Power Quality and Utilisation Guide

Section 8 – Distributed Generation

Small Hydro Power – Investor Guide*

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Contents

1 Definition of small hydro power station

The European Union has no uniform classification criteria for small hydro power (SHP). As a rule, the installed power capacity is the main classification criterion. According to the ESHA (European Small Hydro Association), the European Commission and the UNIPEDE (International Union of Producers and Distributors of Electricity), SHP refers to units up to 10 MW. However, this limit is set at 3 MW in Italy, 8 MW in France, and 5 MW in the UK.

A distinction is often made for the 'Mini-hydro' subgroup, which comprises units between 100 kW and 1 MW. Sometimes the term Mini-hydro is used to refer to units in the range of 100-300 kW, which feed local loads not connected to the distribution network and which are usually located in rural areas.

2 European drivers of SHP development

The European Commission (EC) supports the development of renewable resources, including hydropower and SHP, by introducing suitable directives and recommendations. In 1997, the EC published the White Paper 'Energy For The Future: Renewable Sources Of Energy' [1], whose main purpose was to establish suitable circumstances for the development of renewable resources. In 2001, the EU Parliament adopted *2001/77/EC Directive (RES)* concerning '*the promotion of electricity produced from renewable energy sources in the internal electricity market*', which established the objective of producing 22.1% of the total electricity consumption in the Community from renewable energy sources by 2010. Following the EU's expansion to 25 countries, this indicative objective is now set at the level of 21%.

The main aims of RES development are:

- to reduce environmental impacts,
- to increase the security of the power supply,
- to create sustainable energy systems.

As a rule, large hydropower station schemes involve large-scale environmental integration activities, which have subsequent consequences. These problems are almost non-existent in the case of SHP up to 10 MW. In general, SHP can be integrated more easily into local ecosystems. Small hydro power stations require modern dedicated equipment to meet the high requirements regarding energy generation efficiency and simplicity and environmental protection.

Basic data concerning SHP in Europe are summarised in Table 1.

	EU - 15	**EU - 10**	**EU – new candidates**
Quantity	14 000	2 800	400
Installed power	10 GW	830MW	600 MW
Average installed power	700 kW	300 kW	1.6 MW
Annual production	40 TWh	2,3 TWh	1.4 TWh

Table 1: EU data on SHP potential

In the EU-25, the SHP potential is concentrated mainly in Italy (21%), France (17%), and Spain (16%). New SHP resources are located primarily in Norway and Switzerland [2, 3].

The EU objective for SHP is 14GW of installed capacity and 55 TWh/a of electrical energy production by the year 2010 (White Paper).

Special attention should be given to modernising existing installations: it is estimated that more than 70% of today's installations are over 40 years old. The European Small Hydropower Association (ESHA) represents this business sector.

3 Why SHP?

There are many reasons for the great interest in small hydro power. The potency of the arguments is relative to the type and scale of the benefits. The most important conditions to be considered by the investor / producer are stable incomes and a relatively high rate of return. These conditions are fulfilled by adequate support mechanisms (e.g. green certificates). From the environmental point of view, reducing CO2 is of great importance as well as helping preserve catchment areas. Very often, abandoned dams are restored and some micro retention objects are renewed, which improves the soil moisture conditions in the adjacent areas. SHP growth can be a valuable part of the so-called 'region sustainable development policy' widely supported by the EU. The main aim of this policy is to ensure supply of energy while protecting the environment and maintaining energy quality parameters at prices acceptable to the general public.

SHP projects should not have to cover the overall cost of new dam construction and hydrologic equipment, as such financial burdens could cancel the economic efficiency of the entire project. Extra benefits from SHP development can be achieved as a result of a synergy of efforts on the local, national and European levels. The adequate financial streams should be a part of this.

Why SHP? Because everyone benefits, but for the investor it could mean business

In order to secure return on investment, every potential investor should accurately define the basic parameters of the investment: in particular, the scale of the investment, potential problems, potential sources of financing, rate of return, basic categories of costs, and operating costs. Therefore, initially, a simplified feasibility study of the project should be developed, which contains the balance of costs and expected benefits. The primary basis of such a preliminary analysis is an accurate estimation of hydro-technical parameters at the site of the power station. Hence, measurement data from competent hydrological services should be used. Where there is no such data, flows can be estimated (interpolated) on the basis of measurements in other points of the catchment area, or the investor can perform his own measurements. This, however, may prove to be too expensive. One of the elements in estimating hydro-power potential is the determination of the Flow Duration Curve. It is also important to become familiar with the conditions of the connection to the grid and to evaluate the project execution schedule and exploitation conditions of the investment.

The initial analysis should answer the following questions:

1. **Does the investment meet my expectations?**
2. **Is it a good investment for me?**

4 Some theory

4.1 Energy potential

Potential and kinetic energy of a mass of water flowing from a higher level to a lower level can be converted into electrical energy. The hydrological potential of water is determined by two parameters: head (**H**) and flow (**Q**). Head is crucial, especially for SHP. It is not really necessary to have the water flowing rapidly.

The **Gross Head** (**H**) is the maximum difference between the levels of falling water. The turbine's actual head is less than the maximum, due to losses caused by friction with construction elements and the internal friction of the water. Sites are classified according to head size:

- 'low head', for H <10 m,
- 'medium head', for H ranging between 10 - 50 m,
- 'high head', for H >50 m.

The **Flow (Q)** - expressed in m^3/s - is the volume of water flowing through a given cross-section of the stream per second.

Electrical power and energy Energy is the amount of work done in a fixed time interval. A turbine converts water pressure energy into the mechanical energy of the turbine shaft, which drives a generator to produce electrical energy. The energy unit is Joule (J); and the electrical energy unit is the kilowatt-hour (kWh): 1 kWh = 3600 J. Power is the amount of energy per time interval unit. Therefore, the electrical power of the generator is defined by the following formula:

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H \tag{1}$$

where:

P - electrical power [W],
η - hydraulic efficiency of the turbine,
ρ - water density, .ρ=1000 kg/m^3,
g - acceleration of gravity, g=9.81m/s^2,
Q - flow – volume of water flowing through the turbine in time unit, [m^3/s],
H - head – effective pressure of water flowing into the turbine [m].

Turbine technology is a mature technology characterised by relatively high efficiency. The efficiency of large hydropower units reaches the level of 80 - 90%. The efficiency of smaller hydro units (<100kW) is about 10-20% less. When estimating the power of small hydro units (e.g. micro-turbines), turbine efficiency is usually assumed to be $.\eta$ = 70-75%. Thus, electrical power can be estimated by the following formula:

$$P \approx 7 \div 8 \cdot Q \cdot H \quad (2)$$

P = [kW], Q = [m^3/s], H = [m]. To estimate energy, assume 4 500 working hours with the power output defined by equation 2:

$$E \approx 4500 \cdot P \quad (3)$$

where: E = energy [kWh].

Flow Duration Curve The flow duration curve (FDC) can be used for more precise estimation of the hydrologic potential of the power station site. FDCs are plotted on the basis of long-term annually registered flows (hydrographs). FDC curves answer the question: 'What amount of energy can be generated annually?' FDC curves should be determined for the years of normal water conditions as well as for the wet and dry years. These curves are graphical representations of flow data: flow levels, number of days at fixed flow, and the percentage of such days annually, ordered according to flow level. An example of such flow data is presented in Table 2.

Flow Q greater than Q_r in [m^3/s]	Number of days	Number of days increasingly	% of year time
8	20	20	5.48
7	25	45	12.33
6	50	95	26.03
5	60	155	42.47
4	90	245	67.12
3	120	365	100.00

Table 2: Water flow data

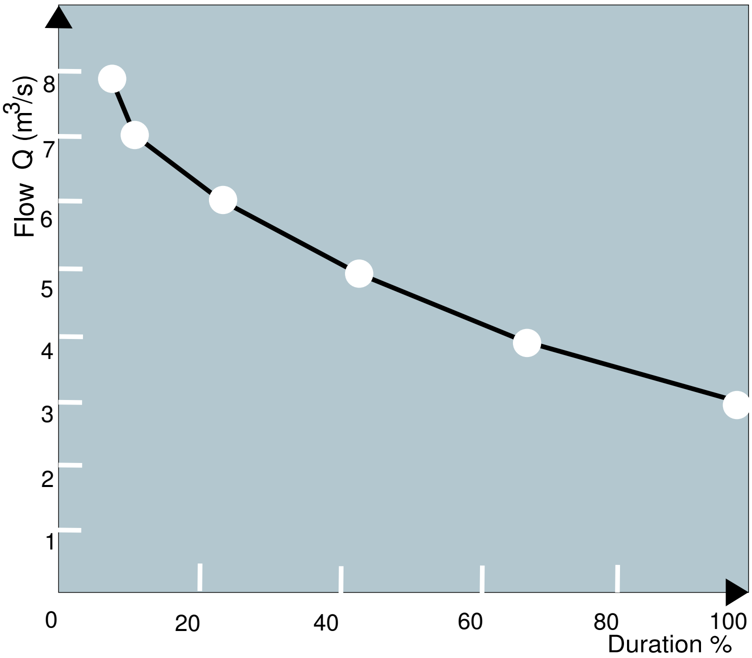

Figure 1: Flow Duration Curve (probability of flows greater than Q_r)

Energy is a measure of power maintained at a fixed level over a particular time interval. Hence, the FDC curve determines the probability of the event: *'Over how many days will a given level of flow be attained'*. The area below the FDC curve is the amount of energy generated. This area should be as large as possible. Good flow systems are characterised by a rather flat curve high above the X-axis, which corresponds to stable and uniform flows over all the days of the year.

