2 Hydroelectric power

2.1 Introduction to hydroelectric power

[Th. Strobl, F. Zunic]

Water power is a form of primary energy which was used very early in human history. It is an ideal combination of two kinds of regenerative energy: solar- and wind energy. In the hydrologic cycle, water evaporates from the oceans and from land surface and is carried over the continents in atmospheric circulation as water vapor. After precipitating as rain or snow, it provides runoff on land surface and discharges into creeks and rivers. Ultimately it flows out into the oceans, where the procedure repeats itself. The streaming water consists of potential energy because of its altitude and its kinetic energy when discharging downhill. Jointly these energy forms are called water power. It is a regenerative (renewable) power source because it is renewed continuously in a natural way. In fact, water power is not spent like e.g. fossil or nuclear energy but only transformed into mechanical or electric power. Also it is a clean power source, because there is no air pollution or radioactive waste problems associated with it. Since water power produces no carbon dioxide, it does not contribute to global warming.

Man is using water power since the beginning of civilization. Along with the burning of wood for light and heating, water power was used as the main source for generating mechanical driving power. Today water power is used almost exclusively for producing electricity. Afterwards this electric power can be easily transformed into light, heating or mechanical power.

In almost every industrial nation, the economically exploitable resources of water power are used to a high extent. Depending on the hydrological conditions in a country and the total need of electric power, the percentage of water power varies significantly. In Germany for instance, only 3% of the electricity is produced in water power plants, whereas in Brazil or Norway the percentage is over 90% (Table 2.1.1).

Regarding the world's electricity production, about 20% of the demand is contributed by water power plants, ranking second behind thermal power generation (65%) and nuclear energy (15%). So hydropower remains the major source of electric power in many parts of the world. In many countries of Asia, Africa and South America there are still huge resources of water power which are still unused. Of course, one has to differ between theoretically, technically and economically exploitable resources. Ecological aspects also have to be considered. Table 2.1.2 shows the available hydropower resources of the world, estimated and published in the seventies.

Table 2.1.1. Production of electrical power in some countries [78Cot].

Country	Total power generation [TWh/a]	Water power generation [TWh/a]	Percentage [%]
Germany	525	17	3
United States	3620	325	9
Austria	56	37	66
Brazil	315	290	92
Norway	115.5	114.5	99

Table 2.1.2. Unused economically exploitable resources [78Cot].

Geographic region	Capacity [GW]	Energy [TWh/a]
Europe (without USSR)	215	700
USA	200	1300
USSR	269	1100
Japan and China	380	1450
South and Central America	328	1850
Africa	437	2000
Asia (without Japan, China and Siberia)	309	1200
Australia and Oceania	38	200

2.1.1 Development of hydro power

Simple water wheels have been in use for thousands of years. In the beginning they were applied for lifting irrigation water and grinding grain. Later on they powered mills, smithies and sawmills. One of the most widespread water wheels has been and in many countries still is the so-called *undershot water wheel* (Fig. 2.1.1). In hilly regions the topographic situation was taken advantage of to exploit water power. Where water fell over natural waterfalls, *overshot water wheels* were installed using the potential energy of the creeks. Often the water was diverted into channels, thus providing the necessary head to drive the water wheels.

But it was not before the 19th century that water power was used in the today known technical and highly efficient way in river power plants. The reason for the new era of water power was the invention of turbines, put into powerhouses and coupled with generators. The power of the discharging water drove the turbines and through their rotation coupled generators transformed the mechanical energy into electric power. There are three types of turbines in particular, all invented by engineers in the 19th and early 20th century:

1) Francis turbine, invented by the American J. B. Francis in 1849;
2) Kaplan-turbine, invented by the Austrian V. Kaplan in 1912;
3) Pelton turbine, invented by the American L. A. Pelton in 1880.

For low-pressure power plants only types 1) and 2) are used (Fig. 2.1.2 and Fig. 2.1.3). The Pelton turbine is only applied in power plants with heads of more than 100 m.

