A Review of Current Knowledge

THE ROLE OF WATER IN THE PRODUCTION OF ENERGY

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This review is one of a series of Reviews of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

THE ROLE OF WATER IN THE PRODUCTION OF ENERGY

El Chocon Dam, Rio Limay, Argentina

Author: Dr W R White

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1 Introduction

This revised ROCK is concerned with the role of water as one of the many sources of energy. Other sources include solid fuels, oil, natural gas, nuclear, biofuels and waste, together with smaller contributions from geothermal, solar, wind and heat.

The original ROCK was published in 2013 and was largely based upon published data available at the time. This mainly referred to conditions in 2010. The purpose of this revision is to update the information for an energy market which is changing rapidly. Data is now available from governmental sources for the years 2013 and 2014 but, to some extent, conclusions are clouded by changes in the definition of renewable / non-renewable fuels.

The latter half of this ROCK describes the methods which are used to extract energy from water. These methods remain largely unchanged in recent years.

Hydropower, power from water, makes a relatively small contribution towards the overall provision of worldwide energy. According to the International Energy Agency (IEA), the contribution from hydropower was 1.8 per cent in 1973 rising to 2.3 per cent in 2014. By far the largest energy supplies come from solid fuels, oil and natural gas. These three fuels supplied 81 per cent of the worldwide energy consumption in 2014. The overall worldwide use of energy in 2014 was 2.2 times the use in 1973.

Hydropower, however, plays a more significant role in the provision of electrical energy. At present this energy comes almost entirely from large scale hydroelectric plants involving major quantities of stored water and large dams to create high potential energy. In 1973 hydropower provided 21 per cent of the world's electrical energy and the corresponding figure for 2013 was 16 per cent. This is not to say that hydropower has declined over the last four decades. The generation of electrical energy by hydropower has increased by a factor of 3.0 between 1973 and 2013. The worldwide generation of electrical energy increased by a factor of 3.8 over this period, mainly provided by a major increase in the use of power stations burning solid fuels and natural gas.

Fuels are often classified as either renewable or non-renewable. As mentioned above, definitions of these terms are difficult because most fuels are renewable, eventually. However, geological time scales are involved with such fuels as coal, oil and natural gas and these are generally classified as non-renewable. Other fuels such as wind, solar heat and precipitation, are regarded as renewable. Wood burning fits somewhere between the two classifications. However, in recent years it has been classified as a renewable fuel in that reforestation can replace lost trees in a matter of decades.

Energy from water is probably the most abundant renewable source. It is truly renewable for the foreseeable future in that it depends upon climatic and hydrological conditions which are reasonably constant when measured over 10 to 50 years. The acquisition of energy from water is currently dominated by large scale hydroelectric schemes but alternative methods involving rivers, tides and waves are available or are being developed.

To compare the energy available from different fuels, such as oil and gas, the energy has to be brought to a common unit. For example, one tonne of oil contains a certain inherent amount of energy and this has to be compared with other fuels including electrical energy which is measured in kilowatt hours. Conversion factors are given in the appendix and, for clarity, the ROCK uses mainly the electrical energy unit of kilowatt hours, and its larger multiples.

The first two chapters of this ROCK consider energy derived from all sources, with both a worldwide and then a United Kingdom focus:

- Hydropower in the context of worldwide energy consumption
- Energy consumption in the United Kingdom including targets for renewable energy

Later chapters consider the alternative methods of extracting power and energy from water:

