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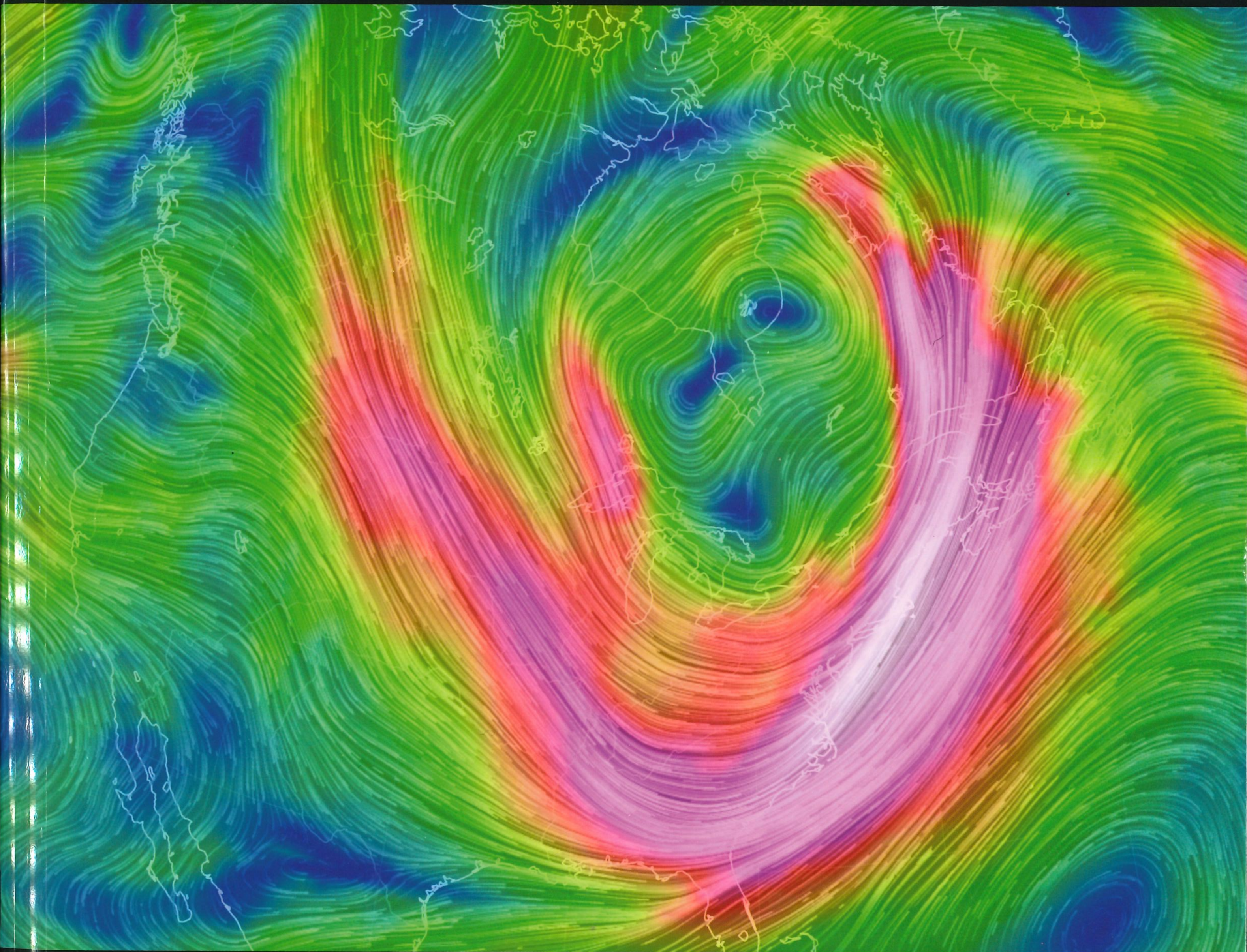

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Chapter 6

Hydroelectricity

By Janet Ramage and Bob Everett

6.1 Introduction

> How to promote socio-economic development and eradicate poverty, whilst simultaneously halting environmental degradation, is one of the greatest challenges at the start of the 21st century. This challenge is most conspicuous in the policy for water and energy, as both are essential elements for human life.
>
> (Sustainable Hydropower, 2011a)

Water power, like most renewable energy sources, is indirect solar power, and like others such as the wind, it has been contributing to local energy supplies for many centuries. It is, however, unique in that it became a major 'modern' energy source over a hundred years ago, supplying the input for some of the earliest power stations. Hydroelectricity has become a well-established technology, delivering in 2016 about a sixth of the world's annual electricity supply (Figure 6.1).

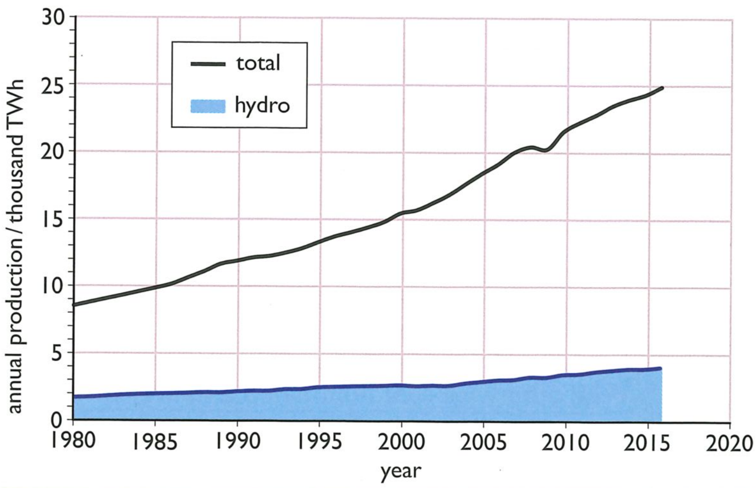


Figure 6.1 World total electricity production and hydro contribution, 1980–2016 (source: BP, 2017)

To introduce the terminology and main features of hydroelectric systems, this chapter starts with an account of one relatively modest hydro scheme. Commissioned over three-quarters of a century ago and still operating with much of its original plant, this group of power stations in Scotland exemplifies both the technical and economic aspects of hydroelectricity.

The chapter continues with a discussion of the nature of the hydro resource and its present contribution to world energy. This is followed by a summary of the basic science and a brief history of the development of water power, leading to the modern turbine systems that are the subject of Sections 6.7 and 6.8.

The remaining sections are concerned with the problems and the potential of hydroelectricity. We find the familiar issues of cost, firmness of supply and integration which arise for all renewable sources, but for large-scale hydroelectricity the questions are rather different: whether there are limits to growth, what determines these limits, and whether we are already reaching them.

6.2 The Galloway Hydros

The Galloway Hydroelectric Scheme on the River Dee in south-west Scotland makes an interesting study for several reasons. Initially commissioned in 1935, it was the first major UK scheme designed specifically to provide extra power at times of peak demand. Its six power stations are controlled as one integrated system. Several of its dams are on major salmon-fishing rivers, raising environmental issues common to many hydro schemes. It is also technically interesting because significant differences between the site conditions at the power station locations mean that across the system several types of turbo-generator are used.

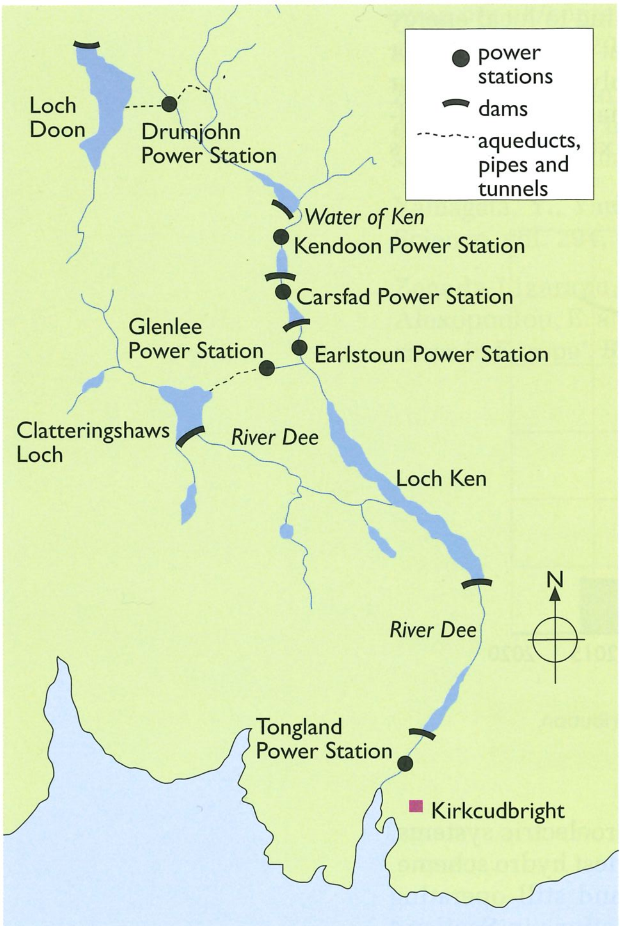


Figure 6.2 The Galloway Hydros (source: adapted from Hill, 1984)

Origins

The Galloway Hydros owe their origin to local pride and individual enthusiasm, and an Act of Parliament (ScottishPower, 2011). The first proposals to use the rivers and lochs of south-west Scotland for hydropower appeared in the 1890s, but the scheme became feasible only with the establishment of a National Grid in the 1920s. This meant that the great industrial conurbation of Glasgow became a potential customer, and also that the hydro system could meet the need for a plant that could quickly respond to daily and seasonal peaks in the otherwise coal-dominated grid system.

The scheme

The system (Figure 6.2) has three main elements. The first is Loch Doon, which provides the main long-term seasonal storage. Its natural outflow is to the north, but a dam now restricts this and the main flow is diverted eastwards through a 2 km tunnel into the upper valley of the Water of Ken. An interesting feature is the Drumjohn Valve: when demand for power is low, this directs the flow from two eastern tributaries of the

Water of Ken through the tunnel in the 'reverse' direction *into* Loch Doon, adding to the stored volume. The level in the loch can vary by 12 metres, releasing 80 million cubic metres of water. Falling through the 200 metre height difference down to the final outflow at Tongland, this represents a gross release of some 150 million MJ of energy – over 40 million kWh.

The second element of the system, for fast response to short-term demand variations over the course of a day, is the series of dams and power stations along the course of the Water of Ken: Kendoon, Carsfad and Earlstoun, and the Tongland plant near the mouth of the River Dee.

Clatteringshaws Loch, the third element, is fed by the tributaries of the Dee, rising to the west of the main valley. This is the only completely artificial reservoir in the system, and its main outflow, through a tunnel nearly 6 km long and pipes with a fall of over 100 metres, supplies the 24 MW Glenlee power station before joining the Ken below Earlston. The remaining natural flow of the Dee and its tributaries is south-east into Loch Ken (into which the Ken also flows).

Table 6.1 gives key details for the different power plants in the scheme.

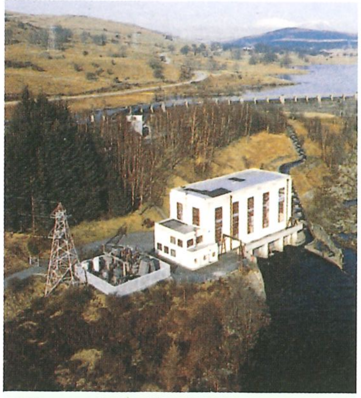


Figure 6.3 Carsfad power station and dam

Power

The essential characteristics of a hydro site are the **effective head** (H), the height through which the water falls, and the **flow rate** (Q), the number of cubic metres of water passing through the plant per second. As we shall see in Section 6.5, there is a simple approximate relationship between these two quantities and the power delivered by the water (P) at the *input to the turbine*, measured in kilowatts (kW):

$$P\,(\text{kW}) = 10 \times Q\,(\text{m}^3\,\text{s}^{-1}) \times H\,(\text{metres})$$

The conversion of energy carried by water into electrical energy is carried out by the **turbo-generator**: a rotating turbine driven by the water and connected by a common shaft to the rotor of a generator. (The electric power *output* will of course be rather less than this input, for reasons discussed in Section 6.5.)

Table 6.1 The Galloway power stations

Power station	Average head / m	Maximum flow / m^3s^{-1}	Output capacity / MW	Number of turbines
Drumjohn	11	16	2	1
Kendoon	46	55	24	2
Carsfad	20	73	12	2
Earlstoun	20	71	14*	2
Glenlee	116	26	24	2
Tongland	32	127	33	3

*Although the *average* head and flow are similar to Carlsfad, a slightly higher dam at Earlstoun allows it to take advantage of seasonal variations in flow.

Source: ScottishPower, 2011

BOX 6.1 Capacity factor – a reminder

As we saw in Chapter 1, the annual capacity factor of any plant is equal to its actual annual output divided by its output if it were to generate continuously at its full rated power, expressed as a percentage.

So, if Carsfad, with its capacity of 12 000 kW, generates 30 million kWh of electricity in a year (remembering that there are 8760 hours in a year), its capacity factor will be:

$$30 \times 10^6 \,/\, (12\ 000 \times 8760) = 0.285, \text{ or } 28.5\%$$

Of course, in practice, the annual capacity factor of a plant depends on both the demand for its output and the power that it can produce at any given time.

The turbines

The head and the required power are critical in determining the most suitable type of turbine for a site. Glenlee's high head puts it at one extreme in the Galloway system, with Drumjohn's very low head and power rating at the other. Of the four river plants, Kendoon and Tongland have intermediate heads and fairly high power ratings whilst Carsfad and Earlstoun have almost identical low heads and powers.

All turbines consist of a set of curved blades designed to deflect the water in such a way that it gives up as much of its energy as possible. The blades and their support structure make up the turbine **runner**, and the water is directed on to this either by channels and guide vanes or through a jet, depending on the type of turbine. The Galloway plants include two types of runner – 'propellers' and Francis turbines (see Figure 6.17). As discussed in more detail later, 'propeller' types are most suitable for large flows at low heads and Francis turbines for medium to high heads. Comparison of Tables 6.1 and 6.2 shows that this is true for the Galloway scheme.

Table 6.2 The turbines

Power station	Turbine rating /MW	Turbine type	Rate of rotation* / rpm
Drumjohn	2	Propeller	300
Kendoon	12	Francis	250
Carsfad	6	Propeller	214.3
Earlstoun	7	Propeller	214.3
Glenlee	12	Francis	428.6
Tongland	11	Francis	214.3

*The significance of these rates is explained in Section 6.7.
Source: ScottishPower, 2011

The salmon

The principal environmental issue raised during the approval process was the possible effect on salmon fishing. Several dams blocked rivers below their salmon spawning pools, and concern was expressed about the fate of adult salmon making their way upstream and young smolt on the reverse journey. The response was the incorporation of fish ladders at four dams. These are a series of stepped pools with a constant downward flow of water to attract the fish, which leap up from pool to pool (Figure 6.4). The Doon dam had insufficient space for a long series of pools, so the fish ladder there is partly inside a round tower – it is claimed that the fish do not find this spiral staircase a problem. The issue does not arise at Glenlee since salmon do not use the man-made Clatteringshaws Loch. (It is worth noting that a much more detailed environmental impact statement would be required today.)

