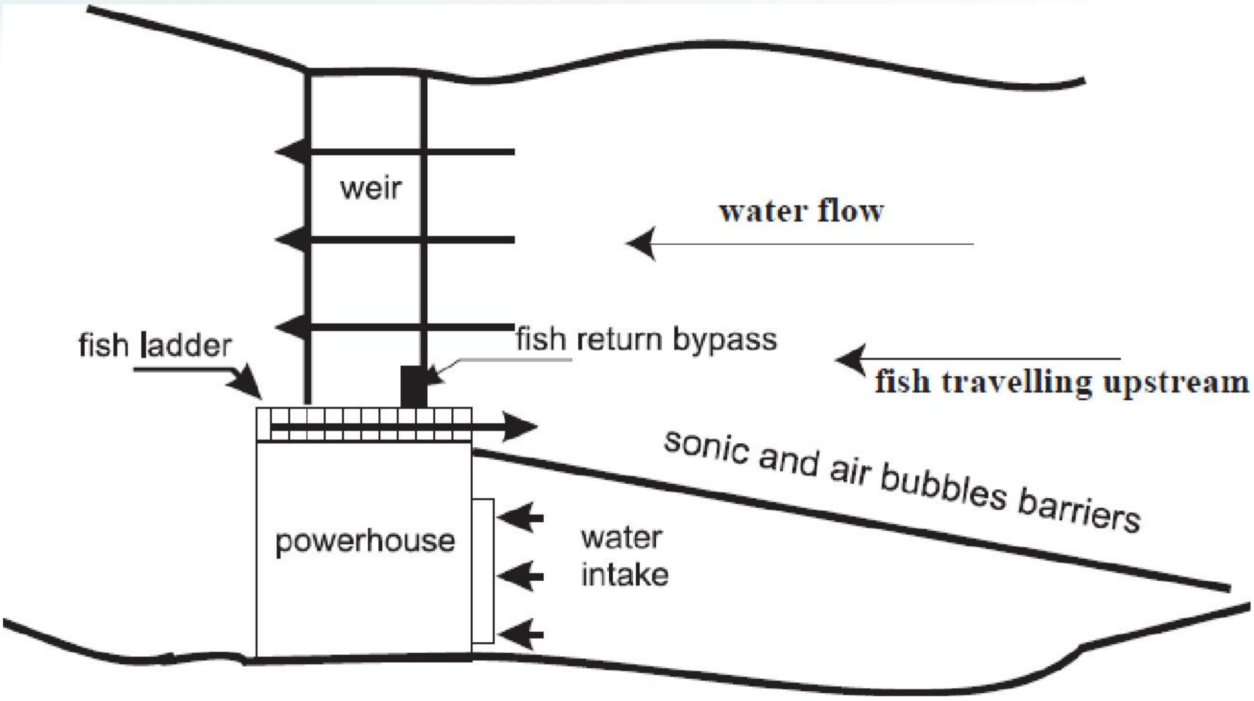


Figure 62: Bio-Acoustic Fish Fence (Source: ESHA)

- ***Collection and release systems***

These use concepts similar to those of the devices used in ascending pathways: collect fish before they reach the water intake then ship them by truck or similar means. However, the task of collecting is more complicated than ascending steps, where fish come to a point of concentration, attracted by the undertow. Here, very thin monofilament mesh must be used, as fishing nets. The fish collected through this system show signs of stress and superficial wounds, so that it is not recommended. These systems are the ones that ensure the exclusion of eggs and larvae, although it has been shown that eggs and larvae suffer virtually no damage with reaction turbines.

- ***Return path or bypass***

The screens placed at the entrance of the water supply need not return line because the fish washed away, parallel to the screen, return to the river over the spillway that controls the environmental flow. The experience concludes that the decline in average height overflow causes a reduced mortality rate (certainly less than that produced by the passage through the turbines), especially if well designed.

When the screen is placed within the intake, it is necessary to have a way to return fish to the river. To achieve this, fish must be prevented from swimming against the flow. So, the line must be below the screen supposedly installed with a certain angle to the stream. The entrance to the canal should be wide since fish are reluctant to enter small ducts. With vertical fixed screens, the tube should have a rectangular section with a width of around 45 cm and should be adjustable through the use of metal walls in order to control the water flow, which must not exceed the ecological one.