Analysis of water resources and production – chosen elements A basic knowledge of fluid mechanics and hydraulic equipment engineering is useful for estimating the water potential. The energy of the jet of water flowing through a pipe is specified by Bernoulli's rule for so-called laminar flow. Without details:

The energy of the water defined by Bernouli's rule is the sum of:

- **potential energy described by head,**
- **energy of a pressure,**
- **kinetic energy.**

In practice, during the flow some energy is lost due to friction against the walls of the channel and specific internal friction determined by the viscosity of the liquid. These energy losses can be calculated by specialists. The friction coefficient of the channel walls (determined by the material the wall is made of) is of great importance. For the laminar flows and tubular draught of inlet water, the energy losses are proportional to the speed of the water and inversely proportional to the square of the diameter of the pipe.

In the cases of non-laminar flows, the friction coefficient for the energy losses in the water can be calculated from the Moody graph [4]. This parameter is an empirical function of the quantity e/D, where e is the so-called roughness factor and D is the diameter of the channel. The value of the roughness factor is determined empirically: e.g., for new steel e=0.025, for wood e=0.6, for concrete e=0.18. The energy losses for channels with walls made of wood can be significant, and they can be even greater on various kinds of bends and valves. In this case, the diameters of the channels should be enlarged.

Knowledge about the places where energy is lost and about the possibilities of reducing these losses - taking the local conditions of the plant site into account - is one of the major determinants of project optimisation.

Water flows in open canals For the purposes of water flow analysis and the proper estimation of the flow (Q) in the canals , it is very important to determine the average flow velocity.

The distribution of the flow velocity depends on the flow profile. Examples of different profile shapes are shown in Figure 2.

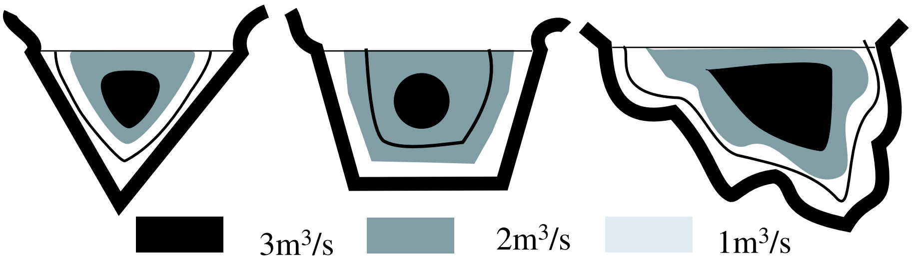

Figure 2: The distribution of water velocity for various flow profiles (iso-velocity lines)

For the steady flows (i.e. for which the depth, cross-section, and velocity in a given place do not change), the flow velocity can be calculated using more or less complicated mathematical formulas [4]. This velocity depends on channel roughness parameters, shapes (hydraulic radius), and the slope of the canal.

One of the major challenges is the selection of canal parameters - e.g. the depth or level of water in the canal.

4.2 Types and characteristics of the SHP station

One of the most important parameters of hydro power stations is the head, which is the difference in meters between the level of inlet water (i.e. useful water) and the level of outlet water.

A scheme of a hydro power station with a high head is shown in Figure 3.

The construction of a power station depends on the head profile and geomorphology of the location. These parameters determine the type of turbines to be used, their power output, the number required and their configuration. Depending on the way the water enters the hydro station and on the location of the hydro technical objects, hydro power stations can be classified into three groups:

- near dam,
- with canal derivation,
- with pipe derivation.

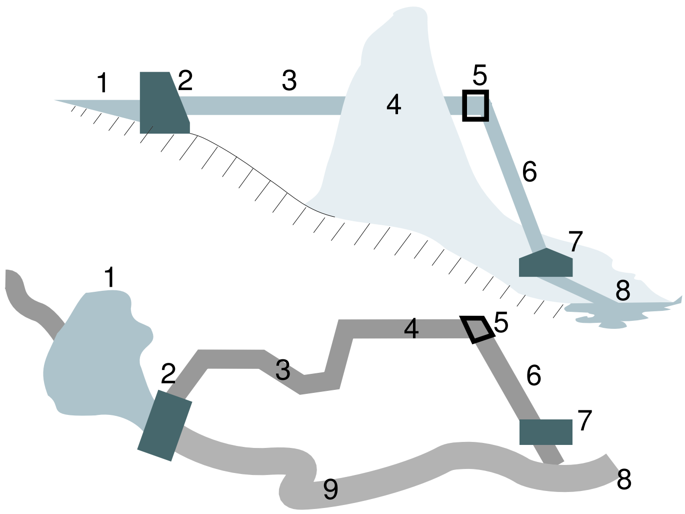

Figure 3: Hydro power station scheme with high head (1- lake, 2- dam, 3- canal, 4- tunnel, 5- intake, 6- penstock, 7- powerhouse, 8- outlet, 9- river)

Small investors are generally interested in the near-dam power stations or in the stations with pipe derivation. Hydro power stations with canal derivation are usually much larger, attracting larger institutional investors. Near-weir SHPs are usually built in the lowlands where the natural head is rather small. They often work as a damming element. Near-weir hydro power station turbines are often installed in dam pillars. Such a solution allows for savings on building materials. Turbines can be built in the dam construction – in this case, horizontal axis turbines are often used. In the case of hydro power stations with a small head, the two schemes of turbine positioning and water feeding are typically used: with a short feeding pipe, as in Figure 4; or with a small dyke and vertical axis turbine, as in Figure 5.

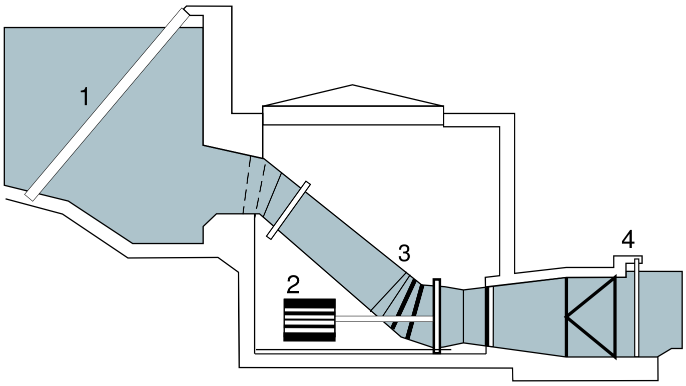

Figure 4: Scheme of hydro power station with short feeding pipe and horizontal axis turbine (1- trash rack, 2- generators, 3- penstock, 4- outlet)

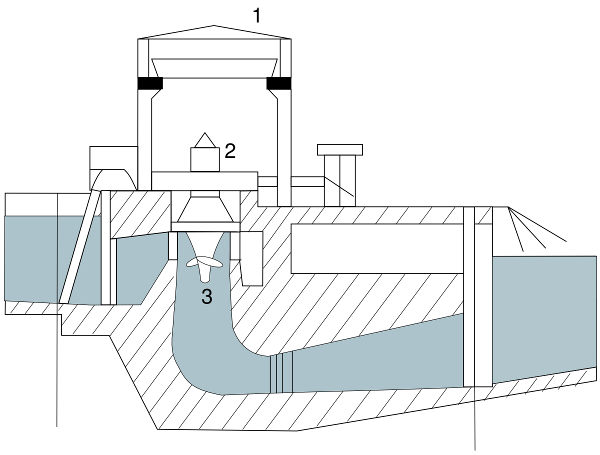

Figure 5: Cross-section of near-weir hydro power station with internal check dam and vertical axis turbine (1- powerhouse, 2- generators, 3- turbine)

Canal derivation is often used on river bends, as in Figure 6.

A canal can shorten the natural river passage in order to achieve a greater head. The features of such a system include upper inlet and tail-water canals. The tail-water canal takes the water down to the river bed.

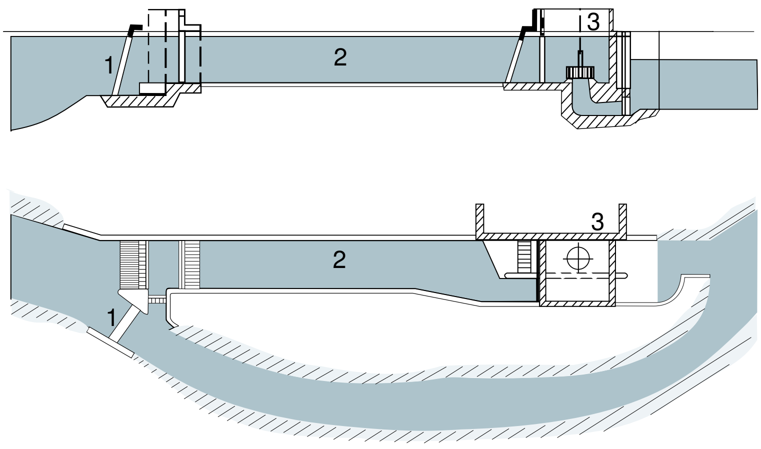

Figure 6: Hydro power station with canal derivation (1 - weir, 2 - canal, 3 - powerhouse)

Pipe derivation with pressure pipe is used in the cases where the head is greater than 20-30m and where the powerhouse is far from the water inlet (Figure 7).

