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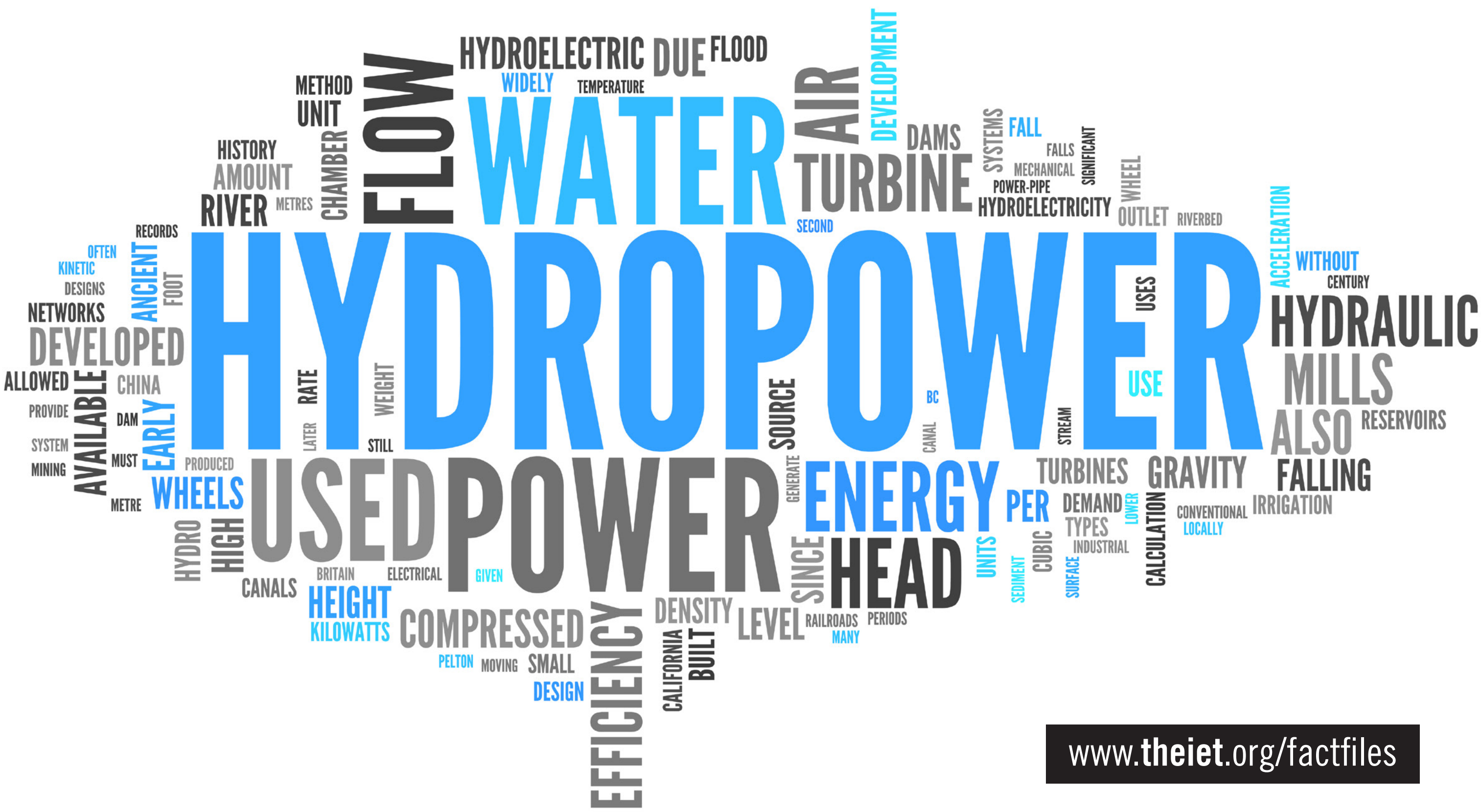
# Hydroelectric **power**

A brief guide to the generation of electricity using hydroelectric power.



# Introduction and perspective

Hydropower is by far the most significant renewable resource of electricity exploited to date. According to the *International Energy Agency's (IEA's) 'World Energy Outlook 2013'*, hydropower output worldwide is projected to increase from 3,490 TWh in 2011 to between 5.5 and 5.9 TWh by 2035, at a steady 15% or so of total global electricity generation.

In 2001 hydropower was the world's second largest source of electricity. In 2013 it ranks fourth behind coal (37% now, changing to between 33 and 40% by 2035, depending on scenario assumptions), gas (22% now, and remaining roughly at this percentage until 2035) and nuclear (12% now, reducing slightly to 2035). According to the IEA, the share of hydropower in electricity production will remain flat at its current share of 16%, or decline slightly by 2035, yet only about one third of the economic potential worldwide has been built to date.