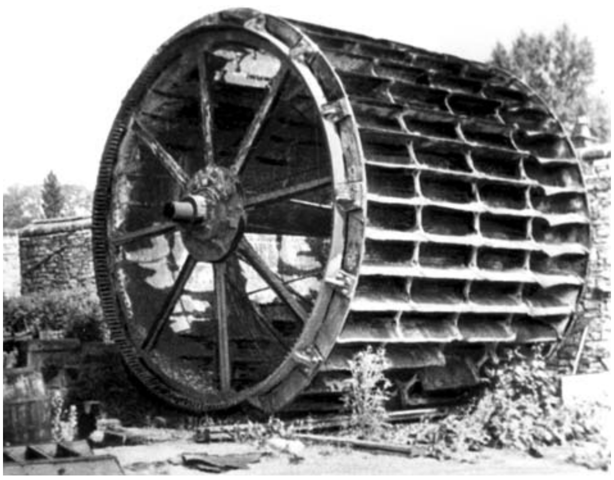

Fig. 2.1.1. Undershot water wheel [97Koe].

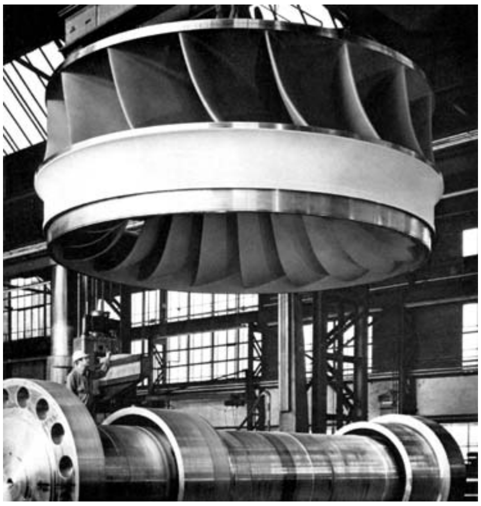

Fig. 2.1.2. Francis turbine (vertical axis) [97Koe].

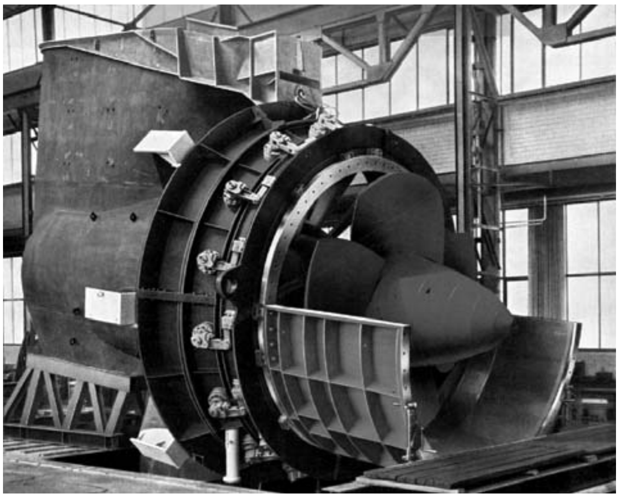

Fig. 2.1.3. Kaplan turbine (horizontal axis) [97Koe].

The development of the turbines was supported by another important invention – the possibility to transport electric energy via high voltage power lines. Since then the usage of water power was not restricted to the region where it was produced. Electricity from water power could now be delivered to consumers who were not necessarily located in the vicinity of the power station. Trade and industry were evolving with high speed because of the availability of electric power. Indeed, the industrial revolution was powered to a large extent by machinery driven by falling water.

In industrial countries like Germany, the hydro power at major rivers is almost completely exploited. As an example, Fig. 2.1.4 shows the situation at the river Lech in Bavaria. A series of more than 20 power plants were installed between 1950 and 1980, contributing to the energy supply in Southern Germany.