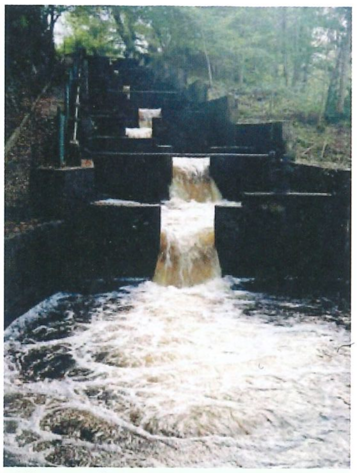


Figure 6.4 The fish ladder at Earlstoun

Economics

The Galloway scheme was built to supply extra power to the grid at times of peak demand. In other words, it was assumed that it would generate for only a few hours a day, resulting in an annual capacity factor of no more than perhaps 25%. This would suggest a poor return on the initial investment, which was in any case higher than the cost of a coal-fired plant of similar capacity. However, a number of circumstances made the scheme financially attractive:

- The company was able to assume a firm demand for the planned output.
- During its first three years the scheme received an annual treasury grant of £60 000 (about £4 million at present-day values), reducing the cost per kWh by about 20%.

From the start, demand, and the consequent economic performance, exceeded expectations, and only in a few years of serious drought has output fallen below the planned level. After more than 80 years, the original five plants are still generating power, joined in 1984 by the 2 MW plant at the Drumjohn Valve. The original construction costs were repaid many years ago.

In 2009, ScottishPower announced a £20 million investment programme to upgrade equipment at three hydroelectric sites, including the Galloways and Cruachan (Figure 6.8), which is intended to safeguard their operation until at least 2035 (ScottishPower, 2010).

6.3 The resource

For hydroelectricity, as for other renewables, the resource is basically an amount of *power* – a rate at which energy is delivered. However, for comparison with other major energy sources, where the resource is effectively a quantity of *stored energy* (tonnes of coal, barrels of oil, etc.), it is usual to express a hydro resource in terms of the total energy it delivers in the course of a year. The customary unit on the national or world scale is **terawatt hours per year, TWh y^{-1}** (1 TWh = 3.6 PJ, or 1 EJ = 278 TWh).

The world resource

We saw in Chapter 1, Figure 1.5 that about 20% of the 5.4 million EJ (1.1 billion TWh) of solar energy reaching the Earth's atmosphere each year is consumed in the evaporation of water. The water vapour in the atmosphere therefore represents an enormous, constantly replaced, store of energy. Unfortunately most of it is not available to us. When the water vapour condenses into water, most of its stored energy is released into the atmosphere as heat, and ultimately re-radiated into space. But a tiny fraction, about 200 000 TWh y^{-1}, reaches the Earth as rain or snow. Roughly one fifth of this precipitation falls on hills and mountains, descending ultimately to sea level as the world's streams and rivers. The 40 000 TWh y^{-1} of energy carried by this flowing water can be regarded as the world's **total hydro resource**.

It is obviously not possible – or desirable – to build hydro plants on every river or stream, so the usable fraction of this flow will be significantly lower, and, in 2017, the world's **technical hydro potential** is estimated to be about 16 000 TWh y^{-1}, or roughly two-fifths of the above total resource (WEC, 2010). This figure must be regarded as approximate, in part due to the different ways countries assess their resource. Some, for instance, include in their 'technical potential' only those sites that have been fully surveyed.

There remains one important question in the assessment of the realistic resource: 'How much hydroelectricity is available at a cost that is competitive with power from other sources?' In other words, what is the **economic potential** for hydroelectricity? The issues involved in financing hydro plants are discussed in Section 6.11, and Chapter 11 considers the relative costs of electricity from different sources; but the economic potential for any country or region must also take into account the social and environmental effects of dam construction and the likely flooding of large areas of land.

This obviously leaves many questions open, and we should not be surprised to find that estimates of the economic potential for hydropower in different countries and regions are generally regarded as much less reliable than the estimates of the total or technical potential. The following discussion of resources therefore considers only the *technical potential*, leaving the financial aspects to Section 6.11.

Regional resources

The first two columns of Table 6.3 show the estimated hydro technical potential for different regions of the world, together with their percentage share of the world's total.

Table 6.3 Regional and world hydro potential and generated output, 2016

	Technical potential		Output	
Region	**Technical potential / TWh y^{-1}**	**% of world technical potential**	**Annual output / TWh y^{-1}**	**Percentage of technical potential used**
North America	2420	15%	680	28%
South America	2840	18%	689	24%
Europe and Eurasia	2760	17%	892	32%
Middle East	280	1.7%	21	7%
Africa	1890	12%	114	6%
Asia Pacific	5820	36%	1627	28%
World	16 000		4023	25%

Sources: WEC, 2010; BP, 2017

The third and fourth columns show the extent to which the regions have actually developed their hydro potential.

Overall world hydro output in 2016 was a quarter of the technical potential, suggesting that a fourfold global increase in output might be possible in future. But there are marked regional differences. There would appear to be considerable scope for development in Africa. It has 12% of the world's total technical hydro potential, but only 6% of this has been developed. One major African scheme, Grand Inga, is described later in Section 6.12.

National resources

Table 6.4 shows data for the 13 countries whose hydro output in 2015 was greater than 50 TWh, together with three other European countries of interest. It is worth noting that several countries, for example Japan, Sweden, Italy and Switzerland, appear to have developed more than half their technical potential already; but, as pointed out above, some may limit their estimates of 'technical potential' to sites that have been studied in detail and possibly passed a full environmental assessment.

Table 6.4 National hydro potential and contributions, 2015

Country	Technical potential / TWh y^{-1}	Annual output / TWh y^{-1}	Installed capacity * / GW	Average capacity factor	Percentage of nation's electricity
China	2500	1115	296	43%	19%
Canada	830	378	79	55%	58%
Brazil	1250	360	92	45%	62%
USA	1340	247	79	36%	6%
Russia	1670	170	49	40%	16%
Norway	240	138	29	54%	95%
India	660	133	42	36%	10%
Japan	140	84	22	44%	8%
Venezuela	260	76	15	58%	59%
Sweden	130	75	16	54%	46%
Turkey	220	67	26	29%	26%
Vietnam	120	57	15	43%	36%
France	100	54	18	34%	9%
Italy	65	46	22	24%	16%
Switzerland	43	38	14	31%	54%
Austria	75	37	8	53%	57%

Note: * excluding pumped storage
Source: WEC, 2010; WEC, 2016; BP, 2017

The output from any hydroelectric plant will of course depend on the available flow of water, but the overall output for an individual country will also depend on the role played by hydroelectricity in the national power system. As Table 6.4 shows, the countries with the highest capacity factors tend to be those where hydropower makes a significant contribution, but where it is not the only major source of electricity – a situation that allows the relatively cheap hydropower to be used to its full potential, with an alternative source of electricity being used when hydropower cannot meet demand.

In general, if almost all of a nation's electricity comes from hydro plants, annual capacity factors are usually lower, because the installed capacity must be large enough to meet the maximum demand experienced during any day (or year). Conversely, it is interesting to note that countries with significant amounts of nuclear power, such as France and Switzerland, have low hydro capacity factors, a consequence of the use of hydroelectricity mainly for providing power at times of high demand.

Compared with the countries in Table 6.4, the hydro resource of the UK is small, only 14 TWh y^{-1}, and the installed capacity in 2015 was under 1.8 GW (BEIS, 2016a), mainly in Scotland. The annual output has varied in recent years between about 3.3 and 6.3 TWh – reflecting year-on-year weather variations throughout this relatively small area. In 2015, the average capacity factor was 40% and hydro supplied only 2% of the UK's electricity.

World output

In 1900, about two decades after the first commercial hydroelectric plants, world annual output had reached an estimated 3.7 TWh from an installed capacity of about 1.3 GW. Despite two world wars and the Great Depression of the 1930s, world hydro generation rose at a continuous annual rate of nearly 10% per year throughout the first half of the twentieth century. Figure 6.5 shows the trend since 1965, an average annual increase of about 60 TWh per year, which has been dominated since 2000 by hydro development in China. This has included the construction of two of the world's largest hydro schemes, the 22.5 GW Three Gorges Dam (described later) and the 13.9 GW Xiluodo Dam.

Total world hydro generation in 2016 was about 4000 TWh and the estimated total installed generation capacity at the end of that year was nearly 1100 GW (REN21, 2017).

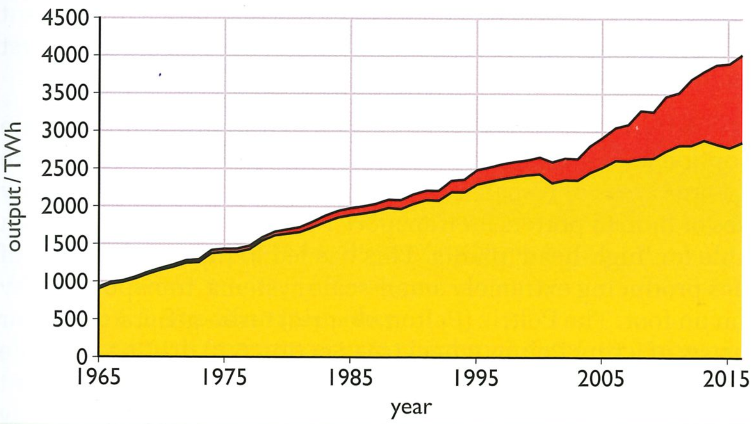


Figure 6.5 World annual hydroelectricity output, 1965–2016 (source: BP, 2017)

The noticeable drop in world output in 2001 was attributed mainly to exceptionally dry conditions in the Americas, the source of about a third of world output.

6.4 Small-scale hydro (SSH)

In the early days of electric power, generators with output ratings between a few kilowatts and a few megawatts were installed on streams or rivers, often using the dams and sluices of old watermills. As late as the mid-twentieth century, many towns in Europe and elsewhere were still served by hydro or other plants in the upper part of this range. However, with continually rising demand for electricity, and the growth of national transmission networks, capacities of several hundred megawatts have become the norm for modern power stations, and plant outputs below about 10 MW are now referred to as **small-scale**. However, this cut-off point is not universally accepted. The figure in the UK is only 5 MW. In 2015 small-scale systems supplied about 15% of the UK's hydro output (BEIS, 2016a). Other countries use higher capacity ratings, for example 25 MW in India, 30 MW in Brazil, 50 MW in Canada and China, and up to 100 MW in the USA (IPCC, 2012). A 'small' hydro scheme could thus include a plant capable of powering a small city.

The term **micro-hydro** is commonly used for plants with capacities below 100 kW and the term **pico** appears occasionally for very small plants; but again there is a lack of agreement between countries on these definitions.

The past few decades have seen growing interest in smaller power plants, for several reasons. In the industrialized countries, environmental issues have increasingly limited the potential for further major hydro development, whilst small-scale schemes (such as the Elan Valley scheme described in Box 6.2), are considered to produce fewer deleterious effects, and have received growing encouragement and financial incentives.

More recently, a market has begun to emerge for micro-hydro plants, generating a few tens of kilowatts for an isolated house or farm.

Small-scale hydro is currently more costly than electricity from large hydro or other conventional sources and in many European countries investment in electricity from renewables during the first decade of the twenty-first century has concentrated on wind and solar PV.

In an entirely different context, small-scale plants are a practicable independent option for electricity in developing countries without extensive grid systems. Large areas of Nepal, for instance, have no electricity supply and only mules or human porters for transport, but do have many mountain streams suitable for 'high-head' plants. This has led to the development of local industries producing extremely small-scale systems, transportable by a single person on foot. The Peltric (Pelton electric) turbo-generator set, for example, consists of a tiny Pelton wheel (see Section 6.8) driving a simple generator. Operating under heads of 50–70 metres, it produces a kilowatt or so of output. With cheap and relatively simple 'civil works', these tiny systems have proved sufficiently popular to be copied in other countries.

BOX 6.2 Elan Valley

The Elan Valley scheme in the Cambrian Mountains in mid-Wales (Figure 6.6) was financed in 1997 under the UK's Non-Fossil Fuel Obligation (NFFO) low carbon electricity incentive scheme. It supported the development of five power stations. Like the Galloway Hydros they are in sequence along two rivers; but these plants use the dams and reservoirs of an existing drinking water-supply system – and their total output capacity is only 4.2 MW.

Table 6.5 gives some details and the contribution from Foel Tower on the Garreg Ddu reservoir is worth noting: its Kaplan turbine (see Section 6.8) sits inside one of the 14 metre diameter pipes supplying water to the city of Birmingham.

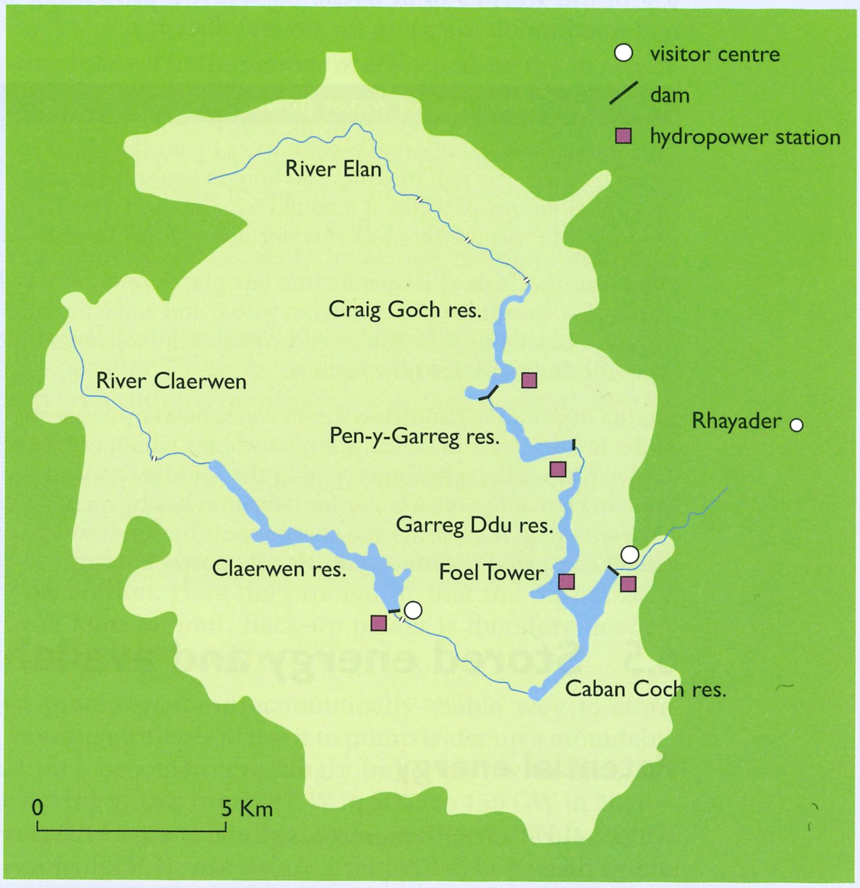


Figure 6.6 The Elan Valley hydro scheme

Table 6.5 The Elan Valley plants

Site	Craig Goch	Pen-y Garreg	Caban Coch	Foel Tower	Claerwen
Head / m	36.5	37.5	37	13.5	56
Capacity / kW	480	810	950	300	1680
Turbine	Francis	Francis	2 × Francis	Kaplan	Francis

All the reservoirs and dams date from the early twentieth century – the latter are listed historic monuments. Caban Coch was already a hydro plant. One of its old turbines was replaced some time ago and the other as part of the NFFO scheme. In a region of great natural beauty and with 90% of its area designated as Sites of Special Scientific Interest, the four new plants have required careful siting. To meet environmental constraints, their turbines make use of existing discharge pipes and their associated buildings are mainly below ground (Elan Valley Trust, n.d.).