The ability to control the turbine depends on the length of the pipeline. This condition must be satisfied: the sum of the products of length and velocity of flows in the pipelines should not exceed the value of the hydro power station's head times 25.

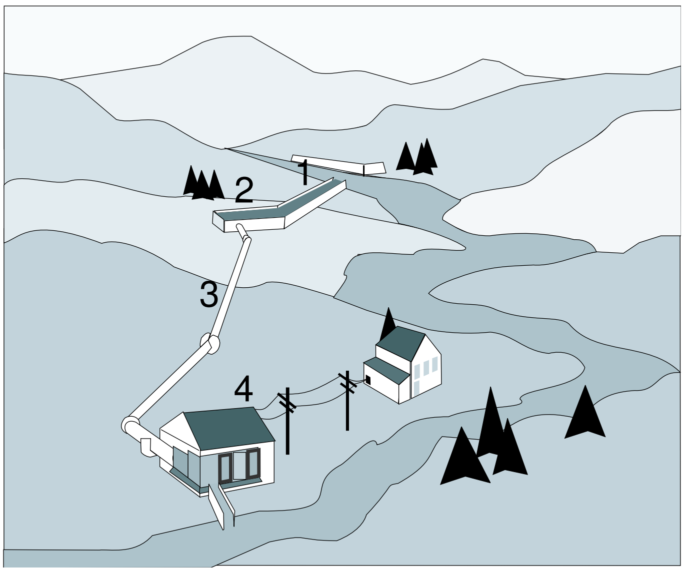

Figure 7: Hydro power station with pipe derivation: Legend: 1- canal, 2 - intake, 3 - penstock, 4 - powerhouse

Near-dam hydro power stations In the case of large heads, between 30 - 100 m, near-dam hydro power station schemes can be considered. They are often incorporated into the dam construction to form an integral complex. The pipelines are generally arranged in a reinforced concrete gallery.

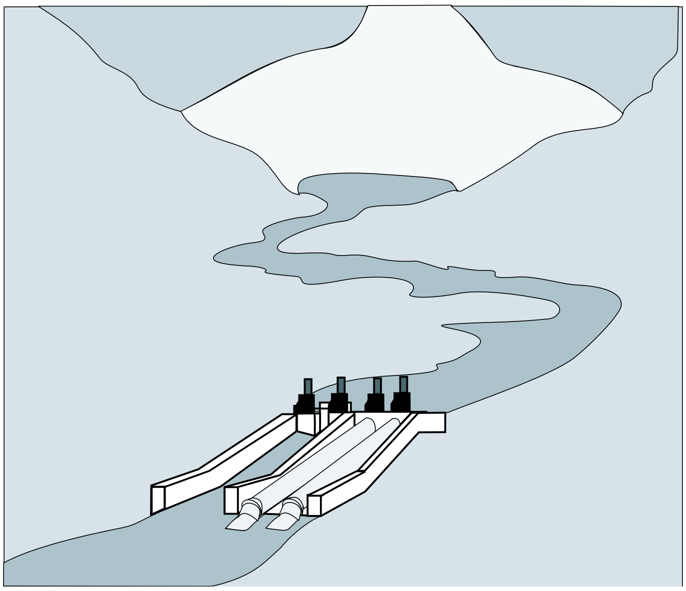

Figure 8: Illustration of near-dam hydro power station

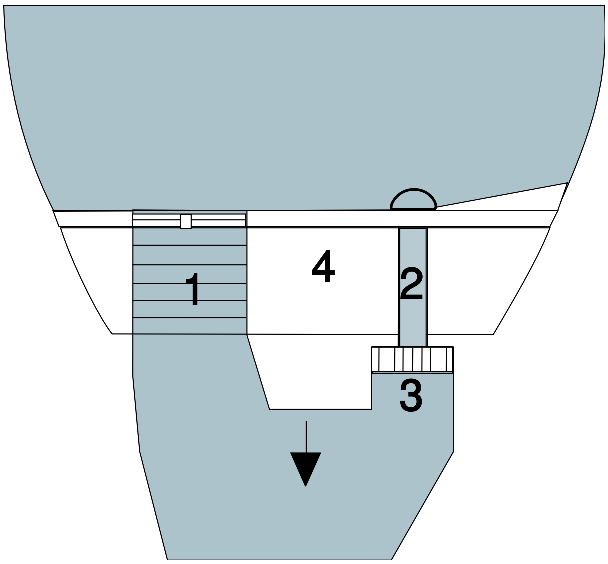

Figure 9: Typical scheme of near-dam hydro power station (Legend: 1- overflow, 2- pipe, 3- powerhouse, 4- dam)

4.3 Basic types of turbines

Turbine technology and parameters Selecting the suitable type of turbine for specific local circumstances is the key to success. This selection depends mainly on the values of the water stream's head and flow. Other important parameters to be taken into account include the assumed speed of the turbine and the ability to work in states of lower flows. Due to the different mechanisms used in the energy conversion process, two types of turbines can be distinguished: impulse turbines, which take advantage of the velocity energy of water; and reaction turbines, which make use of the pressure energy of water.

Energy parameters of the turbine The state of turbine movement is determined mainly by the following energy parameters: head H [m], turbine flow Q [m^3/s], power P_t [kW], and rotational speed of turbine η_t [rev/min]. One can distinguish between levelling (gross) head H_n and usable (net) head H_u. The gross head is the maximum available vertical fall of the water, from the upstream level to the downstream level. Net head is the difference in energy between the intake level and the tail-water level.

Turbine flow Q defines the volume of water flowing into the turbine in the time unit, including all leakages and water taken into the system that decrease the pressure on the axis.

The theoretical turbine power $P_t$depends on the net head and flow:

$$P_t = 9.81 \cdot Q_t \cdot H_u [kW] \quad (4)$$

The available power of the turbine P_u is the power on the turbine shaft, which depends on the theoretical power and the efficiency of the turbine η as defined by formula 1.

The efficiency of the turbine is the ratio of the available power to the net power. This efficiency is the product of the volume efficiency η_v, hydraulic efficiency η_h, and mechanic efficiency η_m:

$$\eta_t = \eta_v \cdot \eta_h \cdot \eta_m \quad (5)$$

The volume efficiency is affected by the volume losses resulting from fissure leaks and leaks in the rotor relief system. The hydraulic efficiency is affected by the losses resulting from the water striking the turbine blades, whirls at the discharge edge, and flows through the blade channels.

One of the essential elements in estimating SHP productivity is the proper calculation of power on the turbine shaft. The power depends on the head, water speeds at the upper and lower basins, and the losses resulting from leaks and the water flows through hydraulic equipment.

For the initial, simplified calculation, formula 1 can be used.

Mechanical losses are caused mainly by the friction of the shaft against the turbine bearings and in glands and by the friction of rotating elements in the water. The hydraulic efficiency generally ranges from η_h=0.88-0.95, whereas the mechanical efficiency of the turbine is in the range of η_m=0.98-0.99. The efficiency of the generators can be estimated as η_g=0.94-0.97, and that of the power output system as η_u=0.98-0.99.

Types of turbines The head and flow at the SHP site are critical factors for selecting the turbine type. Other factors to be taken into consideration when selecting the turbine include:

- depth of the turbine seating in the SHP's hydro-technic construction,
- efficiency,
- costs.

Pelton turbine Impulse turbines use the water's velocity to move the shaft and unload the water pressure to the atmospheric pressure. The turbine rotor consists of blades in the shape of buckets mounted around the wheel.

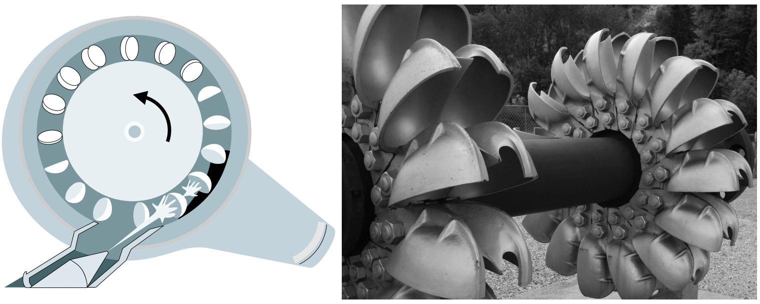

Figure 10: Pelton turbine: a) idea of operation, b) turbine

Impulse turbines are mainly used at the high heads A representative of this group is the Pelton turbine, which is usually used where the high head ranges between 30 - 400 m. Pelton turbines can be mounted on both horizontal and vertical shafts. The wheel and the number of discharge jets can be varied to create different solutions. In general, these turbines can work in a wide range of flow levels - from 5 to 100%.

Banki-Michell turbine Flow turbines are usually shaped like a cylinder, with blades mounted in the special chamber or directly in the derivation canal. The construction of the blades often enables doubly effective flow through the blades, which improves the efficiency of the turbine.