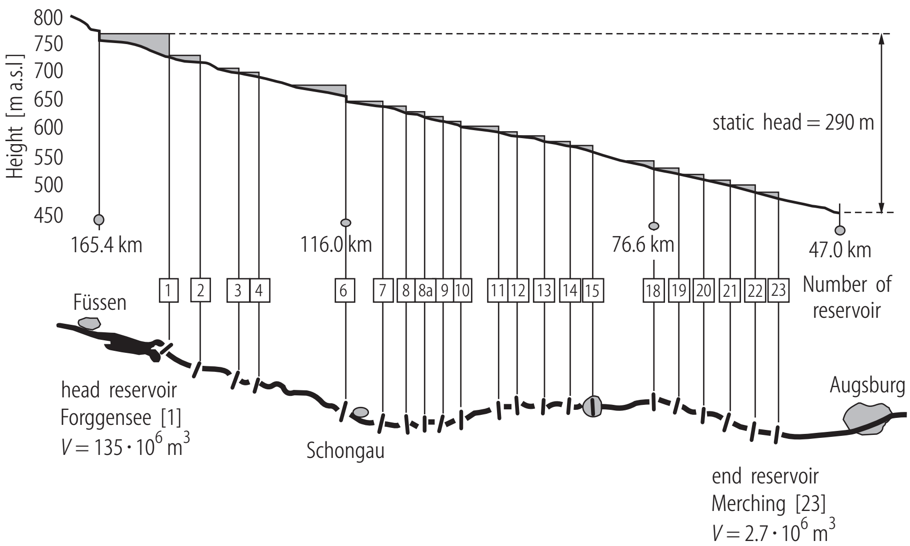

Fig. 2.1.4. Power plants at the river Lech in Bavaria [84BLW].

2.1.2 Water power equation

Modern water power plants extract 80 to 90 percent of the potential energy. That's why hydropower is the most efficient of the major sources of electric power generation. The potential energy available for power generation at a Hydro Powerplant (HPP) is called net available head h or simply *net head*. It differs slightly from the *static head*, which is the difference between the water-surface elevation at the tail water of the powerhouse and the water-surface elevation of the forebay or reservoir (Fig. 2.1.5). Because of friction losses at the intake structures, penstocks and outlets, some head losses have to be deducted from the static head. The resulting net head is to be used in calculating the energy output.

In combination with the actual discharge Q, the electrical power output can be expressed by the water power equation

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot h,$$

where P is the available power in [W], Q the discharge in [m^3/s], h the net head in [m], ρ the water density in [kg/m^3] and g the gravitation in [m/s^2]. The overall efficiency η is the product of the turbine efficiency and the generator efficiency. The turbine efficiency is between 0.85 and 0.95 (Fig. 2.1.6), depending on the type and design of the turbine used, and considers efficiency losses due to friction and turbulence between the entrance of the turbine and the end of the draft-tube. Friction losses within the generator lead to heat and noise in the machinery and powerhouse, and are included in the generator efficiency. The overall station efficiency can be raised by increasing the number of installed units, especially when flows are fluctuating. Hydraulic turbines and generators will be subject to a more detailed discussion in Sect. 2.7.

Assuming that the overall efficiency is about 80 to 85%, the water power equation can be simplified to

$$P \approx 8 \cdot Q \cdot h.$$

This equation yields the available power P in [kW] and is often used to estimate the power of a HPP by a rough guess of the head and the discharge at site. As an example, a midsize river with an average discharge of $Q = 100$ m^3/s and a head of 10 m produces energy with a power of

$$P = 8 \cdot 100 \cdot 10 = 8000 \text{ kW} = 8 \text{ MW}.$$

If the power plant would operate under these conditions during 5000 h within a year, the amount of electric power E that could be generated in one year would be

$$E = 5000 \cdot 8000 = 40{,}000{,}000 \text{ kWh} = 40 \text{ GWh},$$

which is approximately the energy consumption of about 8000 private households in Germany.

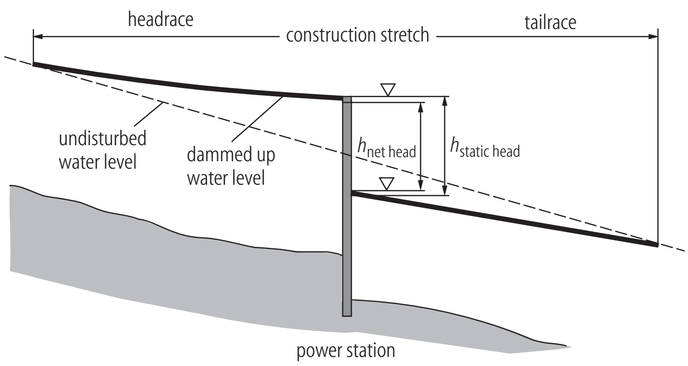

Fig. 2.1.5. Definition of the different heads.