In the OECD countries the best sites have already been exploited and environmental regulations constrain new development, although the construction of smaller size plants proceeds apace in many countries, and there is considerable activity in the refurbishment of existing schemes to extend their lives and, in many cases, increase their outputs. New hydro projects in developing countries are a massive area of development activity, following a maturing of our understanding of how to balance environmental, social and energy concerns. Projects now tend to have less water storage and hence smaller environmental footprints and reduced need to resettle people from inundated lands, but are still able to contribute controllable low carbon electricity at what is usually a competitive price. The largest projects are able to do this on a vast scale compared to most other renewable energy resources, and also bring enhanced electricity security and reduced foreign exchange requirements for imported fossil fuels to the countries they serve.

# Energy Conversion Principles

Hydro-electric engineering is concerned with the efficient and economic conversion of energy ' freely available' from a supply of water deposited at a suitable head by the action of the cycle of evaporation and rainfall produced by the effect of solar radiation. An essential requirement is, therefore, that the water should be at a suitable height above a lower reference point to where the water could flow and be discharged. The difference in levels between the water and discharge point represents the potential energy that would become available for use should water be allowed to flow between the two levels.

Since earliest times the direct conversion by gravity of the potential energy existing in differences in heights of water levels has been

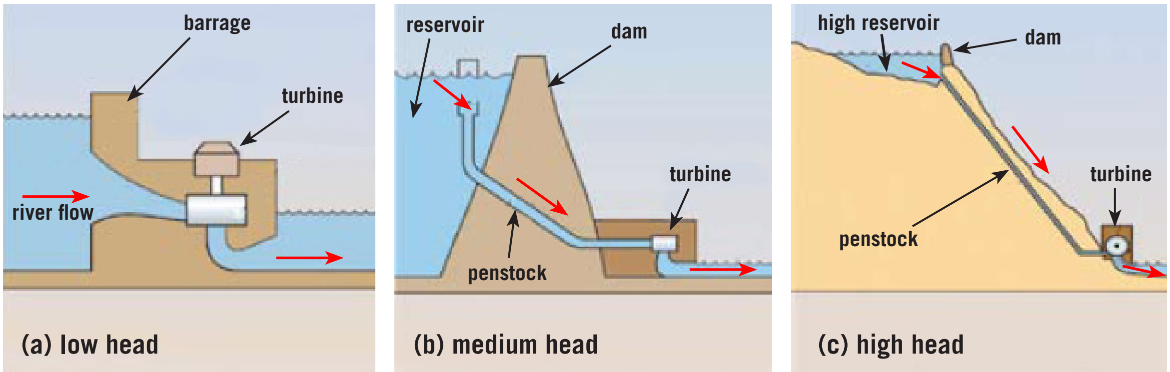



**Figure 1.** ***Types of hydroelectric installation. Reproduced from Boyle 2012 by kind permission of the Open University.***

employed in the shape of the bucket water wheel. The efficiency of conversion is not very high as only a part of the potential energy is available due to water spilling out of the buckets before they reach the lowest part of travel. The undershot paddle type of water wheel has also been used; here, the water strikes only the bottom of the wheel, and the water, in falling down a channel or flume, has its velocity increased to provide more striking force on the paddles. Although the workings of such schemes are self-evident, it should be noted that the potential energy of water is converted into rotating mechanical energy.

Hydroelectric plants, on the other hand, convert the potential energy of water into an electrical output. The process involves flow of water from the source, through the turbine to the turbine outflow (tailrace), which acts as a sink. In the process of conversion, use is made of water turbines, of associated civil structures and of rotating electrical machinery.

The power generated is proportional to the head (the height of the water), the flow rate, and the conversion efficiency of the turbine.

Hydroelectric projects are normally considered in terms of the gross heads they create. Exploitable heads vary from a few metres to 2000 m.

The greatest outputs, on modern units, have been achieved at net heads of around 120 m where flow rates of 700 t/s yield outputs of 715 MW. Similar rates of flow have been considered for some feasible low head, tidal installations.

Given a reasonable amount of rainfall and run-off, the essential physical requirements are: provision for collecting water at a suitable head; and means for taking it to a piece of machinery for conversion of energy to power output. There are only two basic types of arrangement of the powerhouse within a scheme: either 'run-of-river' or 'diversion', although there are variations. In run-of-river schemes the power house is local to the dam, i.e. is built into in the dam or is

***Archimedean screw turbine, Osbaston, Wales (with kind permission of MannPower Consulting Ltd)***

situated alongside it. In diversion schemes the water supply is taken from a damned river or lake and flows through a 'head race' canal to a head pond or 'forebay' in the vicinity of the remote powerhouse and thence down through a system of pressurised pipes ('penstocks') to the turbines.

# Rainfall and run-off

Rivers, upland lakes, coupled with their catchment areas, estuarial tidal cycles and upper reservoirs of pumped storage plants can provide the source of energy to be converted. Considering Scotland as an example, the western part of north Scotland consists of mountains at a high elevation above sea level, falling sharply to the sea in the west and falling more gradually and cut by deep valleys to the east. The topography of the Highlands has generally facilitated hydro-electric development.

