CRANFIELD UNIVERSITY

Lorenzo Micheli

Feasibility Study for a Hydroelectric Installation on the Arno River (Italy)

School of Engineering
Department of Power and Propulsion

MSc by Research

Academic Year: 2010 - 2011

Supervisors:
Prof. David Mba and Dr. Joao A. Teixeira

May 2011

ABSTRACT

Energy need is a primary requirement of our society. Many interests and concerns turn around this matter. It includes policy, economy, environment, etc... Renewable energy is considered to be a good alternative from fossil sources and nuclear power. Renewable sources are known as “green” because of the low impact on the Earth equilibriums. Furthermore they are not exhaustible because they utilize the ecosystem cycles. Hydroelectricity is an established technology. In most of the industrialized countries large scale hydropower has been widely exploited, but there are possibilities of growth for mini-hydro schemes. In developing countries the unexploited potential is considered to be bigger. This thesis details an analysis into various aspects of hydropower, in particular it deals with micro-hydro and pico-hydro applications. A literature review about existing plants is presented; a few cases are shown in which pico hydro plants are used for the electrification of remote communities in developing countries. A feasibility study has been carried out for a hydroelectric installation on the Arno river (Italy). Three different solutions have been proposed for the realization of the scheme. One of them is a pico hydro installation. Hypothetical benefits from the plant realization have been evaluated, together with the scenario in which this plant would operate.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my supervisor Dr. Joao A. Teixeira, for his precious and numerous advice, for his continuous support to the project and for his patience and motivation.

My sincere thanks goes also to Prof. David Mba who gave me the opportunity of undertaking this Msc by Research at Cranfield University, and followed the progression of my work along this year.

Thanks' to all the people that encouraged me to keep going in difficult situations.

Thanks' to all the persons, circumstances and experiences that made my last year not only an important academic progression, but also a deep and precious path of human growth and awareness achievement.

And thanks' to my little swallow Marta that brought the spring into my heart.

I said to the man who stood at the gate of the year
"Give me a light that I may tread safely into the unknown."
And he replied,
"Go into the darkness and put your hand into the hand of God
That shall be to you better than light and safer than a known way!"
(The gate of the year, Minnie Louise Haskins)

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NOMENCLATURE

ACRONYMS

AC	Alternative Current
AR	Arezzo
BEP	Best Efficiency Point
BFI	Base Flow Index
BHA	British Hydropower Association
CFLs	Compact Fluorescent Lamps
COP	Coefficient Of Performance
DC	Direct Current
ENEL	Ente Nazionale Energia eLettrica
ERF	Environmental Requirement Flow
FDC	Flow Duration Curve

GSE	Gestore Servizi Energetici	
HDPE	Hight Density PolyEthylene	
IGC	Induction Generator Controller	
LED	Light-Emitting Diodes	
p.c.d.	Pitch Circle Diameter	
PAT	Pump As Turbines	
PBT	Pay Back Time	
PVC	Polyvinyl-Chloride	
ROR	Run Of River	
rpm	Revolutions per minute	

ROMAN SYMBOLS

A	Catchment area	[km^2]
B	Base flow	[mm_{water}/day]
B	Trapezium minor base	[m]
C	Velocity	[m/s]
C	Annual cost	[€/year]
C	Wave speed	[m/s]
C’	Unit cost	[€/kWh]
D	Turbine diameter	[m]
D_{jet}	Jet diameter	[m]
D_{runner}	Pitch Circle Diameter	[m]
E	Evapotranspiration	[mm_{water}/day]
E	Yearly produced energy	[kWh/year]
E	Energy	[kWh/year]
F	Grid frequency	[Hz]

F	Funning friction factor	[-]
G	Gravity acceleration	[m/s^2]
H	Trapezium height	[m]
H_0,H,H_{site}	Gross head	[m]
H_{bep}	Best efficiency point height	[m^3/s]
h_L, h_f	Head losses	[m]
H_{net}	Net head	[m]
H_t	PAT rated head	[m]
I	Infiltration	[mm_{water}/day]
I	Slope	[m/m]
K	Gaukler-Strickler coefficient	[$m^{1/3}/s$]
L	Length	[m]
L	Head race length	[m]
L, L_{pipe}	Penstock length	[m]
N	Rotational speed	[rpm]
N_g	Rotational speed in induction generators	[rpm]
N_m	Rotational speed in induction motors	[rpm]
n_p	Rotational sped in pump mode	[rpm]
Ns	Specific speed	[rpm]
n_t	Rotational speed in turbine mode	[rpm]
P	Number of polar pairs	[-]
P	Number of poles	[-]
P	Pressure	[bar]
P	Exceedance probability	[-]
P	Probability	[-]

P	Power	[kW]
P	Precipitations	[mm_{water}/day]
P	Perimeter	[m]
P_{in}	Pump electrical power	[kW]
Q	Flow	[m^3/s]
$Q_{7,10}$ $Q_{7,2}$	Flow indexes	[m^3/s]
Q_{bep}	Best efficiency point flow	[m^3/s]
Q_{max}	Maximum flow	[m^3/s]
Q_t	PAT rated flow	[m^3/s]
R	Runoff	[mm_{water}/day]
R	Equivalent radius	[m]
R	Allievi graph ordinate	[-]
Re	Reynolds number	[-]
S	Wall thickness	[mm]
S	Sleep factor	[-]
S	Section	[m^2]
Tc	Closure time	[s]
V	Flow speed	[m^3/s]
Y	Piezometric height	[m]
ΔH	Head losses	[m]
Δp	Pressure losses	[bar]

GREEK SYMBOLS

μ	Dynamic viscosity	[Pa· s]

Δ	Friction losses	[kJ/kg]
E	Absolute roughness	[mm]
ε_r	Relative Roughness	[-]
H	Efficiency	[-]
η_{ausil}	Efficiency of auxiliary electrical devices	[-]
η_g	Generator efficiency	[-]
η_{max}	Maximum efficiency	[-]
η_t	Turbine efficiency	[-]
Θ	Allievi graph abscissa	[-]
Π	Pi	[-]
P	Density	[m^3/s]
Σ	Material strength	[bar]
σ_{amm}	Admissible stress	[Bar]
X	Friction coefficient	[$m^{1/2}$/s]
Φ	Allievi graph parameter	[-]

1 INTRODUCTION

1.1 Preface on an historical note

...

io ebbi vivo assai di quel ch'io volli,

e ora, lasso!, un gocciol d'acqua bramo.

Li ruscelletti che dè verdi colli

del Casentin discendon giuso in Arno

facendo i lor canali freddi e molli,

sempre mi stanno innanzi, e non indarno,

che l'immagine lor vie più m'asciuga

che 'l male ond'io nel volto mi discarno.

...

(XXX Inferno, Divina commedia, Dante Alighieri)

These words by Dante Alighieri create an atmosphere of hopelessness and desperation. Mastro Adamo speaks, a man who falsified money under commission by the Counts Guidi, a powerful family of the ancient dukedom of Tuscany. He was caught and sentenced to be burnt alive by the law.

What Dante found in the 30th circle of the hell is the soul of Mastro Adamo condemned to eternal damnation. His punishment consists of being afflicted by a terrible disease called dropsy. Its effects on the body are terrible. The organism is no longer able to absorb liquids and brings deformations of the human shape, and indeed Adamo is described to resemble a lute. One of the principle symptoms is thirst and no one and nothing in Hell can please his desire.

In this canto, Mastro Adamo reveals his heartbreaking story. He talks about Casentino Valley, the place where he died. This place is located in the eastern part of Tuscany, the valley studied by our project. It is a hilly place rich with small rivers that flow downstream in the first tract of the river Arno. Mastro Adamo is constantly tormented by this memory so much that, he says, the image of Casentino with its rivers is even more painful than the disease itself. He had everything he wanted in his life and now he would beg for even a single drop of water.

Casentino's water, unfortunately, would never reach the 30^{th} circle of the hell to satisfy Mastro Adamo's thirst and make him feel better, but it can possibly contribute to meet the electricity request of our demanding society.

1.2 Hydro power

The energy problem is strictly related to human needs and represents one of the first concerns for the human race. It covers a wide range of fields: technical, political, social, environmental and sometimes ethical. It may be no exaggeration to say that the future of the world and every single country depends upon it.

In 1997 most of industrialized countries agreed the Kyoto protocol to set some emission reduction targets in order to preserve the environmental and climatic equilibrium of the world threatened by the greenhouse effect, ozone depletion etc.. The use of renewable energies is a way to overcome those problems and to meet international targets. European directives are to reach the target of 20 % renewable energy from final energy consumption by 2020.

Hydroelectric energy is one of the renewable sources. It is considered to be a simple and reliable technology available in many regions of the industrialized and non-industrialized world. Right after the discovery of hydroelectricity, this technology had a fast and wide development in many countries such as Italy. Considering the Italian case, with the expansion of thermal and nuclear power, hydroelectric technology lost much of its pre-eminence. While existing plants continued to play an important role in the energetic balance, the development of hydropower slowed down with a significant reduction in the number of plants constructed. Furthermore big scale hydro power, rated as the cheapest, was at a point of saturation because most suitable sites had already been exploited. This is not the case of the world wide scenario, in which that capacity has not being fully exploited.

Public perception of hydropower was sometimes negative, given that catastrophic accidents took place involving large hydropower schemes. One such case was the Vajont disaster of 1963 in northern Italy, A section of a mountain slid down into the basin causing the escape of vast amounts of water. The giant wave generated overflowed the dam and destroyed the entire village causing more than 2000 victims. People started to fear this technology and hydro generation was no longer considered a reliable and safe technology. Popular opinion was in error as it is generally unknown that the proportion of the plant is directly proportionate to any risks involved. In other words, small hydropower is less risky than larger hydropower, and not all hydroelectric schemes require the construction of a big dam.

ENEL (electric energy national institution) was established in Italy in 1962 as a result of the nationalization of the energy market. Consequently, hydro plants became ENEL property, and a large number of them, mostly the small size plants, were decommissioned because they were not considered to be compatible to Enel's market strategy.

In a recent times hydro power has been re-evaluated and supported as being a precious green technology with an interesting development prospective especially regarding small scale. For this reason there is now a legislative framework that supports hydropower as green energy production. However many obstacles are still to be overcome for those who want to invest in this field.

1.3 Thesis structure

This project delves into various aspects of hydropower, and presents a feasibility study for a new small scale hydro plant to be installed in the Casentino valley (Italy).

Chapter 1 is a summary of the project, and to the problem of energy needs. It highlights the fact that water is one of the renewable sources and that the produced energy is green, pollution and Co2 free.

Chapter 2 outlines an historical prospective about hydroelectricity and turbines evolution. It also outlines hydropower characteristics and presents a few hydropower classifications. Pico hydro and micro hydro have been distinguished and separately analyzed.

Chapter 3 describes the state of the art turbine technology with particular attention to the theoretical aspects and to the turbine selection procedure. It also outlines the difference between pico turbines and bigger ones accordingly to the requirements they have to meet.

Chapter 4 is concerned with additional aspects of hydropower. It includes other plant components, methodologies of analysis of river flows, hydrologic modelling, hydro plant design methodologies and a brief survey about present Italian legislation in the matter of hydropower.

Chapter 5 is a review of existing plants of both scales: pico and micro types.

Chapter 6 describes some features of the Arno river and of the Casentino valley with a view to establishing the methodology to be employed in the assessment of the hydric resources of the target location.

Chapter 7 focuses on the project development, producing three technical solutions projecting the scheme, together with a rough financial analysis of the competing solutions.

Chapter 8 is for discussion and further work.

2 MICRO HYDRO

2.1 Historical perspective

Harnessing water resources to produce mechanical power is a time honoured practice. Earliest examples took place before Christ, at the time of the ancient Greeks. Generally speaking, more than 2000 years ago water was exploited to drive wheels for grinding grain for the production of flour. In the 1700's mechanical hydropower was in widespread use for milling and pumping. In the following century, at the time of the industrial revolution, water was extensively used to provide mechanical power in industrial fields such as sawing and textiles.

Figure 1 Lanificio 1930. Textile factory by the Arno affluent Staggia. Stia (AR) Italy (Della Bordella, 1998)

For example Figure 1 and Figure 2 show the historical textile factory located in Casentino Valley (Stia, AR) that harnessed water from one of the Arno tributaries. It was also in this period that water wheels were substituted by turbines.

Figure 2 Mechanical hydropower to drive textile machines (Della Bordella, 1998)

In 1820, Jean-Victor Poncelet proposed an inward-flow turbine, in which water was flowing into the wheel rather than along the wheel as in the earlier prototypes. Some years later (1826) Benoit Fourneyron developed an 80% efficient outward-flow turbine with a runner made up by one dimensional curved blades. In 1844 Uriah A. Boyden proposed an improvement of Fourneyron's turbine with curved runner blades. In 1849, James B. Francis brought the inward flow design to over 90 % efficiency, realizing the modern reaction turbine prototype, which by the way is called **Francis**.

Another brilliant design of water turbine is dated 1913 by Victor Kaplan (**Kaplan** turbines) that proposed an evolution of the Francis turbine, with fewer and bigger blades, suitable to exploit very low head. Kaplan turbines have the possibility of regulation for both stator and rotor, while the Francis turbine regulation relies only on stator blades through a Fincher distributor.

All the modern reaction turbines are inward flow design because they are found to have a better mechanical arrangement.

Beside reaction turbines, in 1966, Samuel Knight invented a machine that took the impulse system to a new level. He developed a bucketed wheel which captured the energy of a free jet generated from the conversion of high head into pressurized water. In 1879, Lester Pelton developed a double bucket design with other improvements in respect to Knight wheel. Some years later, around 1885 William Doble improved the design again, bringing it to 92% efficiency (**Pelton** turbines).

By the beginning of the last century water turbines began to be used for electricity production. Hence, many existing plants were soon converted from mechanical to electrical power output, and many other plants rapidly appeared to supply electric power to the new increasingly demanding electrified world.

2.2 Characteristics of hydropower

Hydropower is likely to be one of the most reliable and cost-effective technologies among the renewable sources. Its specifications can be summarized as follows.

- High efficiency for the hydraulic turbine (70-90 %)
- High capacity factor (generally > 50%), compared with those of wind (30%) and Sun (10%)
- High level of predictability, being dependent on annual rainfall patterns.

- Slow rate of change. The produced power varies gradually from day to day, not from minute to minute, making the produced power easy to handle.

- It is a robust and long-lasting technology. Expected life for well engineered plants is generally 50 years or more.

Many experts estimate Italian hydropower potential to be 65TWh/year. GSE reported hydropower production to be equal to 49.1 TWh in 2009. This was achieved with 2,249 plants and a total installed power of 17.7 GW. Hydroelectricity was then the predominant renewable resource in Italy with respectively 69 % of the installed renewable power and 71 % of the produced power.

McKay (2003) estimates that, in UK, the plausible practical limit, for hydroelectric production, is 1.5 kWh per day per person. Considering that the actual hydroelectric production in UK is 0.2 kWh per day per person, it's expectable that the possibilities of growth are in the order of 7 times the actual installed power.

In 2001 the world installed hydropower was 47,000 MW and the European one was 9,500 MW (Energia Lab, 2001). Hence large possibilities for growth of this technology are expectable.

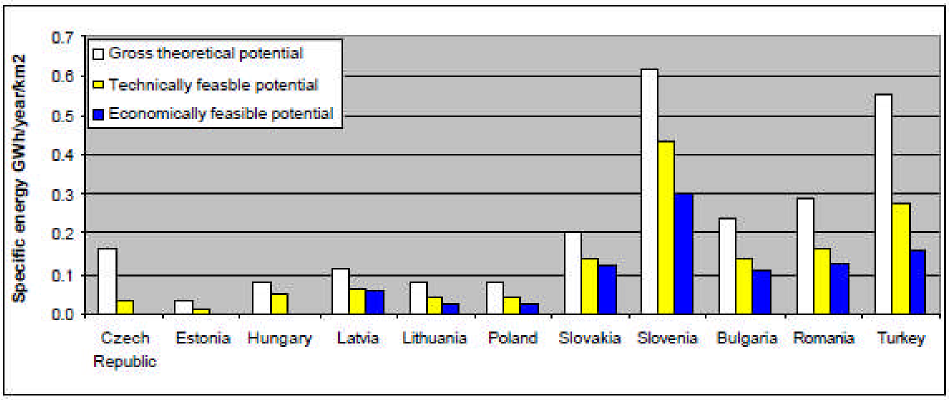

Figure 3 Hydropotential for small scale hydropower in Eastern Europe and Turkey (Golebiowski and Krzemien, 1998)

Most of the unexploited potential concerns small scale hydro plants, especially in developed countries, where large and medium scale plants have been built where possible.

2.3 Classification of hydroelectric plants

Hydroelectric plants can be classified as **impoundment plants** and **run of river plants (ROR)**, in terms of their operational mode.

Impoundment plants (Figure 4) are characterized by the existence of a reservoir which enables flow regulation. As a consequence, the producible power can be independent from the flow regime. These characteristics make reservoir plants suitable to accomplish a power regulation service i.e. to cover the peaks on the load curve (Figure 5).

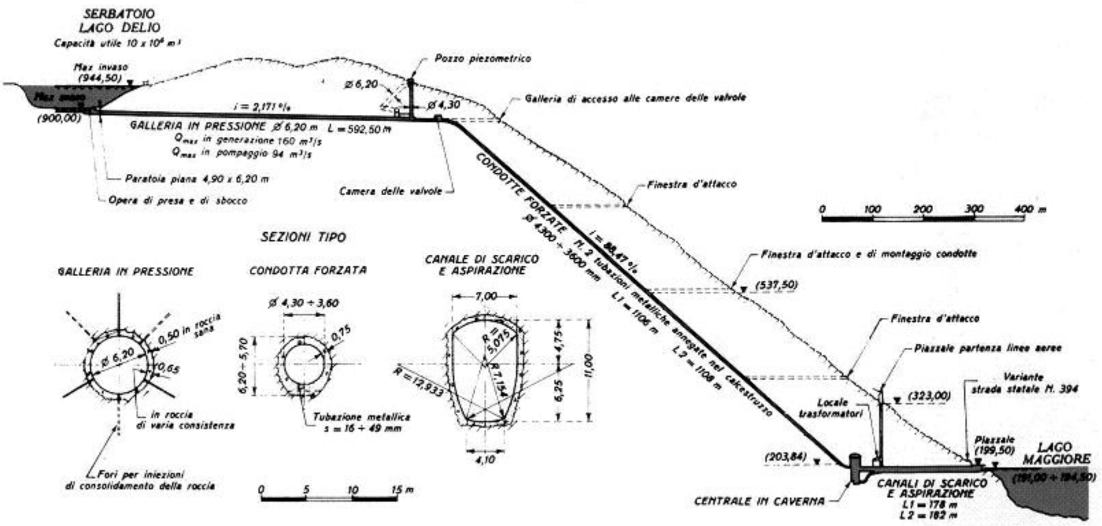

Figure 4 Impoundment scheme sample. Delio Lake, Roncovalgrande, Italy (http://www.fmboschetto.it/lavori_studenti/lavori_fisica_studenti/Roncovalgrande_Bonaita/Descrizione.htm)

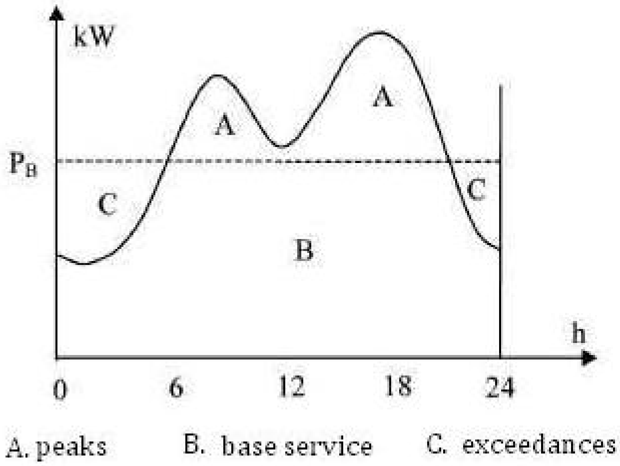

Figure 5 Typical daily load curve

Run of river plants depend on the natural flow rate of the watercourse and changes in the watercourse flow rate affect directly the output. Thus, this kind of plant is suitable for base service instead of to cover load peaks.