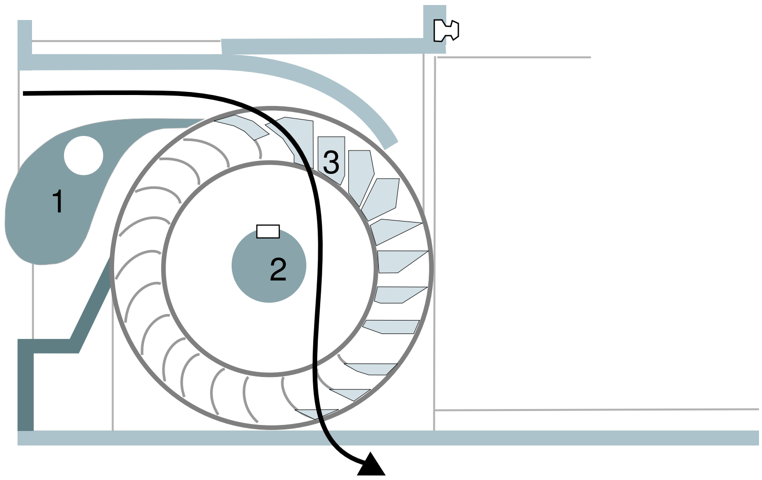

Figure 11: Cross-section of Banki-Michell turbine: Legend; 1- distributor, 2 - runner, 3 - blades

Banki-Michell turbines can have discharge capacity from 20 dm^3/s to $10m^3/s$ and they are used at heads ranging from 1 to 200 m.

Kaplan turbine Reaction turbines generate power using both the pressure and the movement of the water. The driving mechanism is submerged in the water. The water stream flows over the blades, not hitting them directly. A**s compared to impulse turbines, reaction turbines are generally used at sites with a small head and greater flow.** Propeller turbines belong to this class. Propeller turbines have their drive element equipped with three or six blades, which have uniform contact with the water. The blades' angle of contact is adjustable.

Figure 12: Water turbine propeller

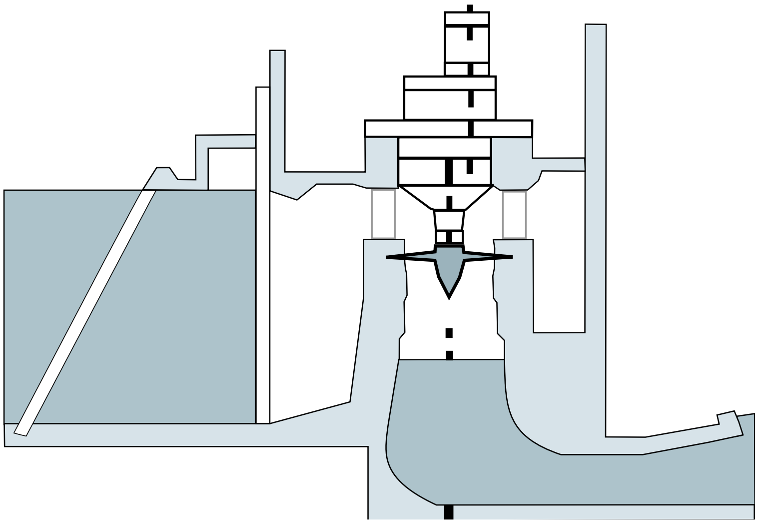

Figure 13: Kaplan vertical axis turbine

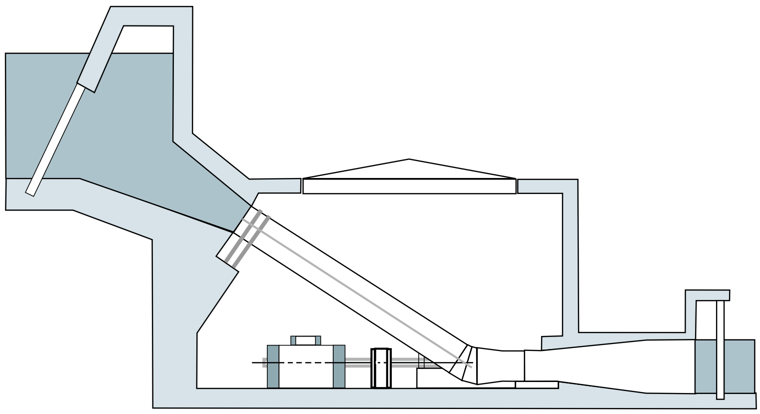

Figure 14: Kaplan turbine, S-configuration

A typical representative of the class of propeller turbines is the Kaplan turbine. Both blades and gaps are adjustable. Different systems of positioning the turbine are used: horizontal axis, vertical axis, S-configuration and others. Two sample solutions are shown in figures 13 and 14.

Francis turbine The Francis turbine consists of a wheel, rotor, feeding pipe and encasement, with water supplying the elements, usually in the shape of a spiral. The wheel ensures the supply of water and sufficient stream. In the rotor, the energy of the water is converted into mechanical energy. The direction of the flow can be changed from radial to axial at the water outlet. The shape of the rotor and its blades depends on the size of the head. The basic advantage of the Francis turbine is the ability to produce in different construction solutions. This situation allows optimal turbine choice - i.e. optimal adaptation to the local circumstances, hydro-technical equipment, powerhouse, etc. Francis turbines with vertical axis located in an open chamber are most common, especially in SHP up to 5MW. Turbines with vertical axis in spiral casing, including multi-rotor turbines, are also used.

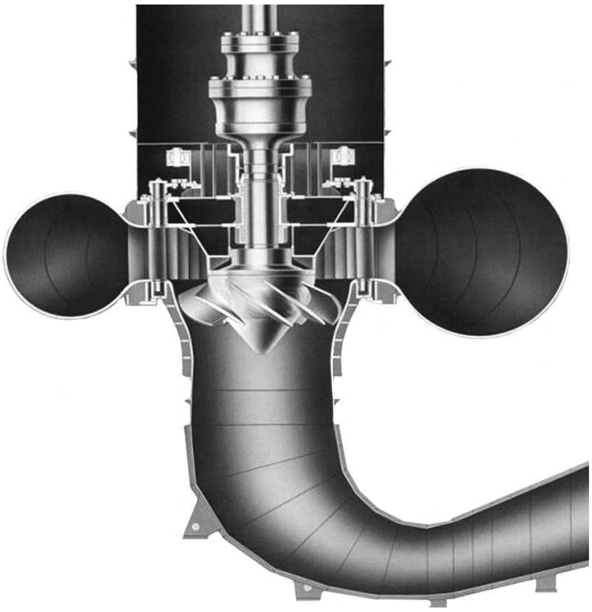

Figure 15: Francis turbine with vertical axis

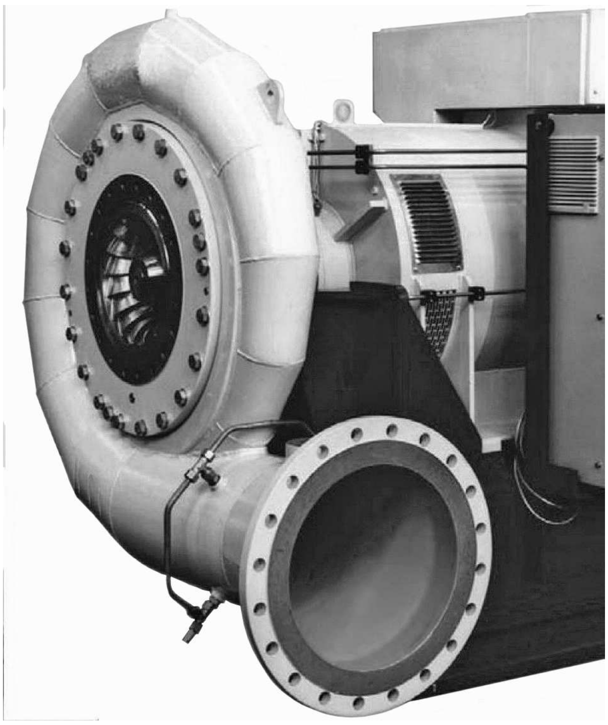

Figure 16: Francis turbine with horizontal axis

Kinetic turbines Kinetic turbines are classic cross-flow systems with the so-called free flow. The kinetic energy of the flowing water is converted into electrical energy. In this case, potential energy resulting from the head is small. **The advantage of such solutions is that they do not require any additional canals or major hydro-technical works.** Existing hydro-technical structures - such as bridges, dams, weirs, and canals - are suitable for setting up such a hydro power station.

Type of turbine		Range of speed [rpm]	Range of head [m]
Kaplan	L	350-500	30-40
	M	501-750	10-30
	F	751-1100	$\leq$ 10
Francis	L	50-150	110-300
	M	151-251	50-110
	F	251-450	$\leq$ 50
Pelton	L	2-15	1000-1300
	M	16-25	700-1000
	F	26-50	100-700
Banki-Michell		30-200	5-100

Table 3: Classification of turbines according to speed and head

L - low-speed turbine,

M - medium-speed turbine,

F - fast-speed turbine

4.4 Electrical diagram, automation and protection

The circuitry of the hydro power station usually consists of a generator circuit and a station service circuit, which are connected to the bus-bar. The bus-bar is usually connected to the power grid system through the power output line and transformer. The main loads connected to the station service circuit include:

- control of position of wheel apparatus,
- control of main water cut-off,
- automation and protection,
- lighting and power connector circuits.

The station switch gear can be equipped with a metering system to measure power load and output, a hydro-generator control system and a reactive power compensation system. The battery of capacitors should be switched on/off automatically after the main circuit breaker has been switched on/off.

The hydro-power station can be fully automated with the full control of the hydro-generator according to the amount of water available to maximise the production of electrical energy.