## Variations in Rainfall

For the design of hydro-electric schemes the following information is required about the rainfall over the catchment area:

- The mean annual rainfall
- The mean monthly rainfall
- The maximum and minimum rainfall for a year and for each month
- The maximum intensity, duration and extent of major rain storms.

Rainfall in Britain is mainly orographical in character, i.e. due to the prevailing moisture-laden westerly winds being deflected upwards by high ground. Rainfall of this type tends to be persistent rather than of high intensity. An important feature, therefore, is that it is due to permanent physical features and can be depended upon. In Britain rainfall distribution at sea level is generally such that it is wetter in the north than in the south and likewise in the west compared to the east. Rainfall on the westward or windward slopes of hills increases with altitude and has a corresponding tendency to decrease on leeward slopes. The configuration of the high ground has, therefore, an important bearing on the pattern of rainfall in a particular area.

Rainfall is measured by gauges which should be distributed over the catchment area and, if possible, over the adjoining territory and cover a range of altitudes.

Fluctuations occur in the amount of rainfall comparing one year with another and since it is necessary to obtain the long-term average rainfall, records should be available over a number of years. The error inherent in the estimate is related to the number of years for which records are available.

In north Scotland records have been taken of rainfall going back in one case to 1881 and these have proved invaluable in the development of hydroelectric power there. For areas of reasonable size, the annual variation in rainfall can be expected to vary from 70% in a dry year to 150% in a wet year. Rainfall distribution through the year is reasonably even and, averaged over a number of years, as shown in **Table 1** below.

## Losses - Run-off

Having made an estimate of the amount of rainfall, it is necessary to allow for certain losses. Some of the rain is lost by evaporation from soil water and vegetation surfaces, some absorbed by vegetation and some lost by percolation, which, depending on the geology might reappear as springs outside the catchment area.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 11.0 | 9.5 | 7.0 | 8.5 | 4.0 | 5.0 | 5.5 | 7.0 | 9.0 | 10.5 | 10.5 | 12.5 |

**Table 1.** ***Average monthly rainfall in north Scotland as percent of annual rainfall***

In the Highlands of Scotland, for example, temperatures are moderate and humidity high which, combined with a high degree of cloud cover, means that evaporation losses are small particularly in winter. Evaporation, nevertheless, accounts for the major proportion of loss, amounting to some 30 cm (12 ins.) of which 22 cm (8 1/2 ins.) is lost during the period April to September.

Due to the presence of impervious rocks and absence of serious faults in most of the development areas, losses due to percolation are small.

The higher rate of evaporation in the summer has the effect of altering the distribution of monthly run-off compared with rainfall. The winter run-off is nearly twice that occurring during the summer. The monthly distribution is shown in **Table 2**.

River flow records, representing run-off, are used to plot a flow duration curve. A typical flow duration curve for a Highland river shows such rivers as "flashy" i.e., have a large ratio of maximum flow to minimum flow, and few of them carry their average flow for more than one-third of the year. The extent of the diversity of flow gives a measure of the amount of water storage that has to be provided to ensure continued operation during dry periods.

# Storage

## Purpose of Storage

Storage is provided in order that water may be made available when required to meet the electrical system load. The average annual load cycle may not coincide in amount or time with the average run-off cycle and, therefore, the provision of storage means that the water may be utilised at a different period to that when it came into storage. This is called seasonal storage. In addition to such variations within a year, variations can occur comparing one year with another and storage can be provided to offset such variation. This is called long term storage.

Seasonal storage under average conditions may not present any great difficulty if the average run-off cycle very nearly coincides with the load cycle, but considering short spells of two to three months, variations from average can be quite large and in practice provide the main operational problem.

Increasing the amount of storage eases operation of the scheme to meet load requirements, but the cost of storage can be high. Topography and perhaps geological conditions limit the amount of storage possible. If the amount of storage is small in relation to the average yearly run-off, generation may have to take place at times when the load conditions do not merit it and, in very wet weather, run-off can be wasted if it occurs at a greater rate than can be dealt with by the plant. Conversely, in dry weather, the installed plant capacity should be available when required to meet the load, in order that this capacity can be regarded as "firm." Any additional capacity provided in order to save, or to reduce, spillage from the reservoir would have to be justified solely on this basis.

## Methods of Storage

The most suitable method of providing the required storage depends on a number of factors, topographical, geological, climatic and such availability of skilled labour and materials. The construction of a dam may not be feasible or its provision may not be justified economically due, perhaps, to the open nature of the country at the reservoir mouth, in which case there is the simple arrangement of a natural reservoir from which the power station draws water at a lower level.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 12.0 | 10.0 | 7.5 | 8.5 | 3.5 | 3.5 | 4.0 | 6.0 | 9.0 | 11.0 | 11.5 | 13.5 |

**Table 2.** ***Average monthly runoff in north Scotland as percent of annual runoff***

In most cases, however, the construction of a water retaining structure is economically justified. With such structures, the primary consideration affecting design is that of safety.