Pumped storage plants and **tidal power plants** are other types of water plants but they differ in their operation mode from conventional hydroelectric schemes and are therefore not included in above mentioned categories.

Hydroelectric plants are also classified in terms of plant size as listed below

- Large scale (more than 100 MW)
- Medium scale (15 - 100 MW)
- Small scale (1 - 15 MW)
- Mini scale (above 100 kW, but below 1 MW)
- Micro scale (from 5kW up to 100 kW)
- Pico scale (from a few hundred watts up to 5kW)

The present study focuses on ROR plants from a few hundred kW down to few hundred watts. Accordingly the hydroelectric schemes considered are in the Micro and pico scales.

The most common layouts for ROR hydroelectric plants are presented in Figure 6.

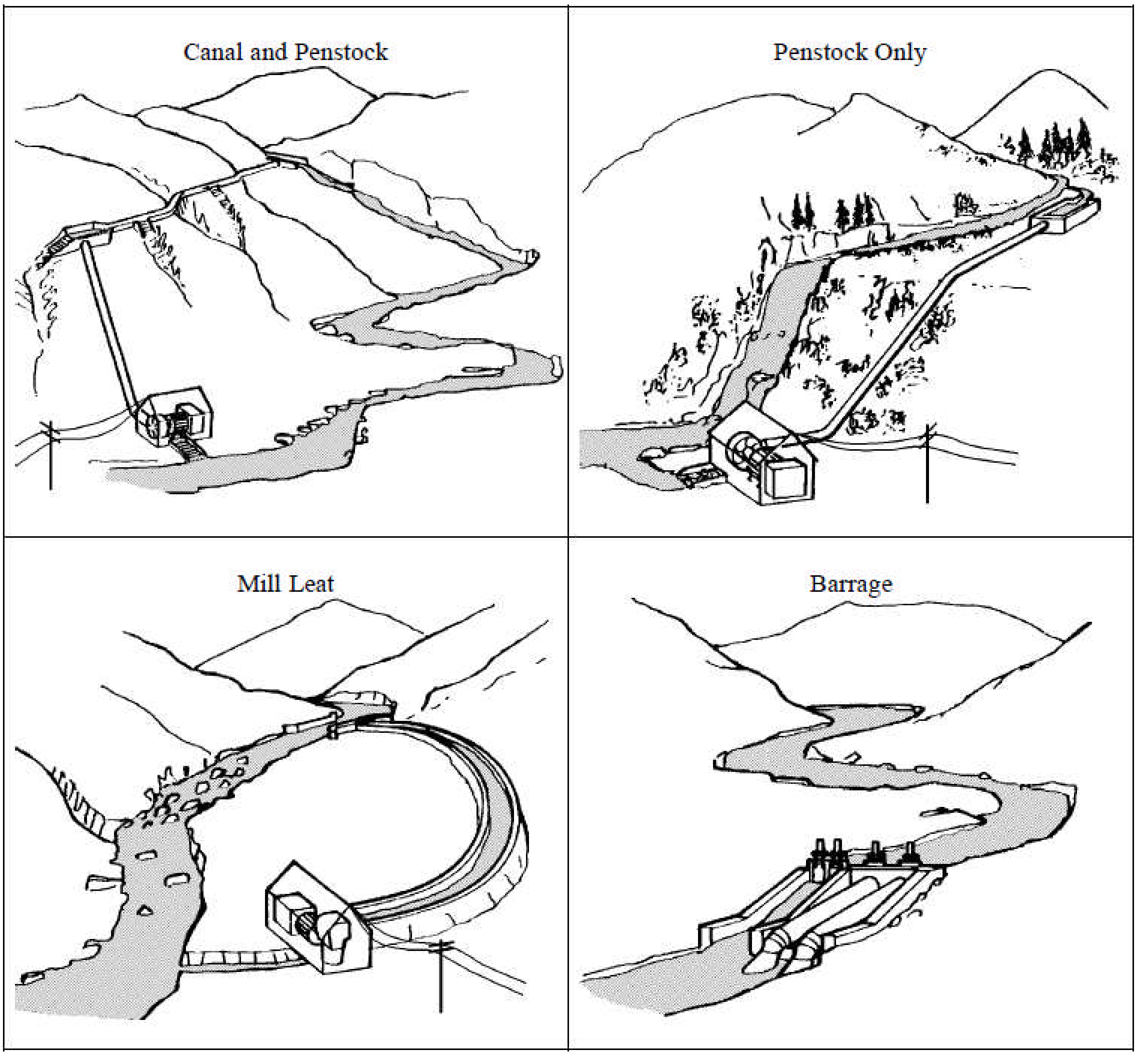

Figure 6 Four most common layouts for a mini hydro scheme (British Hydropower Association, 2005)

In the literature, pico hydro power indicates water power up to 5 kW. pico hydro plants have similar characteristics in design, instrumentation and civil works. They are also cost-effective and competitive with bigger hydro plants. This designation signifies the need to have a different way of thinking in contrast to micro, mini and larger hydropower schemes.

2.4 Pico hydro plants

Although pico and micro hydro schemes are based on similar but scaled technologies, the distinctiveness of pico schemes is such that it is worthwhile to appropriately introduce them and to highlight the essential differences from more conventional hydro plants.

In recent years there is a growing interest in the literature in very small hydropower plants as an effective solution to produce renewable energy. Pico hydro schemes are a cost-effective option for the electrification of remote rural communities (Williams and Simpson, 2009). Williams and Simpson (2009) also point out that the use of standardized equipment and of low cost approaches to scheme design can make the technology even simpler and cheaper, despite the fact that each hydropower site is unique and requires a bespoke solution.

This can change life of communities that would otherwise have no access to electricity as remarked by Cannel et al. (2005).

The University of Nottingham has an established tradition of research in the field of pico hydro research. There are thousands of sites where, although people have a source of falling water, they do not have access to electricity. In such cases pico hydro is the lowest cost technology for generating electricity, (Williams and Simpson, 2009).

Derakhshan and Nourbakhsh (2008) state that more that 200 small hydropower stations can be installed in Iran and Murthy et al. (2006) affirm that there may be more than 10,000 sites in India with power generation capacity of 1-100 kW.

Williams and Simpson (2009) published a study entitled “Pico hydro - reducing technical risk for rural electrification” in which various possibilities to implement pico hydro schemes are described. Factors that can possibly deny the technical and economical feasibility of this technology are also outlined in the same study.

Pico hydro plants have a low environmental impact given that they don't introduce large civil works in the river.

The need of little civil works, together with the affordability of off-the-shelf turbines, are the main factors that make pico hydro a cost effective technology.

Standardized equipment and design could reduce the instalment costs but there are parameters of scheme design that are strictly site specific, like the arrangement and dimensions of the penstock pipe and the layout of the distribution system. A non-optimum design can bring about higher installation costs.

Pico hydro costs are dependent on many parameters like site arrangement, machinery affordability and kind of equipment utilized.

A recent report on electrification technology by the World Bank Energy Unit shows that, of the options currently available for off-grid generation, pico hydro is likely to have the lowest cost as shown in Figure 7 (Williams and Simpson, 2009).

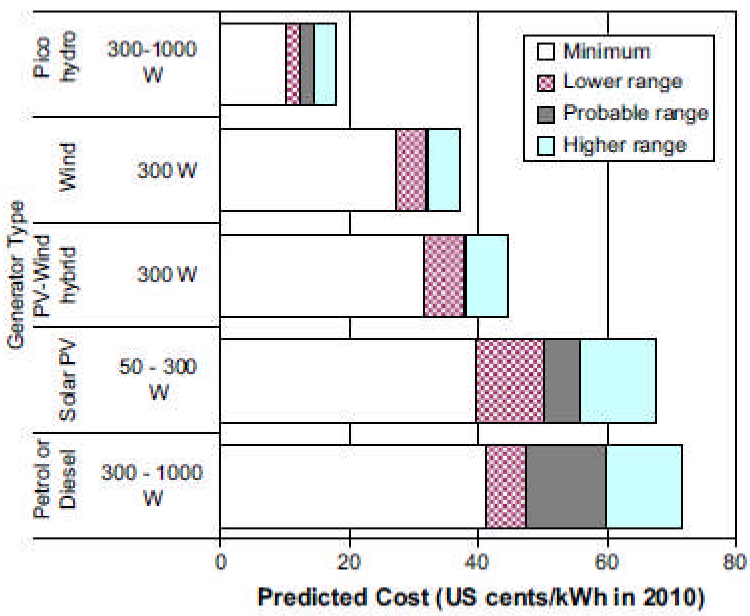

Figure 7 Predicted costs for off-grid electricity - data from World Bank (Williams and Simpson, 2009)

Compromises between costs and efficiencies must be carefully considered in the implementation, a bigger initial investment (higher technology) is possibly paid back in a shorter time.

The value of the additional energy produced by a turbine with 5% higher efficiency will typically justify a 10% higher turbine cost, based on a three-year payback (Williams and Simpson, 2009).

Descriptions of the principal application fields for pico hydro are presented below.

2.4.1 Electrification of remote communities

These plants are nowadays widely utilized in developing countries to provide electrification to remote communities where the cost of national grid extension would be higher. Since remote areas are by definition not easily reachable, it follows that the transportation and installation of grid elements would become exceedingly expensive and hardly affordable for local habitants. In these cases pico hydro is found to be cost effective for this purpose as demonstrated by the large number of examples found in different countries such as Nepal, Malaysia, Thailand, the Lao’s Democratic Republic, Kenya, Sri Lanka, Peru, India etc..., (Williams, 2007).

The available cheap alternative to electrification is represented by petrol lantern illumination, which actually is what tends to be used where other technologies are not available. Such lanterns are characterized by low efficiency and bad influence on health. In terms of costs they are found to be more expensive than pico hydro because, despite a very low investment, they require a higher running cost.

Pico hydro provides power for the lighting of private houses, but also battery recharging availability for mobile phones and other electric devices. Furthermore pico hydro makes electrification possible in schools and other public buildings, allowing the use of computers and television.

Those applications are characterized by a load curve that shows a peak on evening hours when natural light is unavailable. During daytime hours the produced power can be utilized to drive small machines for community activities such as sawing, pumping etc... Since in most cases there is no possibility to store excess power, because of voltage regulation the exceeding power is wasted diverting it into ballast loads (Figure 8).

Availability of compact fluorescent lamps (CFLs) allows a reduction in costs for pico hydro electrification, with these devices being more efficient and less expensive. In this case the average power load per household is some 20W. In that case 2 kW are enough to illuminate 100 houses.

Another illumination technique, presenting a new frontier in technology, is based on white light-emitting diodes (LED). A LED based lamp consists of up to 20 diodes. The light emission of three 1,5W LED lamps can compare with the one produced by a 10W CFL lamp.

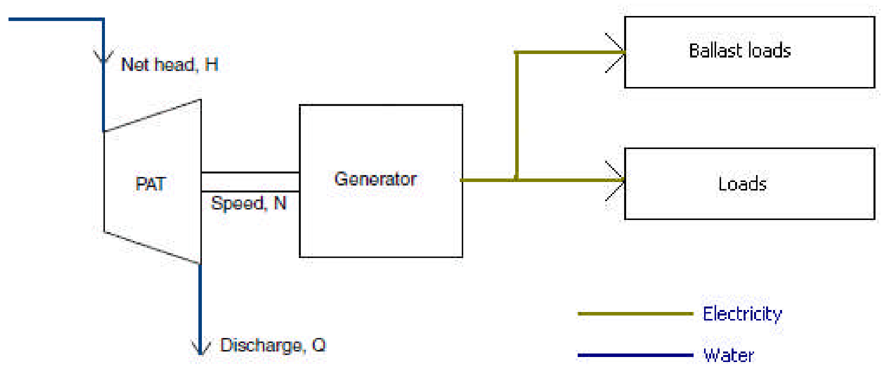

Figure 8 Block scheme for electrification of remote communities

2.4.2 Stand alone applications and family hydro

Pico hydro can alternatively be used for providing energy to remote locations like mountain refuges, isolated houses etc.

Generally the user requirement is to have a plant able to provide a given amount of electricity on a continuous basis. Sometimes the AC electricity provided by the water generator is directly sent to the user load.

These applications are widespread in countries like Vietnam because of their suitability in terms of technical simplicity and reliability, ease of installation, affordable price. These types of machines are pico propellers able to exploit very low heads of the order of 2 metres. They come as a turbine-generator set. They are available in some developing-country markets like Vietnam for prices around US$ 300 per installed kW (Green, 1993).

When the plant does not match the electricity demand, a solution can be represented by the utilization of DC batteries. This arrangement enhances the flexibility of the plant despite a greater technical complexity and more instrumentation requirements, Figure 9.

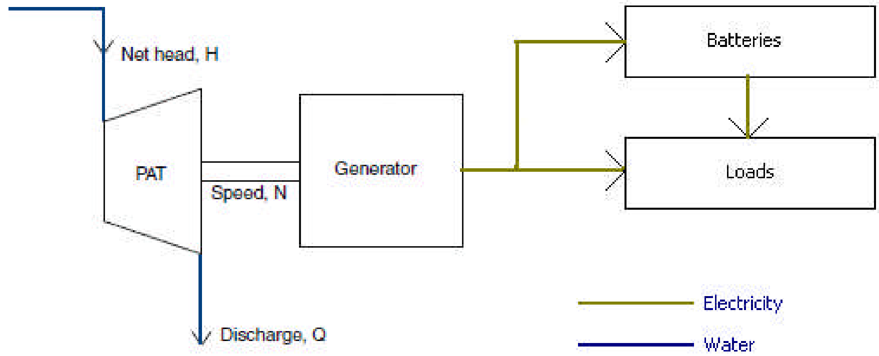

Figure 9 Block scheme for stand alone applications

2.4.3 Parallel operation

In this case electricity can be either used to feed local loads or sold in the national grid. This plant requires a specific instrumentation to perform the desired regulation functions together with a facility to provide connection and disconnection from the grid, Figure 10.

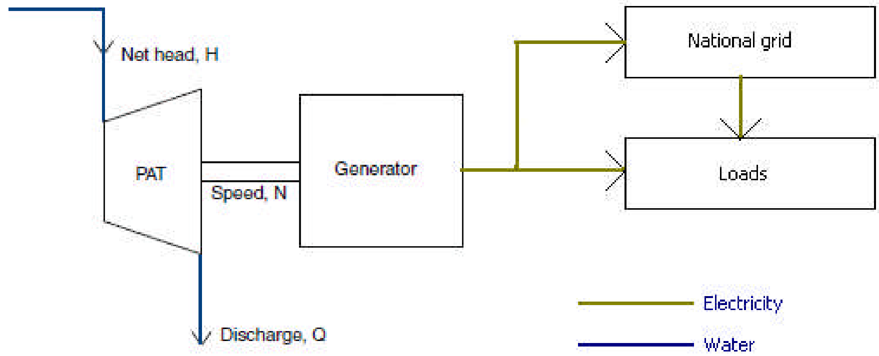

Figure 10 Block scheme for parallel operation

3 TURBINE TECHNOLOGY

This chapter aims to present a perspective of the existing turbines that can be used for the exploitation of small hydropower sources. Turbines can be classified in two big families: reaction turbines and impulse turbines (Table 1).

Each reaction turbine is characterized by a certain value of the degree of reaction:

$$X = \frac{energy\ extracted\ in\ the\ rotor}{total\ extracted\ energy}$$ **Equation 1**

For impulse turbine this value is equal to zero.

Turbines can be classified also as low, medium, high head depending on the kind of site. This is related to the turbine geometry and then to the specific speed.

Turbine Type	Head Classification		
	High (>50m)	*Medium (10-50m)*	*Low (<10m)*
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	Crossflow
Reaction		Francis (spiral case)	Francis (open-flume) Propeller Kaplan

Table 1 Impulse and reaction turbines (British Hydropower Association, 2005)

The technology for medium and high head turbines is essentially mature. This is not the case for low head technology (H<5m) where efficiency improvements are required especially regarding small size applications.

3.1 Medium-high head turbines (10-1000 kW)

3.1.1 Pelton turbines

The Pelton wheel is an impulse turbine. It is characterized by having a series of split buckets set all around its circumference. Water is directed tangentially at the wheel through one or more high velocity jets. Once the jet hits the bucket it divides into two streams, and according to the bucket shape, they are turned and deflected back almost through 180°, Figure 11.

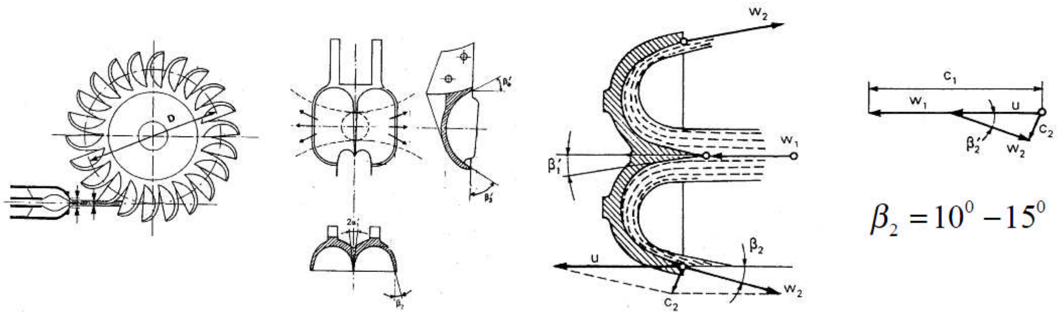

Figure 11 Pelton turbine, bucket shape and velocity triangle. (Caputo and Arrighetti, 1997)

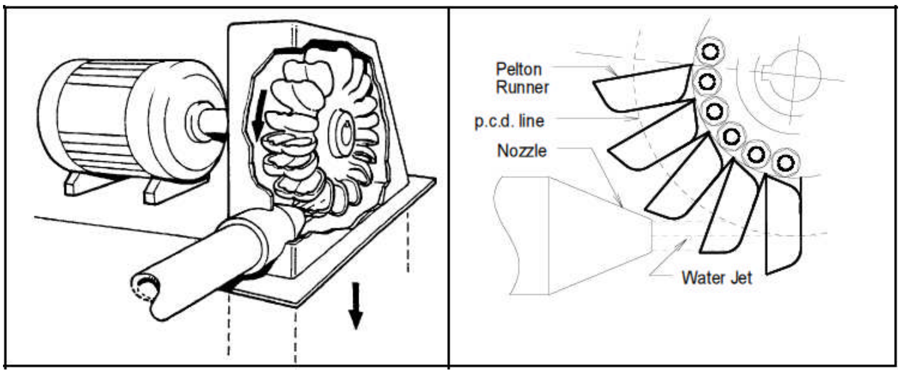

Figure 12 Pelton turbine (British Hydropower Association, 2005 & Maher and Smith, 2001)

One of the most important parameters for both designing and choosing a Pelton turbine is the Pitch Circle Diameter (p.c.d. Figure 12) also called D_{runner} [m]. It is defined as twice the distance between the rotational centre and the jet shaft. Equation 2 gives an expression for this parameter.

$$D_{runner} = \frac{38 \cdot \sqrt{H_{net}}}{n}$$ **Equation 2**

Where H_{net} is the gross head [m] reduced by the head losses and n [rpm] is the turbine rotational speed, imposed by the generator structure, in terms of number of poles, and by grid frequency f (Equation 3).

$$n = \frac{120 \cdot f}{p}$$ **Equation 3**

The maximum flow that a Pelton turbine (Figure 13) can operate under depends on net head, number of jets and jet diameter (Equation 4).

$$Q_{max} = 1000 \cdot \frac{D_{jet}^2 \cdot \pi}{4} \cdot \sqrt{2 \cdot g \cdot H_{net}}$$ **Equation 4**

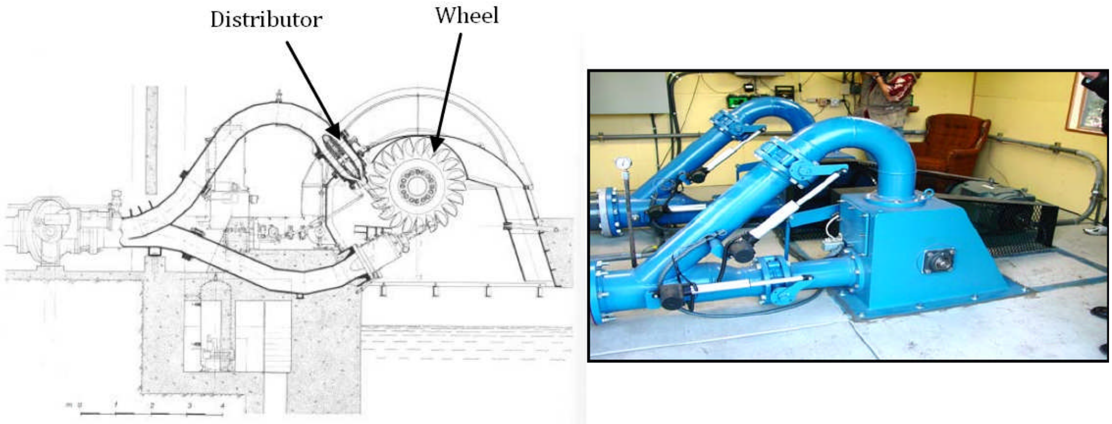

Figure 13 Pelton turbine (Oregon office of energy, 2003)

A Pelton wheel can work nearly to the design conditions for part-flow performance down to 30% of the design flow, Figure 14.