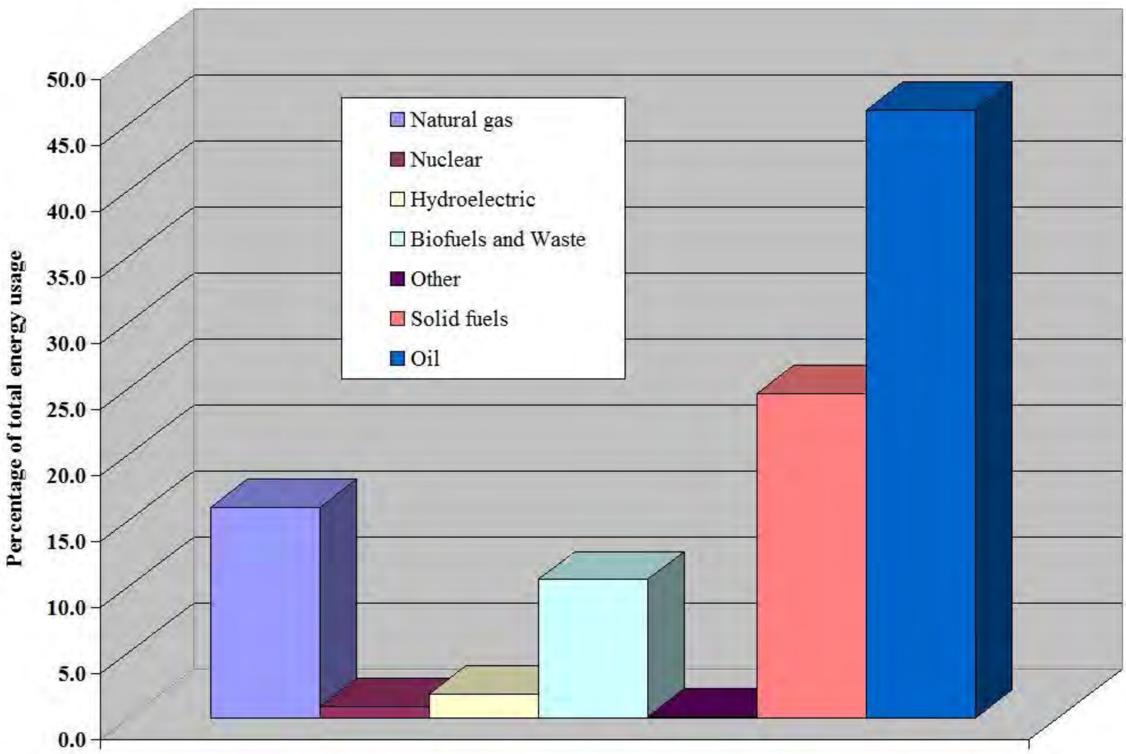
- Large scale hydroelectric schemes
- Run of the river hydroelectric schemes
- Pumped storage schemes
- Tidal barrage schemes
- Energy from waves and tidal currents.

2 Hydropower in the context of worldwide energy consumption

2.1 Worldwide energy consumption

The overall energy scene is complex and has changed dramatically in the last few decades, as reported by the International Energy Agency, see ***International Energy Agency (IEA), 2015***. Energy is used by various sectors including industry, transport, agriculture, commercial services, public services and domestic users. Energy is derived from a range of fuel sources including natural gas, nuclear, hydroelectric, biofuels and waste, solid fuels and oil, together with a range of minor inputs from geothermal, solar and wind sources.