In the design of any dam, certain forces have to be taken into account. Firstly, there are those that are a function of fluid pressures and weight density of materials and, secondly, there are those due to earthquakes, silt deposits, ice, uplift pressures, and effects of floods. Those in the first category are amenable to calculation, but coping with the remainder depends largely on experience. When there are fishing interests, provision may also be made for the passage of fish both into, and out of, the reservoir.

A variety of dam designs exist as follows:

**Embankment Dams** - an earth or rock-filled dam across the reservoir outlet. This form of construction is nearly always cheaper than any alternative particularly if rock-spoil is available from tunnelling.

**Solid Gravity Dam** - Dams of this type rely on their weight for stability and the weight usually provided entirely by the quantity of concrete or the masonry in the structure. A sound foundation, usually on rock, is required.

**Buttress Dams** - With the potential for seepage in its foundations the gravity dam is subject to an unavoidably large area exposed to uplift forces and, as a result, the stresses and factors of safety against overturning are low in relation to the strength of the concrete. Buttress type dams were developed in order to achieve:

- Reduction of uplift forces by having minimum downstream area in contact with the ground.
- Utilisation of the stored water pressure to give stability by sloping the upstream face and, therefore, reducing the amount of concrete required.
- Utilisation of the strength of the concrete to a safe minimum.

**Pre-Stressed Concrete Dam** - Another way of counteracting the uplift forces and increasing the stress in the gravity dam is to replace part of the mass by preloading the structure.

**Arch Dam** - Arch dams are characterised by their extreme thinness in relation to their height having this ratio as low as 0.15 and even lower for cupola arch dams with curved cantilever sections. The design of such dams involves complex calculation of stress and model testing is often resorted to.

***Roxburgh hydroelectric power station, New Zealand***

## Hydraulic System

The natural catchment area may be extended by diverting adjacent streams or by tunnelling from an adjacent watershed. Unless the power station is constructed within the dam, it is necessary to provide an aqueduct between the storage and power station. In such 'diversion' schemes the supply is taken from a dammed river or lake, from which water flows through a headrace canal to a head pond or forebay in the vicinity of the remote powerhouse. From the forebay the water flows to the turbine through a system of pressurised pipes known as penstocks.

The purpose of the forebay is to ensure that sudden changes in rates of flow caused by changes in turbine control do not result in unacceptable changes of the water levels in the canal.

In a variation of this scheme a low-pressure tunnel replaces the canal and takes the water to as near as possible to the power station where there are two possibilities for completing the route. If the rock cover over the route near the station is good and generally steeply sloping, it will usually be economic to provide either a sloping tunnel or combined vertical section and horizontal tunnel. This latter section of tunnel or pipeline is referred to as the high-pressure section.

To permit quick starts of the turbine without loss of head caused by the need to accelerate water quickly within the tunnels, and in order to protect the low pressure tunnel from pressure surges (water hammer) where turbine control conditions lead also to sudden decreases of rates of flow, use is made of a surge chamber or surge tank. These are usually most conveniently located at the junction between the high and low-pressure sections. A free water surface is thus provided at this point.

The period of oscillation set up in the tank/chamber in this way is usually of the order of several minutes. In the absence of flow in the tunnel the oscillations can take several hours to die away appreciably. Such oscillations in the surge chamber level are presented to the turbine as a variable head, and if the turbine is speed governed, it will adjust the flow in such a way that unless the oscillations are quickly damped by friction they could, if the chamber were incorrectly proportioned, impose a forced oscillation upon the mass of water in the chamber and produce dangerous conditions.

***Large Hydro Electric Power Plant Generators***

The chamber has to be designed so that under all conditions of load change, the oscillations are damped to give stable operation. It is important to ensure that the draw down in the chamber is not such as to allow air to be drawn into the tunnel.

Underground power stations must also have a length of tunnel for the tailrace. If the tailrace tunnel contains water under pressure, it would have to be considered in relation to surges in the same way as for a high-pressure system and a surge chamber may be provided.

## Power Station

### Structure

Unless the power station is to be incorporated in a dam, the station can either be constructed on the surface or located underground. Provided underground rock is sound an underground station has a number of advantages. For instance, the length of high pressure tunnel and amount of steel lining and reinforcement can be kept to a minimum, the tailrace tunnel can be unlined and the superstructure required for a surface station becomes unnecessary.

Depending on the layout of a scheme, the turbines, their auxiliaries and the electrical plant may be housed either at or below ground level. Run of the river stations are invariably housed at ground level and are located either inside or alongside the dam. On very low head schemes they may be housed within the structure of a submerged weir, with provisions for spilling excess flow over the roof and side of the station. In diversion schemes, the power station is housed either in a purpose-built structure at ground level or in an underground cavern. The underground arrangement is also attractive from the amenity aspect. The relative costs are a little different, but the underground arrangement does use less steel and the reduction in the amount of tunnel lining work can save time.