In the case of isolated island operation, the control of flow through the turbine is carried out to stabilize the speed of the generator. The speed controller is used in this case. Controllers with a centrifugal sensor of rotation speed are usually used in SHP stations. In the case of grid connection, the power controller is used, which cooperates with the sensor of the top water level. The frequency in this case is maintained by the power grid, and the aim of the controller is to stabilize the top water level.

The automation of the hydro power station should include:

- hydro generator emergency shut-off,
- monitoring of hydro generator operation and signalling of emergency states,
- control of the angle of the wheel blades in function of the top water level,
- automatic re-connection of hydro generator to the grid.

Many SHP stations are quipped only with the simple and absolutely necessary automatic control and protection systems. This situation is improving because new micro-processor control devices and relatively cheap automation systems are now available on the market. More and more investors realise the need to install modern and efficient control systems. As SHP stations are often built in remote areas, this is one of the reasons for focusing the attention of investors on remote control systems. Such systems should be able to continuously optimise the generation process without any staff intervention, which would enable the maximisation of profits. The factors directly increasing the economic efficiency of hydro power stations - and thus justifying the necessity of applying modern control systems - include the following:

- reduction of SHP station downtime after emergency shutdown (e.g. as a result of voltage collapse in the electrical grid) through automatic start-up of the generator and its reconnection to the grid,
- continuous maintenance of the nominal top water level by changing the turbine opening, and continuous maximisation of the output power for a given water flow,
- monitoring of the generator's operational parameters to identify and properly react to emergency states and, consequently, extending the failure-free working time of

the hydro power station.

The necessity to maximise efforts to use available resources and to develop technology offers an acceptable return on investment period. The investment in automation and control systems yields a return on investment period of 1 to 2 years. This period is shorter in the case of larger power stations and may be longer for smaller hydro power stations.

Various media are used for remote transmission, including radio. The use of mobile phones with digital file transmission (GPRS) is a quite popular solution.

The automatic protection and control systems for the network, circuits and equipment of SHP stations are usually installed within the minimum scope required to meet the requirements for the technical conditions of the connection and to ensure the correct operation of the hydro power station.

The use of asynchronous generators, or even asynchronous engines as generators, in SHP stations requires resolving unusual problems, such as those associated with overheating of mechanical elements.

Protection of power network Every power station, including SHP, is equipped with protection systems. The basic types of protection used in SHP stations include:

- Over-frequency protection (activated when frequency exceeds the upper-frequency limit).
- Under-frequency protection (activated when frequency drops below the lower-frequency limit).
- Over-voltage protection.
- Under-voltage protection.
- Protection from voltage dips on the low voltage bus-bar.

5 Details of project analysis

An initial step in the SHP project analysis should cover these three basic areas:

1. determination of available water resources, including annual energy for different average states of stream (i.e. for wet, medium and dry years).
2. determination of the investment range, obtaining applicable permissions and licences from the competent water service, local or regional administration, environment protection.
3. determination of electrical parameters: loads, connection, cooperation with the grid.

The project analysis should also determine the basic economic indicators, including the balance of costs and revenues, ways of financing, and environmental interaction. The following parameters should be defined in the technical part of the project analysis:

- water levels (high, medium and low),
- water head (so-called gross head),
- flow in the stream for fixed cross-section of dam,
- installed gullet of the turbine - i.e. maximal volume of water flowing across turbine in unit of time (based on the medium annual flow),
- nominal power of hydro power station,
- turbine and transmission gear parameters,
- generator parameters,
- structure and type of switch gear,
- control systems, automatic control and protection systems,
- parameters of the line and transformer sub-station connecting the hydro power station to the power grid,
- annual energy production volume estimated on the basis of knowledge of the volatility of the water flow,
- time of power utilization from the power station.

5.1 Analysis of hydrological potential of the site

One of the categories of data that should be obtained from adequate hydro-meteorology services are characteristic flows. These quantities should be determined on the basis of long-term statistics, or, in the case of lack of direct data, interpolated from the site. The group of characteristic flows includes:

HOF – highest observed flow,

AOMaxF – average from observed maximal flows,

AOTF – average from observation time,

AOMinF – average from observed minimal flow,

LOF – lowest observed flow.

The next group of data includes maximum flows with the fixed probability of occurrence – Flow Duration Curve (FDC) – see Table 4.1. Maximum flows should be determined with the following probability levels of occurrence: 0.1%, 0.3%, 1%, 10%, 50%. These quantities should be used for determining the FDC curves (see Figure **??**). For the determination of flow estimation errors, FDC curves should be determined for at least a wet, a medium and a dry year.

5.2 Scheme and location of planned SHP

Planning the location and scheme of SHP is a complicated iterative process that entails taking environmental effects into consideration and analysing different technological options from the point of view of economic efficiency. In particular, the following issues should be addressed in the document called '*Feasibility study*':

- topography and geo-morphology of the SHP site,
- site selection and method of exploiting water resources,
- basic solutions for hydro-technical equipment and powerhouse,
- evaluation of the project's economic efficiency and financing possibilities,
- description of administrative procedures with regard to obligatory permissions and licences.

The important step, particularly when designing a completely new hydro-technical infrastructure for the hydro power station, is choosing the method of feeding the turbine with water and, consequently, the selection of the turbine. The investment in hydro-technical equipment can be the critical cost component that determines the success of the investment. This includes the selection of shapes and parameters for the canals or penstock, the water basins, and construction of the dam and gullet. Knowing the parameters of this equipment is essential to correctly evaluating the power productivity. Hydro-technical structures at the SHP site must guarantee the maintenance of the watercourse parameters in accordance with the environmental requirements and licenses granted. One of these parameters is the so-called compensation flow: i.e. the minimum amount of water that must be left in the watercourse for biological and societal reasons. The value of this parameter may affect the evaluation of the power station's productivity and its exploitation. The quantity of compensation flow is strongly related to the quantity of overflow above the top edge of the weir. Maintaining overflows at the required levels is an administrative requirement resulting from environmental regulations. In the case of small inflows, the overflow can be minimal or even non-existent. Control of the overflow can have significant impact on the level of power plant production, because, at small overflows, the feeding canals may have to be closed and the generator shut down.

Fish passes and sluices The construction, structure and maintenance of fish passes depend on specific local circumstances and are one of the major environmental requirements. Like the maintenance of overflows, maintaining a continuous flow through the fish pass is a challenge. The flow through the fish pass depends on the medium flow value in the watercourse.

The next element to be taken into account in some solutions is sluices. In the case of sluice analysis, it is necessary to consider the number of crossings through the sluice, if such crossings exist, and turnover of sectors (up and down). Sluice crossings can decrease energy production considerably due to variations in the water level and the possibility of having to shut down the machines (e.g. at minimal water levels).

5.3 Turbine choice

The choice of the turbine type and its parameters - size, rotational speed, and suction - depends on the flow and head at the site of the power station. For the reaction hydro power stations, this mainly depends on maximum and medium flows and FDC curves. At this stage, the cost-price effectiveness components should also be taken into account. The optimisation of the costs per 1kWh as a function of turbine power should be carried out. This stage of analysis is illustrated in Figure 17.

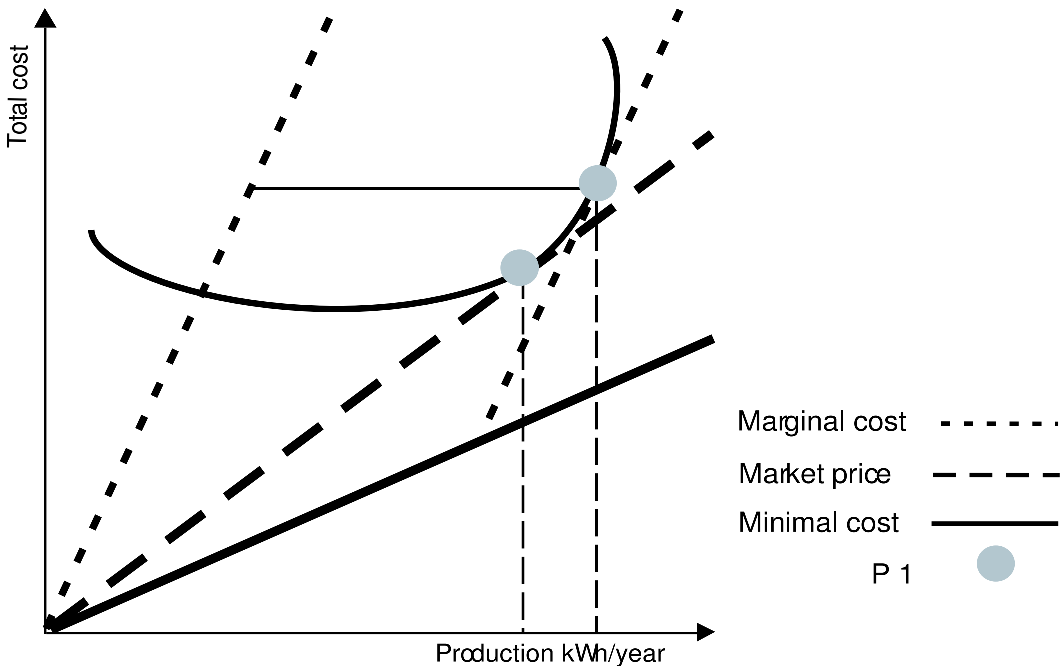

Figure 17: Cost optimisation in function of turbine power. P1 determines the point of return on investment

The initial choice of the turbine type and size can be made using appropriate diagrams of turbine efficiency. An example of such a diagram is presented in Figure 18. The analysis of such diagrams indicates that Pelton turbines should be used at high heads, whereas Kaplan turbines are suitable for high flows and small heads. Detailed characteristics, as in Figure 18, are provided by turbine producers.