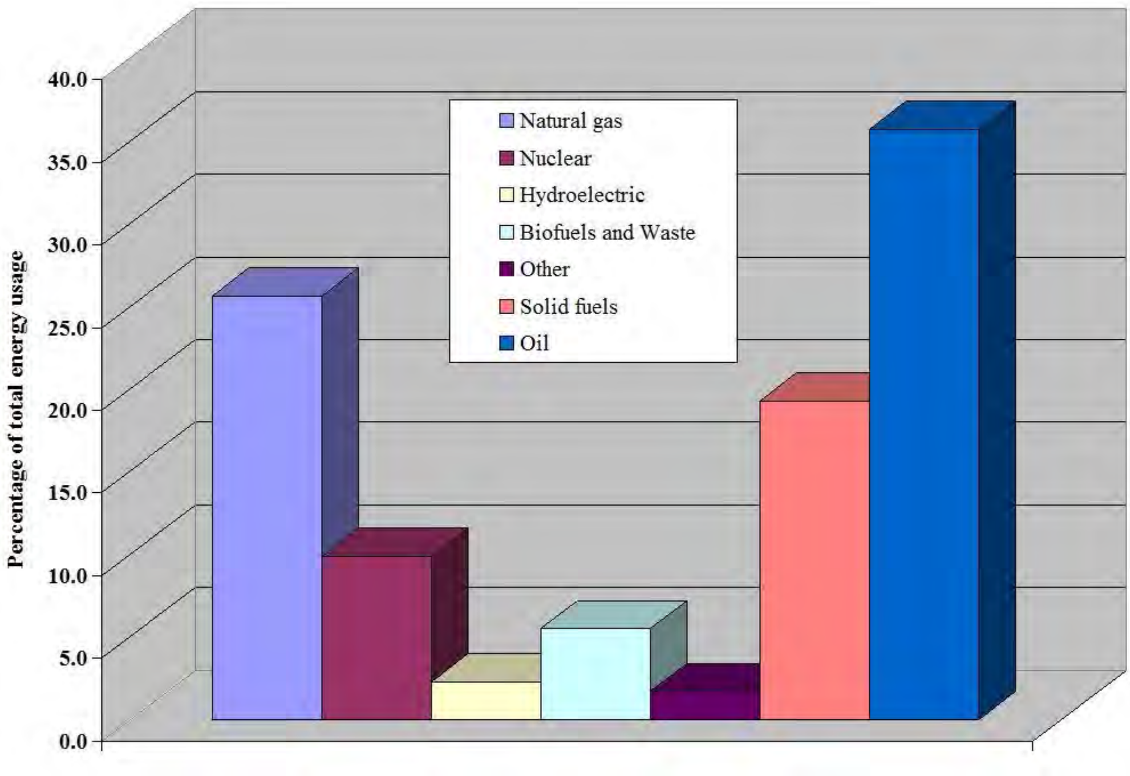
Figure 1 shows details of the worldwide energy supply situation in 1973. Energy from oil represented almost half the energy supplied, 46.1 per cent. Solid fuels provided 24.6 per cent of energy supplies and natural gas 16.0 per cent. Energy from water, almost exclusively from large scale hydroelectric plants, represented 1.8 per cent of worldwide supplies. The total worldwide energy supplied in 1973 was 71 000 terawatt hours (TWh) or 6 100 million tonnes of oil equivalent (Mtoe). See the appendix for conversion factors.



[Other includes geothermal, solar, wind, heat, etc.]

Figure 1 Worldwide energy supply in 1973
Source: International Energy Agency

Figure 2 shows details of the worldwide energy supply situation in 2014. The balance between the various fuels, in the 41 years between the two plots, changed quite dramatically. Energy from oil is still the highest contribution but the proportion has reduced to 35.7 per cent. Contributions, by percentage, from natural gas (25.6 per cent), nuclear (9.9 per cent), hydroelectric (2.3 per cent) have all increased between 1973 and 2010. The use of solid fuels has reduced from 24.6 per cent to 19.3 percent over the period.



[Other includes geothermal, solar, wind, heat, etc.]

Figure 2 Worldwide energy supply in 2014

Source: International Energy Agency

There was a major increase in worldwide energy supplies from all fuel sources between 1973 and 2014. The 2014 supply (157 500 TWh) is well over twice that of the 1973 supply (71 000 TWh). Table 1 shows supplies from individual fuels.

Fuel	Energy supplied (TWh)			Ratios	
	1973	2010	2014	2010/1973	2014/2010
Oil	32 740	47 920	49 100	1.464	1.025
Natural gas	11 360	31 650	34 900	2.786	1.103
Nuclear	640	8 430	7 600	13.17	0.901
Hydroelectric	1 280	3 400	3 800	2.656	1.118
Biofuels and waste	7 460	14 790	16 200	1.983	1.095
Solid fuels	17 470	40 380	45 700	2.311	1.132
Other	70	1 330	200	19.00	0.151
Total	**71 020**	**147 900**	**157 500**	**2.083**	**1.065**

Table 1 Energy contribution by fuel, 1973, 2010 and 2014
Source: International Energy Agency

The data in Table 1 is shown graphically in Figure 3.