It is generally agreed that world output from small-scale hydro plants is rising; but because many countries do not report their statistics separately it is impossible to estimate either the total output or the installed capacity with any reasonable precision. A World Energy Council survey in 2010 (WEC, 2010) suggests that the global total small-scale capacity (<10 MW) at the end of the 2009 was about 60 GW (including an estimated 33 MW from those plants in China that meet the <10 MW criterion). This is about

6% of the world's total hydro capacity, a proportion that seems to have remained much the same for several decades.

BOX 6.3 Direct uses of water power

Although the generation of electricity is by far the major use of water power today, other uses still remain. The kinetic energy of moving water (or the potential energy of water at a height) can be used directly to drive machines – indeed this was the sole use of water power until the mid-nineteenth century.

Old watermills do still operate in a few places in today's industrialized countries, grinding corn or sawing wood; and some mountain railways use a counter-balancing tank filled with water at the top and emptied at the foot of the hill. But these are now rarities.

In the developing countries, direct water power plays a slightly greater role. In Nepal, for instance, simple turbines which can be produced locally are used to drive machinery, and in the Middle East and Asia the use of a flowing stream to raise water for irrigation has by no means disappeared. Nevertheless, the worldwide energy contribution from direct use is negligibly small compared with the hydroelectric power output.

6.5 Stored energy and available power

Potential energy

Water held at a height represents stored energy – the gravitational potential energy discussed in Chapter 1. As we saw, if M kilograms are raised through H metres, the stored potential energy in joules is given by the following simple equation:

$$\text{potential energy (joules)} = M\,(\text{kg}) \times \text{g} \times H\,(\text{m})$$

where g here is the acceleration due to gravity (about 9.81 m s^{-2}, although for rough calculations, 10 m s^{-2} is often used). Thus about 10 joules of energy input are needed to lift one kilogram of anything vertically through one metre against the gravitational pull of the Earth.

However, here we are concerned with large reservoirs, whose capacities are almost always given in *cubic metres*, rather than kilograms. The necessary conversion is simple, because one cubic metre of fresh water has a mass of 998 kg, which is so close to 1000 kg that the tiny difference is not significant in most calculations. We can therefore say that, within this degree of precision, the energy stored by a volume of V cubic metres of water raised through a height H is:

$$\text{stored energy (joules)} = 1000 \times V \times \text{g} \times H \qquad (1)$$

and this is therefore the energy that will be released when this volume of water *falls* through a vertical distance H.

The joule is a very small unit of energy. A more familiar unit of energy is the kilowatt-hour which is 3.6 MJ. Storing 1 kWh requires raising 1 cubic metre of water through a height of 360 metres. This is perhaps quite a sobering view of the amount of energy required to run a one bar electric fire for an hour.

Pumped storage

There has been growing interest in the *storage* of electrical energy in recent decades. One major reason for this that has been steadily emerging since the 1960s has been the growth in the size of power plants, both fossil and nuclear, which can now easily exceed 500 MW output. A failure of a turbine, or an electrical fault, could mean that this amount of generating capacity could suddenly disappear from the grid. It might take an hour or more for other conventional power plants to 'ramp up' their generation to provide extra power.

Similar problems can result from the synchronization of consumer electrical demand. The end of a popular TV show or football match can produce a rapid 'demand pickup' of hundreds of megawatts as thousands of electric kettles are turned on.

The need to provide rapid short-term back-up for a period of several hours is thus vital to prevent power cuts.

The second reason is the increasing use of renewables such as PV and wind for electricity generation. Here the problem is that the output may vary considerably from hour to hour. Back-up power is therefore needed which can be brought on stream quickly.

At present the most practicable and economically viable way to store electrical energy in large quantities is to use it to pump water up a mountain. Pumped storage has thus become increasingly important, with installed capacity worldwide having grown from 78 GW in 2005 to 150 GW in 2016 – equivalent to one seventh of the world's total hydro capacity (REN21, 2017).

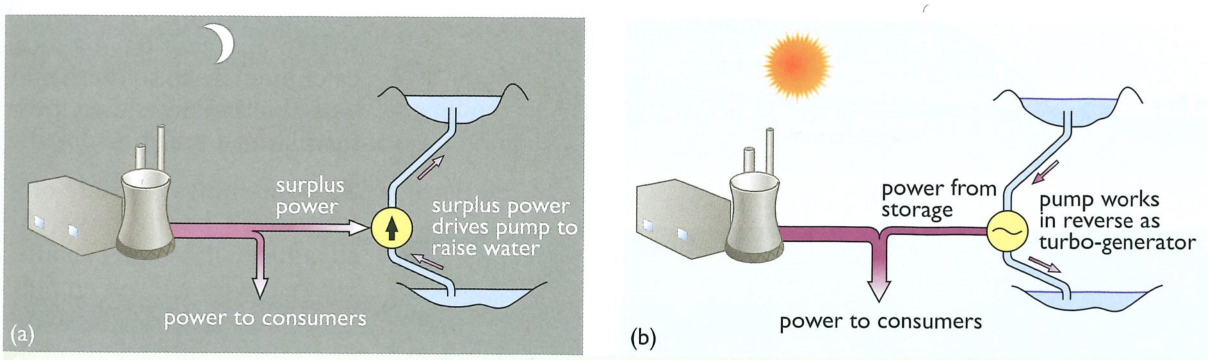


Figure 6.7 Pumped storage system: (a) at time of low demand, (b) at time of high demand

The principle is simple. Electrical energy is converted into gravitational potential energy when the water is pumped from a lower reservoir to an upper one, and the process is reversed when it is released to run back down, driving a turbo-generator on the way (Figure 6.7). The economic viability of the method depends on two nice technological facts.

- A suitably designed generator can be run 'backwards' as an electric motor: the machine which converts mechanical energy into electrical energy can perform the reverse process.
- A suitably designed turbine (Section 6.8) can also run in both directions, either extracting energy *from* the water as a turbine or delivering energy *to* the water as a pump.

The complete reversal is thus **turbo-generator** to **electric pump**. The machines must of course be designed for this dual role, but the cost saving is obviously significant.

There will, as always, be losses associated with the conversion processes, but turbines and generators are very efficient, and nearly 80% of the input electrical energy can be retrieved as electrical output when needed. The value of the system is enhanced by its speed of response: any of the six 300 MW Francis turbines of the Dinorwig storage plant in Wales (commissioned in 1984) can be brought to full power in just 12 seconds if initially spinning in air, and even from complete standstill the process takes only a few minutes (Dinorwig, n.d.). Pumped storage is thus particularly useful as back-up in case of sudden changes in generation or demand, or a failure elsewhere in a grid system.

The location must of course be suitable. A low-level reservoir of at least the capacity of the upper one must be available, or must be constructed. Sites such as Cruachan in Scotland (Figure 6.8), where the mountains rise from a large loch or lake, are obviously ideal. The high-level reservoir, behind a large dam, provides an operating head of 365 metres. Running the four 100 MW reversible machines for 20 hours at full capacity, as electric pumps or turbo-generators, raises or lowers the reservoir level by about 15 metres, storing or releasing about 8 million kilowatt-hours of energy (Cruachan, 2017).

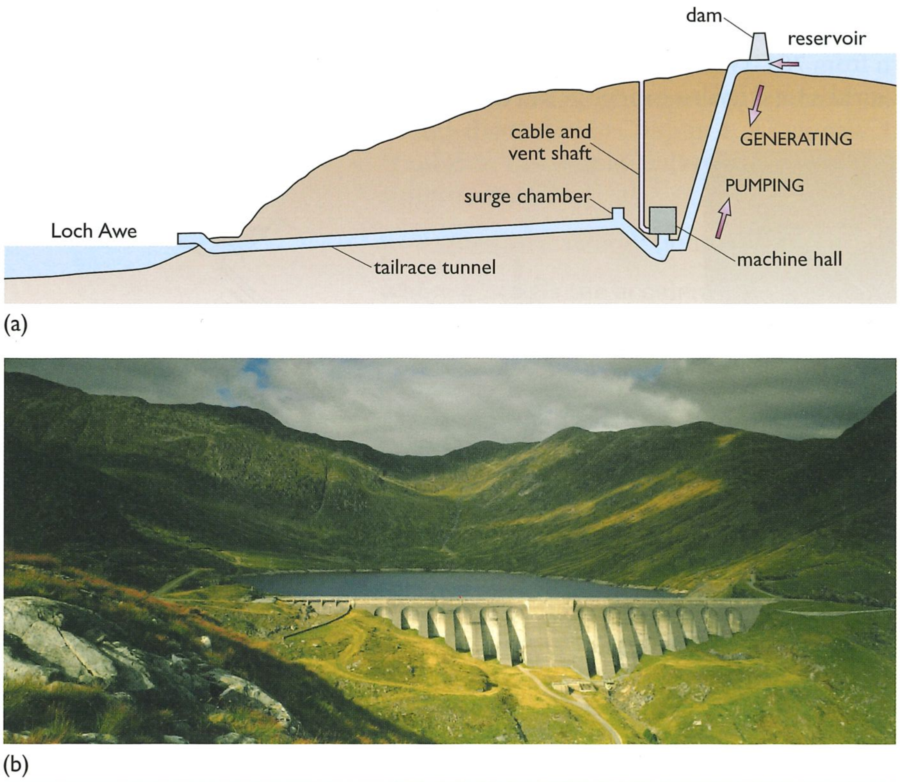


Figure 6.8 Cruachan pumped storage plant, commissioned between 1965 and 1967 (a) the installation, (b) the dam

Pumped storage can be combined with 'normal' hydroelectric generation in locations where the potential exists. The upper reservoir will in any case have a local catchment area, so there may be a positive net output from the plant.

There are however trade-offs. Very high heads have the advantage of needing smaller reservoirs for a given amount of stored energy, but the types of turbine most suited to high heads (see Section 6.8) cannot be run 'backwards' as pumps. At the other extreme, very low heads need much greater volumes of stored water, but the switch from pumping to generating may be achieved simply by reversing the pitch of the propeller-type Kaplan turbines used in such circumstances.

Power, head and flow rate

In estimating the value of any proposed hydroelectric plant, the *power* available at any time is probably the most important factor. The power supplied by a plant, the number of *watts*, is the rate at which it delivers energy: the *number of joules per second*. This will obviously depend on the **volume flow rate** of the moving water. Note that this is not just the speed of the water; it is the number of *cubic metres per second* passing through the plant, usually represented by the symbol Q (think quantity). It then follows from Equation (1) above that the power P (in joules per second or watts), will be

$$P \text{ (watts)} = 1000 \times Q \text{ (m}^3\text{ s}^{-1}) \times g \times H \text{ (m)} \qquad (2)$$

However, resource estimates must take into account energy losses. In any real system the water falling through a pipe will lose some energy due to frictional drag and turbulence, and the **effective head** will thus be less than the actual, or **gross head**. These flow losses vary greatly from system to system: in some cases the effective head is no more than 75% of the actual height difference, in others as much as 95%. Then there are energy losses in the plant itself. Under optimum conditions, a hydroelectric turbo-generator is extremely efficient, converting all but a few per cent of the input power into electrical output. Nevertheless, the **efficiency** – the ratio of the output power to the input power, usually expressed as a percentage – is always less than 100%. With these factors incorporated, the output power becomes:

$$P = 1000 \times \eta \times Q \times g \times H \qquad (3)$$

where H is now the effective head and η (Greek letter eta) is the turbo-generator efficiency. (Note that although efficiency is often quoted as a percentage, in an equation like this it will be a number between 0 and 1. For example, 85% becomes 0.85.)

If we now express P in kilowatts, and use the approximation $g = 10 \text{ m s}^{-2}$, we obtain a very useful, simple expression:

$$P \text{ (kW)} = 10 \times \eta \times Q \text{ (m}^3\text{ s}^{-1}) \times H \text{ (m)} \qquad (4)$$

Box 6.4 shows how this can be used for rough calculations of power output.

BOX 6.4 Available power

As examples of power calculations, we can consider two systems, each with a plant efficiency of 83%, but of very different sizes.

The first site is a mountain stream with an effective head of 25 metres and a modest flow rate of 600 litres a minute, which is 0.010 cubic metres per second. Using Equation (4), we find that the power output will be

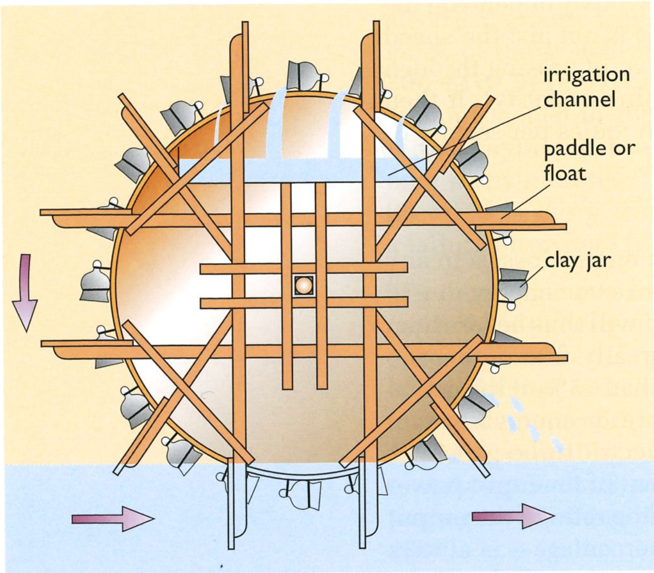
$$P = 10 \times 83\% \times 0.010 \times 25 = 2.075 \text{ kW}$$

In contrast, suppose that the effective head is 100 m and the flow rate is 6000 cubic metres per second – roughly the total flow over Niagara Falls. The power is now

$$P = 10 \times 83\% \times 6000 \times 100 = 4.98 \text{ million kWh, or nearly 5 GW}$$

6.6 A brief history of water power

The prime mover



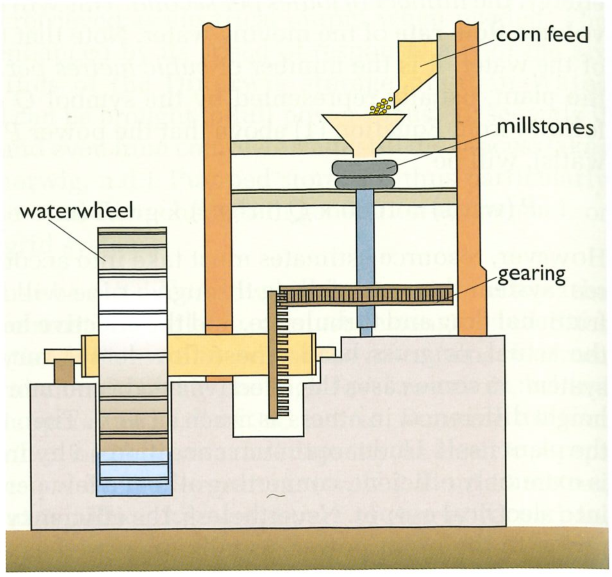


Figure 6.9 (a) A noria – in this earliest waterwheel the paddles dip into the flowing stream and the rotating wheel lifts a series of jars, raising water for irrigation, (b) A Roman mill – this corn mill with its horizontal-axis wheel was described by Vitruvius in the first century BC (note the use of gears)

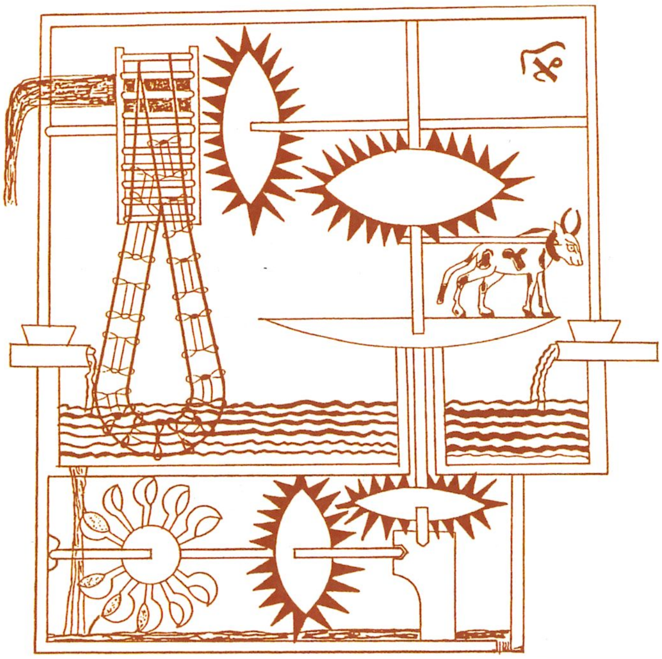


Figure 6.10 Medieval saqiya. The diagram comes from the Book of Knowledge of Ingenious Mechanical Devices of al-Jahazi, written in Mesopotamia 700 years ago. (The ox is a wooden cut-out designed to fool the public, who can't see the hidden waterwheel and gears below.)