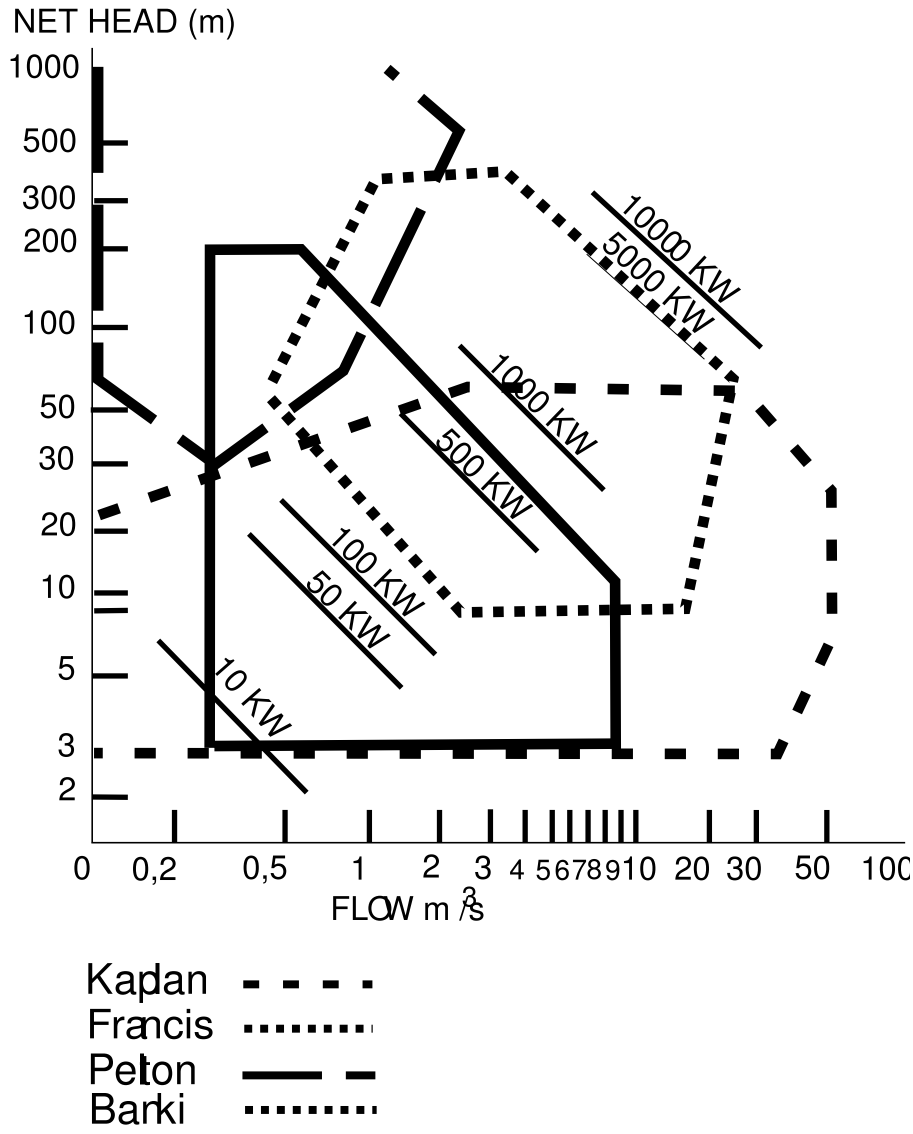

Figure 18: Diagram – comparison of efficiency of different turbine types

The variability of the flow is an important parameter and has great impact on the choice of turbine. This impact is illustrated in Figure 19.

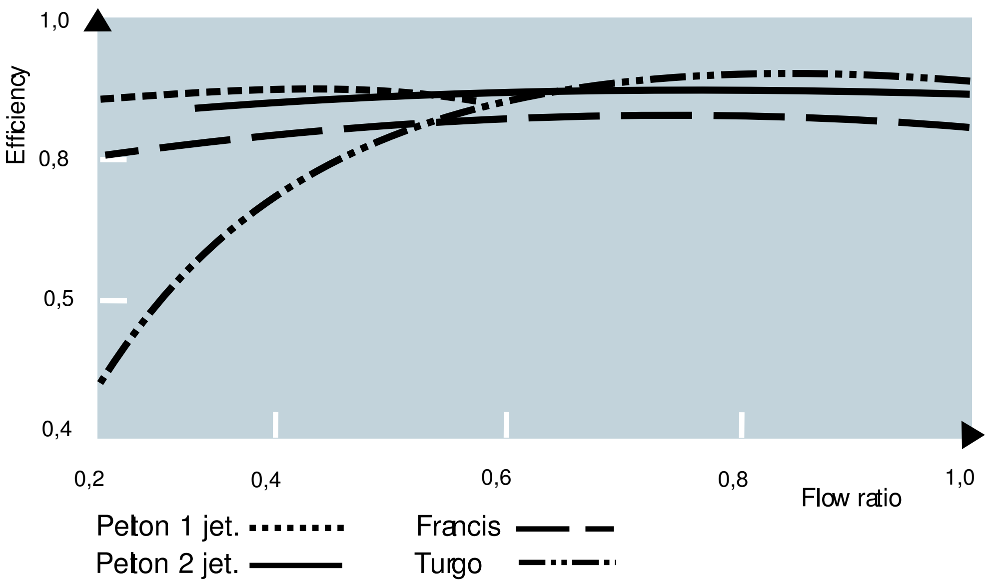

Figure 19: Efficiency of different types of turbines

The next step is determining the turbine size. For this purpose, the high-speed discriminator should be determined - i.e. the rotational speed of the geometrically similar turbine for the so-called reduced head. The high value of this parameter means that it is possible to achieve more power using a turbine with a smaller impeller diameter. In the next step, the impeller diameter should be determined using the formulas for particular turbine classes and sizes. Generally, the choice of turbine is quite a complicated task. An error at this step can decrease the cost efficiency of the project (e.g. due to the incomplete utilization of the hydrological potential of the watercourse).

5.4 Selection of generator

As a rule, asynchronous generators are used in the SHP stations. The reasons for this are economic – to lower the investment costs. Construction is simpler as compared to synchronous generators, and asynchronous generators are lighter, cheaper and do not require synchronisation or voltage controls. Asynchronous engines are often employed as generators. In this case, attention should be focused on the following problems:

- **reactive power compensation** (the greater the induction of reactive power, the greater the costs of compensation),

- **profile of current paths** (the necessity of using larger profiles),
- **generator loads** (operation in lower power range, higher working temperature of generators),
- **necessity of rebuilding the power output.**

These problems can increase both investment and operational costs.

Three-phase synchronous generators with permanent magnet may also be used in small hydro power stations. These generators have high efficiency (up to 97%), which is much higher than asynchronous generators or direct current generators.

5.5 Automation and protection

Choosing suitable automation and protection systems is one of the major steps in the process of selecting SHP parameters. The functions to be performed by the automatic control systems depend on construction, operational mode (e.g. isolated network operation), and remote control. The primary aim should be to maximise the generation of electric energy. The basic purpose of SHP automation is to ensure safe operation (e.g. emergency shutdown of the generator and regulation in response to varying water conditions).

More and more investors are realising the need to install modern control systems. Because SHP stations are often built in remote areas, investors focus their attention on the remote control systems.

Such a system ensures the continuous optimisation of power generation, without any staff intervention, and thus maximises profit.

Protection of power grid Power grid protection requirements are defined by the owner of the local network (power distribution company) to which the SHP station is to be connected. The SHP protection devices are usually required in their minimum configuration as specified by the network operator, even though the cost share of protection devices in the total investment costs is small. The growing requirements regarding grid security and connected customer equipment are contributing to the installation of more modern and reliable protection systems.

The basic network protection system includes:

- frequency protection,
- voltage protection.

6 Documentation

6.1 Structure and project preparation

Project documentation should contain the rationale of the investment and its profitability. The positive balance of costs and returns, as well as good return on investment, is the basis for obtaining the necessary investment funds and bank loans.

Figure 20: Project preparation: analysis of costs and revenues

Methodology and procedures For chosen pipe profiles, passages, sluices and canals, the water flows should be determined according to the following procedure:

- estimate the depth and speed of the water flow in the canal,
- determine the heights of the flow control structures - e.g. dams, weirs, places of potential overflows,
- analyse return flows and the impact of dams on such flows,
- establish the height and width of transport canals,
- determine whether the flow is sub-critical or super-critical (this allows the level of flow stability and irregularity to be predicted),
- determine the slope of the canal to minimise turbulences,
- establish optimal canal parameters from the point of view of cost (i.e. determine the best dimensions for maintaining the required level of flow),
- calculate the required smoothness of the canal; reduce costs by using suitable material for canal formwork, which should assure maximum depths,

- determine the minimum size of the pipe in order to avoid increased pressure flows,
- compare different shapes without changing the intake levels.

The documentation of the project and its implementation should be prepared and carried out according to applicable standards and requirements.