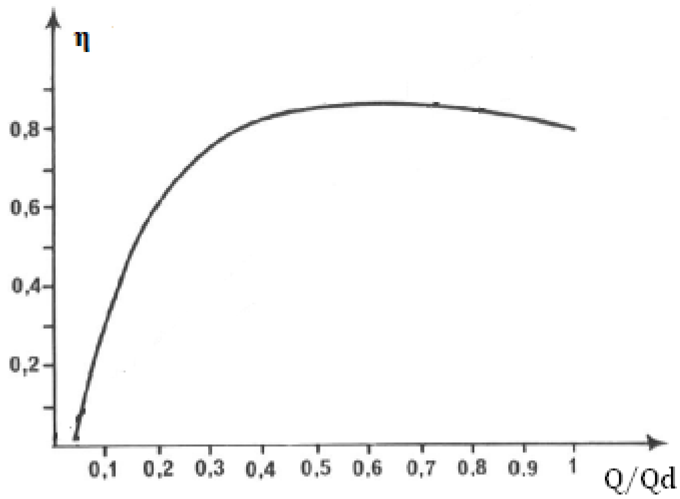

Figure 14 Pelton turbine efficiency curve

3.1.2 Turgo turbines

This kind of turbine is in some respects similar to the Pelton turbine. The buckets are differently shaped however; the high speed water jet hits the plane of the runner at an angle typically of 20°, Figure 16. In this way the jet enters from one side of the bucket and exits on the other. The Turgo turbine is not affected by flow interfering problems between two adjacent buckets like in the case of Pelton turbines; hence for the same power a Turgo turbine can have a smaller diameter than a Pelton machine.

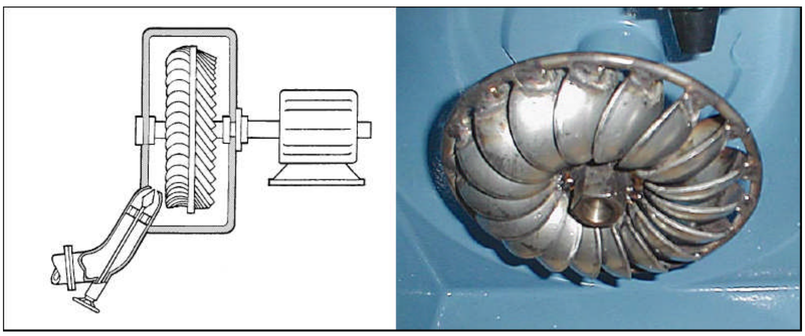

Figure 15 Turgo turbine (British Hydropower Association, 2005)

3.1.3 Crossflow

A crossflow turbine is an impulse turbine that consists of a drum-like rotor with two solid disks at both ends. The two disks are joined through gutter-shaped “slats”. A jet of water enters the top of the rotor passing through the curved blades, emerging on the far side of the rotor by passing through the blades a second time, Figure 16. Blades are shaped in such a way to let the water transfer some of its energy at each passage, before falling away with little residual energy. Crossflow turbine efficiencies are around 70-75%.

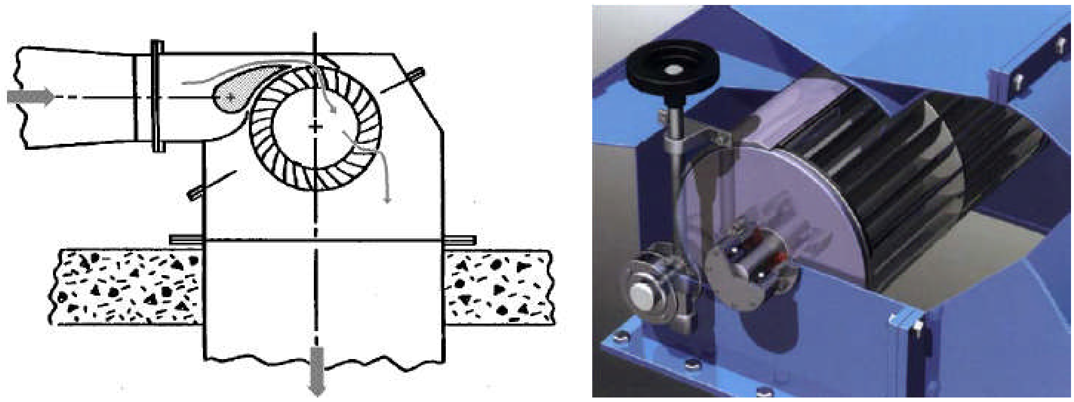

Figure 16 Crossfow turbine (British Hydropower Association 2005 & http://www.irem.it/categorie/4/Idroelettrico.html)

Crossflow turbines are bigger and more slow-running and generally less cost-effective for low head schemes. They can be an interesting solution for schemes under 10 kW and heads down to 2 m. Part flow performance of Francis turbines is shown in Figure 20.

3.1.4 Spiral-case Francis turbine

Spiral case implementation is typical for medium-head schemes.

Francis turbines are radial-axial flow reaction turbines. Water flows radially inward into the runner and is turned to emerge axially, Figure 17. Regulation capabilities are devolved to internal adjustable guide vanes (Fink distributor) while the rotor blades have a fixed geometry, Figure 18.

It is rare for this turbine to be used in plants of less than 100 kW; in those cases cheaper solutions are preferable in order to make the plant cost-effective.

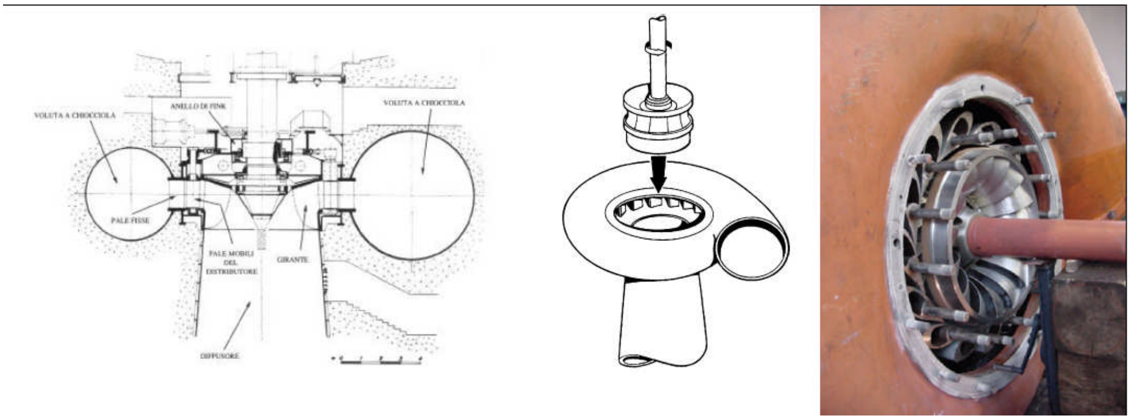

Figure 17 Francis turbine (Caputo and Arrighetti 1997, British Hydropower Association 2005)

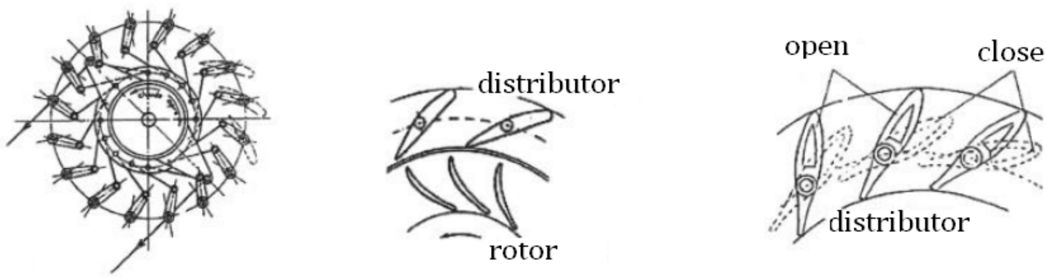

Figure 18 Fink distributor (Arrighetti, 2007)

Francis turbines are not found to be a good solution for low head scheme, not even the fastest. Compared with propeller turbines they are characterized by a greater technical complexity and for small scale schemes the cost of Francis turbines is generally prohibitive.

3.2 Low head turbines (10-1000 kW)

As far as multi-megawatt low head projects are concerned (P>500kW per turbine) Kaplan turbines represent a consolidated and efficacious solution. Common implementations for this machine are vertical-shaft Kaplan and bulb turbine (Figure 19), both in use since 1930.

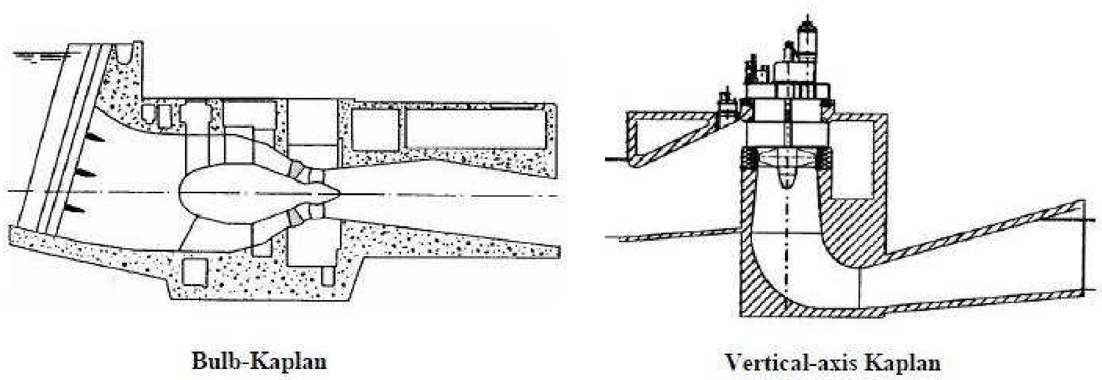

Figure 19 Conventional low-head turbine arrangement (Davison and Bacon 2004)

Focusing on small scale projects (few 100kW or less), Kaplan designs do not always represent the optimum solution especially because of the prohibitive cost that this choice introduces.

What follows is a list of the main technical options for low head schemes:

- Propeller turbines
- Crossflow turbines
- Open-flume Francis turbines
- Water wheels
- Archimedean screws

Propeller and Francis turbines are reaction types. They run full of water and create pressure differences across the blades to extract energy from the available head.

Designs of propeller turbines can give high specific speeds. Also Francis as well, even though not as high as the propeller ones. A high value of Ns matches well low head sites as the turbine can be smaller and faster, and it implies a cost reduction on the shaft, generator and gearbox. On the other hand a bigger operational speed augments the flow velocity through the rotor and consequently the friction losses.

3.2.1 Propeller turbines

Propeller turbines represent the most widespread solution and one of the most interesting in terms of characteristics, application and possible development. They can be classified as follows, according to blades regulation capabilities.

- Basic propeller turbine (fixed rotor blades, fixed guide vanes)
- Kapellar (fixed propeller rotor, adjustable guide vanes)
- Semi-Kaplan (fixed guide vanes, adjustable rotor blades)
- Full Kaplan (adjustable guide vanes, adjustable rotor vanes)

As the water flow varies it is possible that, over certain periods, it does not meet the turbine demand. In this case the turbine can keep operating only through changing its internal geometry, in a process called regulation. A fixed geometry propeller does not allow operation out of the design conditions while a Kapellar turbine does, even though at efficiencies not as high as Semi-Kaplan. In Figure 20 performances of a few different turbines have been compared.

Kaplan design represents the most versatile propeller in terms of part flow performance, Figure 20. This characteristic can sometimes justify the higher cost and technical complexity that such turbines introduce. Efficiencies for Kaplan are around 75-80%.

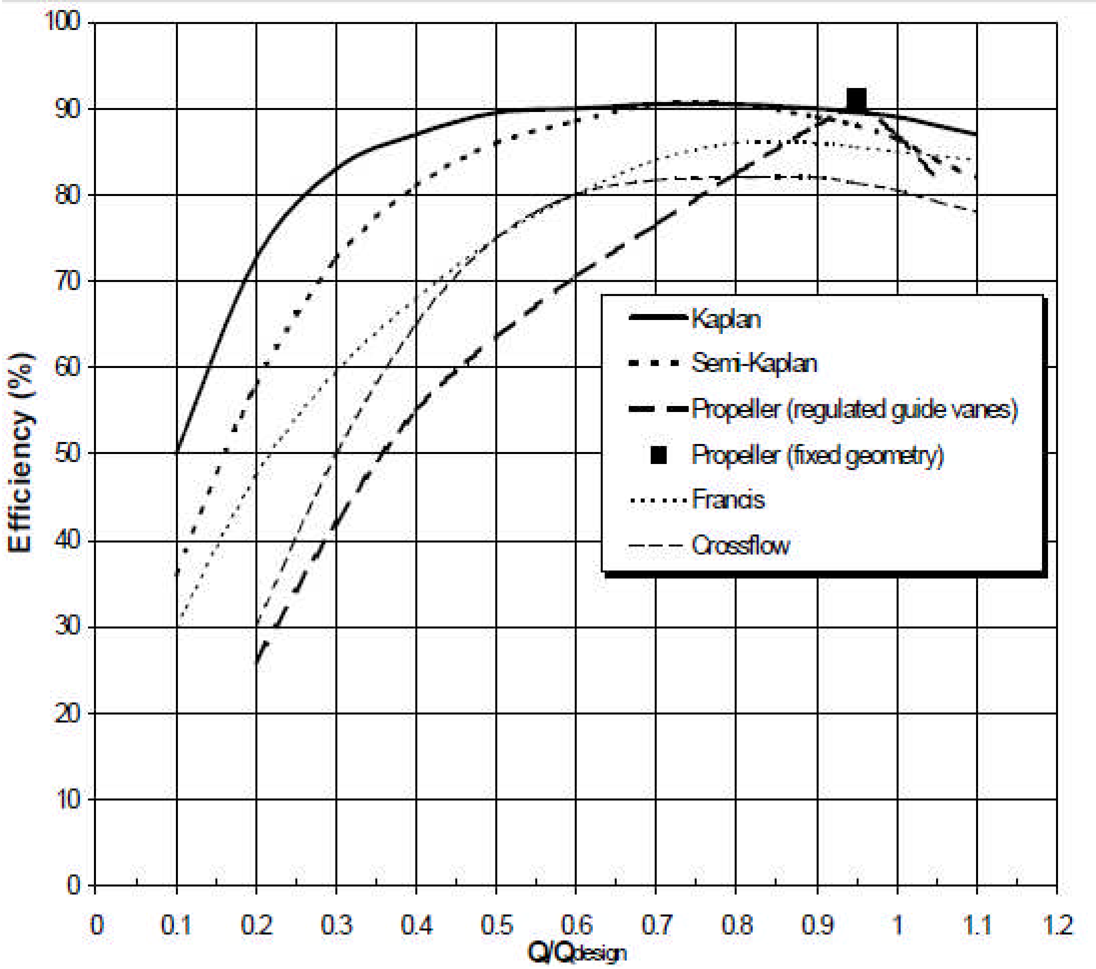

Figure 20 Part-flow efficiency of low head turbines (Davison and Bacon 2004)

The most widely used propeller turbines for micro hydro schemes (few 100 kW or less) are listed below:

- Tube turbines (Figure 21)
- Open flume turbines
- Pit Kaplan (right-angle drive)

- Submersible turbines (mini-bulb turbines)

These solutions are less expensive than Kaplan and help to achieve the economic feasibility of the micro-hydro plant. Main components of such schemes are basically the same with respect to bigger scale: an intake, a set of guide vanes, a runner and a draft tube.

Tube turbines (Figure 21) are characterized by having a tube around the propeller with an ‘elbow’ put into it, so that the shaft is brought outside to couple with the speed increaser and the generator.

Figure 21 Tube propeller turbine (Davison and Bacon, 2004)

Figure 22 shows a few arrangements for tube turbines depending on the ratio H/D where H is the available head and D is the Turbine diameter.