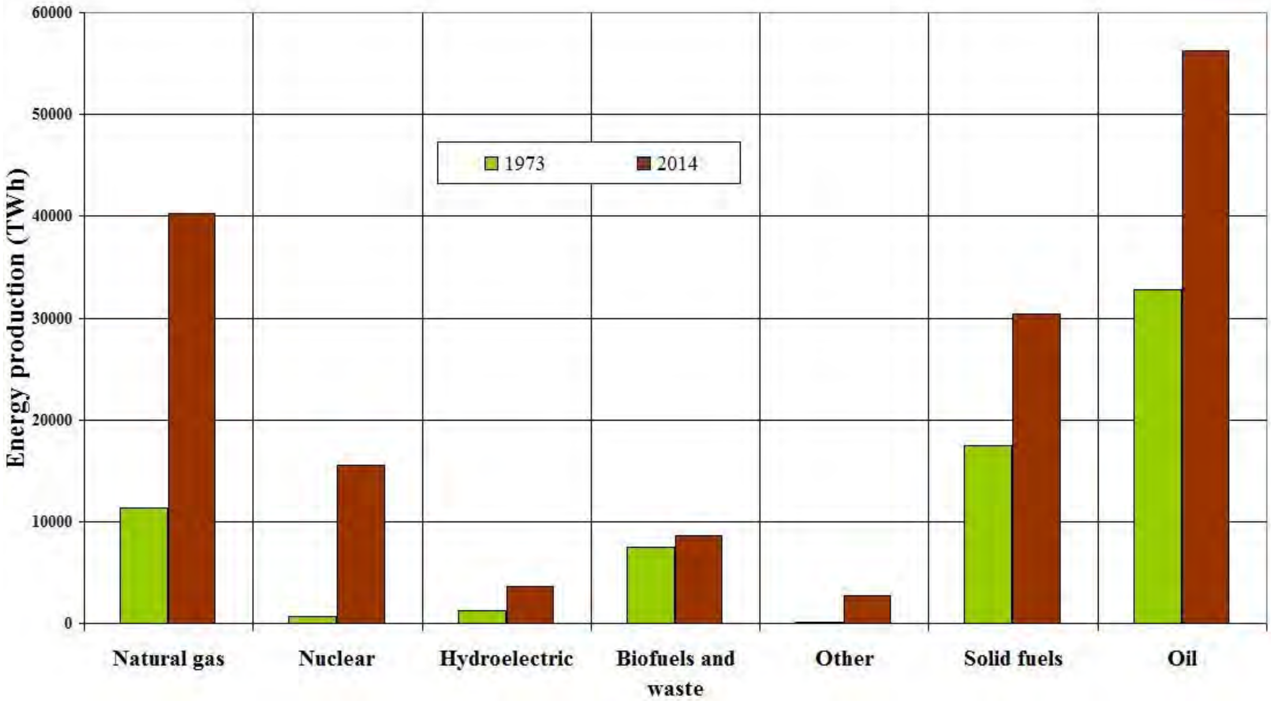


Figure 3 Energy contribution by fuel, 1973 and 2014
Source: International Energy Agency

2.2 Electrical energy consumption

Moving from the overall energy scene to that sector of the energy spectrum which is derived from water, electrical energy becomes the focus. The only exception is where water movement is converted to mechanical energy alone. An example is where water drives a mill wheel which is used directly to grind flour. However, wherever significant quantities of energy are generated by water, that energy is electrical. In hydroelectric schemes the water drives turbines which are connected to electrical generators and the electricity is distributed through a network of power lines. This is a very efficient process.