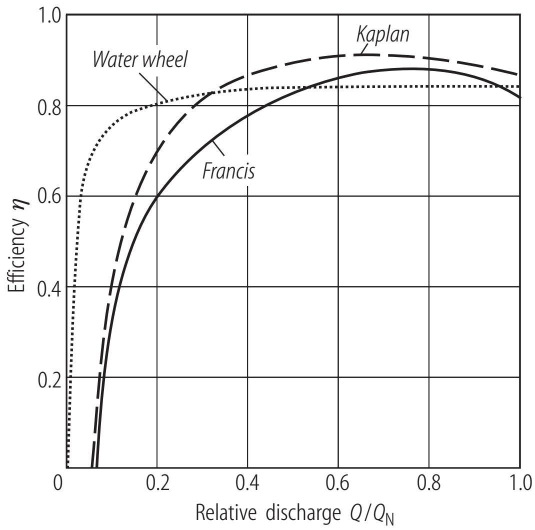

Fig. 2.1.6. Efficiency curves of a Francis and Kaplan turbine, compared with a water wheel [98Haa].

One of the largest hydro power plants on earth, the Itaipu HPP, is situated at the border of Paraguay and Brazil at the river Parana. Its installed capacity is 14600 MW, and since the 20 generators are producing almost constantly at hydraulic capacity it produces almost 95000 GWh of electric power per year. This is an equivalent of about 12 nuclear reactors.

One of the most significant advantages of water power is the high grade of energy output in comparison with the energy that has to be invested in the building and maintenance of the HPP structure and into running the site. During the lifetime of a power station, which not seldom exceeds 80 years without much rehabilitation work, this ratio usually reaches values above 50.

2.1.3 Energy output

The discharge in a river varies of course from day to day, so a power plant will not operate continuously at a constant rate. As mentioned before, current power generation and energy output at a run-of-river depends on the available discharge in the river. The expected daily flows during a year are a random process and are given in hydrographs with a duration of one year (Fig. 2.1.7, left curve). To calculate the expected amount of energy, which can be produced during a year, the mean daily flows have to be sorted by size. This leads to a flow-duration curve, showing the period of time within a year in which a certain flow is reached or exceeded (Fig. 2.1.7, right curve).

In addition to the flow duration curve, some other curves have to be included into the diagram such as the mean duration curve of

(1) the water surface elevation in the reservoir,
(2) the downstream water surface elevation,
(3) the overall efficiency.

Subtracting (2) from (1) leads to the duration curve of the gross head. Adding these curves leads to a power plan, where the yearly energy output can be calculated by integrating the water power equation over the year (Fig. 2.1.8).

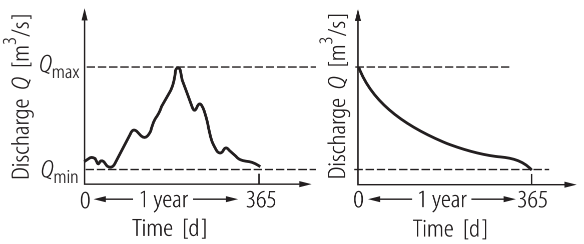

Fig. 2.1.7. Hydrograph (left) and flow duration curve (right).

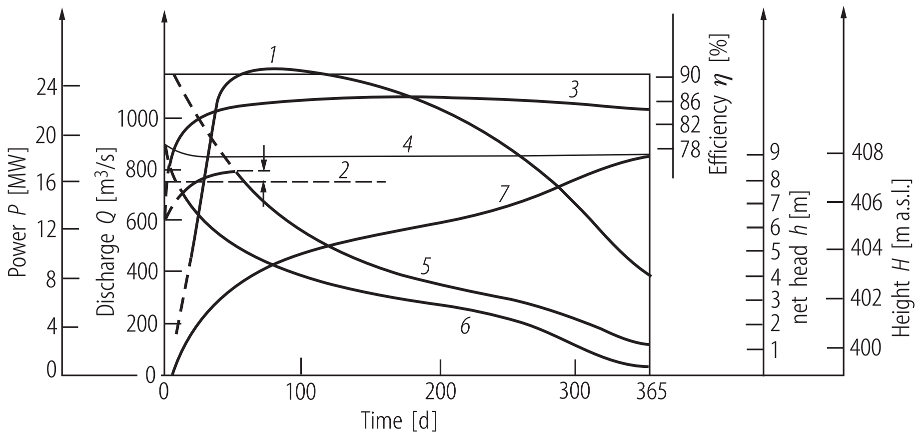

Fig. 2.1.8. Power plan of a HPP.