Moving water was one of the earliest energy sources to be harnessed to reduce the workload of people and animals. No one knows exactly when the waterwheel was invented, but irrigation systems existed at least 5000 years ago and it seems probable that the earliest water power device was the *noria*, used to raise water for this purpose (Figure 6.9(a)). It appears to have evolved over a long period from about 600 BC, perhaps independently in different regions of the Middle and Far East (Strandh, 1989).

The earliest **watermills** were probably corn mills, which seemed to appear during the first or second century BC in the Middle East, and a few centuries later in Scandinavia. In the following centuries, increasingly sophisticated watermills were built throughout the Roman Empire and beyond its boundaries in the Middle East and Europe (Figures 6.9(b) and 6.10). In England, the Saxons are thought to have used both horizontal- and vertical-axis wheels. The first documented mill was in the eighth century, but three centuries later the Domesday Book of

1086 AD recorded about 5000, suggesting that every settlement of any size had a mill.

Raising water and grinding corn were by no means the only uses of the watermill, and during the following centuries the applications of this power source kept pace with the developing technologies of mining, iron working, paper-making, and the wool and cotton industries. Water was the main source of mechanical power, and by the end of the seventeenth century England alone is thought to have had some 20 000 working mills.

There was much debate on the relative efficiencies of different types of waterwheels (Figure 6.11), and the period from about 1650 until 1800 saw some excellent scientific and technical investigations of various designs. These revealed output powers ranging from about one horsepower to perhaps 60 for the largest wheels (in modern terms roughly 1–50 kW) with overshot wheels being in principle the most efficient. They also confirmed that for maximum efficiency the water should pass across the blades as smoothly as possible and fall away with minimal speed, having given up almost all its kinetic energy: two features that were to be important in modern turbines.

But then steam power entered the scene, putting the whole future of water power in doubt.

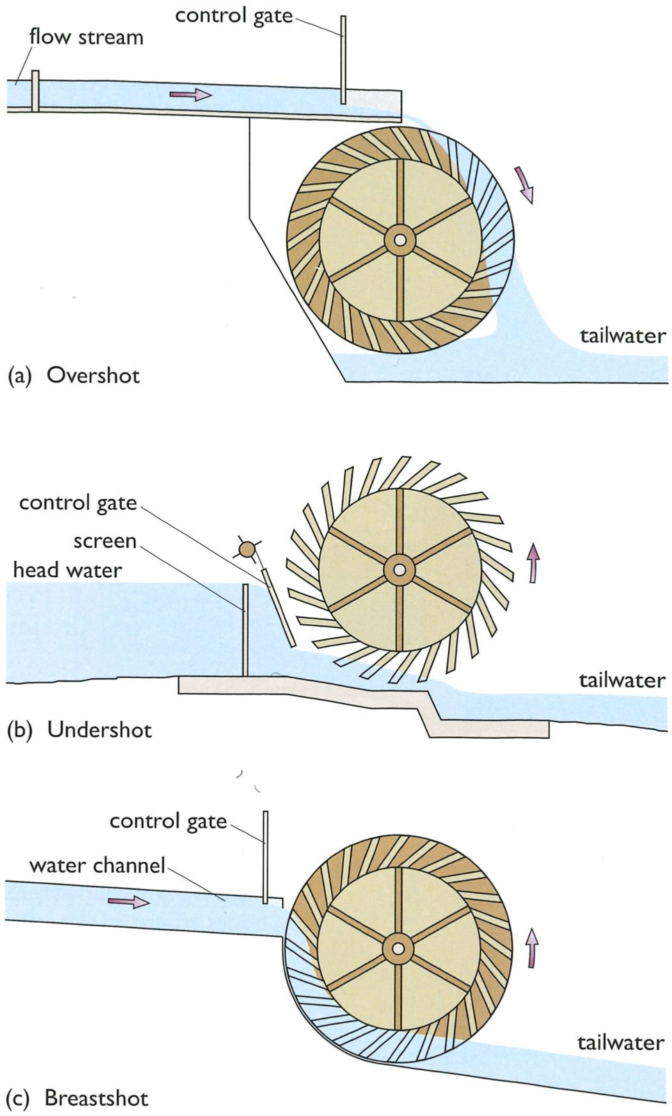


Figure 6.11 Types of waterwheel (a) Overshot – water falls onto blades with closed sides, (b) Undershot – driven by water pressure against lower blades, (c) Breastshot – water strikes paddles at about the level of the wheel axle

Nineteenth-century hydro technology

An energy analyst writing in the year 1800 would have painted a very pessimistic picture of the future for water power. The coal-fired steam engine was taking over and the waterwheel was fast becoming obsolete. However, like many later experts, this one would have been suffering from an inability to foresee the future. A century later the picture was completely different: the world now had an electrical industry and a quarter of its generating capacity was water powered.

The growth of the electric power industry was the result of a remarkable series of scientific discoveries and developments in electro-technology during the nineteenth century, but significant changes in what we might now call *hydro technology* also played their part. In 1832, the year of Faraday's discovery of the principle of the electric generator, a young French engineer, Benoît Fourneyron, patented a new and more efficient waterwheel: the first successful water **turbine**. (The name, from the Latin *turbo*: something that spins, was coined by Claude Burdin, one of Fourneyron's teachers.) The traditional waterwheel, essentially unaltered for nearly two thousand years, had finally been superseded.

Fourneyron's turbine (Figure 6.12) incorporated many new features. It was a vertical-axis machine, itself something of a novelty. But the important innovations were that the turbine ran *completely submerged* and that the water entered the turbine vertically, *along the axis*, and was directed outwards by **guide vanes** fixed on to the *blades* mounted on the *runner*, which was free to rotate. These are the features that ensured the smooth flow of water, which is essential for high efficiency. The water entering at the centre travelled horizontally outwards almost parallel to the faces of the runner blades as it reached them. Deflected as it crosses the faces, it exerted a sideways pressure that transmitted energy to the runner. Having given up its energy, it then falls away into the outflow.

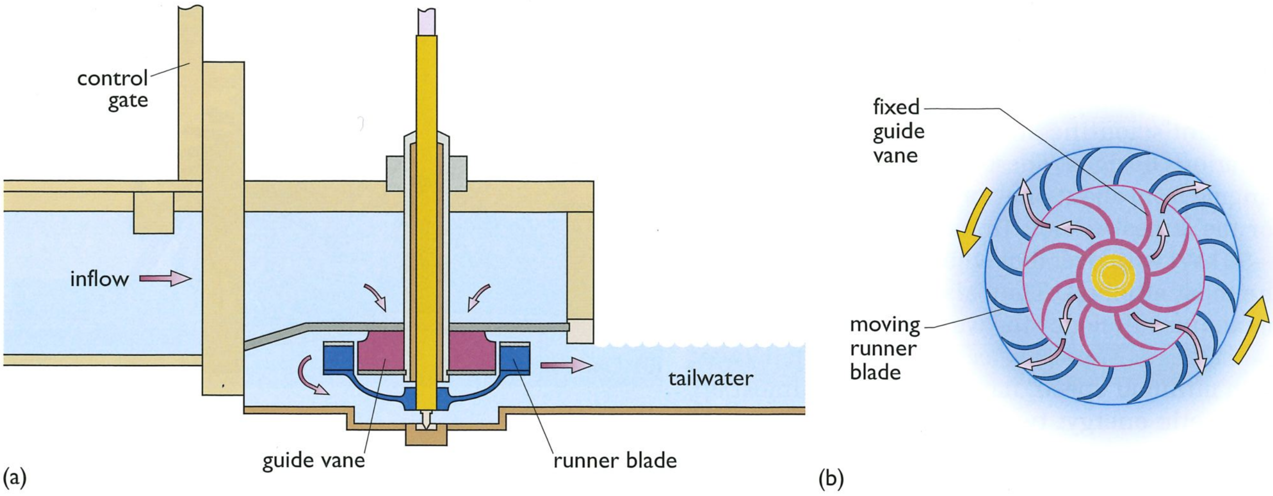


Figure 6.12 Fourneyron's turbine – the runner consists of a circular plate with curved blades around its rim and a central shaft (a) vertical section, (b) the flow across guide vanes and runner blades

Tests showed that Fourneyron's turbine converted as much as 80% of the energy of the water into useful mechanical output – an efficiency previously equalled only by the best overshot wheels. The rotor could also spin much faster, an advantage in driving 'modern' machines. The first pair of these turbines to come into use were installed in 1837 in the small town of St Blasien in the Grand Duchy of Baden (now part of southern Germany). Development did not stop there, and within a few years the American engineer James Francis started his experiments on *inward-flow radial* turbines which ultimately led to the modern machines known by his name (see Section 6.8).

These turbines were of course used to provide *mechanical* power. Half a century of development was needed before Faraday's discoveries were translated into a major electrical industry. In 1878 Lord Armstrong, a wealthy Victorian engineer and inventor, installed one of the first 'hydro-electric' plants to provide electric lighting in 'Cragside', his house in the north of England (National Trust, 2017). This house has now been re-equipped with a modern Archimedes Screw generator (see Section 6.8).

About three years later and 300 miles south, the small town of Godalming opened the world's first public electricity supply, powered by the

River Wey. Unfortunately, the water source proved unreliable and the waterwheel was soon replaced by a steam engine. Credit for the first *successful* public hydroelectricity scheme therefore usually goes to a little 12 kW plant on the Fox River in Wisconsin, USA, providing lighting for local paper mills from 1882.

From these primitive beginnings, the electrical industry grew during the final decades of the nineteenth century at a rate far exceeding that of any earlier technology. The capacities of individual power stations, including many hydro plants, were also rising, increasing tenfold, from about 100 kW to over 1 MW, during the 1890s. This growth was to continue. As described in Section 6.3 world total hydro output rose over a thousand-fold from 3.7 TWh in 1900 to over 4000 TWh in 2016. Over the same period, the outputs of the largest turbo-generators rose to over 780 MW. Of these, 18 have been deployed in the Xiluodu dam in western China, giving a total capacity of nearly 14 GW (Daily Fusion, 2013).

It is interesting to note, however, that not only the modes of operation but the main components of today's enormous turbo-generators (and today's small- or micro-hydro plants) are very similar to those of their much smaller precursors of over a hundred years ago. These components, mainly the turbines, are the subject of the next section.

6.7 Types of hydroelectric plant

Present-day hydroelectric installations range in capacity from a few hundred watts to more than 20 GW – a factor of some hundred million between the smallest and the largest output. We can classify installations in different ways:

- by the effective head of water
- by the capacity – the rated power output
- by the type of turbine used
- by the location and type of dam, reservoir, etc.

These categories are not of course independent of one another. The available head is an important determinant of the other factors, and the head and capacity together largely determine the type of plant and installation. We start therefore with the customary classification in terms of head, but shall soon see that it is really the fourth criterion that matters.

Low, medium and high heads

Two hydroelectric plants with the same power output could be very different: one using the huge volume flow of a slowly moving river and the other a relatively low volume of high-speed water from a mountain reservoir. Sites, and the corresponding hydroelectric installations, can be classified as *low*, *medium* or *high* head. The boundaries are fuzzy, and tend to depend on whether the subject of discussion is the civil engineering work or the choice of turbine; but **high head** usually implies an effective head of appreciably more than 100 metres and **low head** less than perhaps ten metres. Figure 6.13 shows the main features of the three types.

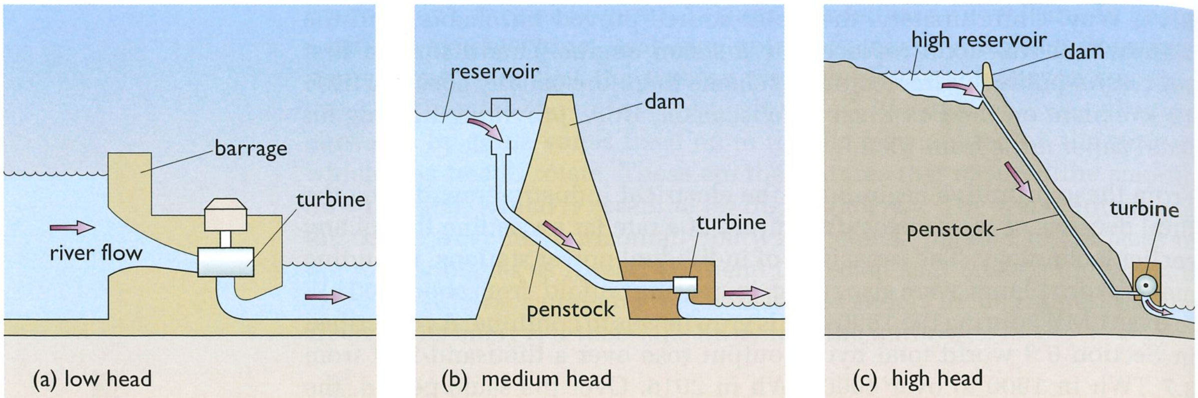


Figure 6.13 Types of hydroelectric installation

The low dam or barrier of the installation in Figure 6.13(a) serves to maintain a head of water and also houses the plant. It may incorporate locks for ships (or as we have seen above, a fish-ladder for salmon). '*Run-of-river*' power stations of this type, having relatively little storage capacity, are dependent on the prevailing flow rate and can present problems of reliability if the flow varies greatly with the time of year or the weather. The large volume flow through a low-head plant means that the plant and the associated civil engineering works are likely to be massive, which means high capital cost, although this may be ameliorated where there is a second function such as flood control or irrigation.

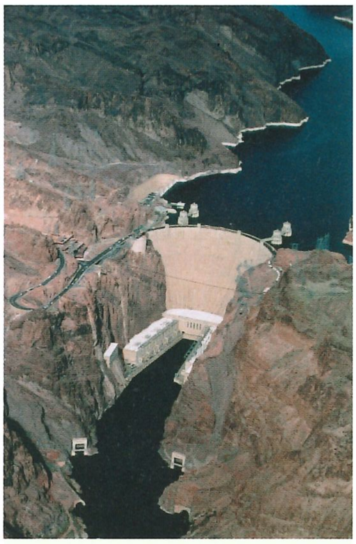


Figure 6.14 The Hoover Dam, 1936. This dam on the Colorado River (originally called the Boulder Dam) is 220 metres high and its reservoir, Lake Mead, holds 35 billion cubic metres of water. The 2.1 GW power plant is at the foot of the dam.