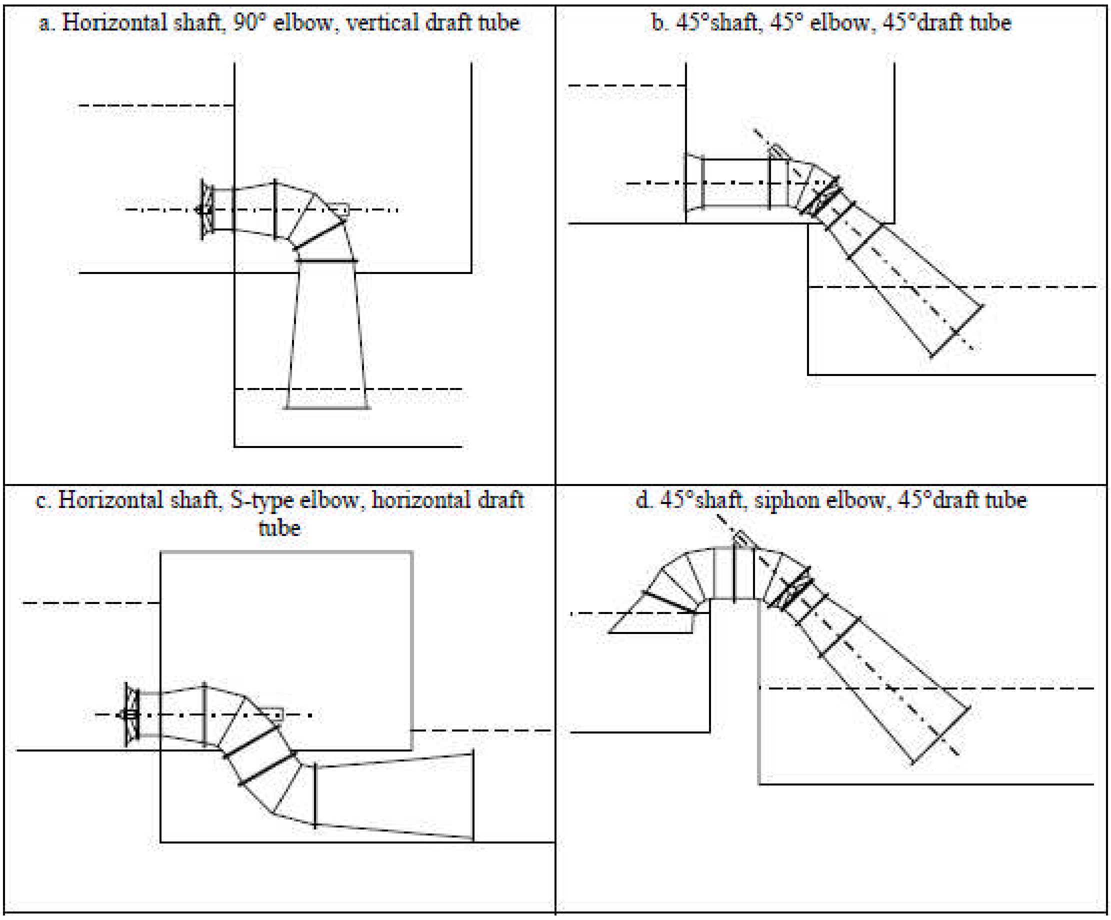

Figure 22 Tube turbine layout examples for decreasing head (Davison and Bacon, 2004)

It is worthwhile mentioning the siphon turbine (Figure 22 case d) because of its relevant technical characteristics. This design allows the exploitation of ultralow heads. It requires less civil works since no intake gate and draft tube gate are needed. Siphon turbines can be installed onto existing structures like weirs or sluices. Turbines and generators are located above water level for ease of inspection and maintenance.

An open flume propeller turbine is characterized by not having an intake section narrowing down to feed the flow into the turbine. The intake consists of a large chamber where the guide vanes are located, Figure 23. Despite the fact that this design requires less components than other propeller turbines, a significant amount of civil works is required to place the machine on site. For this reason these types of propellers are generally used only to replace old open flume Francis on restructuring existing mills.

Figure 23 Intake of an open flume propeller turbine (Davison and Bacon, 2004)

Figure 24 shows a few possible arrangements for open flume propeller turbines.

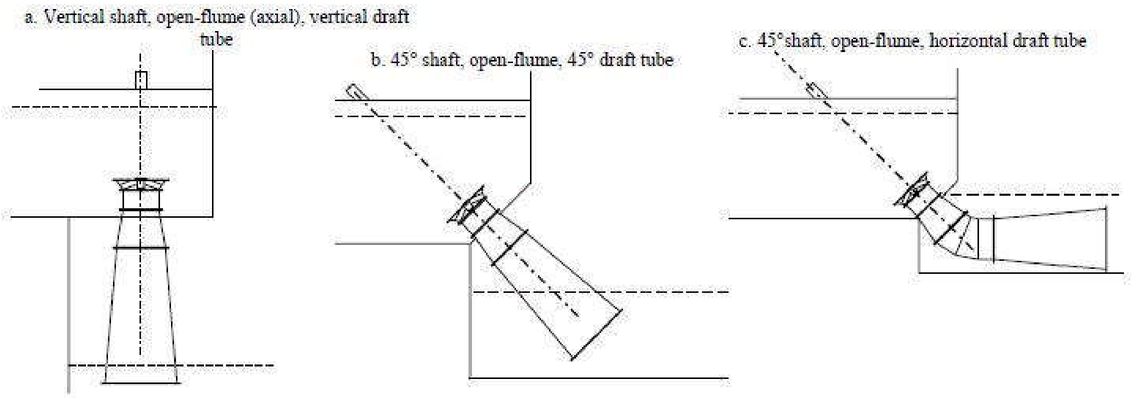

Figure 24 Open flume propeller turbine arrangements (Davison and Bacon, 2004)

A good description of a Pit-Kaplan is found in Davison and Bacon (2004). These turbines were originally conceived as a low-cost alternative to the bulb turbine. In Pit-Kaplan turbines the shaft of the runner passes into a sealed 'pit' which runs from the base of the intake up into the powerhouse. The flow passes either side of the pit to reach the guide-vanes and runner. The pit itself contains a right-angle drive gearbox from which a vertical shaft ascends into the powerhouse to drive the generator. An alternative arrangement utilizes a belt drive in place of the gearbox to reduce costs.

Figure 25 presents a three-dimensional aspect of a Pit-Kaplan turbine.

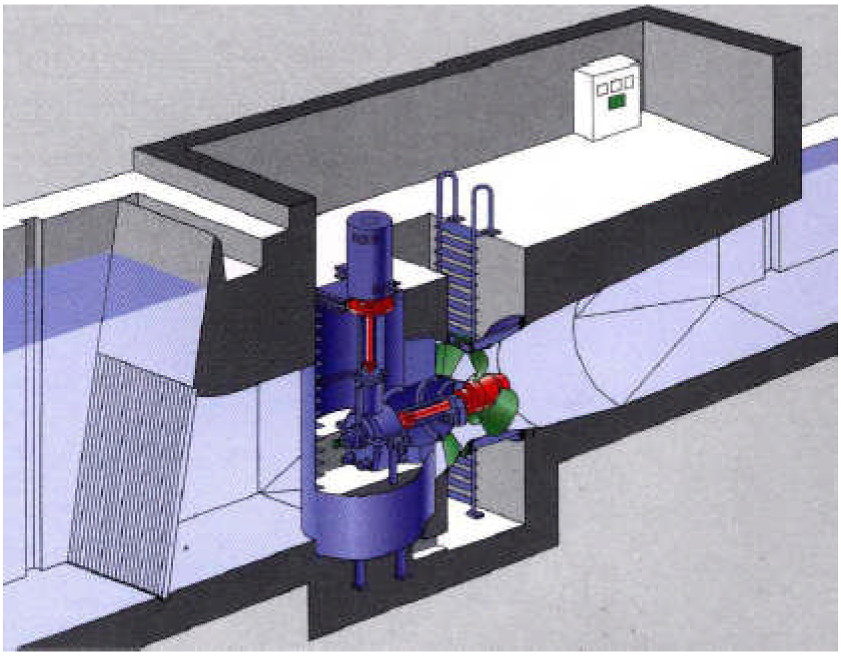

Figure 25 Pit-Kaplan (Davison and Bacon, 2004)

Submersible turbines (Figure 26) represent a smaller scale version of bulb turbines. They are also called mini-bulb turbines. They are close to the submersible pump design since the generator is submerged in a small water-tight bulb. With respect to bulb turbine there is no possibility of inspection and maintenance for the generator and gearbox. In this case the bulb represents the power house itself. The visual and noise impact of the scheme is greatly reduced. The scheme design is simpler but the machine is more complicated to handle in case of maintenance.

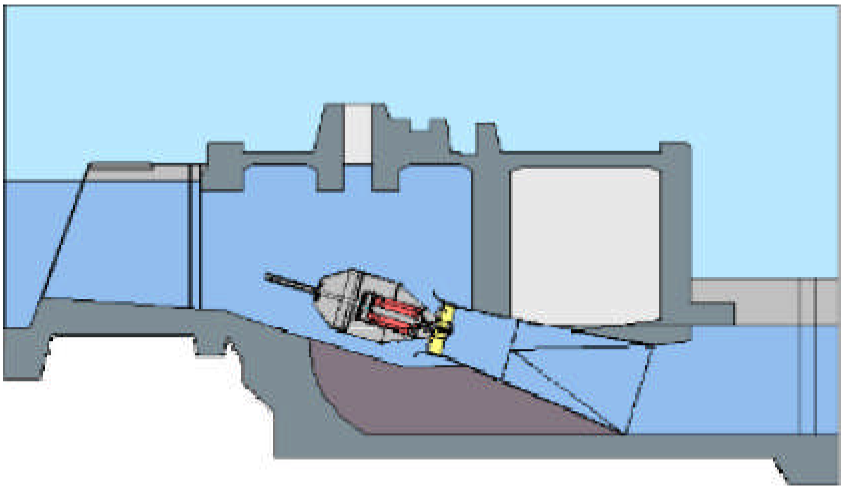

Figure 26 Submersible bulb turbine (Davison and Bacon, 2004)

3.2.2 Open flume Francis Turbine

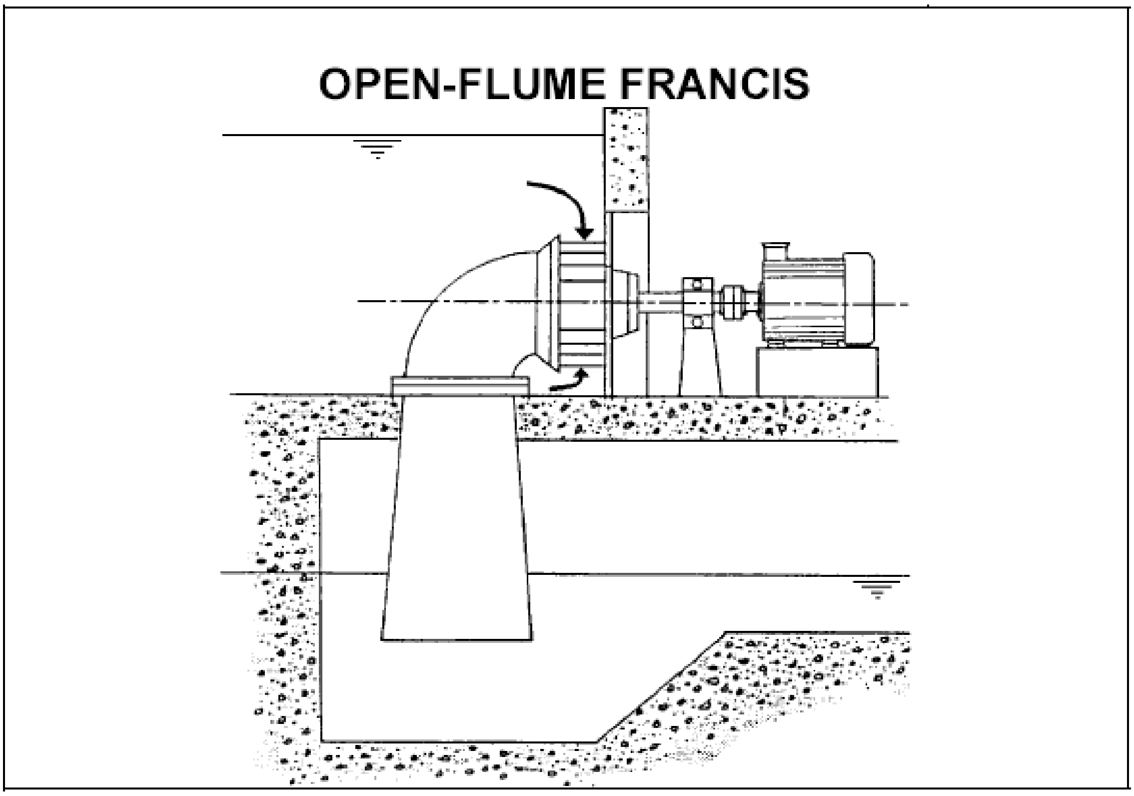

Figure 27 Open flume Francis (British Hydropower Association, 2005)

Although historically open-flume Francis turbines have been employed in low head applications, like in old mill sites, nowadays it is supplied only for replacement of an existing machine. Part flow performance of Francis turbines is shown in Figure 20.

3.2.3 Waterwheels

Waterwheels, Figure 28, are less efficient machines when compared to other modern low head turbines. Their technical simplicity makes them cheaper to built, install and maintain. Waterwheels can operate over a variable range of flow conditions.

Figure 28 Modern waterwheel installation in Germany (Davison and Bacon, 2004)

There are two types of water wheels:

- Overshot wheels
- Undershot wheels

In an overshot wheel water is fed from the top into buckets or cells and released at the bottom. In an undershot wheel the water is fed from a point lower than the wheel axis.

Efficiencies for both waterwheels are around 60%. With these machines it is possible to exploit heads from 2 to 5 m with a flow rate under 1 m^3/s for overshot design, giving an output of 10 to 55 kW; meanwhile for undershot design heads range from 1 to 3 m and flow rates from 1.5 to 6 m^3/s, with electrical outputs from 4 to 45 kW.

3.2.4 Archimedean screw

The Archimedean screw, Figure 29, is a simple device with only one moving part and two bearings. This device represents an aged technique in pumping applications, but it can be used also as an energy converter. The screw can handle floating particles and small pieces of debris very well. Study cases of this machine demonstrated efficiencies of around 80% for a range of flows from rated to about 60% of it. The efficiency drops to around 70 % when the flow reaches 40% of the rated flow. The optimum screw angle was found to be 30°.

Figure 29 Archimedean screw turbine (co2sense.org.uk)

This succinct review shows that there is still scope for the optimization and innovation in the technology employed in the exploitation of low head hydric resources.

3.3 Turbines for pico hydro applications

Turbines utilized in pico hydro applications vary in size from some hundred watts to 5-10kW. They are generally referred as pico turbines.

A big variety of pico turbines have been developed to suit a range of different sites. They can exploit heads up to 100m and flows from 10l/s up to some cubic meters per second.

Standardized technology can help in the diffusion and utilization of pico hydro, and indeed batch production reduces machinery costs. In developing countries the aim is to create their own market with local manufacturers.

Turbine designs should then be efficient and simple, to allow local manufacturing; furthermore they should be cost-effective and reliable.

The essential features, in terms of performance, cost, maintenance requirements and potential damage induced by the transport of silt for the main turbine designs are listed in Table 2 due to Maher and Smith (2004):

Turbine Name	Head Range	Cost for 5kW	Maintenance	Damage by Silt
Pelton	Medium and high	Low	Simple and robust so low maintenance	Little effect from silt
Cross Flow (Michel-Banki)	Medium and low	Low / Medium	More turbine maintenance required than Pelton	Little effect from silt
Turgo	Medium and high	Medium - more complex than pelton	Low maintenance	Little effect from silt
Propeller	Low	Low / Medium	More maintenance required than Pelton	More problems with silt over time
Pump-as-Turbine	Medium and low	Low	More maintenance required than Pelton	More problems with silt over time
Francis	Medium	High - uneconomic at 5 kW	More complicated to maintain	Not for use with heavily silt-laden water

Table 2 Pico turbines specifications (Maher and Smith, 2004)

The Pelton turbine represents one of the most efficient designs among pico turbines. It is largely used on harnessing small stream energy when heads are bigger than 20 meters. The Pelton runner is a wheel fully covered by buckets around the circumference. One or more nozzles transform water pressure into jets. When a jet hits tangentially the buckets it transfers energy from the water to the shaft, making the wheel to run at rated rotational speed. It is therefore an impulse turbine type.

The Turgo turbine has a similar design to that of a Pelton turbine. A Turgo turbine can be used to exploit streams of different qualities.

Cross flow turbines are impulse turbine in which water flows into the cylindrical runner radially from the external circumference to the centre. Blades can be adapted to the flow regime maintaining a good efficiency over a wide range outside the rated conditions.

Propeller turbines, also called axial turbines, are made up of a smaller number of blades with a bigger size when compared to other turbines. They are used to exploit low head sources.

3.4 Turbine selection

Each turbine, depending on its characteristics, is suitable to exploit a certain type of source.

Specific speed (Ns) is a number that is purely a factor of the geometry of a turbine and which describes the performance characteristics of a given design, independently of the size (Davison and Bacon, 2004).

Ns is a number that comes out from the similitude laws for hydraulic turbines. There are many different definitions of Ns, but in this work only the most common definition has been considered:

$$N_s = n\frac{\sqrt{Q}}{H^{\frac{3}{4}}}$$ **Equation 5**

Where Ns is the specific speed expressed in revolutions per minute, n is the operational speed (rpm), Q is the flow (m^3/s) and H is the head (m).

The type of generator utilized is directly related to Ns through n.

$$n = \frac{60f}{p}$$ **Equation 6**

Hence the generator choice directly affects the turbine selection and vice versa.

Turbines can be classified according to specific speed (Table 3).

TURBINE TYPES	Ns (rpm)
Pelton single jet	<25
Pelton multi-jet	25-70
Slow Francis	50-100
Normal Francis	100-200
Fast Francis	200-400
Fixed geometry propeller	400-700
Propeller with adjustable vanes and/or rotor blades	400-1300

Table 3 Turbine classification according to specific speed (Arrighetti, 2007)

Fast turbines are the ones with high Ns, slow turbines those with low Ns. This definition is not related to the actual operational speed but to the speed that a turbine would have when operating under 1 meter of head producing 1kw (Ns). Pelton turbines, despite being “slow turbines”, are generally directly coupled to generators while low head turbines (fast turbines) generally need to be used with a gear box (Arrighetti, 2007/2008).

Figure 30 presents a graph useful for turbine selection for pico hydro applications when water flows do not exceed 0.2 cube meters per second. It focuses on the exploitation of medium to high head sites. The coordinates are expressed in terms of H and Q.

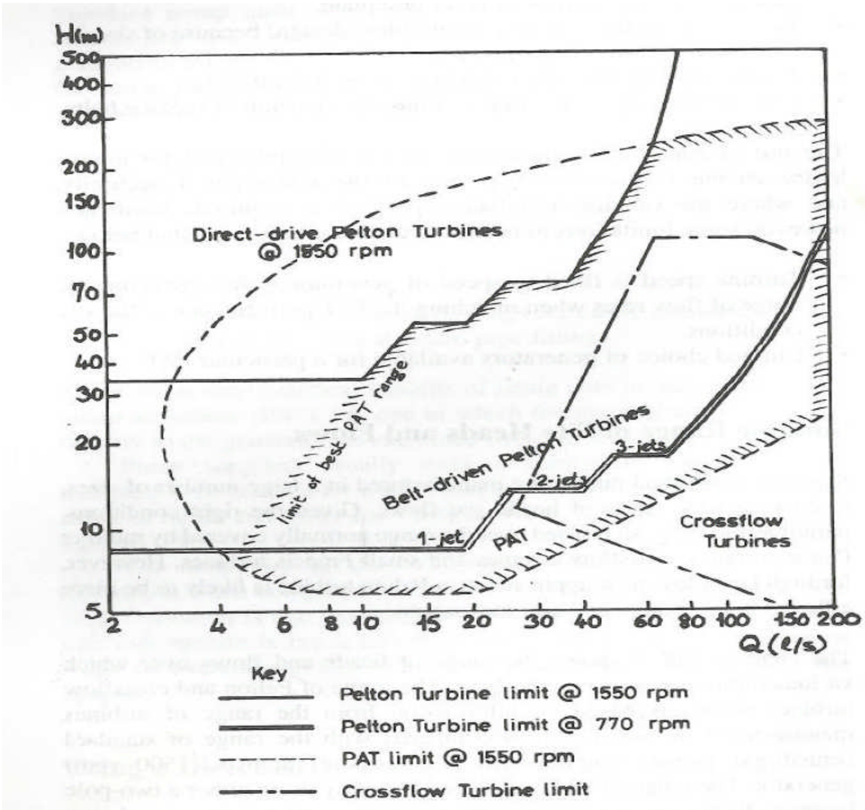

Figure 30 Turbine selection (Williams, 2003)

In Figure 31 another graph which is useful for turbine selection is presented.