In underground stations special attention has to be given to guarding against flooding, fire and leakage of carbon dioxide from fire fighting equipment.

***River Drina hydroelectric power station, border of Serbia and Bosnia***

## Layout

By comparison with thermal stations, the number of auxiliary systems that must be housed either within, or in the vicinity of, a hydroelectric power station is fairly limited. Such systems that are essential include the following.

- Gates and/or valves used for isolating the turbine, together with the associated pumping sets and pressure receivers.
- Governors, actuators and servomotors.
- A compressed-air system capable of charging and topping up the pressure receivers (used by above bullet points).
- Duplicated de-watering system with a proportion of the de-watering pumps supplied from a secure battery based supply. (Dewatering is the process of emptying the system of water so that it can be maintained)
- Cooling systems for generators, transformers, pumping sets and for thrust and journal bearings of the turbo-generator.
- A heating and ventilating plant capable of maintaining the required degree of comfort.
- Voltage regulators and controllers
- Instrumentation and controls for monitoring and operating the units and their auxiliaries, including automatic synchronising equipment.

In addition to the generators, the electrical plant housed within or in the neighbourhood of the plant consists of low and high-voltage switchgear, transformers and generator busbars. With generator voltages employed in hydroelectric sets tending to be in the range 8-15 kV, considerations of the cost of bus-bars dictate that the main transformers must be placed in close proximity to the generators. Thus in underground stations the main transformers are normally housed in galleries running alongside the turbine hall.

On installations on which large pump turbines are employed, pump-starting equipment also has to be housed within the stations.

Given the variety of possible locations and machine types and configurations, a multiplicity of competitive station designs has been established over the years.

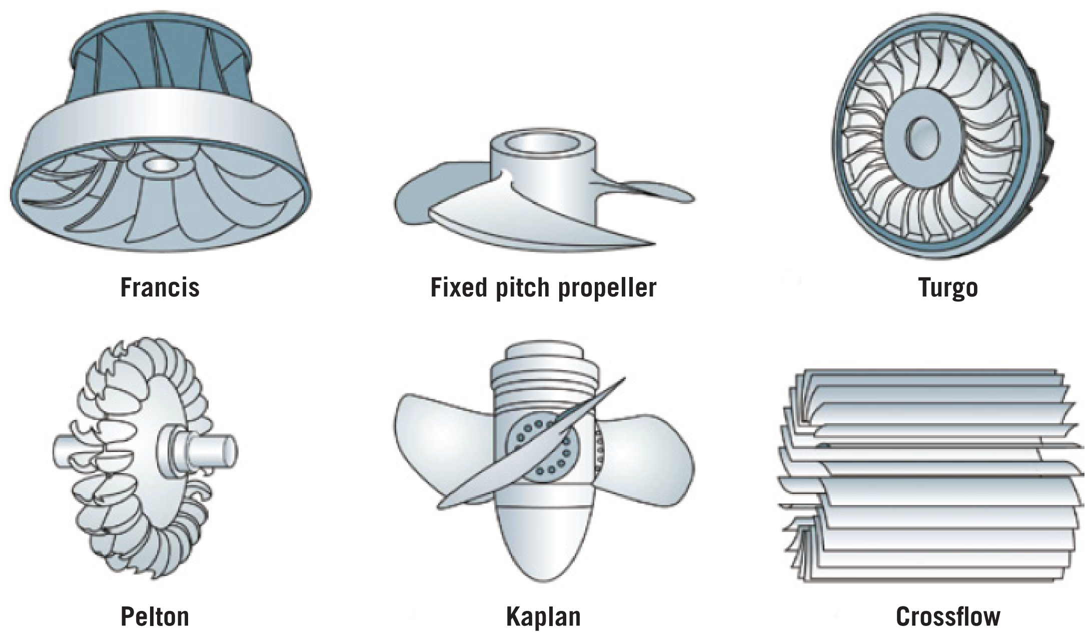



**Figure 2.** ***Types of turbine runner. Reproduced from Boyle 2012 by kind permission of the Open University.***

# Turbines

## General principles

Consideration of hydraulic conditions at the turbine runner leads to the division of water turbines into two main groups:

- the impulse turbines represented in modern turbine practice mainly by Pelton wheels (**Fig. 3**) and
- reaction turbines, a group covering both mixed flow and axial flow machines including Propeller, Francis and Kaplan or Deriaz turbines (**Fig. 4**).

In an impulse turbine, all the available energy is converted into velocity before the water enters the runner, while in a reaction turbine the process of conversion takes place partly before and partly after the water has entered the runner. The division of water turbines into these two groups is based on general usage and does not imply any difference in the method of energy transfer between the water and the runner. At its simplest, the principle of a water turbine is that of a rotating duct, through which flows a stream of water. The stream and the duct interact; the stream is deflected and, as a result, a force is exerted on the duct. The moment of this force, about the axis of rotation of the duct is equal and opposite to the change in the moment of momentum of the stream.