The plant in Figures 6.13(b) and 6.14 is typical of the very large hydroelectric installations with a dam at a narrow point in a river valley. The large reservoir behind the dam provides sufficient storage to meet demand in all but exceptionally dry conditions. (It will also have flooded an extensive area and may not have been entirely welcomed by the population (see Section 6.10).) The USA has some of the world's largest dams of this type, including the Grand Coolee (170 m high), which when completed in 1942 had the distinction of being the first artificial bulk structure with a volume greater than the Great Pyramid! On this scale, the civil engineering costs are obviously considerable, but the large reservoir normally ensures a reliable supply. Systems of this type don't of course have to be on a gigantic scale, and quite small reservoirs can provide power for a hydroelectric plant located below their dams.

To call the 220 metre head of the Hoover Dam 'medium' may seem rather surprising, but it illustrates the fact that the distinction between this and high-head systems lies more in the type of installation. Figure 6.13(c) shows the difference. In the high-head plant the entire reservoir is well above the outflow, and the water flows through a long **penstock** – possibly passing through a mountain – to reach the turbine. (The penstock was originally the wooden gate or 'stock' which controlled the flow of 'penned-up' water. It later came to mean the channel, or the pipe, carrying the flow.)

With a high head, the flow needed for a given power is much smaller than for a low-head plant, so the turbines, generators and housing are more compact. But the long penstock adds to the cost, and the structure must be able to withstand the extremely high pressures below the great depth of water – as much as 100 atmospheres for a 1000 metre head (Box 6.5).

BOX 6.5 Height, depth and pressure

The pressure in a liquid (or gas) is the force with which it presses on each square metre of surface of anything submerged in it.

Atmospheric pressure, due to the weight of the air above us, is equivalent at sea level to the weight of a 10 tonne mass acting on each square metre of any surface. As you move up through the atmosphere, the pressure decreases, initially by about 1% per 100 metres vertically.

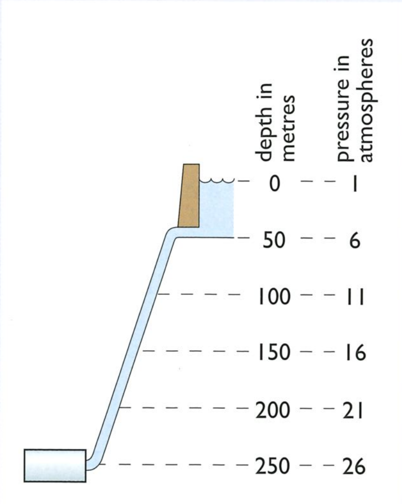


Figure 6.15 Depth and water pressure

As you move down through any body of water, the pressure increases due to the increasing weight of water above. Since water is several hundred times denser than air, the change is much more noticeable – at a depth of about 10 metres the pressure is twice that at the surface: a pressure of two atmospheres. This increase of about one atmosphere per 10 metres continues as the depth becomes greater (Figure 6.15).

Rates of rotation

The **rate of rotation** of a turbine is the number of completed revolutions per minute (rpm), and, as we saw for the Galloway plants in Table 6.2, this can vary appreciably depending on the site and the turbine type. However, if the turbine drives the generator directly, only certain rates of rotation are permitted, for the following reason.

The alternating voltages from all the power stations contributing to any grid system must have the same frequency. In European countries and many others, the agreed frequency is 50 Hz (hertz, or cycles per second).

So in a very simple generator, consisting of a magnet and a pair of coils, the magnet (or the coils) would need to spin at 50 Hz, that is 50 cycles per second, which is $50 \times 60 = 3000$ rpm. In the usual terminology, this simple system would be called a **two-pole generator.**

A large power-station generator will have more than one pair of coils on its spinning rotor (see Figures 6.16 and 6.22). A 20-pole machine, for instance, would need to rotate at only 300 rpm, a tenth of the above rate, to produce the required 50 Hz. A little arithmetic reveals that all the rates of rotation shown earlier in Table 6.2 are sub-multiples of 3000 rpm.

Note however that in the USA and other countries where the supply frequency is 60 Hz, the rates of rotation are sub-multiples of 3600 rpm. (Generators are discussed in more detail in Chapter 9, *Electricity*, of Everett et al., 2012.)

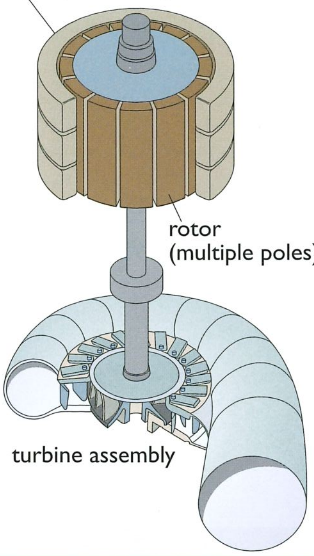


Figure 6.16 Multi-pole generator in a hydro power plant

Estimating the power

Reliable data on flow rates and, equally important, their variations, is essential for the assessment of the potential capacity of a site. Stopping the flow and catching the water for a measured time is hardly practicable for large flows or as a routine method. The preferred techniques depend on establishing empirical relationships between flow rate and either water depth or water speed at chosen points. Simple depth or speed monitoring then provides a record of flow rates. For many major rivers, particularly in developed countries, such data has been accumulated for years.

Where such records are not available, an entirely different approach is to determine the annual precipitation over the catchment area. This gives the total flow into the system and is particularly suitable for large systems. However, allowance must be made for losses due to processes such as re-evaporation, take-up by vegetation or leakage into the ground, and as these could account for as much as three-quarters of the original total they are hardly negligible corrections.

Dealing with time variations adds further problems. In most areas there will be seasonal changes, but these at least come at known times. The more serious problems are with changes over very long or very short periods. Year-to-year variations can be large: the average annual precipitation on the catchment area of the River Severn in the UK, for instance, is 900 mm but it can range from as little as 600 mm to as much as 1200 mm. For countries which depend heavily on hydroelectric power a succession of dry years can mean a serious supply shortage.

At the other extreme, the installation must be designed to survive the '100-year flood', the sudden rush of water following unusually heavy rain. As in any power system, the need to guard against rare but potentially catastrophic events adds to the cost.

6.8 Types of turbine

Present-day turbines come in a variety of shapes (Figure 6.17). They also vary considerably in size, with runner diameters ranging from as little as a third of a metre to some 20 times this. In the next four subsections we look at how they work, the factors that determine their efficiency, and the site parameters that determine the most suitable turbine.

Francis turbines

Francis turbines (Figures 6.17 to 6.20) are by far the most common type in present-day medium- or large-scale plants, being used in locations where the head may be as low as 2 m or as high as 200 m. They are radial-flow turbines, and although the water flow is inwards towards the centre instead of the outward flow of Fourneyron's turbine, the principle remains the same.

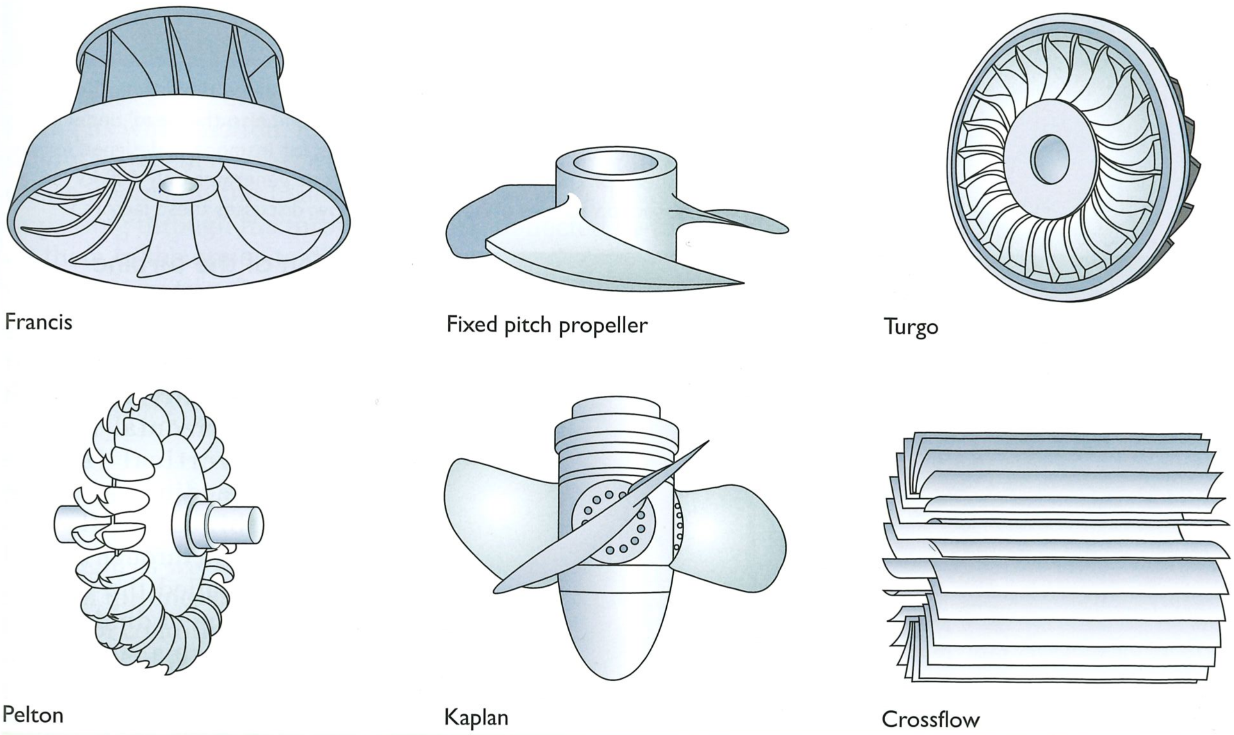


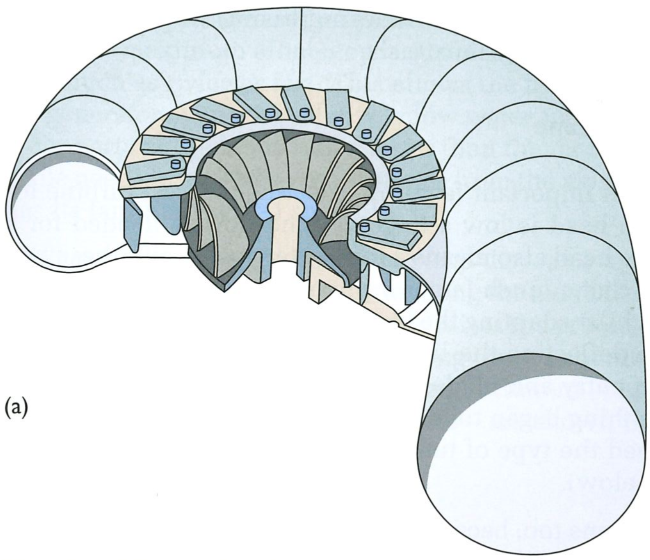
Figure 6.17 Types of turbine runner

Figure 6.18 The photograph shows six Francis runners and behind them three Turgo runners. The different sizes and shapes reflect their outputs and also the 'head' under which each will operate. The largest of the Francis turbines, for instance, is designed for an output of 10 MW at a head of 280 m, whilst the smallest one generates only 600 kW at a head of 80 m. (The subsection Ranges of Application, below, discusses these factors.)

Figure 6.19 The 450 kW horizontal-axis Francis turbine of a small-scale plant in Scotland, commissioned in 1993. The inflow (at lower right) is 2.1 $m^3 s^{-1}$ at a head of 25 m. Part of the generator casing can be seen on the left and the adjustment mechanism for the guide vanes is also visible.

Action of the turbine

As the Francis turbine is completely submerged, it can run equally well with its axis horizontal (Figure 6.19) or vertical (Figure 6.20). In medium- or high-head turbines the flow is channelled in through a scroll case (also called the volute), a curved tube of diminishing size rather like a snail shell, with the guide vanes set in its inner surface. Directed by the guide vanes, the water flows in towards the runner. The shapes of the guide vanes and runner blades and the speed of the water are critical in producing the smooth flow that leads to high efficiency (see below). Francis turbines run most efficiently when the blade speed is only slightly less than the speed of the water meeting them.



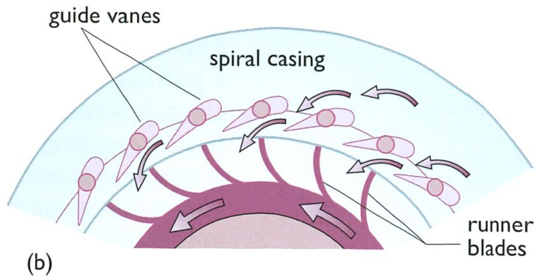


Figure 6.20 Structure of a Francis turbine, showing the central runner blades, the pivoting guide vanes and the surrounding volute

As it crosses the curved runner blades the water is deflected sideways, losing its whirl motion. It is also deflected into the axis direction, so that it finally flows out along the central draft tube to the tail race. That the water exerts a force on the blades is obvious because it has changed direction in passing through the turbine. In being deflected by the blades, it pushes on them in the opposite direction – the way they are travelling – and this reaction force transfers energy to the runner and maintains the rotation. For this reason, these are called **reaction turbines**. An important feature of this type is that the water arrives at the runner under pressure, and the pressure drop through the turbine accounts for a large part of the delivered energy.

Maximizing the efficiency

Although, as we saw above in Section 6.5, there are always energy losses, modern turbines can achieve efficiencies as high as 95% – but only under optimum conditions. Maintaining exactly the right speed and direction of the incoming water relative to the runner blades is important, and this leads to a problem. Suppose demand falls: the output power can be reduced by reducing the water flow, and in a Francis turbine this is done by turning the guide vanes; but this changes the angle at which the water hits the moving blades and the efficiency falls. This is a characteristic which must be accepted with this type of turbine. (As we'll see below, some 'propeller' types allow adjustment of the pitch, changing the angle of the blades to match the new conditions.)

A rather different cause of less than 100% efficiency is that the water flowing out carries away kinetic energy. A partial remedy is to flare the draft tube. If the tube becomes larger but the volume flow stays the same, the actual speed of the water must decrease, reducing the energy loss. It may seem strange that this change *after* the water has left the turbine makes any difference to its efficiency, but the effect of the deceleration is to reduce the pressure back at the exit from the turbine, increasing the pressure drop across it and therefore the energy it extracts.

Limits to the Francis turbine

The available head is an important factor in selecting the best turbine for a particular site. If the head is low a large volume flow is needed for a given power. But a low head also means a low water speed, and these two factors together mean that a much larger input area is required. Attempts to increase this area whilst adapting the blades to the reduced water speed and at the same time deflecting the large volume into the draft tube led to turbines with wide entry and blades which were increasingly twisted. Ultimately the whole thing began to look remarkably like a propeller in a tube, and this is indeed the type of turbine now commonly used in low-head situations (see below).

High heads bring problems too, because they mean high water speeds. As mentioned above, Francis turbines are most efficient when the blades are moving nearly as fast as the water, so high heads imply high speeds of rotation. A look at Tables 6.1 and 6.2 in Section 6.2 reveals that the turbine at Glenlee, with its much higher head, rotates at up to twice the speed of the other Francis turbines in the Galloway system. For sites with very high heads, the Francis turbine becomes unsuitable, and yet another type takes over, as we shall see.