Due to the implementation of UE requirements for project practice, the preparation and realisation of the investment should be carried out according to the guidelines provided by UNIDO [9] (see Figure 21).

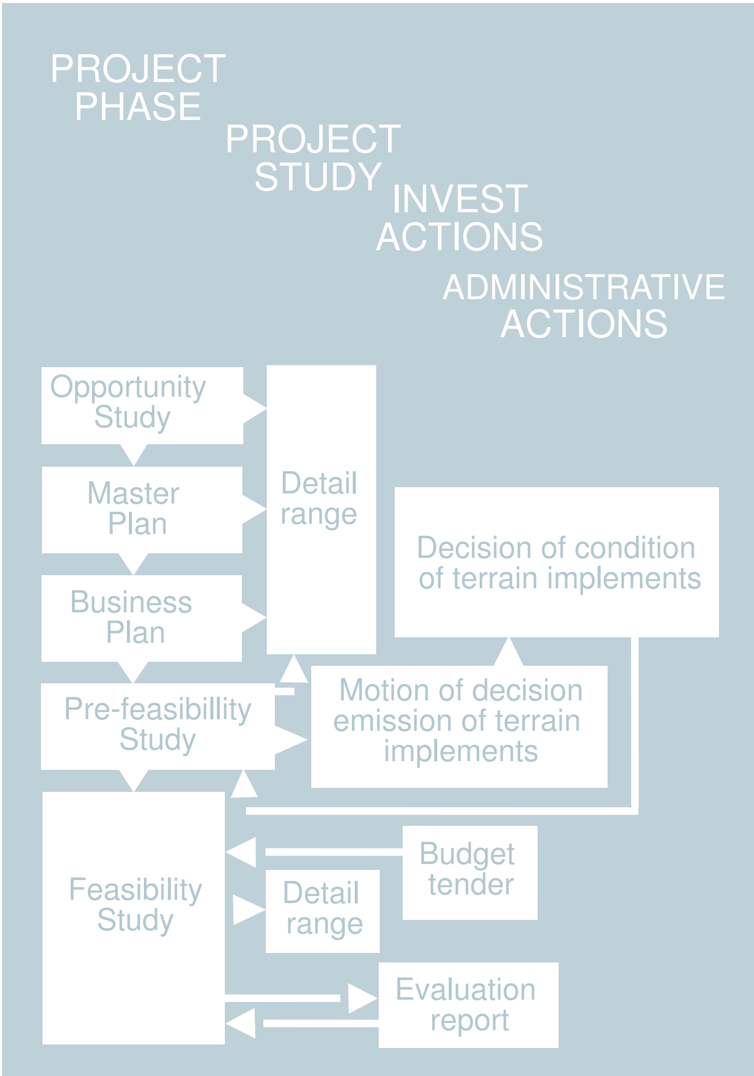

Figure 21: Stages of SHP project preparation

6.2 Administrative licences for water use

The RES Directive of the European Parliament provides general requirements concerning administrative actions for the promotion of energy from renewable sources. The provisions of this Directive oblige administrative bodies to reduce all barriers limiting energy production from renewable sources.[1]

The rules of SHP investment preparation are similar in almost all of the EU countries where licenses concerning land use and environment are required. In general, specialised agencies and local communities need to be consulted regarding the way environmental resources are to be used, especially in the case of large projects. Official permissions are known as licences. The content of these documents is defined by applicable laws (e.g. the *Water Law*). The superior regulations are defined in the so-called Water Directive (WFD)[2] of the European Parliament. In Norway, where almost all energy is produced from hydro power stations, licences are issued pursuant to the *Water Regulation Act and Energy Act*. The procedure for obtaining a licence is quite long and complicated, and is overseen at many stages. For SHP projects, the duration of this procedure ranges from 1 to 5 years (2-3 years on average)[3]. This process also needs to be approved by the local communities. A project may have to be changed (e.g. its scope may have to be limited) before the licence is finally issued by the proper authorities (MPE).

In Greece, obtaining appropriate licences also requires community consultations and is quite complicated. Licences are authorised by the Ministry of Development following their acceptance by the energy commission - RAE (Regularity Authority for Energy). The procedure usually lasts from 6 to 12 months.

In Austria, where the energy market is fully open [4], licences are issued by the provincial authorities, but for SHP schemes up to 500kW, such licences are not required.[5].However, the local distribution company is not obliged to purchase SHP energy, and the sale of energy is done using market prices.

In Switzerland, the certification of SHP projects is in accordance with ***green hydro*** standards, where SHP projects have to meet the environmental standards. For SHP schemes, the procedures for acquiring licences and certifications are simplified - some SHP types do not require licences.

[1] DIRECTIVE 2001/77/EC of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market

[2] DIRECTIVE 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy

[3] The Licensing Procedures for Hydropower Development in Norway, http://www.nve.no

[4] The Energy Liberalization Act – ”Energieliberalisierungsgesetz” (BGBl I 2000/121; in the following ”ELG”)

[5] The Transposition of Directive 96/62/EC on the Internal Market in Electricity into Austrian Law, http://www.dbj.at

In the UK, the following licences are required:

- **Abstraction Licence**, for hydro power stations with derivation canals,
- **Impoundment Licence**, for all hydro-technical structures affecting water relations,
- **Water and Drainage Consent**, if any works are to be carried out in the main channel,

Section 158 Agreement contains certain further requirements [12].

In Poland, the use of water resources is regulated by the 'Water Law' [7], which sets out the obligations of administrative bodies with respect to water management. These bodies issue required water-law permits, which define the aim and range of water utilisation and further environmental, social and economic requirements. The application for a water-law permit is submitted with an additional document called the 'Water-Law Survey', which contains:

- characteristics of the waters covered by the water-law permit,
- determination of impact of water utilisation on the surface and underground waters,
- procedures to be carried out in certain operational cases, accidents, etc.,
- layout of water equipment and functional diagram.

7 Financing

Financing sources Financing of SHP projects is incorporated in the mechanisms of the support and financing of RES. Evidence of RES support are the applicable EU Directives and resulting national development plans. Financial support of RES comes from both private and public sources. The range of finance fluctuates from macro- to micro-scale, depending on project size, as in the case of home-based and micro hydro stations. Recently, more and more banks are interested in financing RES projects, as this is seen as a good business opportunity. A significant role is played by bank institutions, with the European Investment Bank and the European Bank for Reconstruction and Development (EBRD) as examples of such institutions in the EU. Financial support also comes from different kinds of organisations and government agencies, e.g. the German Development Finance Group (KfW). In 2004, the KfW managed about 180 million euro for RES development. In this case, the German government allots about 500 million euro to the KfW for RES support in the developing countries. In the case of smaller investments, some financial support for RES can be expected from various non-government organisations (e.g. industrial networks, private foundations). A good example is the Renewable Energy Policy Network (RENv21). There are also other financial instruments of great importance such as grants, subsidies, preferences, facilities and taxes. These instruments may depend on local or regional conditions.

In Poland, one of the major financing sources for RES, including SHP, is the National Fund for Environment Protection and Water Management. The Bank of Environmental Protection grants preferential loans for investment in the area of environmental protection.

The major channels of SHP support include the so-called Norway Financial Mechanism and the European Industry Area Financial Mechanism. These sources of finance are additional to the EU Structural Funds, which benefit the new EU countries. Norway, Iceland and Liechtenstein (EFTA) are the donors.

Conditions of financing When creating a financial plan for SHP, the following should be taken into consideration:

- large costs of hydro-technical infrastructure,
- project lifetime of SHP is longer than period of capital return.

In the case of SHP, a major cost component can be the preparation of project documentation and the feasibility study - this can even amount to 50% of the costs. In the project, inexpensive and typical solutions should be applied. The contractor may have a substantial cost impact, so this must be fully authorised. The investment loans of 60-80% of the project value may be granted, and they come mainly from government institutions. The projects are often co-financed by local institutions, industry, and financial institutions interested in long-term financing.

Most investors do not have sufficient resources for project investment. Due to the high risk of investment, the cost of acquired capital can be expensive. It may be obtained from several sources, which can also increase the costs. Because this is regarded as a high risk investment, banks may require additional guarantees or special supervision of the development process. In some cases, a consumer loan is also possible. The period of capital return on investment is estimated to be 10 to 20 years, and up to 10 years in the case of commercial banks. The key to success is a properly prepared project, including an accurate estimation of future revenues.

8 Economy

Cost of investment The costs of an SHP project depend on:

- type of SHP (run of river, reservoir),
- installed power and number of hydro-generators,
- useable head,
- capacity of water reservoir,
- local circumstances (terrain configuration, length and height of any basin embankment, hydrological conditions, costs of land use, etc.).

Unit investment costs for SHP are illustrated in Figure 22.

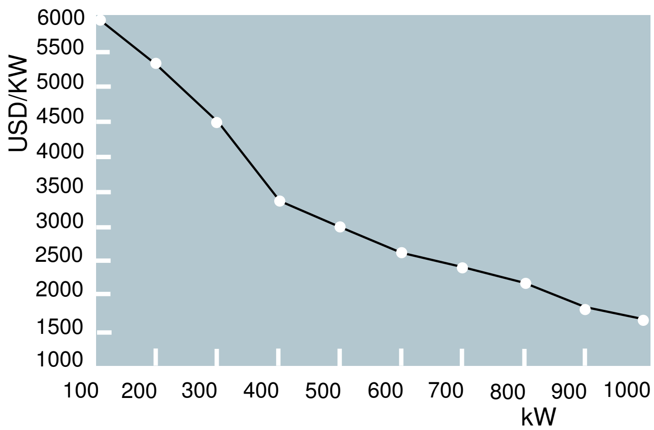

Figure 22: Unit investment costs of SHP (for head of H=10m)

A general SHP project cost level is very difficult to present, because projects are neither uniform nor comparable. Depending on the local environmental conditions, different solutions are used for different locations, hydro-technical constructions, turbines, and electrical equipment.