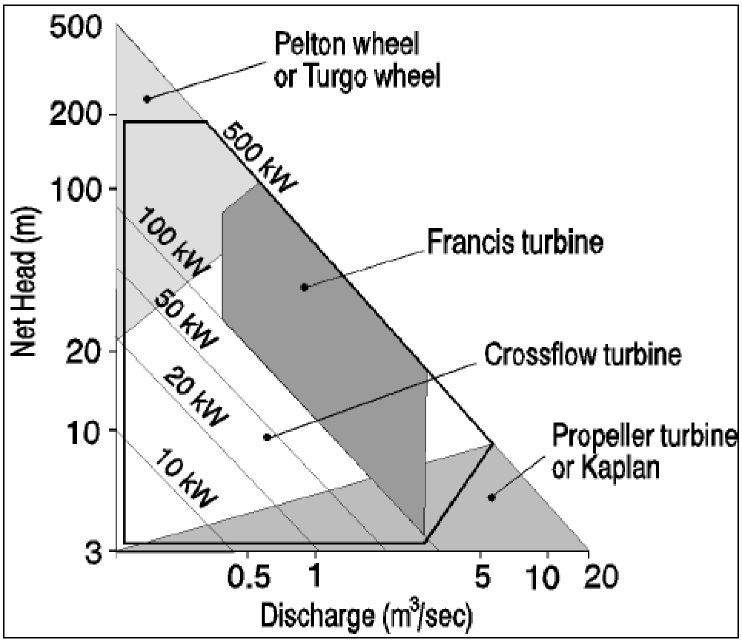

Figure 31 Turbine selection (The British Hydropower Association, 2005)

Another similarly useful graph is presented in Figure 32. It deals with selection of low head turbines for micro and mini hydro generation. Coordinates are expressed in terms of H and P. In this graph the range of interest for turbines to be used in schemes in the South East of England is plotted.

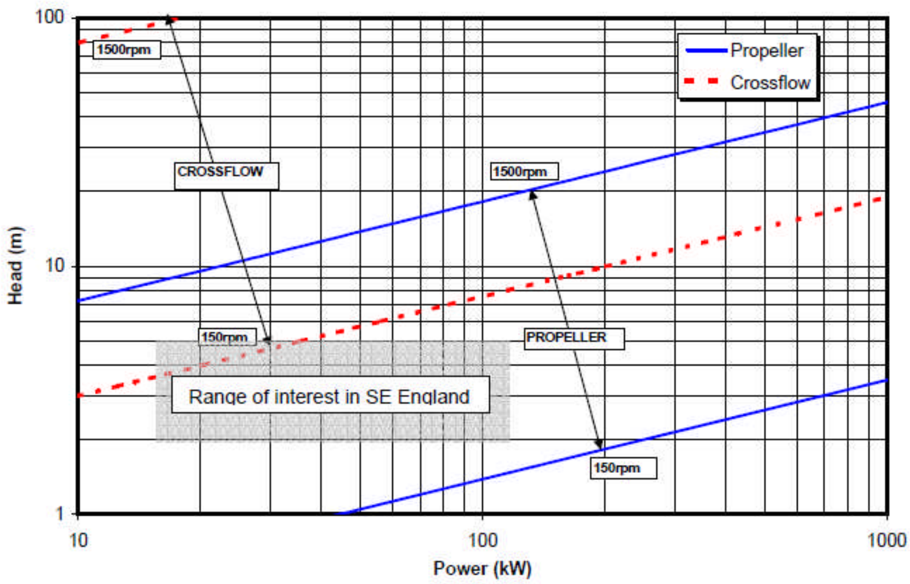

Figure 32 Range of operation for crossflow and propeller-type turbines (Davison and Bacon, 2004)

Below 3 m of head the only technical solution is represented by propeller turbines, either as a fixed geometry machine or as a full Kaplan or a semi-Kaplan configuration.

3.5 Pumps as turbines

Several studies have been carried out for pumps working in reverse because of their applicability in fields like pico hydro generation and energy recovery schemes.

Regarding pico hydro, the pros and cons of using pumps as turbines (PAT) over conventional turbines can be summarized as follows:

Availability of a wide range in terms of flow and head with large number of different commercial standards, mass production that allow low prices, ease of spare parts availability, short delivery time, easy installation, and if they come as an integral unit (direct driven electric pumps) then the machine results even more efficient, compact, simple and reliable even though it issues limitations on generator choice and fixed turbine speed according to the generator.

The main drawback of PAT is the lack of regulation possibilities, hence the need to run at a fixed operational point in terms of head, flow and speed (referring to the limitations outlined before for integral unit).

Studies of PAT aim to determine how a certain type of pump will work as turbine. It is not easy to obtain this kind of prediction with high accuracy. There are formulae, prediction models and experimental analyses that have been carried out over many years to overcome this difficulty. Once a pump matches a system at its BEP, it will work close to the maximum efficiency of the pump, but no regulation will be possible without a drastic efficiency reduction.

Among all the existing kind of pumps only standard centrifugal pumps and submersible pumps have been found to be suitable to work as turbines.

Regarding centrifugal pumps, the ‘end-suction’ design, so called because of having a single suction pipe, is the most suitable. ‘In-line’ and ‘double suction’ designs can work in reverse but with a lower efficiency.

Standard centrifugal pumps lead in terms of availability and economical accessibility among the others. Their main applicability fields are water supply and irrigation. Small ones can have a simple round casing that substitutes the spiral volute. This kind is been found to be not suitable to work as turbines.

Utilization fields for submersible pumps are wells pumping and drainage of construction sites. They come as integral units. Dry-motor jacket cooled is practically the only suitable design for this category. Unfortunately sometimes this kind of pump can have rubber linings on diffuser part to avoid the impeller to run in reverse. Wet-motor submersible borehole pumps can be used as turbines but usually their design involves a non-return valve and specific bearings that can not work in turbine mode.

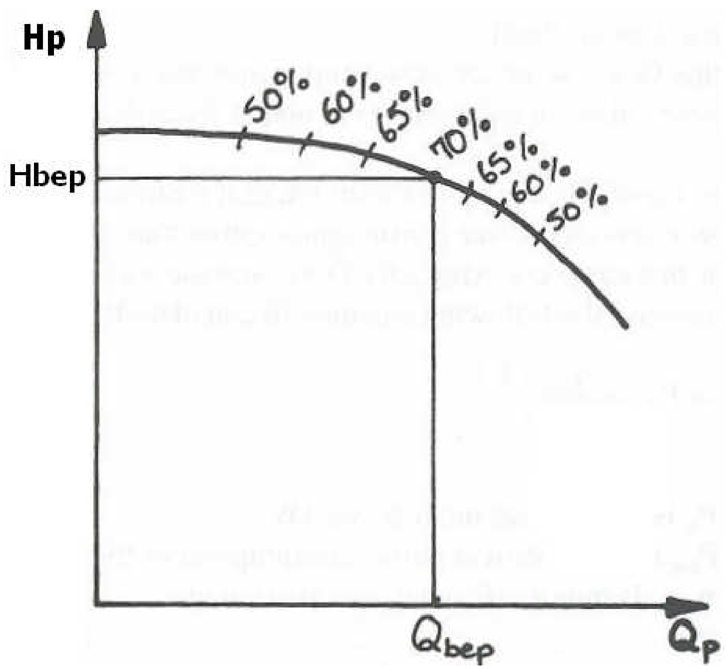

Figure 33 Pumps performance curve (Williams, 2003)

The first step on understanding how a pump will work as a turbine is to know how the machine works as a pump. A performance curve relates head and flow delivered by the pump over the operability range (Figure 33).

The best efficiency point (bep) is the point with the highest efficiency. It ranges from 40% to 80% depending on the pump design. Bep is clearly shown as the peak point on the pumps efficiency curve (Figure 34)

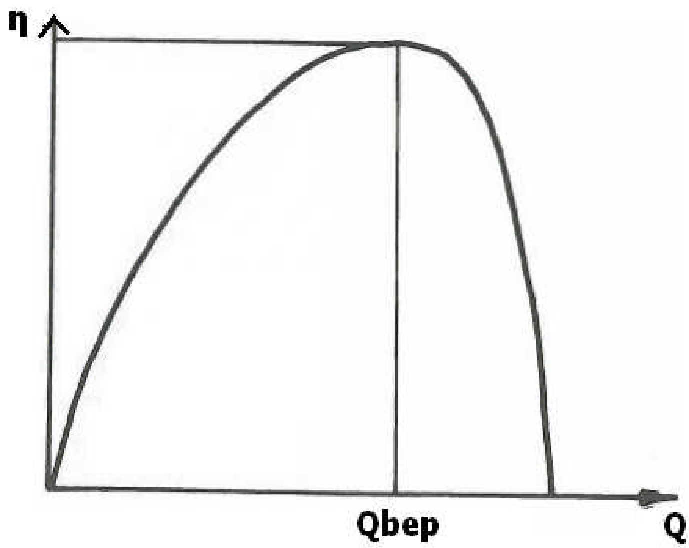

Figure 34 Pumps efficiency curve (Williams, 2003)

Conditions of best performance are referenced as Q_{bep} and H_{bep}.

Pumps manufacturers generally provide a pump performance curve, but it does not always come with the efficiency curve. If the efficiency curve is not available it is however possible to identify the best efficiency point by using Equation 7

$$\eta = \frac{H \cdot Q \cdot 9{,}81 \cdot \rho}{P_{in}} \qquad \textbf{Equation 7}$$

Where η is the pump efficiency if P_{in} is the mechanical input, or η is the pump and motor efficiency if P_{in} is the electrical power.

Sometimes the best efficiency point can be seen in the pump plate or if not available can be identified as an approximation value to be verified with the measurements of some parts of the pump. For further information see (Williams, 2003).

When a pump works as turbine the flow increases with the head (Figure 35)

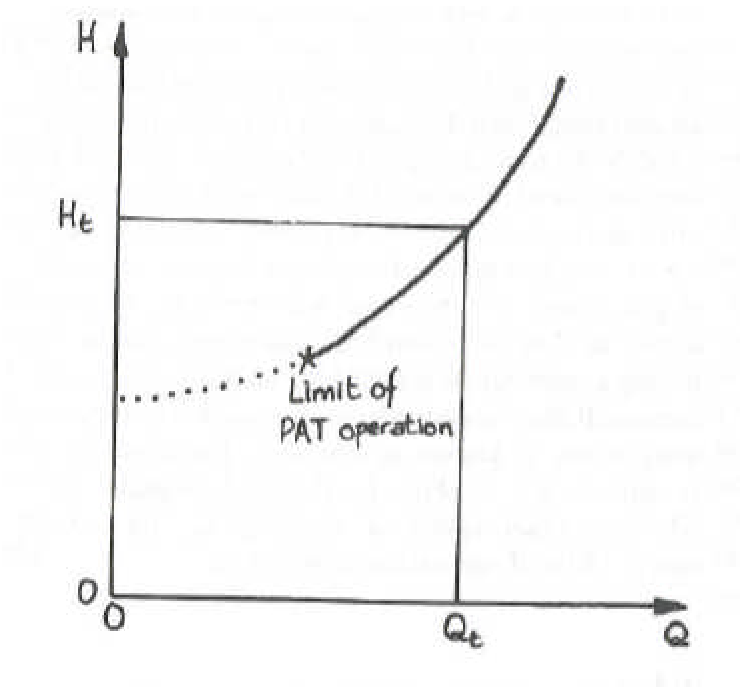

Figure 35 Pump as turbine head and flow for the normal operating speed (Williams, 2003)

The normal operating speed depends on many factors and is determined at the design phase. The operating point can be determined by the intersection of the turbine operational curve and the site curve (Figure 36) where the site curve is the head less friction losses.

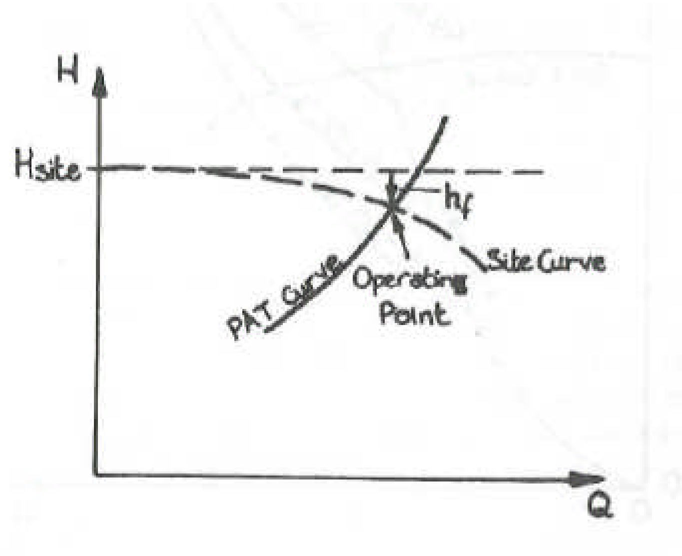

Figure 36 Turbine curve and site curve (Williams, 2003)

The greatest difficulty to overcome when using pumps as turbines is to match the machine to the site in the way that it will operate at acceptable efficiency.

Empirical equations have been found to identify the best efficiency point of the pump when working as a turbine. Those running conditions (H_t and Q_t), will differ a lot from the pump ones even though the respective efficiency values will be approximately the same. Equation 8 and Equation 9 give the best PAT operational conditions when rotational speeds are the same for pump and turbine operations.

$$\boldsymbol{Q_t = \frac{Q_{bep}}{\eta_{max}^{0.8}}}$$ **Equation 8**

$$\boldsymbol{H_t = \frac{H_{bep}}{\eta_{max}^{1.2}}}$$ **Equation 9**

Where Q_{bep} and H_{bep} are flow and head of pump's best efficiency point, Q_t and Ht are the correspondent values in turbine mode and η_{max} is the efficiency of pump at bep.

When the pump rated speed is different from the rotational speed in reverse operation Equation 10 and Equation 11 must be used in place of Equation 8 and Equation 9.

$$Q_t = \frac{n_t}{n_p}\frac{Q_{bep}}{\eta_{max}^{0.8}}$$ **Equation 10**

$$H_t = \frac{n_t^2}{n_p^2}\frac{H_{bep}}{\eta_{max}^{1.2}}$$ **Equation 11**

This method, unfortunately, provides approximated values of Q_t and H_t that can differ by about ±20% from the actual value. Before the matching it is then recommended to test the pump in reverse obtaining the real performances of the PAT.

The procedure of pump selection is made up of a few steps. What is known is the site condition in terms of H (gross head less the losses expressed in metres) and Q (the dry season flow available all the year), that represent the terms Ht and Qt in equations Equation 10 and Equation 11. The following step is to guess what the pump's rotational speed will be. It is possible to refer to pumps with a rated power close to the expected plant output, and take into consideration standard rotational speeds for that type of pumps. If it is assumed the pump to be driven by an induction generator the rotational speed n_t needs to be calculated (Equation 29). Next step is to establish a plausible pump η_{max} (Figure 37)

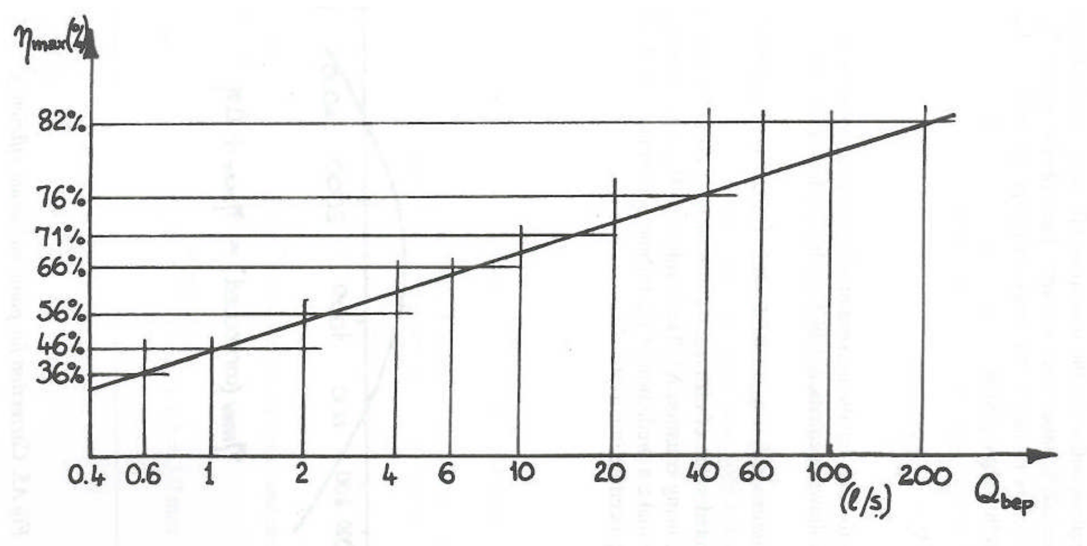

Figure 37 Pump maximum efficiency related to flow rate (Williams, 2003)

This value has to be corrected once H_{bep} and Q_{bep} have been calculated with equations. Figure 38 provides a graph to evaluate the correction factor.

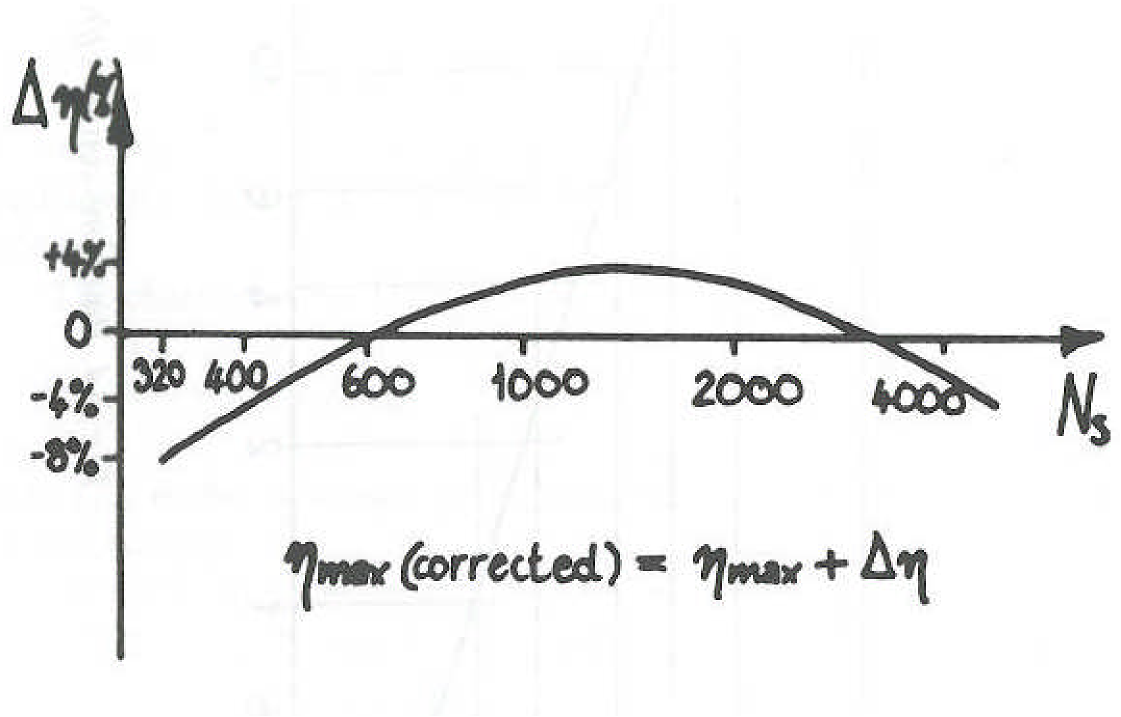

Figure 38 Correction for pump maximum efficiency (Williams, 2003)

Where η_{max} in the equation in Figure 38 is calculated through the graph in Figure 37 using Q_{bep}. If this value is close to the one established before for the H_{bep} and Q_{bep} calculation then those values are acceptable.