The return duct may have a tubular or a channeled section, preferably open, both to facilitate preservation and to avoid the darkness that is generally rejected by fish. If the tubular section is filled, eddies must be avoided too since fish are likely to absorb them and be damaged when reaching lower pressure zones. The duct must end in a low turbulence area so that fish can recover quickly and not be exposed to predators.

3.3.4.3.3. In the terrain

Open flumes may sometimes be an obstacle to the free passage of animals. To avoid this, nowadays, open flumes are entirely buried and even repopulated with vegetation so that they do not represent any barrier. In contradiction, the burial of water conveyance structures is said to be a loss of aquatic habitat for several purposes. It is reported that, sometimes, animals may fall into an open flume without any chance to get out due to its rectangular cross section. Certain ladder constructions may serve effectively at rather low cost. Other construction works in connection with small-hydropower plants will not produce an ecological impact worth mentioning.

3.3.4.4. Archaeology, cultural objects

During the construction phase, any archaeological remain of some value must be prevented from being affected or lost. The problem is more severe when reservoirs are used, as objects can be flooded and even monuments of historical value.

3.3.5. The impacts of transmission lines of electricity

3.3.5.1. Visual impact

While it is true that current trends lead to highly dominant structures and, consequently, significant changes in the landscape, a structure built now will one day be part of the landscape and even become, in the future, legacy of the past. It seems clear, however, that power lines and their associated corridors have a negative aesthetic impact on the landscape. Adapting the lines to the landscape or even burying them can mitigate these impacts.

The optimal solution for a power line from a technical and financial perspective is the one that generally yields the worst impact. Indeed, to achieve a greater separation, pylons are placed at the top of hills, so that lines become a dominant feature of the landscape. Although a priori it cannot be said that a broken line performs better from a visual standpoint that a straight line, in general, the latter has more impact.

3.3.5.2. Impact on humans

After years of conflicting reports, experts say now that living in areas near power lines do not increase the risk of cancer and, more specifically, childhood leukemia. This is the conclusion reached by a team of researchers from the Cancer Institute of the United States, as published in June 1997 in the prestigious magazine "The New England Journal of Medicine". This publication shows that no such risk exists and even claims that it is high time to stop wasting resources on these studies and to use them to discover the true biological cause of leukemia. In any case, given the strain used in mini-hydropower plants (generally < 66 kV) electromagnetic fields are lower than those generated by electric appliances such as microwaves.

3.3.5.3. Impact on birds

Although birds are morphologically and aerodynamically adapted to move in the air, there are limits in terms of their ability to save artificial barriers. Power lines that pass near key areas from the ornithological point of view, should be located near the base of the cliffs, or close to the screen of trees, to compel the birds to fly above the wires. The danger of electrocution (touching simultaneously two phases or phase and neutral) is virtually zero for lines over 130 kV, and very low for the rest if suspended isolators are used instead of rigid ones.

3.3.6. Environmental regulations

Environmental regulations differ from region to region and country to country. To see a more in-depth analysis in your particularly territory please refer to RuralRES document D3.2 combined report for your country, and the Training section of the website which contains the pertinent environmental laws (http://ruralres.diphuelva.es/).

3.3.7. Conclusions

The conclusion is that it is possible to build a minihydro power plant in a natural park, with minimal impacts and avoiding the release of many tons of carbon dioxide, the main cause of the greenhouse effect. If a coal power station were to be installed plant were to be located within 300 km of a park, the impacts would be immeasurably greater as it could destroy the forests that the denial of the authorization for hydropower plants intends to protect.

- ***Advantages***

- It is renewable
- It does not consume. It takes water from a point and returns it to another at a lower level
- It is local and therefore avoids foreign imports

- It is completely safe for people, animals or property
- It does not generate heat or pollutant emissions (acid rain, greenhouse effect, etc.)
- It generates jobs during its construction, maintenance and operation
- It requires considerable investment being made in mountain areas typically very depressed economically
- It generates easily exportable expertise and technology to developing countries

- ***Disadvantages***

- It alters the normal development of biological life (animals and plants) in rivers
- The plants that have a reservoir have the problem of evaporation of water: there, the relative humidity increases due to water evaporation in the reservoir
- In the case of plants that had reservoirs built in tropical regions, studies have shown that they generate, as a result of stagnant water, large pockets of bacteria and infectious diseases
- The silt accumulated in the reservoir nutrients impoverishes the rest of the river

3.3.8. Preventive and corrective measures

The purpose of introducing preventive measures and/or corrective ones is:

- To avoid, reduce, modify, cure or compensate for project impacts on the environment
- To take as much advantage as possible of the opportunities provided by the environment for better project success

3.3.8.1. Air factor

- Conducting periodic irrigation during the transport of materials and vehicles
- Use of covered trucks

3.3.8.2. Vegetation factor

- The demolition process will require pruning and general cleaning of vegetation and the surrounding trees to facilitate the operation of machinery on the construction project. During the pruning, trunks should be protected with stakes and a mesh should be used to collect the branches that interfere with normal working. Any action that affects the bottom or tree roots will be executed under the supervision of a specialist officer. The perimeter of influence of the tree will be limited.