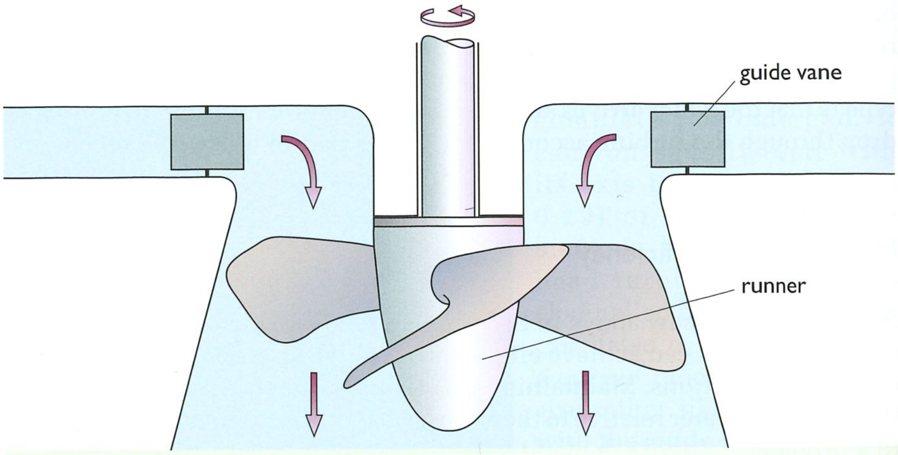


Figure 6.21 A 'propeller' or axial-flow turbine

'Propellers'

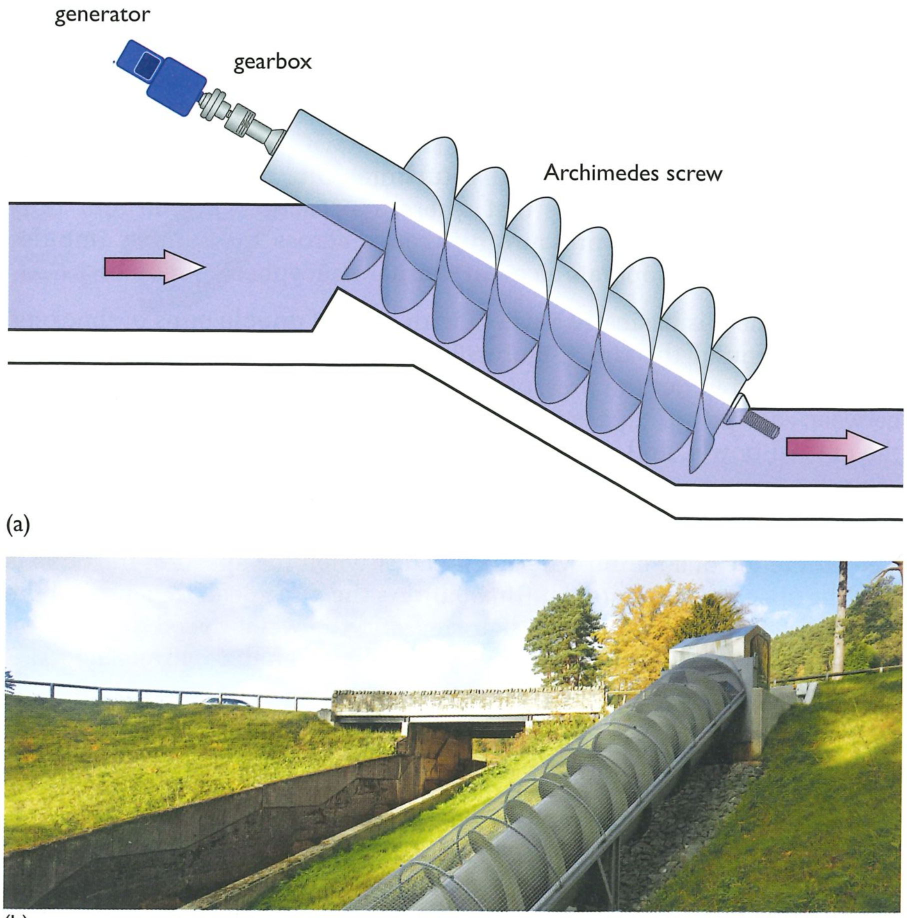
In the 'propeller' or **axial-flow** turbines shown in Figures 6.17 and 6.21, the area through which the water enters is as large as it can be: it is the entire area swept by the blades (these turbines are, again, reaction turbines). Axial-flow turbines are therefore suitable for very large volume flows and have become usual where the head is only a few metres. They have the advantage over radial-flow turbines in that it is technically simpler to improve the efficiency by varying the angle of the blades when the power demand changes. Axial-flow turbines with this feature are called **Kaplan turbines**. These are used in both hydro plants and in tidal barrage schemes, described in Chapter 7.

An important feature of 'propeller' turbines is that their optimum blade speed for maximum efficiency is appreciably greater than the water speed – as much as twice as fast. This allows the high rate of rotation needed by the generator even with relatively low water speeds. (Note that because the outer parts of the blade move faster than the more central parts, the blade angle needs to increase with distance from the axis. This is why a propeller has its familiar twisted shape.)

With axial flow there is no need to feed the water in from the side, and it is obviously simpler to let it flow in along the axis instead of being deflected through a right angle. However, this raises the problem of where to position the generator; if located directly along the axis of the turbine it will either get in the way and/or get wet! Several different solutions to this problem – rim generators and tubular turbines – are shown in Chapter 7.

Archimedes screw

The Archimedes screw can be thought of as an extended propeller in a trough (see Figure 6.22). Its name suggests that it was invented by the famous Greek mathematician, but it was probably in use as a water pump in Egypt well before his time.



(a)

(b)

Figure 6.22 The Archimedes screw (a) schematic (b) the 12 kW turbine installed at Cragside house in Northumberland in 2014

The metal screw only half fills the trough, giving good accessibility for cleaning. The screw only turns slowly with the generator running at a higher speed, driven through a gearbox. The generator and gearbox are mounted at the top, again easily accessible for maintenance. They are used for small schemes with heads from 1 to 8 metres and need to be manufactured 'to size' with the screw occupying the full head height and with a diameter (sized to match the flow rate) of up to 5 metres. Power ratings for single screws are in the range 5–500 kW, though higher powered schemes are likely to use multiple screws.

Archimedes screws have been increasingly used in the UK since about 2007 in 'run-of river' projects. A 300 kW system using two screws each 4 metres in diameter was installed at Romney Lock on the River Thames in 2013 to provide power to Windsor Castle. The engineering work required modifications to the 200-year-old lock.

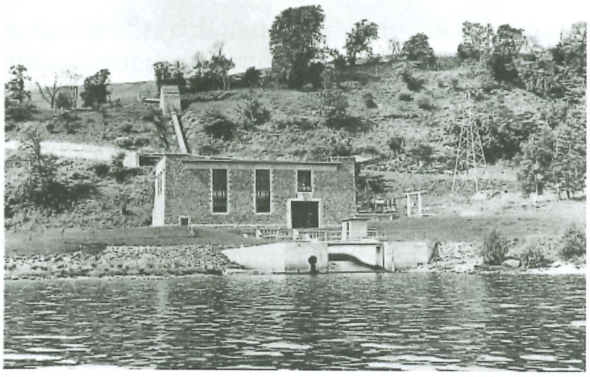
It is claimed that, given an adequate gap between the blades, this technology is 'fish friendly' allowing fish to pass right through the turbine unharmed (Kibel and Coe, 2011).

Pelton wheels

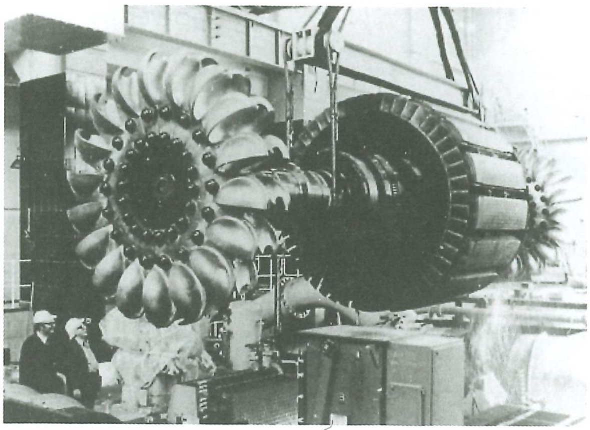
For sites of the type shown in Figure 6.13(c), with heads above 250 metres or so (or lower for small-scale systems) the **Pelton wheel** is the preferred turbine. It evolved during the gold rush days of late nineteenth century California, was patented by Lester Pelton in 1880, and is entirely different from the types described above. It is, in contrast to the reaction turbines discussed previously, an **impulse turbine**. One important difference between the turbine types is that whereas a reaction turbine runs fully submerged and with a pressure difference across the runner, impulse turbines essentially operate in air at normal atmospheric pressure.

A Pelton wheel is basically a wheel with a set of double cups or 'buckets' mounted around the rim (Figures 6.23a and 6.24). A high-speed jet of water, formed under the pressure of the high head, hits the splitting edge between each pair of cups in turn as the wheel spins. The water passes round the curved bowls, and under optimum conditions gives up almost all its kinetic energy. The power can be varied by adjusting the jet size to change the volume flow rate, or by deflecting the entire jet away from the wheel.

The efficiency of a Pelton wheel is greatest when the speed of the cups is half the speed of the water jet (Box 6.6). As the cup speed depends on the rate of rotation and the wheel diameter, and the water speed depends on the head, there is an optimum relationship between these three factors.



(a)



(b)

Figure 6.23 The 16.5 MW Finlarig power station, on the shores of Loch Tay, draws its water from Loch na Lairige at a head of 415 metres. Its average annual output is 70 GWh (SSE, 2005) (a) the power station, (b) the original double twin-jet Pelton wheel and horizontal-axis 30 MW multi-pole generator.

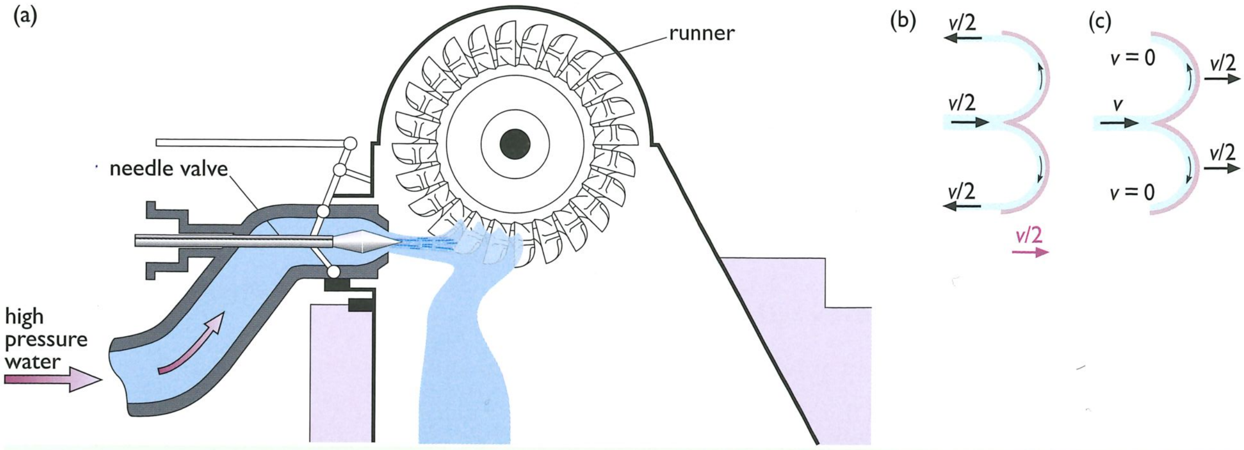


Figure 6.24 Structure of a Pelton wheel turbine: (a) vertical section, (b) water flow as seen from moving cup, (c) actual motion of water and cup

BOX 6.6 Optimum speed for a Pelton wheel

The following informal argument shows that a Pelton wheel extracts the maximum energy from the water if the cups move at half the speed of the water jet.

Consider the situation when water at speed v approaches a cup which is already moving in the same direction at half this speed ($v/2$). As seen from the cup, the water will be approaching at the difference between these two speeds, which in this case is also $v/2$.

Suppose now that the water passes smoothly round inside the curved cup until it leaves travelling in the opposite direction – as seen from the cup. You now have water moving backwards at speed $v/2$ relative to a cup that is moving forwards at just this speed. A person on the ground would see the cup moving on while the water simply falls vertically out of it. The water has given up all its kinetic energy to the wheel. 100% efficiency, in principle!

In practice this is only approximately true, and the best cup speed is a little less than $v/2$.

Input power

The power input to a Pelton wheel is determined, as usual, by the effective head and the flow rate of the water. Box 6.7 below shows that, ideally, the volume rate of flow Q in $m^3 s^{-1}$ corresponding to an effective head H in metres is:

$$Q = A \times \sqrt{(2gH)}$$

where A is the area of the jet in m^2.

BOX 6.7 Effective head, water speed and flow rate

Although there are in practice always energy losses in forming a jet, we'll assume here that the water leaves the jet at the speed that it would have gained in 'free fall' through the effective head.

We know from Equation (1) in Section 6.5 that the potential energy in joules lost by M kg of water in falling through H metres is given by:

potential energy = MgH

In Chapter 1 we saw that the kinetic energy of a moving object is proportional to its mass and the square of its speed:

$$\text{kinetic energy} = \frac{1}{2}Mv^2$$

So if all the lost potential energy is converted into kinetic energy, we have:

$$\frac{1}{2}Mv^2 = MgH$$

so $v^2 = 2gH$ and

$$v = \sqrt{(2gH)} \tag{5}$$

If this water flows as a jet with a circular area of A square metres, the volume flowing out in each second Q in $m^3 s^{-1}$ will be equal to A times v. So the volume flow rate for an effective head H is given by:

$$Q = A \times \sqrt{(2gH)} \text{ cubic metres per second}$$

Equation (2) in Section 6.5 shows that the input power to a turbine is:

$$P \text{ (watts)} = 1000 \times Q \times g \times H$$

so substituting for Q we find that:

$$P = 1000 \times A \times \sqrt{(2gH)} \times g \times H$$

Using the approximate value of g (10 m s^{-2}), the power in kilowatts becomes

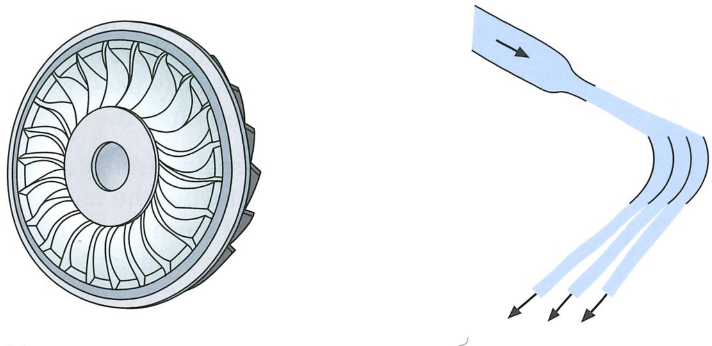
$$P \text{ (kW)} = 45A\sqrt{(H^3)}$$

If adjacent cups are not to interfere with the flow, the wheel diameter needs to be about ten times the diameter of the jet. But two or even four jets can be spaced around the wheel to give greater output without increasing the size. If the number of jets is j, the power equation becomes

$$P \text{ (kW)} = 45jA\sqrt{(H^3)}$$

Turgo and cross-flow tubines

A variant on the Pelton wheel is the **Turgo turbine** (Figures 6.17 and 6.25), developed in the 1920s. The double cups are replaced by single, shallower ones, with the water entering on one side and leaving on the other. The water enters as a jet at a low angle to the plane of the turbine, striking the cups in turn, so this is still an impulse turbine (and the relationships in Boxes 6.6 and 6.7 still apply). However, its ability to handle a larger volume of water than a Pelton wheel of the same diameter gives it an advantage for power generation at medium heads.