At this point there is enough information to identify a suitable pump.

PAT utilization is an attractive option for small hydropower plants. It can make more feasible a plant realization especially because of the consequent cost reduction, in fact it is stated that capital payback time for PAT from 5 kW to 500 kW is two years or less. The main problem with PAT utilization consists of predicting how a pump will work as a turbine (performance prediction model) and consequently to select those suitable for a particular site (PAT selection), (Derakhshan and Nourbakhsh, 2008).

Around a dozen of prediction models for PAT performances have been published so far (Singh and Nestmann, 2010).

As shown before Williams (2003) provides a method based on empirical equations obtained from affinity laws, where the actual performances can potentially differ by ±20%.

Arriaga (2001) carried on a feasibility study for a PAT installation in Laos and used this method to predict performances of PATs, despite uncertainties in the results. He compared those values with the ones obtained from other methods. One is by Derakhshan and Nourbakhsh (2008) the other is by Ramos and Borga (2000).

A discrepancy of 5% and 3% in the head value has been recorded when compared with Arriaga's result.

Pump selection is carried on considering a few pumps and their behaviour as turbines in terms of rated Q and rated H. Those values have been than compared with the site conditions Q and H to verify the compatibility. After this operation the author identified three models of pumps that could be suitable to work as turbine under the given conditions. If once the PAT is installed the output value differs from the one expected, the impeller diameter can be reduced to increase the efficiency.

Another approach has been proposed by Derakhshan and Nourbakhsh (2008). They tested four different centrifugal pumps as turbines, with specific speeds from 14 to 56 rpm, and derived some relations to predict the BEP of PATs. During this study they installed a small hydroelectric plant, so they could make pump testing in laboratory (Figure 39).

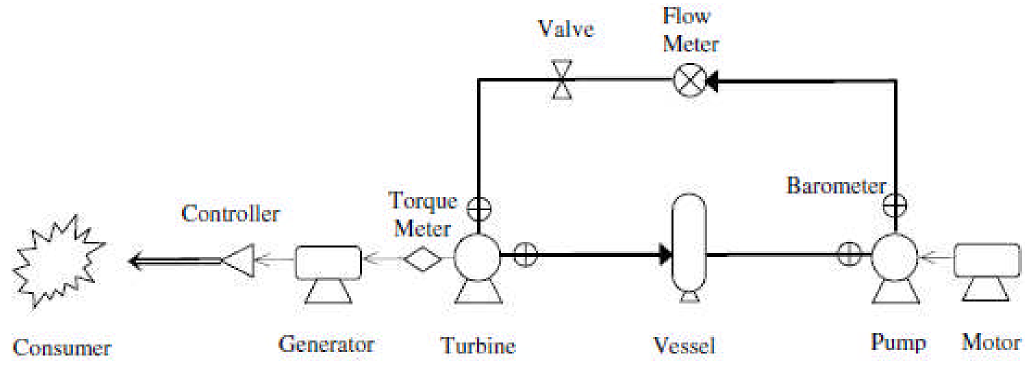

Figure 39 The mini hydropower established in the University of Tehran (Derakhshan and Nourbakhsh, 2008)

Experimental results from Derakhshan and Nourbakhsh (2008) investigation demonstrated that a PAT works at higher flow and head compared with the pump mode. The correspondence between pump mode and turbine mode of the four different pumps at best efficiency point in terms of $h = \frac{H_{tb}}{H_{pb}}$, $q = \frac{Q_{tb}}{Q_{pb}}$, $p = \frac{P_{tb}}{P_p}$, $\lambda = \frac{\eta_{tmax}}{\eta_{pmax}}$ can be seen in Figure 40.

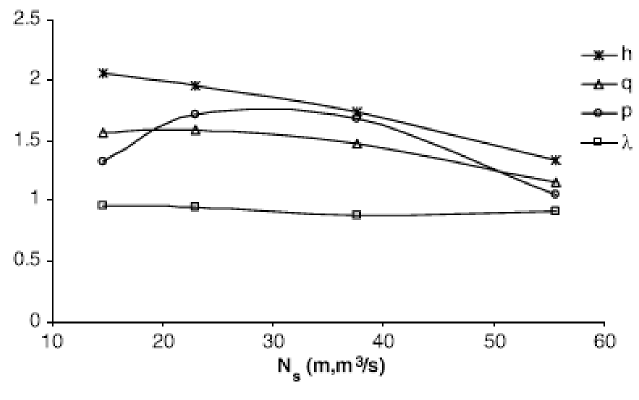

Figure 40 Dimensionless BEP of tested PATs (Derakhshan and Nourbakhsh, 2008)

Results have been extended to other specific speeds through relationships that the authors obtained from experimental data, Equation 12 through to Equation 19.

$$\gamma = 0.0233 \cdot \alpha_p + 0.6464$$ **Equation 12**

$$\alpha_p = 0.9413 \cdot \alpha_p - 0.6045$$ **Equation 13**

$$\beta_t = 0.849 \cdot \beta_p + 1.2376$$ **Equation 14**

$$\alpha_p = \frac{N_p \cdot Q_{pb}^{0.5}}{(g \cdot H_{pb})^{0.75}}$$ **Equation 15**

$$\beta_t = \frac{N_t \cdot P_{tb}^{0.5}}{\rho^{0.5} \cdot (g \cdot H_{tb})^{1.25}}$$ **Equation 16**

$$\gamma = (h)^{-0.5} \cdot \frac{N_t}{N_p}$$ **Equation 17**

$$\alpha_t = \frac{N_t \cdot Q_{tb}^{0.5}}{(g \cdot H_{tb})^{0.75}}$$ **Equation 18**

$$\beta_p = \frac{N_p \cdot P_{pb}^{0.5}}{\rho^{0.5} \cdot (g \cdot H_{pb})^{1.25}}$$ **Equation 19**

Some researchers reported that pumps with nearly the same specific speeds may have very different head ratios (h) and flow rate ratios (q) (Derakhshan and Nourbakhsh, 2008). For example, if two pumps have the same specific speed, the more efficient pump operates as a turbine in greater h and q.

Chapallaz et al (1992) reported other set of correlations (Equation 20 to 21) to predict the best efficiency point of pumps with same specific speed and different impeller diameters.

$$h_{new} = h \cdot (0.25/D)^{\frac{1}{4}}$$ **Equation 20**

$$q_{new} = q \cdot (0.25/D)^{\frac{1}{6}}$$ **Equation 21**

$$p_{new} = p \cdot (0.25/D)^{\frac{1}{10}}$$ **Equation 22**

The method presented gives results quite in concordance with experimental data, and can be used for pumps with Ns<60 rpm

Those authors compared 4 different methods to predict the turbine mode operation of a pump with experimental data, including the one they proposed, referred as “the new approach” (Figure 41).

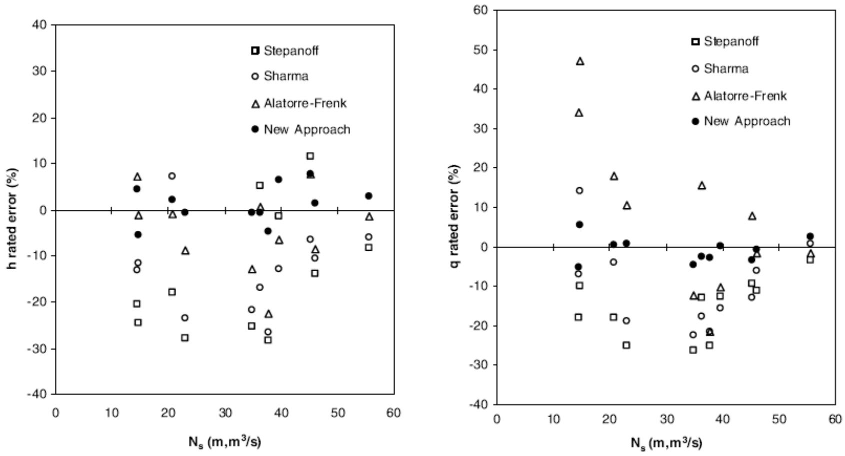

Figure 41 Rated errors of head ratio (h) and flow ratio (q) of PATs from experiment and various methods (Derakhshan and Nourbakhsh, 2008)

None of the methods presented is totally reliable, but among those the new approach is the one with less rated error when compared with experimental data.

Beside investigation on turbine mode operation of a pump they presented a 6 step procedure to identify the specific pump to be used in a particular site, Figure 43. This procedure is considered to be valid only for turbines with Ns<150rpm.

Step1: The pump specific speed in its rated point, N_{sp} can be calculated as

$$N_{sp} = 0.3705 N_{st} + 5.083,$$

where N_{st} (m, kW) and N_{sp} (m, m^3/s) are the turbine and pump specific speeds in their rated points, respectively.

Step 2: γ can be obtained by putting $\alpha_p = \frac{N_{sp}}{g^{0.75}}$ in Eq. (3).

Step 3: Knowing γ and using Eq. (8), h is determined.

Step 4: H_{pr} can be calculated by $H_{pr} = \frac{H_{tr}}{h}$.

Step 5: Q_{pr} can be obtained using N_{sp}, choosing N_p and knowing H_{pr}.

Step 6: The proper PAT can be easily selected when H_{pr}, Q_{pr} and N_p are known.

(3). $\gamma = 0.0233\alpha_p + 0.6464,$

(8). $\gamma = (h)^{-0.5} . \dfrac{N_t}{N_p},$

Figure 42 Six-step procedure for pump selection (Derakhshan and Nourbakhsh, 2008)

Few others researcher like Cohrs and Amelio and Barbarelli have tried to use detailed theoretical models that are based on the pump design, its geometry and assumption of some complex hydraulic phenomena like losses and slip effects in an effort to bring out more accurate turbine characteristic predictions. These methods are definitely comprehensive, but they are difficult to implement and simply beyond the reach of planners, since these models need very detailed information, which is sometimes patented or available only with the manufacturers (Singh and Nestmann, 2010).

To overcome those difficulties on PAT prediction Singh and Nestmann (2010) presented basic models for PAT prediction and selection, and an optimization routine to reduce uncertainties on the obtained results.

The proposed prediction model is based on experimental results of 9 different PATs with specific speed from 20 to 80 rpm (Table 4), and the fundamentals of applied turbomachinery i.e. specific speed specific-diameter plots by Cordier.

Sr. no.	Pump mode BEP (absolute and dimensionless)								Turbine mode BEP (dimensionless)				Comparisons	
	H_p (m)	Q_p (l/s)	N_p (rpm)	D_1 (mm)	N_{qp} (rpm)	ϕ_p	ψ_p	η_p (%)	N_{qt} (rpm)	ϕ_t	ψ_t	η_t (%)	ϕ_t/ϕ_p	ψ_t/ψ_p
Data of 9 PATs from author used in the basic prediction model														
1	14.5	10.8	1500	225	21.0	0.038	4.496	77.0	18.5	0.070	8.000	72.5	1.85	1.78
2	21.5	26.5	1500	258	24.5	0.062	5.070	78.0	18.6	0.117	11.170	76.5	1.90	2.20
3	12.8	25.4	1500	206	35.3	0.116	4.734	78.5	28.1	0.151	7.640	81.0	1.30	1.61
4	8.38	15.3	1450	174	36.4	0.120	4.650	74.4	30.1	0.185	8.000	71.5	1.54	1.72
5	19.8	65.9	1450	264	39.7	0.148	4.772	85.0	35.7	0.200	6.700	83.5	1.35	1.40
6	10.5	33.0	1450	200	45.2	0.171	4.409	80.0	41.1	0.235	6.180	79.5	1.38	1.40
7	5.6	13.5	1450	139	46.4	0.208	4.850	76.0	38.1	0.275	7.600	76.0	1.32	1.57
8	6.4	28.9	1450	165	61.3	0.266	3.949	72.0	57.6	0.414	5.748	74.3	1.56	1.46
9	10.6	103.0	1450	224	79.1	0.379	3.555	84.0	70.0	0.480	4.900	75.5	1.27	1.38
Additional data from Derakshan and Nourbakhsh [2] used in the optimization routine														
1 [2]	17.8	8.0	1450	250	14.6	0.021	4.780	65.0	10.9	0.033	9.800	64.0	1.56	2.05
2 [2]	20.4	23.7	1450	250	23.0	0.063	5.487	76.0	17.8	0.100	10.700	73.0	1.59	1.95
3 [2]	18.1	57.2	1450	250	37.6	0.151	4.855	86.5	31.9	0.224	8.400	74.0	1.48	1.73
4 [2]	17.5	107.0	1450	250	55.6	0.283	4.701	87.0	47.5	0.323	6.300	78.0	1.14	1.34

Table 4 Experimental data for 13 different PATs (Singh and Nestmann, 2010)

The selection model identify those pumps from manufacturer's catalogues that could work under the given conditions H and Q, and together with the prediction model is able to identify the most suitable pump (Figure 43).

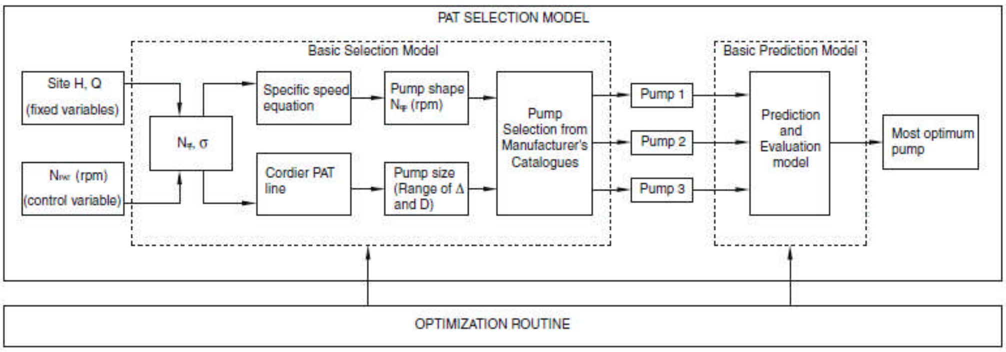

Figure 43 Flow chart for the PAT selection model (Singh and Nestmann, 2010)

The optimization routine improves the reliability of the basic model without changing the philosophy of the methodology used in the basic PAT model. Hence it cannot be called a new model and instead called a routine, which is analogous to a small computer program that forms a loop with the basic model, (Singh and Nestmann, 2010) (Figure 44).

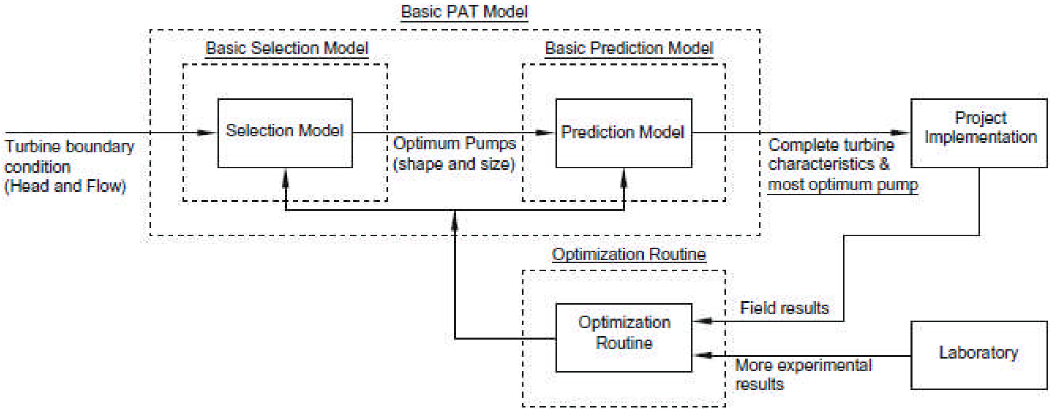

Figure 44 Block diagram of the consolidated model for pumps as turbines with optimization routine (Singh and Nestmann, 2010)

With respect to the prediction model, the optimization routine should reduce the prediction errors to the limits of + or – 4 %. While from the prospective of the selection model, it should be able to make a better choice of a pump for given turbine-mode operating conditions (Singh and Nestmann, 2010).

The optimization routine considers further experimental data provided by Derakshan and Nourbakhsh (2008) in addition to those ones the prediction model relies on.

The optimization routine is evaluated experimentally for three pumps with specific speed of 18.2 rpm, 19.7 rpm and 44.7 rpm, and a significant improvement in the accuracy of the turbine predictions with the errors for all the three pumps falling within the 4% acceptance bands in the full load operating region is found (Singh and Nestmann, 2010).

4 ADDITIONAL ASPECTS OF HYDROPOWER

This chapter investigates various aspects of hydropower. It presents a description of important plant components like the intake, the forebay, the penstock and the generator. It also goes into the explanation of methodologies for river flows analysis, and hydrologic modelling techniques. It concludes with hydro plant design methodologies and a brief survey on current Italian legislation on hydropower.

4.1 Plant components

4.1.1 Intake

Aim of the intake structure is to collect water from the river and divert it into a penstock, or a canal, or forebay. The intake is also formed to avoid the admission of drifting materials like detritus or sand; and floating materials like leaves or wood. These objects are normally carried down river by the stream and must be removed to protect the hydraulic machine and other components from damage.

For run of river plants the standard intake configuration consists of a weir and a collection structure.

A weir is basically, a barrage that maintains the water at a constant level. It does not store water, it just creates a small impoundment.

The intake must assure that the desired amount of water is always supplied to the turbine, sometimes independently from seasonal variations of flow regimes.

In a certain way it must carry out a function of flow regulation.

Pico hydro is likely to avoid the construction of big civil works. The best intakes are the less demanding; sometimes natural impoundments can avoid the entire construction of a weir, some others the forebay can be avoided, and water is collected directly from the river.

Figure 45 shows an example of intake used in pico hydro applications and a description of the components follows.

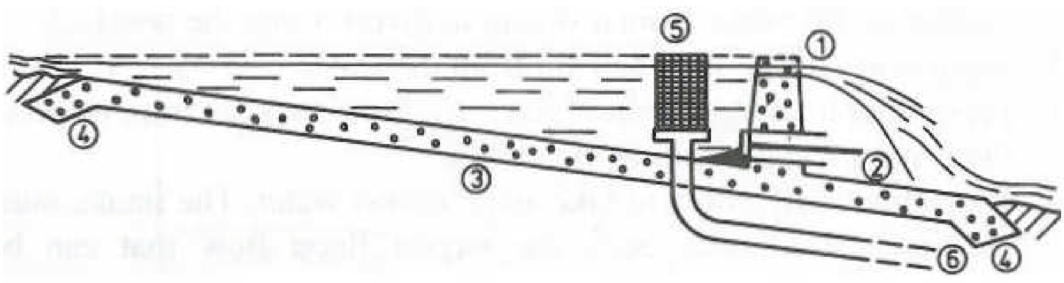

Figure 45 Intake design with weir, penstock and flushing pipe (Williams, 2003)

1) Concrete retaining wall with overflow
2) Drainage pipe to flush away silt, with plunger and hung
3) Smooth concrete base – with max 10% of slope
4) Concrete skirt to prevent undercutting
5) Cylindrical wire mesh trash rack
6) Buried plastic penstock

Weirs can be constructed in concrete, wood or gabions, sometimes even with stones.

Figure 46 Example of an intake design with concrete weir, embedded penstock, and drainage pipe (Smith and Maher, 2001)

This design shown in Figure 46 does not necessitate the presence of a forebay, the silt rests on the bottom of the pond where the penstock is placed. A drainage pipe is a wise addition in that it allows the silt to be flushed away.