1 - power duration curve P [MW];
2 - rated discharge Q [m³/s];
3 - overall efficiency curve η [%];
4 - storage level H [m a.s.l.];
5 - flow duration curve Q [m³/s];
6 - downstream water surface H [m a.s.l.];
7 - head duration curve h [m].

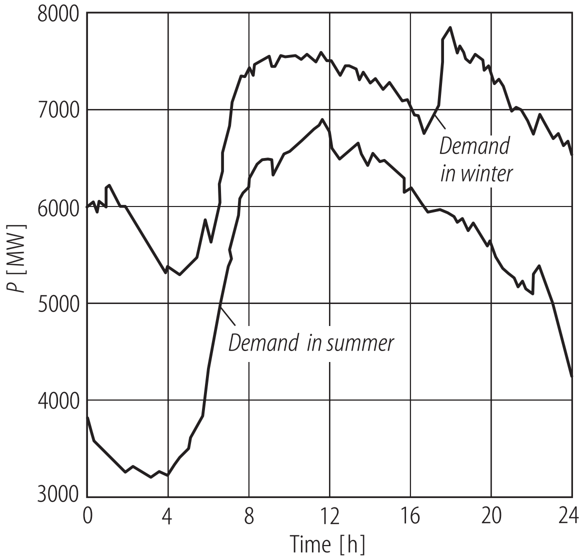

Fig. 2.1.9. Example for the difference in demand for electricity on an ordinary workday in summer and winter.

A good estimation of the expected mean power generation per year is only possible if long-term historical stream flow records are available, usually 30 years or more. By using stochastic hydrology with correlation techniques, short records can be extended to a suitable duration.

Power demand is not constant. Usually in wintertime it is higher than in summer. But even within a normal day, the use of electricity depends on the time of day. During an average winter or summer day there are periods with lower and higher demand for electricity (Fig. 2.1.9). To fit the current requirement for power, the various electricity producers are assigned for constantly delivering power or to meet the peak demand in energy. There are three sectors of demand for electricity, namely base load, center load and peak load. Usually base load is delivered by thermal power plants and nuclear facilities which are operating almost throughout the year (> 5000 h/a). Low pressure run-of-river plants also belong to this category. The needed primary energy for these facilities is cheap (brown coal, uranium) or even gratis (water). Center load is covered by energy plants operating between 2000 and 5000 h per year. They are responsible for increased demands during a day. The utilized primary energy is more expensive (hard coal, natural gas, oil). Reservoir hydro power plants also produce energy to cover this category of demand. The third sector is peak load and hence has to be covered by power plants which can switch into operation very quickly. Usually this demand can be met satisfactorily by gas turbines and of course by reservoir power plants, which can turn on their generators within minutes.

So, water power is represented in each of the load categories, but river power plants usually belong to the category of base load power plants, because they are contributing electricity mainly for constant or base load. This is because of the ability to deliver power reliably over a long period of time.

2.1.4 Economical aspects of water power

As mentioned before, the use of water power for generating electricity is highly effective. Nevertheless, the costs of building and maintaining a power plant are high and one has to consider the economical aspects of water power in relation to other energy suppliers. This is important, because other power plants (coal, gas, nuclear power) are competing when it comes to decision making. In a cost-benefit-analysis all relevant factors have to be considered. Some obvious aspects are

- interest rate,
- service life and
- maintenance cost.

Other aspects are less obvious, often difficult to take into consideration and to assess monetary, for instance ecological aspects like the reduction of carbon dioxide, nitrogen oxide and of dust emission. Nevertheless, it is necessary to have a global view of all economic, ecologic and even social aspects of power generation.

Compared with thermal electric power plants, the building of water power plants requires high investment or capital expenditure, respectively. As shown in Table 2.1.3, the specific investment costs depend on the built-in power capacity. These figures are only rough reference values, because each power plant is a singular object where the individual costs for massive construction, dam, hydraulic steelwork (turbines), electric installation and control engineering crucially depend on the location of the power plant and vary in a wide range. This is also true for the purchase of land when private properties are involved.

Table 2.1.3. Specific investment costs in €/kW installed capacity [88BGW].

Installed capacity [MW]	< 0.1	0.1-0.25	0.25-0.5	0.5-1	1-10
Specific investment [10^3 €/kW]	7.5-12.5	6-7.5	5-6	4.5-5	4-4.5

2.1.5 References for 2.1 and additional literature

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