Impulse turbines are driven by jets of water issuing from one or more nozzles distributed tangentially around the periphery of the wheel. Adjusting the openings of the nozzles controls the power output.

With a few exceptions, reaction turbines are normally equipped with movable guide vanes. These are disposed symmetrically around the runner and control both the velocity of flow and its direction at the entry to the runner. The majority of reaction turbines have runners whose geometry is fixed and invariable. Modern, mixed flow machines, equipped with such runners are known as 'Francis' turbines. The flow at inlet is invariably inward and the flow at exit is usually axial. The axial-flow machine with a fixed geometry runner is known as a 'propeller'. Turbines in which the guides are movable but the runner blades are fixed are said to have 'single regulation'. Part-load performance of such machines tends to be poor. In order to improve performance, machines with both movable guide and movable runner blades have been introduced. Such machines are said to have 'double regulation'.

Axial-flow turbines with double regulation have been employed since the 1920s. They are known as 'Kaplan turbines', after their inventor. Double regulated mixed-flow turbines have been used since the 1950s. Double regulation increases both the size of a machine and its costs. However, the resulting improvement

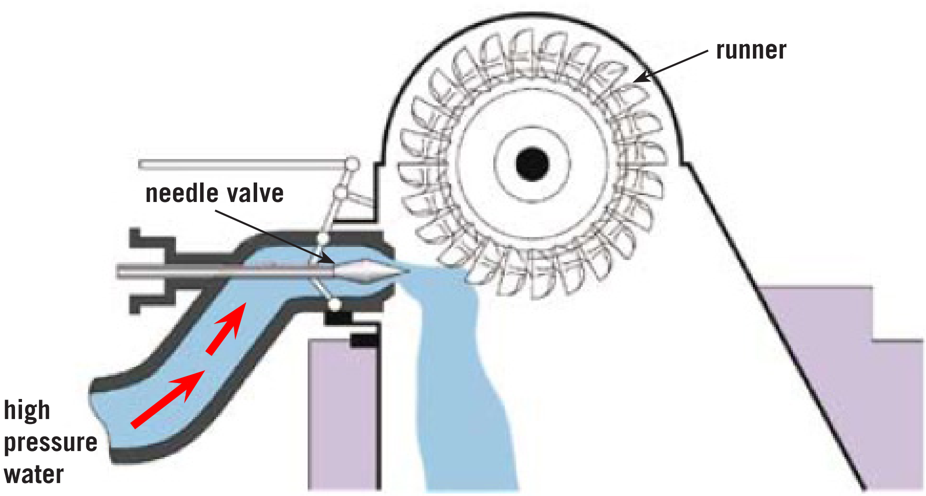



**Figure 3.** ***Pelton wheel turbine. Reproduced from Boyle 2012 by kind permission of the Open University.***

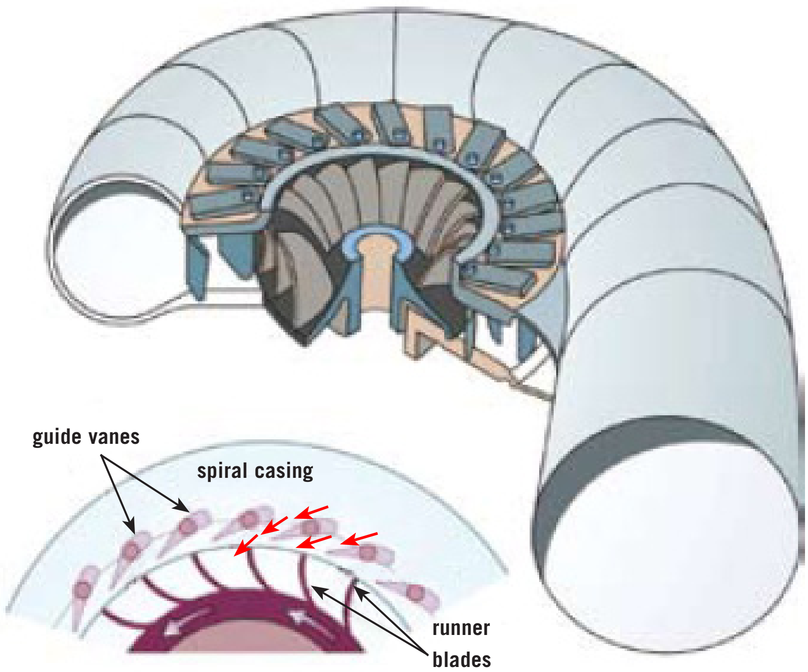



**Figure 4.** ***Francis turbine. Reproduced from Boyle 2012 by kind permission of the Open University.***

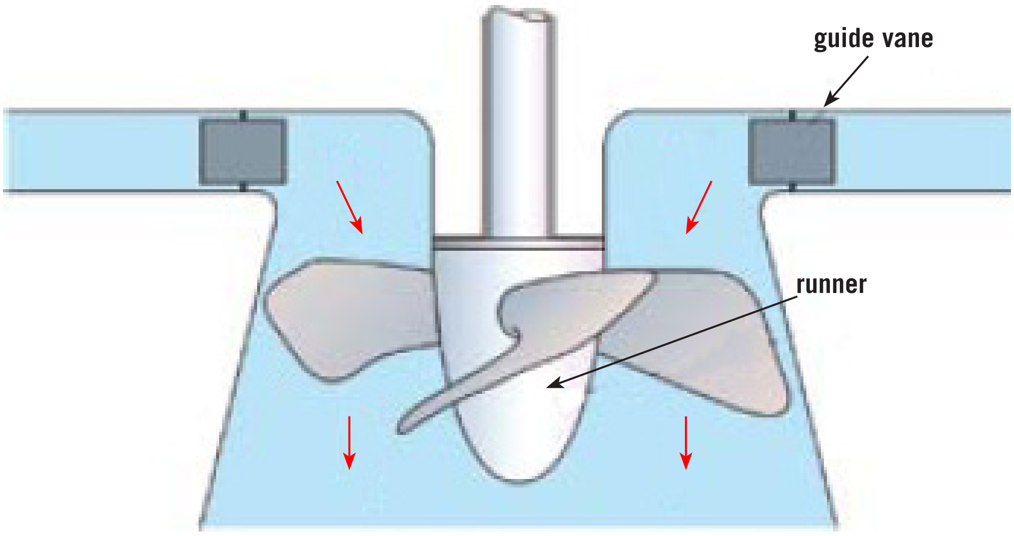