(a) runner (b) water flow

Figure 6.25 Flow in a Turgo turbine

The cross-flow turbine shown in Figure 6.17 (also known as the **Mitchell-Banki**, or **Ossberger turbine**) is yet another impulse type. The water enters as a flat sheet rather than a round jet. It is guided on to the blades, then travels across the turbine and meets the blades a second time as it leaves. As we will see in the next section, cross-flow turbines are often used instead of Francis turbines in small-scale plants with outputs below 100 kW or so, and some ingenious technological ideas have gone into the development of simple types of generator which can be constructed (and maintained) without sophisticated engineering facilities and are therefore suitable for remote communities.

Ranges of application

We have seen that, in general, Pelton wheels are most suitable for high heads, propellers for low heads and Francis turbines for the intermediate ranges. But the effective head is not the only factor determining the most appropriate type for a given situation. The available power also matters.

Figure 6.26 represents one way to display the ranges of application of the different turbines. It shows the ranges of head, flow rate and corresponding power which best suit each type. It should be noted however that the

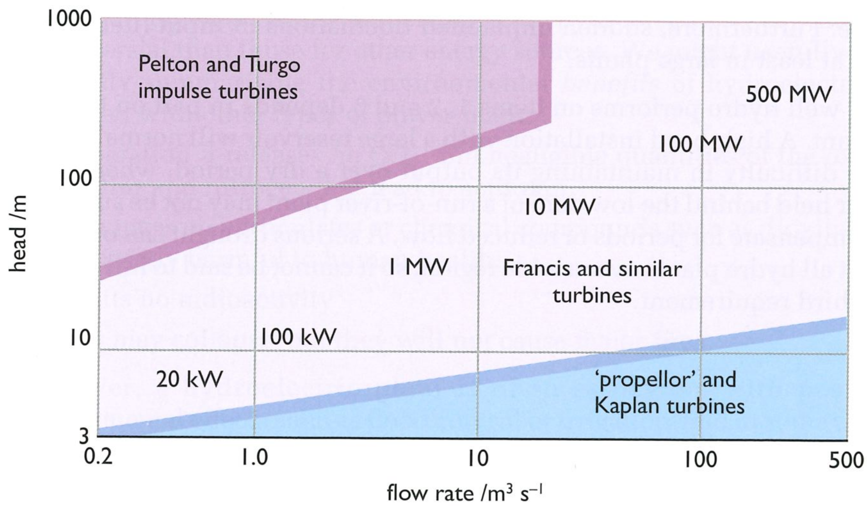


Figure 6.26 Ranges of application of turbines

boundaries are by no means clear-cut, and other technical issues, or criteria such as cost, simplicity in manufacture or ease of maintenance can lead to choices outside these ranges. Locating the site data for the Galloway plants (and others in this chapter) on Figure 6.26 and comparing the turbine types actually used with those suggested by the diagram shows that this is indeed often the case.

Small-scale installations can also be classified by the available head and flow rate, but the ranges may be very different from those of large plants. Many of these plants are run-of-river, with heads of only a few metres, and as little as 10 m could be regarded as 'high head' for a very small plant. The corresponding choices of turbine type may vary appreciably from those indicated in Figure 6.26.

6.9 Hydro as an element in a system

Even if a potential source of electric power is acceptable environmentally and financially, other factors remain that affect its viability. Few large power stations operate in isolation, and the extent to which the proposed plant can form a useful part of a supply *system* is important.

From the point of view of the operator of the system, the characteristics of the ideal power station would be:

1. constant high availability
2. a reserve energy store to buffer variations in input
3. no correlation in input variations between power stations
4. rapid response to changing demand
5. an input which matches annual variation in demand
6. no sudden and/or unpredictable changes in input
7. a location which does not require long transmission lines.

Few, if any, sources meet all these criteria, but each compromise with the ideal adds to the effective cost.

Almost all hydroelectric plants score well on item 4, and, in regions with cold, dark, wet winters, on item 5 as well – unless the water is locked up as ice. Furthermore, sudden unplanned fluctuations in input (item 6) are rare, at least in large plants.

How well hydro performs on items 1, 2 and 3 depends in part on the type of plant. A high-head installation with a large reservoir will normally have little difficulty in maintaining its output over a dry period, whereas the water held behind the low dam of a run-of-river plant may not be sufficient to compensate for periods of reduced flow. A serious drought can of course affect all hydro plants over a wide region, so it cannot be said to fully satisfy the third requirement.

Figure 6.27 The Grand Coolee Dam on the Columbia River, constructed in 1942, is 170 metres high and about 1 km long. The total generating capacity of its 30 turbo-generator sets is 6.8 GW, of which 300 MW is pumped storage plant (USBR, 2011)

The final criterion is the real hurdle. Hydro locations are determined by geography, and whilst run-of-river plants may sometimes be near major centres of population, this is rare for high-head systems.

Is the case different for small-scale hydro? Smaller plants are predominantly run-of-river, or perhaps served by relatively small reservoirs, in either case a less reliable supply. On the other hand, scattered sites with different rainfall patterns could result in increased reliability. Local small-scale plants can reduce the need for long-distance transmission, reducing energy losses and costs; although the generating cost per unit of output may be greater.

Overall, hydroelectricity ranks reasonably well in terms of the above criteria. And it may also offer a bonus. A hydro plant with a large reservoir not only maintains its own reserve of energy – it might, as we have seen earlier, provide a store for the surplus output of other power stations.

6.10 Environmental considerations

The environmental issues associated with hydroelectricity are no less controversial than those for other energy sources. We might usefully start by briefly summarizing the environmental *benefits* of hydroelectricity compared with other types of power plant:

- in operation it releases no CO_2, and negligible quantities of the oxides of sulfur and nitrogen that lead to acid rain
- it produces no particulates or chemical compounds such as dioxins that are directly harmful to human health.
- it emits no radioactivity
- dams may collapse, but they will not cause major fires.

Moreover, a hydroelectric plant is often associated with positive environmental effects such as flood control or irrigation, and in some cases, its development leads to a valued amenity or even a visual improvement to the landscape.

The Hydropower Sustainability Assessment Protocol

The Hydropower Sustainability Assessment Protocol (HSAP) is the result of a collaboration by representatives of different sectors of the hydro industry, led by the International Hydropower Association (IHA). Essentially a list of criteria that should be satisfied by any new hydroelectricity project, it is no doubt the response of the industry to many of the problems discussed above. It was accepted by the membership of the IHA (which now administers its day-to-day operation) in November 2010.

The Protocol (HSAP, 2010) consists of an explanatory background document and four assessment sections, covering the four stages of any new project: Early Stage, Preparation, Implementation, and Operation. Collectively, these impose conditions designed to meet many of the criticisms of largescale hydro. However, by 2015 only 20 large scale hydro projects (in the range 3 MW to 3750 MW) had been assessed.

Environmental effects of small-scale systems

There is general consensus that small-scale hydro plants have fewer deleterious effects than large systems. In some respects this is evidently true – few people have been displaced from their homes by the installation of small 5 MW plants, whilst deaths from the collapse of dams across small streams seem rare.

However, not everyone agrees with the consensus. The claim, made mainly by proponents of large-scale hydro, is that a general world view – 'small is beautiful' – has been allowed to override detailed analysis. It is true that the efficiencies and the capacity factors of small-scale plants tend to be lower, and in some cases the 'reservoir area' per unit of output is greater. But as we have seen, all these factors vary significantly from site to site, and generalization is difficult.

Comparisons

It should not be forgotten that the choice may not be hydroelectricity or nothing, but hydroelectricity or some other form of power station. Despite the 'penalties' discussed above, hydroelectricity scores relatively well in terms of many other criteria. Current issues for hydropower include the question of methane emissions and the costing of long-term compensation for the people displaced by major new hydroelectric installations. Nevertheless, on the criteria used in these studies, hydro appears amongst the least harmful sources of electricity.

6.11 Economics

> Generating plant can be broadly categorized either as being expensive machines for converting free or low cost energy into electrical energy or else lower cost machines for converting expensive fuels into electrical energy.
>
> Mott MacDonald, 2010

No matter how elegant the technology, few will invest in it unless it is going to make a profit. Potential investors need to know how much each kilowatt-hour of output will cost, taking all relevant factors into consideration.

Capital costs

Hydroelectricity is well-established and most of the necessary cost information is easily available. The water-control systems, turbo-generators and output controls are standard items, covering a power range from a few hundred watts to hundreds of megawatts. The expected lifetime of the machinery is 25–50 years, and of the external structures, 50–100 years. Nevertheless, as mentioned in Section 6.3, it is difficult to generalize meaningfully about 'the cost of hydroelectric power', or to assess the economic potential for hydroelectricity in a country or a region.

The difficulty lies in the combination of the extremely site-specific construction costs and the heavy 'front-end loading' of these costs. In other words, the dominant factor in determining the cost per unit of hydro output is the initial capital cost, and a major part of this can be the civil engineering costs, which vary greatly from site to site.

Unit costs

An interesting study on hydro potential in the USA (Hall et al., 2003) assessed the costs for over two thousand sites with potential hydro capacities in the range 1–1300 MW. About half of these were green-field (blue-water?) sites, with no existing dams or hydro plants, and the estimated development costs for these, based on data for similar existing plants, fell mainly in the range US$2000 – US$4000 per kW. (At the time of writing (2017) inflation would have increased these initial costs to about US$2700 – US$5400 or approximately £2200 – £4300 per kW.)

These studies revealed the importance of the *initial costs* in determining the levelized cost of electricity (LCOE) per kilowatt-hour of output.

The civil engineering works typically accounted for 65–75% of this unit cost, whilst meeting the environmental and other criteria necessary for a licence added another 15–20%. In all, 85–95% of the capital cost was 'site' cost, with the turbo-generator and control systems accounting for only 10% or so.

With no fuel costs, and relatively low annual operation and maintenance costs, it is the interest repayments on the costs incurred in building the dams etc. that dominate the cost of energy. Box 6.9 shows the importance of the discount rate used in assessing hydroelectricity costs.

BOX 6.9 Cost comparison of hydro and CCGT plants

A combined cycle gas turbine (CCGT) plant may be regarded as the opposite extreme to a hydro plant. Built quickly, using standard components, its capital costs are relatively low; but the fuel costs are high (and unpredictable for the future) and its lifetime is likely to be much less than that of a hydro plant. Nevertheless, investors may choose to put their money into CCGT plants rather than hydro – as has indeed been the case in the UK in recent years. The following reasoning shows why.

A simple general approach to costing electricity from power plants is described in Appendix B. As described there, the key cost elements of any electrical power plant are:

- initial capital costs
- fuel costs – zero in the case of hydro – but these should include a 'carbon price' for the gas used in the CCGT
- operation and maintenance (O&M) costs
- final decommissioning costs (assumed to be zero here – although they could be significant for a hydro scheme)

Table 6.7 has relevant data for two 100 MW plants based on sample data from recent UK cost assessments (BEIS, 2016b; Arup, 2016). The main differences are obvious: the hydro plant costs much more, but the CCGT has fuel (and carbon price) costs and a much shorter expected life. In the case considered, the high CCGT capacity factor (80%) suggests that it will be in almost constant use, whilst the hydro plant (capacity factor 45%) may be used mainly as backup (or is perhaps subject to flow variations). The final column of the table is calculated from the 100 MW rated output of both plants and their respective capacity factors.

Table 6.7 Financial data and performance factors for 100 MW plants

	Capital cost / £ million	Plant lifetime / years	Average capacity factor	O&M cost per kWh of output	Fuel and carbon cost per kWh of output	Average annual plant output / million kWh
CCGT	55	30	80%	0.5 p	5.5 p [1]	701
Hydro	320	60	45%	1.5 p	-	394

[1]Assuming a bulk gas cost of 1.9 p per kWh and a fuel-to-output efficiency of 53% plus a carbon cost of £50 per tonne

The cost per kWh of electricity from each of these 100 MW plants can be calculated for different discount rates by the method described in Appendix B. Data from Table B1 in that Appendix is used to find the annual repayment for each of the above plants at four selected discount rates, shown in Table 6.8 below. Using the annual outputs in Table 6.7, these are then expressed as repayment costs per kilowatt-hour of output. Finally, adding the other unit costs from Table 6.7 leads to a *total cost per kWh* of electricity from each plant.

Table 6.8 Financial factors

Discount rate	**0%**	**5%**	**10%**	**15%**
CCGT repayment factor / £ per £1000 capital	33	65	106	152
CCGT annual repayment / £ million	1.82	3.58	5.83	8.36
Annual repayment / pence per kWh of output	0.26p	0.51p	0.83p	1.19p
Fuel + O&M cost / pence per kWh of output	6.00	6.00	6.00	6.00
CCGT total cost per kWh of output	**6.26p**	**6.51p**	**6.83p**	**7.19p**
Hydro repayment factor / £ per £1000 capital	17	53	100	150
Hydro annual repayment / £ million	5.44	16.96	32.0	48.0
Annual repayment / pence per kWh of output	1.38p	4.30p	8.12p	12.18p
O&M / pence per kWh of output	1.50	1.50	1.50	1.50
Hydro total cost per kWh of output	**2.88p**	**5.80p**	**9.62p**	**13.68p**

The clear conclusion from the results is that if discount rates are low (5% or less) then hydro is cheaper than gas generation. However if they are high (10% or more) then the reverse is true.

Quite what is a 'correct' discount rate to use is a matter of debate, particularly since 2017 bank interest rates in the UK and the USA are almost at an all-time low. The topic of discount rates and project risk is discussed in Chapter 11, but both large scale hydro power and CCGT generation are 'mature' technologies and are not seen as particularly financially risky.

It has been argued that projects with significant prospects of reducing national CO_2 emissions should be funded with (government) loans at a very low 'social' discount rate of 3.5%. This would give a hydro cost of under 5 p kWh^{-1}. Such low interest finance would, of course, also reduce the costs of rival low-carbon technologies, particularly nuclear power (CCC, 2011).

Obviously there are many other factors that can be adjusted in this calculation to tip the balance one way or the other. For example, although the CCGT is used for almost continuous generation, the hydro plant may be used to meet peak loads, possibly giving extra commercial value to its electricity. A higher carbon price for the CO_2 emissions from the CCGT would also tip the balance in favour of the hydro plant.

Table 6.9 summarizes the estimated electricity costs for new UK hydro plants of different sizes from a recent UK government study (BEIS, 2016b).

Table 6.9 UK hydroelectricity cost estimates

Hydro plant rating	Cost of electricity / p kWh^{-1}
< 100 kW	12.6
500 kW–2 MW	9.5
5–16 MW	9.7
Large storage (100 MW)	8.0

Refurbishing and upgrading

Two other options have been considered – and implemented – in recent years by countries with little remaining accessible hydro capacity:

- the installation of hydro plants at existing dams constructed for other purposes
- the refurbishing and/or upgrading of existing hydro plants.

Both approaches offer the possibility of increased hydro capacity at a lower initial cost and with fewer environmental consequences than green-field development. The US study described above noted the lower cost of these options (at least for relatively modest plants), with estimates of perhaps half the cost of green-field development when the dam already exists, and as little as a third, per 'new' kW, for refurbishment and upgrading of older plant. This option also allows the installation of extra turbines at a relatively low cost to assist with peak demands and complement other variable renewable energy sources such as wind and PV.