The percentage contribution of the main costs to the total cost of investment is shown in figure 23:

Elements of investment	Participation Up to {%}
HYDROTECHNICAL CONSTRUCTION	60
TURBINES	25
BUILDINGS	5
ELECTRICAL EQUIPMENT	10
COSTS OF EXPLOITATION	0,50

Figure 23: Investment cost breakdown

SHP Business Plan A simplified version of the business plan for an SHP project is presented in [8]. This plan refers to the construction of a basic hydro power station with basic automation. It was assumed that *the construction of the powerhouse and the turbine installation will be very cheap, and future energy prices will not drop below the present prices.*

Equipment and parameters

Lever turbine without control of impeller blades. Three blades ∅1000 mm in diameter.

Power on the clamps of generator **32KW**

Fixed water gullet (turbine flow) $2.5m^3/s$

Turbine rotational speed **238 rpm**.

Transmission belt.

Simplified cost calculations (based on Polish prices) :

Material consumption (1 EUR ∼ 4 PLN):

concrete	$51m^3 \cdot 75e/m^3$	=	€3 825
larsen G-4	$1500kg \cdot 1e/kg$	=	€1 500
armament	$\emptyset 10 - 2500kg \cdot 0.75e/kg$	=	€1 875
Total cost of materials		=	€7 200

For construction purposes, it is proposed to borrow G-4 larsen whetstone (40m of wall to the depth of 4 m). Costs about €6 500.

General costs:

Materials	€7 200
Labour	€7 200
Turbine + belt gear	€37,500
Automation for turbine	€1 250
Bars on the inlet	€1 250
Generator	€1 500
Total construction costs	€55,900 (gross)

The VAT tax is recoverable from the above total. The total net cost of an SHP project will usually be less than €50 000.

The balance of costs and revenues should be related to the local water circumstances. To estimate revenues, the energy price of PLN 0.09 c/kWh may be assumed. When the turbine efficiency is assumed to be 70%, the revenues will be:

$$8640 \cdot 0.7 \cdot 32 \cdot 0.09 \approx 17500e/year \tag{6}$$

In such a case, the payback period is about 3 years.

A business plan of the full project with a Kaplan turbine and a generator of a similar size is presented in [13]. The total project cost was approximately $ 200 000 - i.e. $ 2 097/ per kW installed power. **These are obviously quite different cost levels.** The cost level of 1 000-2 000 €/kW is typical.

9 Environment

As a rule of thumb, water management is conducted according to community interests and to avoid environmental pollution.

Fish protection Fish protection is one of the major problems faced by SHP investors. SHP stations must be equipped with the hydro-technical equipment designed for these purposes. Such equipment includes the following:

- fish-passes, fish ladders/lifts,
- by-pass canals,
- screen plates, cover bars.

Fish-passes can vary in construction.

They are often built in the form of multi chamber, cascade canals. The canal with chambers covers the entire head, from high to low water level, and may be used to limit the water speed in the case of fast flow. Such a solution is presented in Figure 24.

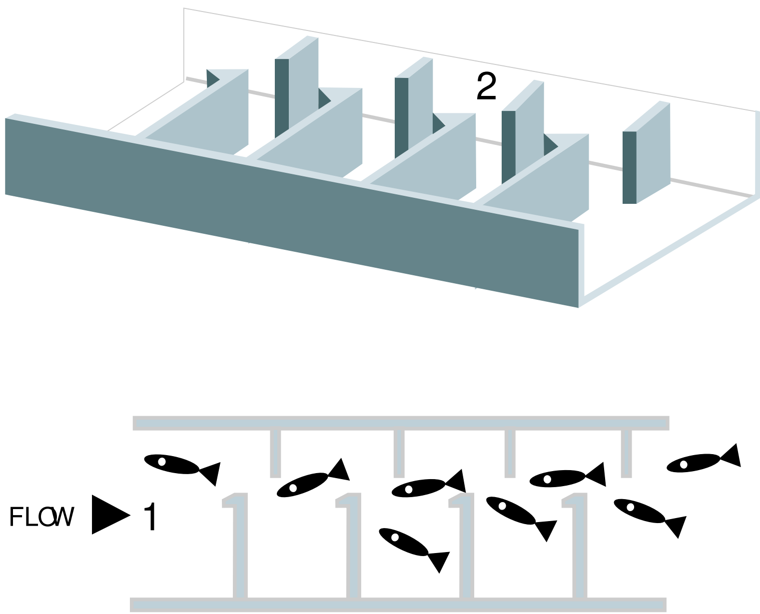

Figure 24: Fish-pass – canal with chambers: 1 – flow, 2 – vertical slot fishway

The most often used and efficient way of fish protection from the upstream level are screen plates made of steel bars with a clearance of 1-1.5 cm. These screens have to be of adequate size and should be mounted far away from the turbine inlet.

The recommended speed of the water near the bars should be at the level of 0.30-0.40m/s. The fixed bar screens should stop the fish and direct them to the opposite river bank or onto the surface. Apart from the fixed screens, screens in the shape of rotated net gates are also mounted.

Sometimes, non-standard solutions are applied, as shown in Figure 25.

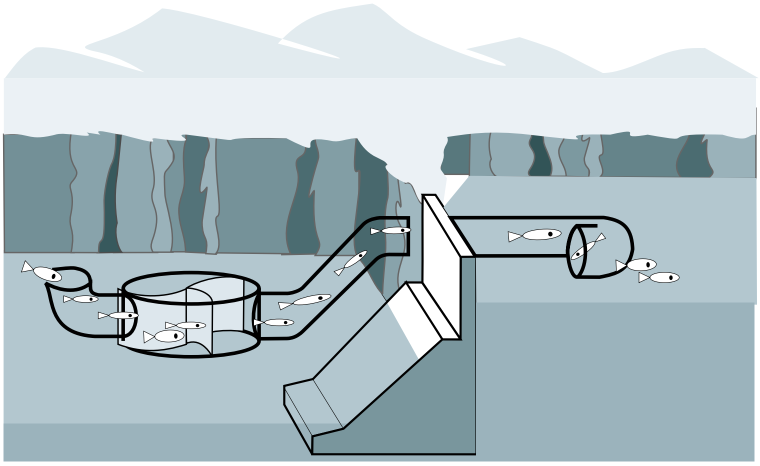

Figure 25: Fish-pass with rotational valve for fish passing

Behavioural barriers, such as sound/light barriers or curtains of air-bubbles, can also be used.

Limitation of emission For the production of 1MWh of electrical energy, about 500 kg of coal is needed. As a result, 850 kg of CO_2, 11 kg of CO, 10 kg of SO_2, and 4 kg of NO_x are emitted to the atmosphere [10].

10 Assistance, consultation

There are some associations and specialty organisations that can provide help and consultation to SHP investors at the stage of project preparation and realisation. The EU leading organisation is the European Small Hydropower Association (ESHA) [11]. The ESHA is the platform for information exchange on the European scale. In the countries in which SHPs are built, national organisations have been established (e.g. the British Hydropower Association (BHA) in the UK). Scientific and research organisations are also available.

11 Summary – essential requirements and threats

Initial stage (before realisation)	
Question: What to do?	**Remarks**
• determine expectations concerning SHP: • financial, • with regard to realisation, • with regard to operations, • become familiar with: • electrical energy trade conditions • legal, technical conditions • investment financing conditions	**'the myth of flowing water'** which is only the source of revenues should be opposed to solid analysis of expectations, which should be fulfilled at each stage of project implementation

if the answer to the question **'IS THIS INVESTMENT FOR ME?'** is positive:	
Question: What to do?	**Remarks**
determine potential locations and initial conditions on the basis of historical data: head, flow	**errors** in determining initial parameters are transferred to subsequent stages and are difficult to correct
obtain initial consultations, agreements concerning SHP location, water management, grid connection, power output	**the chosen place is not always good** with regard to law, technical, security, environmental, financial conditions
determine water requirements, acquire necessary licences	**determine full range of requirements** concerning water use
prepare technical projects for weir, intake, pipes, discharge, powerhouse, turbines, electrical connections, automation	choice of **types and number of** turbines depending on the flow should guarantee the full use of the energy potential of the site and optimise electrical energy production
prepare business plan, feasibility study, financial security of investment	correct determination of costs for **each part** of the project enables the planned technical level of SHP to be reached
realisation of investment	**before starting the project,** it is advisable to consult a broad group of specialists in each area, while taking into account high investment costs
technical acceptance, putting into operation	it is essential to fulfil the requirements concerning **security of operations**, grid protection, metering and settlement system, protection against flooding,
contract on sale and receipt of electrical energy	**market analysis**, contract preparation, fulfilment of energy trade requirements
operations	requirements: • formal and legal, concerning trade of energy, • technical, connected with operations and environment, • financial, connected with operating costs, taxes, etc.

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