**Figure 5.** ***Propeller, or axial flow, turbine. Reproduced from Boyle 2012 by kind permission of the Open University.***

| Head (m) | Low 40 - 50 | Medium 20 - 700 | High 200 - 1200 |
|---|---|---|---|
| Storage | Pondage or Run-of-river | Storage or Pondage | Ample Storage |
| Turbine type | Propellor or Kaplan | Francis | Impulse (Pelton) |
| Speed (revs/min) | **50 - 250** | **180 - 600** | **200 - 1200** |
| Peripheral speed of runner/ Water speed | **2 - 3** | **0.75 - 0.9** | **0.5** |
| Runawayspeed/Normal speed | **2 - 2.2** | **1.8 - 2.1** | **1.8** |

**Table 3.** ***Data for basic types of water turbine.***

in performance under a range of operating conditions can make their use economically justified, either where single or very few machines are installed, or where substantial head variations are encountered.

Data relating to the basic types of turbine are given in **Table 3** and the ranges for applications shown in **Figure 6**.

## Hydrogenerators (large)

Large diameter salient-pole generators are almost universally employed with a maximum design speed not greater than 1000 or 1200 rev/min to produce electricity at the required frequency of 50 or 60 Hz. Small induction generators of up to 5 MW are used in isolated cases. The two requirements specific to hydroelectric installations are the need to take into consideration the very high runaway speeds and the need to provide sufficient rotary inertia to assure both the quality of speed control of the turbine and the stability of the electrical system. In the case of vertical-shaft units the specification often calls for the bore of the generator stator to be of sufficient size that the turbine runner can be withdrawn without the need to remove the stator. Thrust bearings are normally provided on the generator shaft. It is