Many countries now have extensive refurbishment and upgrading programmes for large-scale hydro, resulting in modest increases in output from the existing dam infrastructure.

6.12 Future prospects

As shown in Figure 6.1 at the beginning of this chapter, world total electricity production in 2016 was nearly 25 000 TWh and hydro power provided 16% of this, about 4000 TWh.

The percentage contribution from hydro has been falling gently for many decades, as the building of new plants has failed to keep up with the rapid growth in total world electricity consumption. As shown in Figure 6.5 most of the increase in world hydro output since 2005 has taken place in China where in 2016 hydro provided 19% of the total electricity demand. Here, electricity consumption has been increasing at about 8% per annum, but this growth rate has been matched by hydro construction whose output has more than doubled in the last decade.

According to the estimate shown in Table 6.4, China would appear to have already developed nearly a half of its hydro technical potential. In 2016, it had 331 GW of hydro installed capacity and, according to the International Hydropower Association, the potential to develop a further 200 GW (IHA, 2017). However most of the hydro resource is located in the mountainous west of the country and will require the construction of long distance high-voltage transmission lines to distribute the power to the population centres in the east of the country.

There is also large potential for hydro development in South America, where it already supplies about a half of the electricity. This requires tapping into the flows of large rivers, which may have serious environmental consequences. Two such projects are described in Box 6.10.

BOX 6.10 Large hydroelectric projects in Brazil

Itaipú

Figure 6.29 The Itaipú dam

Construction of the 14 GW hydroelectric plant at Itaipú, on the Paraná River between Brazil and Paraguay, started in 1975, and the last two of its twenty 700 MW generators came on line in 2006–2007.

The effective head is about 200 metres and the reservoir area 1350 km^2, with an average water flow of some 10 000 tonnes a second, peaking at times to over 30 000 tonnes per second.

The plant supplies 95% of Paraguay's power and about a quarter of Brazil's, requiring a feature that must be unique in power stations: all 20 generators produce alternating current (AC) power, but half of them at a frequency of 50 Hz, and the other half at 60 Hz. Moreover, as Paraguay (50 Hz) uses only a fraction of its share, the rest is sold to Brazil, where it is rectified, transmitted as DC, and then re-converted to provide the required 60 Hz supply (Itaipú, 2011).

The total annual output obviously depends on the available flow in the Paraná and plant availability, and could of course be affected by varying demand. Over the five years 2006–2010 the average annual output was 91.1 TWh, implying an average capacity factor of slightly under 75% – significantly below the originally contracted 85%.

The overall electricity output of the dam is comparable to that of the 22 GW Three Gorges Dam in China, however the continuously flowing Paraná River gives a higher capacity factor. In 2016, Itaipú achieved its best annual output, 103 TWh (ABC TV, 2017), equivalent to nearly 30% of the UK's annual electricity demand.

Xingu river project at Belo Monte

The first suggestions for the development of hydro power on Brazil's Xingu river, a tributary of the Amazon, appeared in 1975 (the year in which Itaipú first came into operation). Initial studies led to a proposal for six large hydro plants, but the release of this plan in 1987 led to a vigorous campaign by indigenous people living in the affected areas. Their campaign attracted widespread international support, and the next two decades saw continuing opposition to a range of schemes involving between one and six dams along the Xingu. There were also objections on technical grounds – the variable flow of the river meant that the annual capacity factor of the plant could be as low as 30% (problem also experienced at Three Gorges).

In 2008, a new environmental assessment resulted in a plan involving one main power plant, the *Belo Monte*. However, in order to avoid inundating 'indigenous territory' in the bend of the river, this required the construction of the second, larger *Pimental* dam, which would create two reservoirs: one upstream along the route of the river, and a second filled by the diversion of water through two parallel 500 m wide canals on to previously dry land behind the Belo Monte dam.

In February 2010, the Brazilian government environmental agency granted a provisional environmental licence to this plan.

The following year saw a series of reversals and reinstatements of this approval, culminating in the granting on 1 June 2011 of a full licence to the Norte Energia consortium, which undertook to pay US$1.9 billion to address social and environmental problems (Barrionuevo, 2011).

The dam has now been completed and 2 GW of the total of 11 GW turbine capacity had been brought on line by the end of 2016 (IHA, 2017). Full completion is expected in 2019 and this will also require the construction of a 2550 km long transmission line to carry the electricity to Rio de Janeiro.

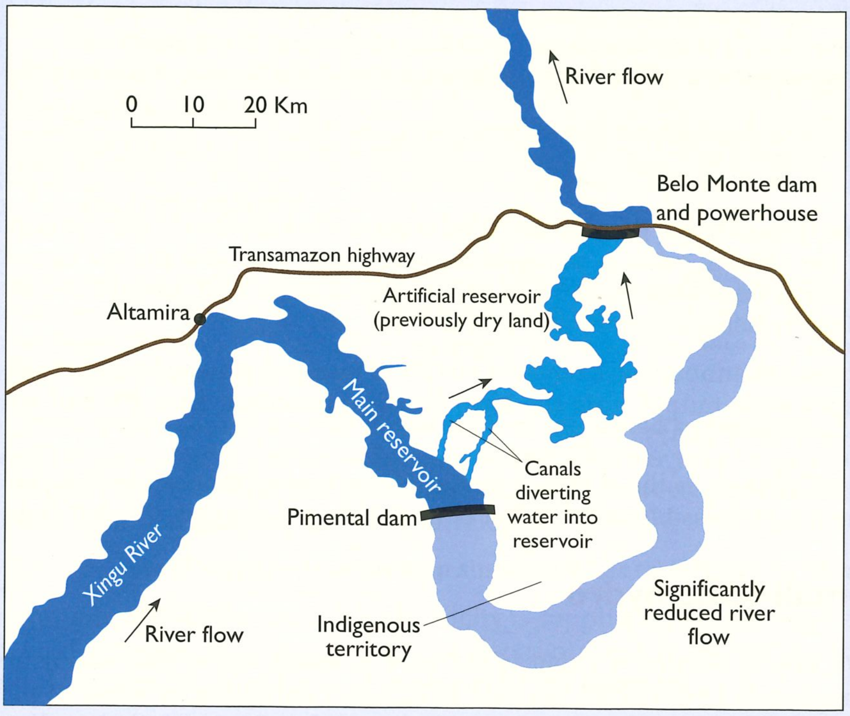


Figure 6.30 The Xingu River project

Africa, as we saw in Section 6.3, has a lower proportion of its hydro technical potential developed than any other major region of the world – a situation that has led to its place at the centre of bitter controversies, typified by the proposals for and objections to the Grand Inga project on the Congo (Box 6.11).

BOX 6.11 Grand Inga

The first Inga power plant, with a rated output of 351 MW from six turbines, was commissioned in 1972 on the Congo river, in the region of the Inga rapids in the then country of Zaïre – now the province of Bas-Congo in the Democratic Republic of the Congo. In 1982, this plant (now Inga 1) was joined by Inga 2, with its rated output of 1424 MW from eight turbines.

Unfortunately, with many financial, political and structural problems, the record of these plants has not been good. In 2008, two top directors of the company were interrogated after the disappearance of US$6.5 million intended for rehabilitation of Inga 2. Renovation work on turbines at Inga 1 and 2 is currently (2017) being carried out with financial assistance from the World Bank.

In 2008, the World Energy Council called for financing for a feasibility study of its **Grand Inga** proposal, whose main features are:

- a third plant, Inga 3, with an output of 40 GW, requiring a 205 metre high dam forming a 15 km-long reservoir
- a pan-African power distribution system reaching to Egypt in the north, Nigeria in the west and South Africa to the south, which would take a large proportion of the electricity.

In 2014, the World Bank announced that it had approved a US$73 million grant for the first phase of the Inga 3 project. However this funding was suspended in 2016 following disagreements with the Congolese government.

Sources: International Rivers 2016, 2017a, 2017b.

One form of hydro development that is generally expected to attract support in the coming years is *pumped storage*. World pumped storage capacity reached an estimated 150 GW at the end of 2016, with about 6.4 GW of capacity being added in that year (REN21, 2017).

China has announced a target of 40 GW of pumped storage by 2020 to help balance the output from the large increase in output from PV and wind power (IHA, 2017).

Finally, there is the hydro potential of the tens of thousands of dams in the world (possibly 30 000) that currently do not support a hydro plant.

Small-scale hydro

We saw in Section 6.4 that is not easy to assess the world output from small-scale hydro given the lack of an exact definition in terms of plant size. However, Box 6.12 summarizes the results of two detailed studies of the potential for small-scale hydro development (under 5 MW capacity) in the UK.

BOX 6.12 Small-scale hydro in the UK

The World Energy Council Resources assessment (WEC, 2010) quoted in Section 6.3 suggested that the hydro technical resource for the whole UK was 14 TWh y^{-1}, of which about 6 TWh y^{-1} has been developed. It is unlikely that any large-scale hydro projects would be given planning permission in the UK, so the future lies with small-scale schemes.

A detailed study in 2008 of the potential for small-scale hydro in Scotland found some 36 000 potential sites, with an estimated total power of 26 000 MW, giving an annual output of about 10 TWh per year. Only about 1000 sites were considered to be financially viable, but even this reduced number, with a total of 660 MW, might contribute some 2.7 TWh per year – a potential increase equal of about 40% on the present total UK hydro output (FHSG, 2008).

Two years later, a study of the potential for small-scale hydro in England and Wales was published (DECC, 2010). This differed from the Scottish study in that it was based on sites identified in an earlier analysis (reassessed in the light of technological and other changes) and also in that it excluded sites that would require the construction of new dams or weirs. Nevertheless, its estimated total potential installed capacity for England and Wales, ranged from a 'pessimistic' figure of 150 MW to an 'optimistic' one of 240 MW.

Given that, as shown earlier in Figure 6.5, world hydro generation has been growing by roughly 60 TWh y^{-1} for the last 50 years, it might be expected to increase by a further 20% by 2030. Scenarios for future world electricity generation, described in Chapter 12, suggest increases of between 15% and

35% with an annual growth rate of only 1-2% per annum. These are rather in contrast to the high continuing growth rates suggested for PV and wind power and are, no doubt, constrained by environmental concerns about new large dam projects.

6.13 Summary

Traditional water wheels, with their driven wheels only partially submerged in water, have been used for irrigation and driving corn mills for over 2000 years. The modern, totally submerged, water turbine was developed in the nineteenth century.

In 2016, hydro power provided one sixth of the world's electricity. The **world technical hydro resource** is about **16 000 TWh per year** – equivalent to two thirds of the world's 2016 electricity supply – however, only a **quarter** of this **technical resource** has been developed.

Most of the **world's hydro development since 2000** has taken place in **China**.

In **Norway, 95% of the country's electricity** is supplied by hydro, however, in the UK, hydro only supplies **2% of electricity** and is mainly used for supplying electricity at times of **peak electricity demand**.

Hydro **can be very flexible in its output**. It can be used to meet peak electricity demands and its generation may complement other renewable electricity technologies such as wind or PV.

Pumped storage plants are mainly used to provide **short-term backup** to the National Grid for up to a few hours. They can cover the **failure of a large fossil fuelled or nuclear plant** or **demand pickup** produced by many thousands of electric kettles being turned on at the end of a popular TV show. They require two water reservoirs, one preferably at least a hundred metres above the other. In order to store energy, water is pumped from the lower one to the upper one by a turbine driven by a large electric motor/generator. The energy can be recovered by allowing the stored water to flow back through the same turbine now driving the motor/generator to generate electricity.

The storage of **1 kilowatt-hour of electricity** requires raising **1 cubic metre of water (approximately 1 tonne)** through at least **360 metres in height**.

The **power from a hydro plant** is dependent on:

- **the efficiency of the turbine and generator (η, typically 85%)**
- **the water flow rate (Q) in cubic metres per second**
- **the effective height (H), in metres, through which the water falls** (this may be less than the 'real' height due to energy losses in flow resistance).

The key equation is:

Power (kW) = 10 × η × Q ($m^3\ s^{-1}$) × H (m)

Hydroelectric plants use **gravitational potential energy**. The key equation for this is:

potential energy (joules) = mass (kg) × g (acceleration due to gravity) × height (metres).

In 2017, the three largest hydro plants in the world were:

- **Three Gorges in China** (22.5 GW)
- **Itaipú in Brazil** (14 GW)
- **Xiluodo in China** (13.9 GW)

Hydro schemes can range in output from **a kilowatt up to hundreds of megawatts**, with the definition of '**small scale hydro**' in the UK considered to be projects of **less than 5 MW output**.

Hydro schemes also have a very long life. Most of the Galloway scheme in Scotland was built in the 1930s and is still operational.

Hydro generation plants may be attached to **specially constructed dams** or **existing dams built for other purposes** (such as the drinking water reservoirs at the Elan Valley in Wales).

Water flows from the reservoir through a long tube called a **penstock** with the turbine situated at the lowest end. **Run-of-river plants** are situated at existing weirs or waterfalls in rivers and may only have low heads.

The **rate of rotation** of a turbine is constrained by the frequency of the electricity generated, which may be 50 Hz (cycles per second) or 60 Hz in different countries.

The **pressure of water** increases by 1 atmosphere for every 10 metres of water height.

The **Francis turbine** is the most common type used in modern hydro plants. Its moving part, the **runner**, is surrounded by **guide vanes** which deflect the water inwards towards the runner. The water then emerges from the centre of the runner. The runner is connected to a shaft that drives an electrical generator. Francis turbines are mostly used for **medium head** schemes of 50 to 200 metres head height. They are available at power ratings of up to 780 MW.

The **Pelton wheel** is commonly used for **high head** schemes of more than 100 metres height. It consists of a set of small buckets spinning in air driven by a high speed jet of water from a nozzle.

Propellor turbines consisting of a propellor in a tube are used for low head (under 15 metres height) applications. The **Kaplan** turbine is a propellor with vanes that can be adjusted with the flow rate. These may be also used in **tidal power plants**.

The **Archimedean screw** is an elongated propellor set in an open trough. These are becoming increasingly used for low head run-of-river schemes.

Hydro power does **not emit CO_2, nitrogen oxides or particulates** whilst in operation. **Fish ladders** allow fish, such as salmon, to swim up past dams to spawn in the water reservoirs.

The main disbenefits of hydro power are:

- **the likely need to dam large rivers**, possibly displacing large numbers of people. For example, the Three Gorges Dam in China displaced over one million people.
- **the risk of dam failures**, again displacing large numbers of people.

- **changes in river flows** – affecting access to inland lakes for fish – and water levels in surrounding land, which may give rise to legal arguments at a local or even international level.
- the eventual **silting up and loss of storage capacity** of reservoirs.
- **possible methane emissions** from rotting vegetation in reservoirs, a topic which still requires further research.

The **International Hydropower Association (IHA)** supervises the **Hydropower Sustainability Assessment Protocol (HSAP)** for the environmental and economic assessment of new large projects.

The key elements of the economics of hydropower are:

- **high initial capital costs**, dominated by the civil engineering works of dams.
- **an expected long operational lifetime** of 50 years or more.
- **modest operation and maintenance costs.**
- **zero fuel costs.**

The unit cost of electricity depends on the discount or interest rate used for any financial borrowing. **A low discount rate favours hydro**, a high discount rate favours fossil fuelled generation. The **refurbishment and upgrading** of existing plants may be highly economic.

Although only a quarter of the world's technical hydro resource has been exploited, scenarios of future expansion are limited by environmental considerations and only see **a growth rate of 1-2% per annum.**

The **potential for future growth in the UK is only modest** and is likely to be limited to small-scale projects.

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