- The risk of forest fire can be analyzed by the application of the RSCIEI to the plant, and considered that the use of the building system has a capacity of fire resistance EI-120, indicating the integrity of the passage of flames and hot gases (E) and thermal insulation (I). Fire protection in the powerhouse, according to the activity that takes place within it, is governed by the instruction MIERAT 14, which requires the provision of portable fire extinguishers and of a bucket for liquid collection with firefighting devices for the refrigerant fluid of the transformer. As a means of fighting, the engine room must be equipped with 6 kg fire extinguishers of 21A and 144B minimum performances, two 5 kg extinguishers of CO2 for electrical boxes and a wagon of 50 kg of ABC powder for the transformer.
- Procedures and regulations must be established to prevent the employees of the plant from damaging the species around it.
- It is likely that the vegetation be destroyed and not regenerate. A possible measure is to repopulate adjacent areas with the same species that have been removed during the project.

3.3.8.3. Landscape factor

- Design of the elevation of the new central building with a compact, low and uniform form to reduce the impact.
- Plantations that hide discordant structures can be cultivated

3.3.8.4. Fauna factor

- The protection of the central building should facilitate the ventilation of machinery, to prevent intrusion, the passage of small animals, the entry of rainwater and accidental contact with parts with voltage.
- During the execution of the work, special care will have to be taken in the breeding season of the local fauna.
- To facilitate fish passage, which is hampered by the waterfall, migration must be facilitated through a fish ladder.
- At the entrance of the turbine, a gate must be installed to prevent from fish entry. This will have to be strong enough and cause no maintenance problems.
- The output of water turbines must have little pressure, so as to minimize the turbidity of water and erosion.

3.3.8.5. Noise factor

- The generation of vibrations by the installed equipment requires the adoption of mechanisms for absorbing or reducing these effects at some points in transition. One option might be to use absorbent rubber sheets with a minimum thickness of 8 mm at the joints to the anchor plates of metal, in support of the equipments on their benches and at the junction of the beam rail.
- Inside the engine room, measures are required to reduce the noise level below 80 dBA: blankets of glass wool insulation on the envelopes of the turbine and generator.

3.3.8.6. Other measures

- An authorized agent from the contractor shall manage any waste generated as a result of the execution of the work. It must be justified by the delivery note in the treatment facilities of such waste.
- It is advisable to have a system of forest fire risk protection for fire prevention in the work area (sufficient extinguishers in the machinery room).
- A program must be established for collecting, sorting, packaging, labeling, temporary storing and disposing of all the waste generated in the construction phase. The collection will have a wide coverage that will capture all the waste through containers distributed in the work area.

3.3.9. Social impact study

The main social impacts that the introduction of a small-hydropower plant involves are generating employment and fostering social awareness about the benefits of renewable energy.

Numerous studies have shown that with the same installed power, production units of energy from renewable sources generate up to five times more jobs than conventional technologies. Therefore, the green energy sector contributes effectively to the creation of employment, including direct job creation in manufacturing, construction and operation of its facilities, and indirect employment derived from the demand for goods of other types that are generated by such activities.

The development of renewable energy also contributes to regional cohesion, since, in most cases, the new facilities are to be located in rural areas.

The employment generated by small-hydropower plants is closely related to the dissemination of renewable energies, so it is important to achieve social awareness throughout the population on this matter. A small-hydropower facility, located in a specific population, being the source of wealth for the people, allows this type of energy to be closer to the people and, therefore, helps the citizens to know the real positive benefits of generating renewable energy.

4. ADMINISTRATIVE PROCEDURE

In the case of Administrative Procedures, each country differs significantly, and sometimes between regions, so it is very important to study the particular case for your territory.

The administrative procedures for each of the RuralRES partner countries is expounded in the RuralRES deliverable D3.2 combined report, available on the RuralRES website (http://ruralres.diphuelva.es/) as well as the relevant specific legal material in the "Training" section of the website.

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