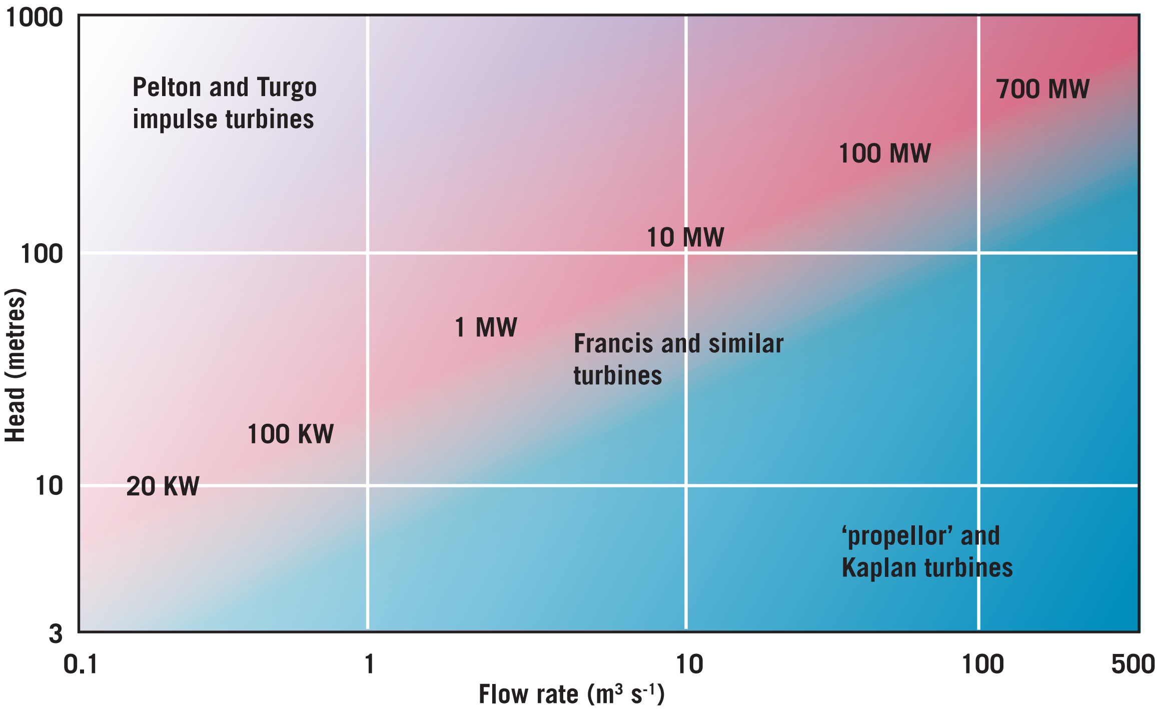



**Figure 6.** ***Range of applications for different turbines. Considerable overlaps of use exist at the boundaries shown***

thus necessary for the generator designer to be acquainted with the magnitudes of hydraulic thrusts appertaining to a range of operational conditions.

As a result of the restrictions on size and weight due to consideration of transport and access to remote sites, generator rotors and stators are often assembled on site using preformed, transportable components. In the case of major schemes it is often economic to construct a dedicated factory at the site of the scheme, rather than to transport large components and subassemblies to the site.

## Pumped storage

In many OECD countries the available water-power resources are becoming fully utilised and, as environmental considerations lead to resistance to further encroachment by developments leading to the inundation of large tracts of land, modern hydroelectric practice is tending towards construction of pumped storage schemes. Currently some 20% of the world's largest turbines are used in this mode.

The location of such installations is not critically dependent on the quality of the catchment area, but there must be sufficient water to fill and make good any losses due to seepage and evaporation. However, any natural inflow to the upper reservoir produces a bonus in output. As the cost of machinery per unit output depends on the available head, there is an incentive to construct such schemes at sites providing. potential heads in the range 300-600 m. Should such sites not be available, lower heads could still be exploited, but at a greater cost.

Availability of pumped storage increases the efficiency of operation of the whole interconnected system and, because of its rapid response capability, removes the need for investment in gas-turbine based peak-lopping units and of operation of thermal units in the spinning reserve mode. Their use, unlike that of conventional hydroelectric units, however, does not strictly speaking qualify as renewable energy.

In Europe, the USA and Japan, many pumped-storage plants have been built. Many more are projected or are in the course of construction, mainly in parts of the developing world. Pumped plants comprise the single most important area of growth of hydroelectric power generation.

## Economics

The economics of hydropower have been transformed in recent years through a mix of value being ascribed to carbon and the rising costs and cost uncertainty of fossil-fuel alternatives. The underlying challenges of high capital cost and long construction periods creating long term equity and debt requirements remain, but strong support from agencies such as the World Bank now mitigate this to a considerable extent. Financing for hydro projects is also available from sources such as Chinese banks, when coupled with a Chinese supply chain and contracting offering.

Smaller projects are often included within renewable energy incentive schemes, making them attractive commercial investment propositions.

This, together with a more mature view of how to manage environmental issues, has caused a focus away from the complex multipurpose projects of the past, justified as much on irrigation and water resource arguments as for electricity production, towards a narrower focus on electricity generation as the major or sole rationale.

## Environmental considerations

Hydroelectric schemes have significant environment and social impacts, especially if large scale energy storage is involved. These include direct impacts on people affected by inundation, habitat loss and associated impact on rare plants and animals, loss of cultural artefacts, and the downstream impacts of changed river flows. These impacts can become cumulative if several hydroelectric schemes are constructed in the same river basin. Over time, extensive quantities of silt can build up behind dams, and potentially impair operation. Tidal range schemes in estuaries can have a significant impact on ecology, including habitat loss for migrating birds.

In recent years a more mature approach to such issues has led to a much more integrated approach to finding good engineering and environmental solutions. Generally projects have less storage, requiring less inundation, and better design solutions and operational techniques can also minimise environmental impact. However there are still cases of environmentally poor hydro schemes being developed, and most investors now apply strict environmental and social impact tests before committing to fund projects, usually referenced to the World Bank environmental guidelines.

## Further Information


- Boyle, G. (Ed.) (2012) Renewable Energy: Power for a Sustainable Future (Third Edition). Oxford University Press / Open University.

The Institution of Engineering and Technology

The Institution of Engineering & Technology
Michael Faraday House
Six Hills Way
Stevenage Herts
SG1 2AY

**T:** +44 (0)1438 765690
**E:** sep@theiet.org
www.theiet.org



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