In the following design the weir acts as a barrage and allows a certain amount of water to be diverted into the head race. A diversion branch is located at a side of the stream. It collects water from the river and brings it to the forebay or to the penstock. It is possible to have a side intake or a direct intake as shown in Figure 47. If a side intake is placed far enough upstream from the weir, it prevents silt to access the headrace, while in a direct intake arrangement silt can be drawn inside, making indispensable the construction of a settle tank.

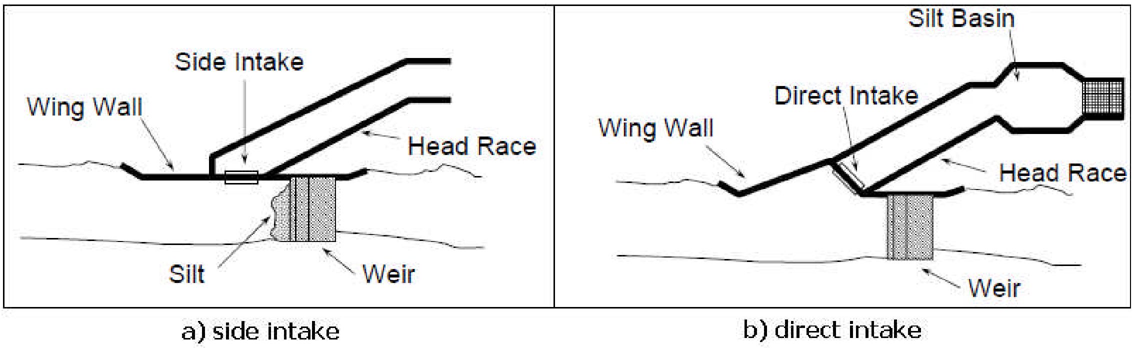

Figure 47 Intake design with weir and diversion branch: side intake and direct intake (http://files.harc.edu/Documents/EBS/CEDP/HydropowerPart1.pdf)

Another widespread intake design in pico hydro is the trench intake (Figure 48). This layout allows large debris to pass over: the rapidity of the flow itself keeps the trashrack clean.

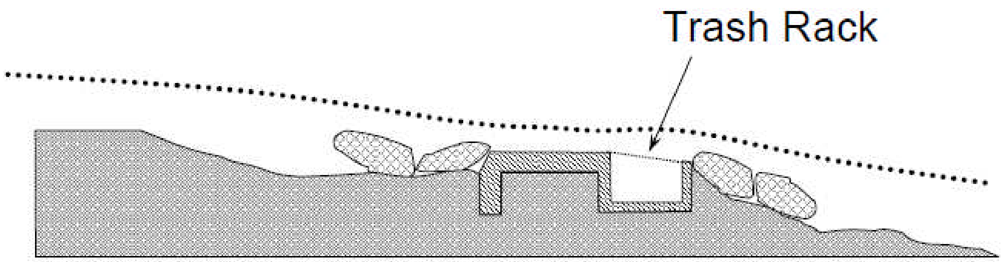

Figure 48 Trench intake design (http://files.harc.edu/Documents/EBS/CEDP/HydropowerPart1.pdf)

Siphon intake (Figure 49) design is used when the flows are low to guarantee a continuous operation. When flows are under the request value the system works intermittently: the intake lets the water in the penstock - when the reservoir level reaches the highest water level - and stops feeding the penstock when the reservoir level decreases to the lowest water level. When the water exceeds the requested flow this system will work continuously providing the rated flow to the penstock and letting the surplus pass over.

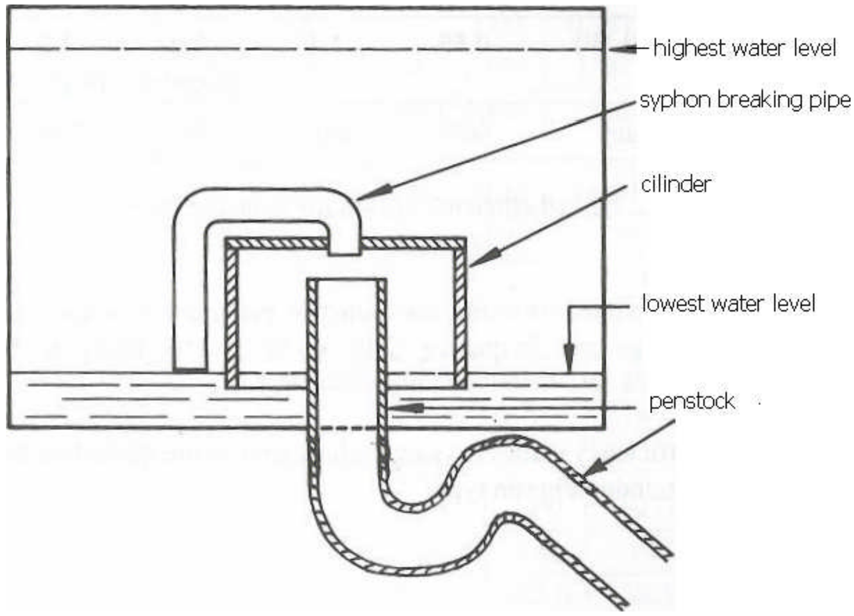

Figure 49 Siphon intake design (Williams, 2005)

4.1.2 Forebay tank

A forebay is a tank designed to let the detritus settle down and to let the overflow rejoin the main stream. It can be constructed in many ways, with different shapes and sizes, and with different materials: sometimes with stones (Figure 50) and concrete, sometimes plastic etc.. It is always provided with an overflow pipe or canal.

Figure 50 Forebay under construction (Singh and Ranjitkar, 2000)

4.1.3 Penstock

The penstock is the pipe line that connects the intake or the forebay with the hydraulic machine. It is constantly filled up with water and the internal pressure depends basically on the net head, i.e. the gross head reduced by the internal losses expressed in metres (head loss). The pressure established at the end of it represents the nozzle pressure that will drive the turbine.

Characteristic parameters of the penstock are: internal diameter, thickness, length, internal roughness and construction material. These measures determine the entity of internal losses and the maximum admissible pressure.

For pico hydro the upper limit to penstock losses is widely recognized as one third of the penstock length, but it is advisable that the penstock design does not introduce losses bigger than 10-20% of the penstock length (Williams, 2005).

Typical penstock materials for pico hydro are plastic: HDPE (High Density Polyethylene) that represents the most suitable option because of its flexibility and capacity of being coiled up to 75mm, PVC (Polyvinyl-chloride) that is suitable only for low pressure penstock, and steel that is used when the flow and the pressure in the penstock are higher. Most configurations of pico hydro plants use the penstock to cover the whole distance from the intake to the power house (Figure 51).

Bigger size hydroelectric schemes split the distance from the intake to the power house between the head race and the penstock (Figure 51), that is generally made of steel. Only sometimes reinforced concrete is used because of the limited pressures it can tolerate (up to 5-7 kg/cm^2). Head race tunnels are generally made with reinforced concrete.

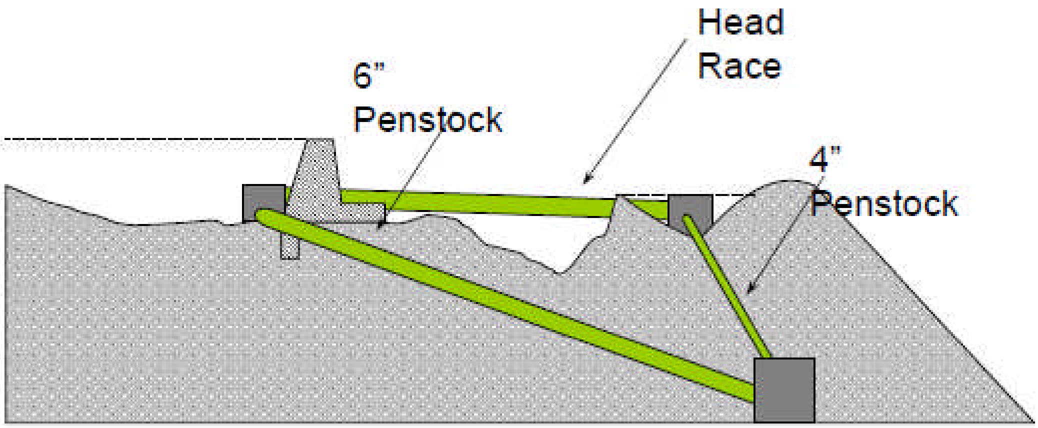

Figure 51 Penstock implementation options (http://files.harc.edu/Documents/EBS/CEDP/HydropowerPart1.pdf)

Pressure losses that occur in a pipeline can be expressed with Equation 23

$$\Delta p = \frac{\rho f L v^2}{2D} = \frac{8\rho f L Q^2}{\pi^2 D^5}$$ **Equation 23**

Where ρ is the water density, f is the friction factor, Q is the volumetric flow, L the pipeline length, D is the internal pipe diameter, v is the cinematic viscosity and g is the acceleration of gravity.

Equation 24 expresses losses in metres obtaining head losses.

$$h_L = \frac{f L v^2}{2Dg} \cong \frac{f L Q^2}{3D^5}$$ **Equation 24**

Where the symbols are explained above.

The friction factor f depends on the turbulence regime and it is expressed on the Moody diagram in Figure 52.

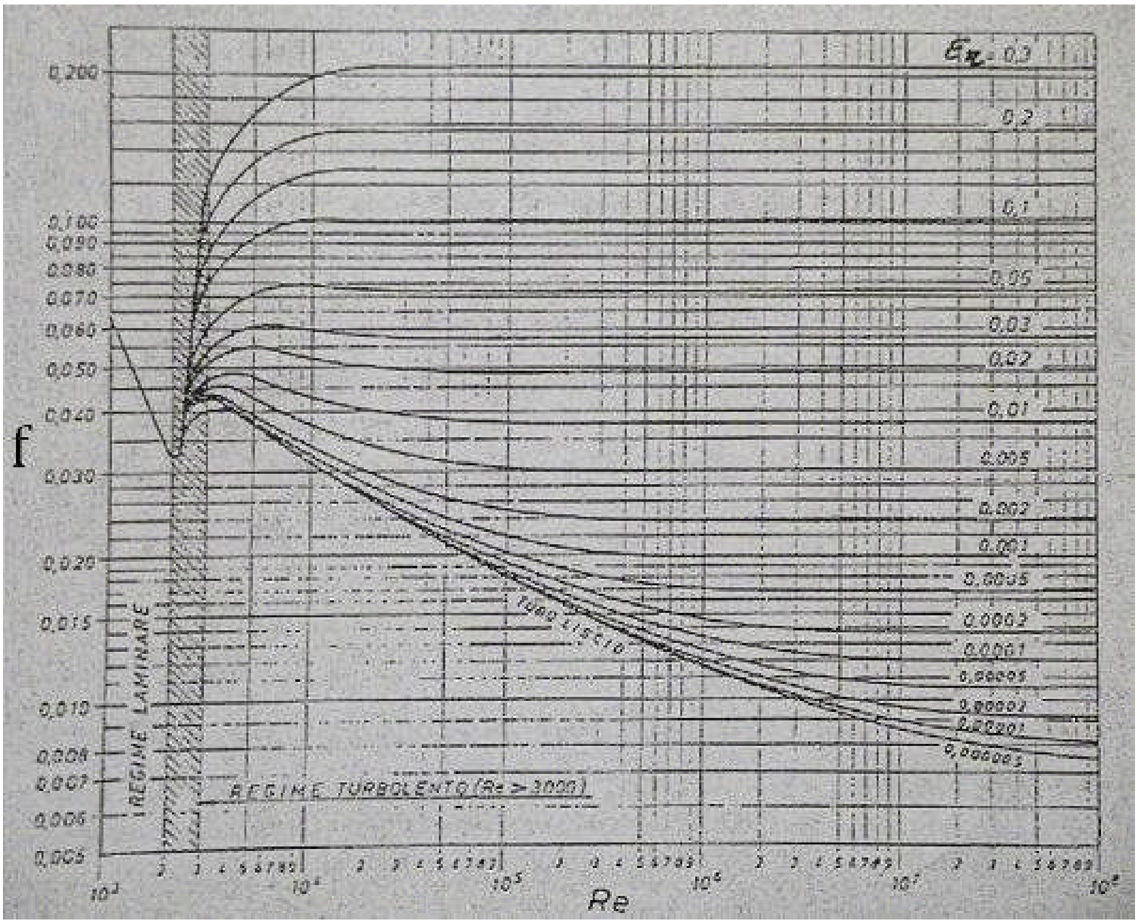

Figure 52 Moody diagram: fiction factor depending on Reynolds number and relative roughness (Arrighetti, 2007)

Williams (2003) provides a simple method for penstock sizing in pico hydro plants. Table 5 presents a few diameters (D_{pipe}) and the related flows (Q_{table}) that ensure a loss not bigger than 1% per unit length with a pipe characterized by a roughness of 0.06 mm.

D_{pipe} (mm)	75	100	125	150	175	200	250	300	350
Q_{table} (l/s)	3.5	7.6	13.7	22.2	33.4	47.5	85.5	138	210

Table 5 Flow rates for various standard pipe sizes (Williams, 2003)

Equation 25 allows the calculation of losses in percentage of gross head for one of the pipe diameters shown in Table 5, with a given length L_{pipe} and a certain flow Q. Q_{table} is the value associated at D_{pipe} in Table 5, h_f is the head loss and H_{site} is the gross head.

$$\frac{h_f}{H_{site}}(\%) = \frac{L_{pipe}}{H_{site}} \cdot \frac{Q^2}{Q^2_{table}}$$ **Equation 25**

Penstock losses must be contained inside the 20% of the gross head.

Penstock thickness is an important parameter that must be sized with accuracy. It can be estimated through Equation 26 (Mariotte equation):

$$s = \frac{p \cdot D}{2\sigma}$$

Equation 26

Where s is the wall thickness (mm), p is the fluid pressure (bar), σ is the material strength (bar).

Penstock prices rise with diameter and thickness. A common practice to reduce costs is to vary pipe thickness (pressure rating) along the penstock according to the local internal pressure. The option of using the same expensive pipe to cover all the penstock length would result simpler but more expensive to implement.

When linear distances between intake and power house are big the penstock price will greatly weigh upon the overall cost. Sometimes the possibility to run a channel or a low pressure pipeline is cost-effective. The penstock will collect water from the forebay at the end of the head race, and the distance to cover will be shorter.

4.1.4 Generators and electrical equipment

In pico hydro applications turbines come generally with generators as a single unit, sometimes directly coupled some others with driven belts. There are cases in which turbine and generator are chosen separately and matched together.

Generators are divided into synchronous generators and asynchronous generators (induction generators). The produced output is AC (Alternate Current), that is the unique possibility to limit losses when long distances must be covered.

A third typology is DC generator (like common truck alternator). They are generally used to charge batteries. Most electric loads are AC but sometimes it is possible to find DC electric loads. Table 6 Comparison of generators suitable for use with pico Hydro Turbines (Smith and Maher, 2001)Table 6 shows and compares various kinds of generators to be used in pico hydro plants.

Type of Generator	Source	Typical Cost for 3kW Machine	Speed (rpm) Options	Disadvantages	Advantages
Induction	Standard industrial motor used as a generator	Low: $200 - $250	1000, 1500, 3000	Needs correctly sized capacitors connected to operate as a generator. Poor motor starting ability	Widely available, slow speed ranges, robust simple construction. Can withstand overspeed. Cheaper than synchronous generators
Synchronous - Brushed	Commonly used with petrol or diesel engines.	Low - medium: $300 - $500	3000, sometimes 1500	Brushes and slip rings wear out and require replacement. Must be strengthened for over-speeding	Higher efficiency than induction at part-load and better motor starting capability
Synchronous - Brushless	Occasionally used with diesel engines	High: $600 - $1000	1500, 3000	Not widely available. Repairs are often complex / expensive. Must be strengthened for over-speed	As synchronous-brushed but with better reliability
DC	Car or truck alternator	Not Applicable Max. output = 500W	Car > 2000, truck > 1200	Not suitable for village electrification. Restricted range of appliances. Brushes and slip rings wear out	Very low cost, no controller required.

Table 6 Comparison of generators suitable for use with pico Hydro Turbines (Smith and Maher, 2001)

It is possible to convert AC to DC with a simple rectifier. Domestic loads require single phase distribution arrangement, while batch produced industrial generators (off-the-shelf) are three phase generators. With a simple 2C-C connection (Figure 53) it is possible to use a three phase generator in a single phase distribution system.

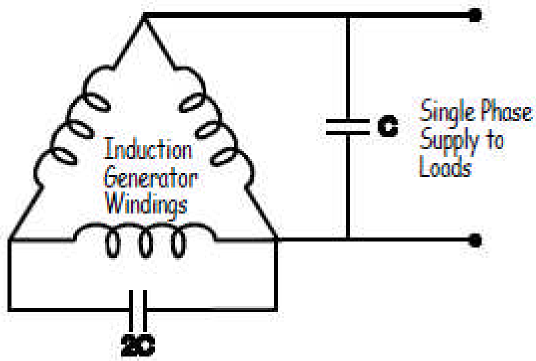

Figure 53 Single phase supply from 3 phase motor (Smith and Maher, 2001)

In this case it is important to size appropriately the capacitors because their values are responsible for the output voltage and generator speed (Williams 2003).

IGC (Induction generator controller) ensures that the electrical output of the generator is held constant in terms of frequency and voltage while consumer load keeps changing. IGC diverts excess power to ballast loads. Ballast loads are water or air dissipaters.

Induction generators are stronger and more reliable than synchronous ones, they have good resistance from damage even under anomalous conditions. Often, especially when utilizing pumps as turbines, induction motors can be utilized as self excited generators.

For applications up to 15 kW it is advisable to use a single phase distribution unless the connected load is a three phase motor or the distance between generator and load is greater than 500 metres (Williams, 2003).

Synchronous generators run at the synchronous speed depending on the number of poles according to Equation 27.

$$N_s = \frac{120}{p} \cdot f$$ **Equation 27**

Where p is the number of poles, f is the electrical output frequency and Ns is the rotational speed.

Rotational speed in induction generators depends also on the sleep factor s, that ranges from 0.02 to 0.05 (Equation 28)

$$N_g = \frac{120}{p} \cdot f \cdot (1 + s)$$ **Equation 28**

In the case of an induction motor the rotational speed will be slightly below the synchronous speed (Equation 29).

$$N_m = \frac{120}{p} \cdot f \cdot (1 - s)$$ **Equation 29**

Motors as generators are often used in pico hydro plants.

A relation between the speed of the machine working as a generator and the speed of the machine working as a motor (Equation 30) can be obtained combining Equation 28 and Equation 29:

$$N_g = \frac{240 \cdot f}{p} - N_m$$ **Equation 30**

Further information on running a motor as a generator can be found on (Smith, 1994) and (Smith and Ranjitkar, 2000).

4.2 Analysis of river streams

4.2.1 Thermodynamic analysis

Water streams move from higher points to lower ones according to gravity law.

$$g \cdot H_0 + \frac{p_1}{\rho} + \frac{c_1^2}{2} = \frac{p_2}{\rho} + \frac{c_2^2}{2} + \delta$$ **Equation 31**

The first principle analysis for 1 kg of an uncompressible fluid stream between section 1 and section 2 (Equation 31) is to consider all the possible energetic variations. Energy conservation assumes that first member in the equation must balance the second one, where: $\frac{c^2}{2}$ is the kinetic term, $\frac{p}{\rho}$ is the pressure term, $g \cdot H_0$ is the quote variation and δ represents the friction losses.

In the case of rivers Equation 31 can be simplified because $\frac{p_1}{\rho} \cong \frac{p_2}{\rho}$ and $\frac{c_1^2}{2} \cong \frac{c_2^2}{2}$ obtaining Equation 32:

$$\boldsymbol{g \cdot H_0 = \rho}$$ **Equation 32**

On natural river streams the gross head H_0 is entirely converted in losses ρ caused by friction (Equation 32). If water is diverted in artificial low friction paths this energy can be recovered and converted in mechanical energy through an hydraulic machine (Equation 33).

$$\boldsymbol{P = \eta \cdot g \cdot H \cdot \rho \cdot Q}$$ **Equation 33**

Where P [kW] is the electrical output power, η is the overall efficiency (Equation 35), ρ [kg/m^3] is the water density, Q [m^3/s] is the volumetric flow and H [m] is the net head (Equation 34):

$$\boldsymbol{H = H_0 - \Delta H}$$ **Equation 34**

ΔH [m] are the losses occurred along the artificial path expressed in metres.

$$\boldsymbol{\eta = \eta_t \cdot \eta_g \cdot \eta_{ausil}}$$ **Equation 35**

η_t is the turbine efficiency, η_g is the generator efficiency and η_{ausil} is the efficiency of other electrical devices, Caputo, 1967.

4.2.2 Flow duration curves

The study of temporal behavior of river flows is an essential problem that project developers have to deal with. In ROR plants, it is essential mainly for two reasons:

- sizing the hydraulic machines
- defining the yearly producible power.

Basic information has a statistical nature and is collected through periodical flow measurements over many years of observation.

Flow fluctuations can be plotted over a period of one or more years (Figure 54) and the resulting curve is given the name of **hydrograph** (chronological streamflow curve).

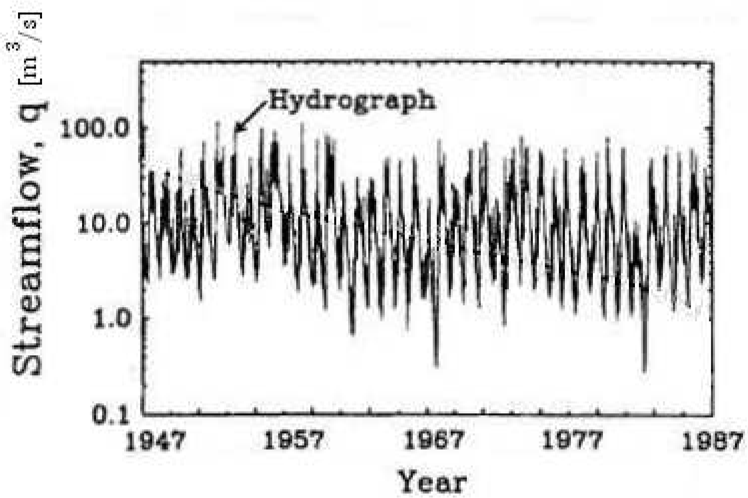

Figure 54 Hydrograph (Vogel and Fennessey, 1995)

More relevance is attributed to the **flow frequency distribution** (Figure 55). In this curve each flow Q is associated with its frequency f. ‘f’ represents the number of days in which a certain flow Q has been recorded over the year, and it is directly proportional to the occurrence probability p* (below explained).

Two distributions can be seen in Figure 55. One is the Gauss curve (dotted line) that represents the flow occurrence distribution if the flow variation phenomenon was completely casual. The other curve (continuous line) represents a real flow occurrence distribution for a river in which the flow variation depends on the precipitations regime (natural phenomenon).

A generic Gauss distribution can be described by the Laplace-Gauss law (Equation 36).

$$y = \frac{1}{\sqrt{\pi}} e^{-X^2} \qquad \textbf{Equation 36}$$

Where x is the generic abscissa, and y the generic ordinate.

In the Gauss distribution in Figure 55 f and Q are related with a law similar to the one presented in Equation 36. Q and f are, in such a way, proportional to y and x.

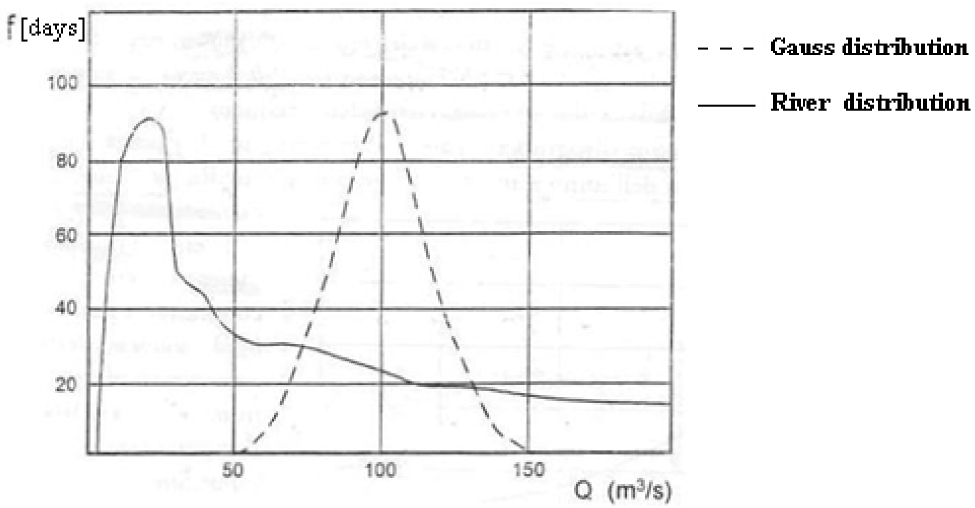

Figure 55 Example of an annual river flow frequency distribution compared to the Gauss frequency distribution (Arrighetti, 2007)

Referring to the river distribution in Figure 55, only a small part of the recorded flows exceeds the norm over the period of record. This result emphasizes how misleading it can be to use the norm as a measure of central tendency for highly skewed data such as daily stream flow.

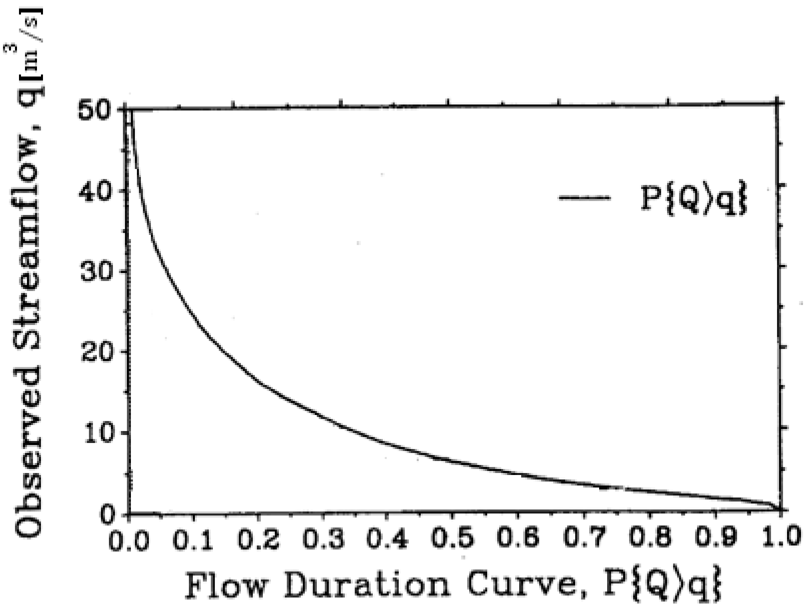

Figure 56 Flow Duration Curve for Acheron River (R. M. Vogel and N. M. Fennessey, 1995)

Vogel and Fannessy (1995) introduce the **flow duration curve** (Figure 56) stating that it represents the relationship between the magnitude and frequency of daily, weekly, monthly (or some other time interval) streamflow for a particular river basin, proving an estimate of the percentage of time a given streamflow was equaled or exceeded over a yearly period.

For example, referring to the flow duration curve in Figure 56, it can be gathered that a flow of 10 m^3/s has a probability of being exceeded during the year of 0.35. It means that during the 35% of the year (128 days) this flow is supposed to be exceeded or equaled.

Vogel and Fannessy (1995) add that a flow duration curve is the complement of the cumulative distribution function of mean daily (or some other time interval) streamflow; each value of discharge Q has a corresponding exceedance probability p, and a flow duration curve is simply a plot of Qp, the pth quantile or percentile of daily streamflow versus exceedance probalility p.

The occurrence probability p* and the exceedance probability (cumulative probability) p are defined by Equation 37 and Equation 38

$$p^* = \frac{f(q)}{total\,number\,of\,records}$$ **Equation 37**

$$p = 1 - P\{Q \leq q\}$$ **Equation 38**

Where f(q) is the occurrence frequency associated to the quantile Q, and P is the probability that the quantile Q would be superior to the other recorded flows q.

The frequency distribution analyzed before in Figure 55 deals with daily records of flowstream over one year time; hence the frequency f is the number of days a certain flow Q has been recorded, and the total number of records would be 365. The resulting p* represents the occurrence probability associated to Q.

The cumulative probability p is defined also in Equation 39

$$p = F(x) = \int_{x}^{x_2} f(x)dx$$ **Equation 39**

Where F(x) represents the "duration" of x, being p(x) is the probability that the variable x is comprised between x1 and x2

The median annual flow duration curve must not be influenced by the occurrence of extreme low flow periods or extreme floods over the period of record; it should capture the frequency and magnitude of daily streamflow in a typical year.

The accuracy in the determination of the characteristic flow increases with the number of years of records.

In other words considering many-years records the resulting characteristic flow curves should cope with the problems which can arise during flood flows and low-flow periods.

4.3 Hydrologic modelling

The aim of this section is to present an hydrologic modelling approach for the estimations of river streams and their behaviour over the year.

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle (Figure 57).

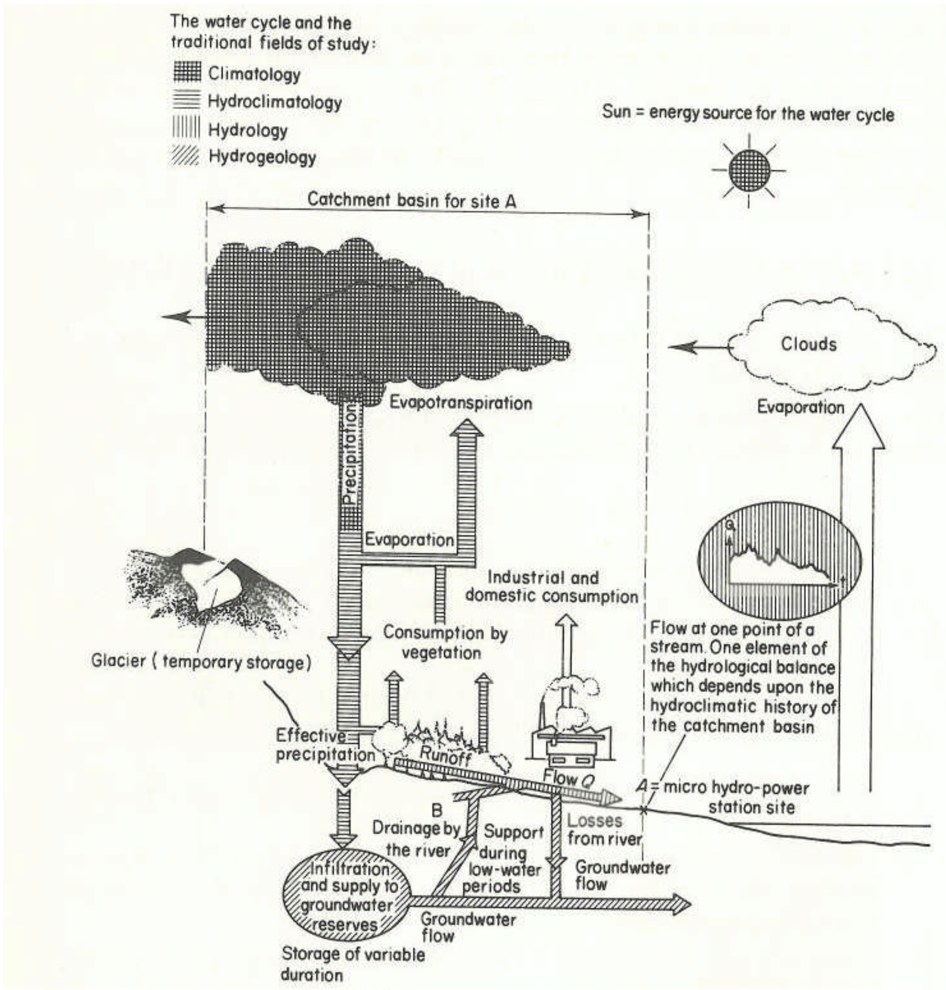

Figure 57 Hydrologic cycle (Monition et al., 1984)

Hydrological balance for a catchment area assumes that the amount of water that enters this surface as rainfall has to be equal to the amount of water that leaves it (Equation 40).

$$\boldsymbol{P = R + I + E} \qquad \textbf{Equation 40}$$

Where P is the precipitations, i.e. the amount of water that falls over a horizontal surface, either in liquid form as rain or in solid form as snow or hail. It is measured in purpose made gauging stations and it is generally expressed in mm of water. Rainfall maps divide the land in equal precipitation areas, isohyets are drawn after a period of observation of more than 10 years and they express the medium value of annual precipitation. The term R represents the runoff, in other words the non-infiltrated water that flows to the river. I is the infiltration into subterraneous nappes, and E is the evapotranspiration of water, that can take place directly trough air contact or indirectly trough vegetation absorption.

River flow Q is affected directly by the runoff coefficient R and indirectly by the infiltrated water that partially goes to form the river base flow B (Equation 41 and Equation 42).

$$\boldsymbol{Q} = \boldsymbol{B} + \boldsymbol{R} \qquad \textbf{Equation 41}$$

$$\boldsymbol{Q} = \boldsymbol{B} + (\boldsymbol{P} - \boldsymbol{E} - \boldsymbol{I}) \qquad \textbf{Equation 42}$$

Where the base flow B is the fraction of the infiltration I that rejoins the watercourse. It is also called groundwater flow or drainage.

Hydrologic models are mainly used to understand hydrologic processes and to obtain hydrologic predictions (water flow, water quality etc..). One of the major current concerns in hydrologic research is the prediction of the hydrologic behaviour of an ungauged basin (Prediction Ungauged Basins). In this case, the aim of the model is to describe the runoff R over a certain catchment area where no or only a few data exist.

Two major types of hydrologic models can be distinguished:

Deterministic models try to describe the hydrologic behaviour of a certain area through the real physical process description (hydrological balance and all the included variables). The runoff estimation R is carried on prior to the determination of groundwater flow, evapotransiration, rainfall ecc.. The river flow is consequent to the surface runoff. These models are likely to be complicated, hard to implement and difficult to use because of the large number of input parameters required and which are sometimes hardly obtainable.

Stochastic models rely on measured and experimental data. They work like a black box system, i.e. they use mathematical relations and statistical concepts to link together a certain input (rainfall) to the model output (runoff). Those models involve techniques like regression, transfer functions and system identification to correctly extend obtained results for a region to all the studying area.

4.4 Plant design methodologies

Smith and Maher, 2001, state that pico hydro projects are generally designed to work constantly at maximum power in the way to avoid regulation equipment that would increase complexity and cost of the plant. In this case, the turbine is selected to work with the maximum flow available all the year (dry season flow).

A different approach has to be adopted for bigger plants, when the adoption of that criterion would mean a considerable waste of producible energy. As reported in section 4.2 flows vary according to the hydrograph and are characterized by a cumulative probability distribution as shown in the flow duration curve.

Davison and Bacon (2004) consider the flow that has been exceeded over 67% of the year (Q_{67}) as the maximum sustainable flow that the turbine can process. This value is responsible for the installed power capacity (Equation 43).

$$\boldsymbol{P_{inst} = \eta g Q_{67} H_{net}} \qquad \textbf{Equation 43}$$

Where P_{inst} is the installed power expressed in kW, η is the plant efficiency (pipeline excluded) and H_{net} [m] is the gross head reduced by the head losses.

There is available in the literature a graphic method for the estimation of the optimum value of workable Q (Q_{opt}), responsible for the turbine selection. This method is based on the minimum cost per produced kWh criterion. In this process the inferior operational limit of the turbine (minimum pragmatic flow) has not been taken into consideration, hence the machine has been considered as a machine capable of exploiting all the flows below the rated one. This hypothesis should be removed in order to perform the real turbine selection.

Generally a typical inferior cut-off value (minimum pragmatic flow) for turbines like the crossflow or Kaplan turbine is between 20% and 40% of the design flow.

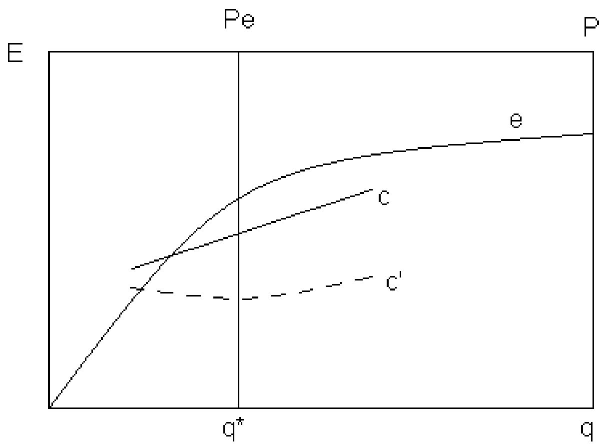

Figure 58 Graphic method for determining the Optimum (Arrighetti, 2007)

The curve **e** represents the yearly produced energy [kWh/year], it increases with the increasingly **q** [m^3/s]. The curve **c** expresses the annual cost of the plant [€/year]; it increases with the increasingly installed power **P** [kW] that depends on the nominal flow **q**. The curve **c'** is obtained through the Equation 44.

$$\boldsymbol{c'} = \frac{\boldsymbol{c}}{\boldsymbol{e}} \qquad \textbf{Equation 44}$$

It represents the cost per unit of produced energy [€/kWh]. The minimum of the curve c' represents the economical optimum, hence the value of q* is the design flow that minimise the kWh cost, and Pe is the corresponding rated power.

British Hydropower Association (2005) states that most of turbines can operate over a range of flows typically down to 20-40% of their rated flow. Kaplan, Pelton and Semikaplan suit well with this statement. Francis, Crossflow and Kapellar are characterized by a sharper decrease below half their normal flow. Fixed propeller turbines can practically operate only in a small range around the design flow; it is rare for them to work under 80% of the rated flow.

When a turbine matches a site it will not run constantly at full power. The Capacity Factor is the ratio that expresses the utilization degree of the turbine (Equation 45)

$$Capacity\ Factor(\%) = \frac{Energy\ generated\ per\ year\ [kWh/year]}{Installed\ capacity\ (kW) \cdot 8760 \cdot hours/years}$$

Equation 45

BHA (2005) also states that most part of Run-off River schemes are designed to exploit flows equal to, or smaller than Q_{mean} (Table 7).

Design Flow Q_o	Capacity Factor
Q_{mean}	40%
0.75 Q_{mean}	50%
0.5 Q_{mean}	60%
0.33 Q_{mean}	70%

Table 7 Capacity factor in relation to the design flow (British Hydropower Association, 2005)

4.5 Italian legal framework

Incentives for renewable energy in Italy guarantees support to producers that want to enter the energy market with green power generation schemes.

Regarding hydro-generation, the law 23/07/2009 n.99 obliges GSE (the entity that runs energy services in Italy) to buy, and take into the National Grid, hydro power from plants with rated power under 1 MW that were brought into the market after 31 December 2008. Producers can benefit of incentives calculated with specific coefficients depending on the plant characteristics, or of the sale of power at the special fare of 0.22 €/kWh for 15 years. After 15 years fares are