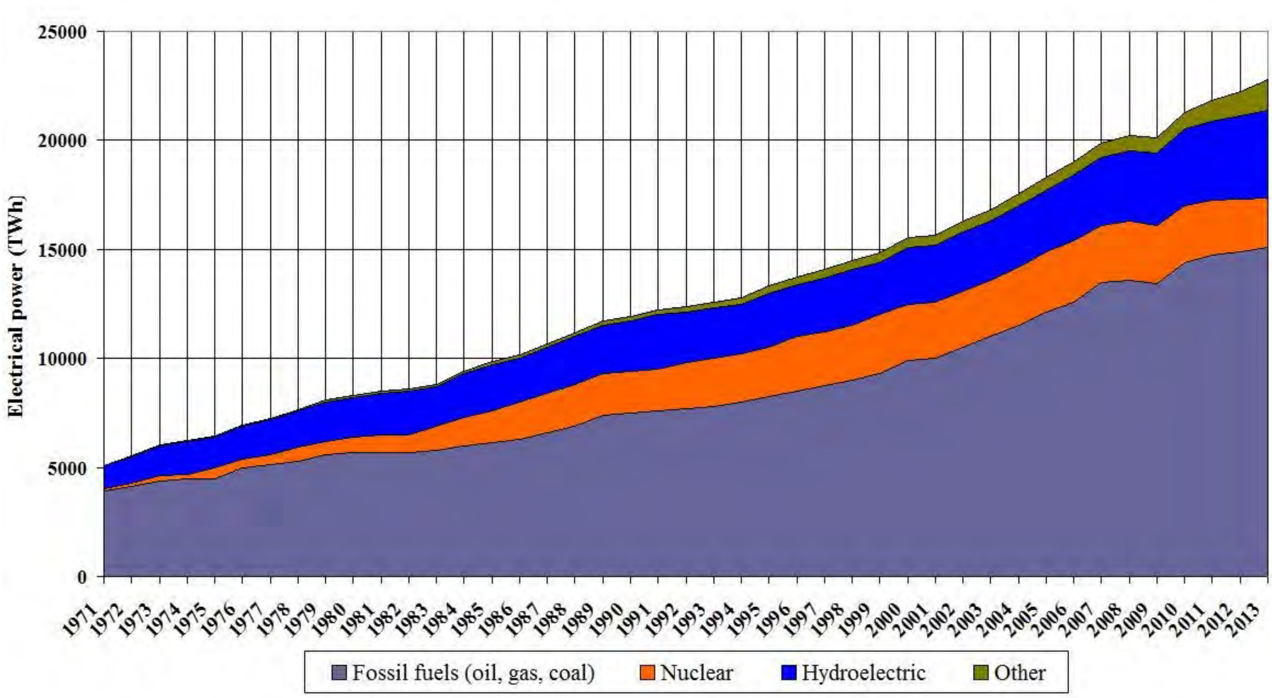
Electricity is also generated in other ways using other fuels. Conventional power stations may use solid fuels, oil or natural gas as the basic provider of energy. The heat energy inherent in these fuels is used to drive steam turbines which in turn drive electrical generators.

Table 2 compares the amount of electricity derived from the basic fuels in 1973 and 2013.

Fuel	**Electrical energy supplied (TWh)**		**Ratio 2013 / 1973**
	1973	**2013**	
Oil	1 510	1 026	0.68
Natural gas	740	5 061	6.84
Nuclear	202	2 472	12.24
Hydroelectric	1 284	3 801	2.96
Biofuels and waste, geothermal, solar, wind, heat	37	1 329	33.49
Solid fuels	2 342	9 631	4.11
Total	**6 131**	**23 322**	**3.80**

Table 2 Fuels for the worldwide generation of electricity
Source: International Energy Agency

Figure 4 shows how the balance between the basic fuels developed between 1971 to 2013.



[Other includes geothermal, solar, wind, biofuels and waste, and heat, etc.]

Figure 4 Worldwide generation of electricity, 1971 to 2013
Source: International Energy Agency

The top ten countries generating electricity from solid fuels, oil and natural gas in 2013 are listed in Table 3.

Solid fuels		Oil		Natural gas	
Country	**TWh**	**Country**	**TWh**	**Country**	**TWh**
China	4 111	Japan	150	United States	1 158
United States	1 712	Saudi Arabia	134	Russia	530
India	869	Iran	71	Japan	402
Japan	337	Mexico	48	Iran	178
Germany	293	Kuwait	39	Mexico	166
South Africa	237	United States	37	Saudi Arabia	150
Korea	223	Pakistan	36	Korea	145
Russia	162	Iraq	28	Egypt	129
Australia	161	Indonesia	27	Thailand	117
Poland	140	Brazil	27	Italy	109
Rest of world	1 338	Rest of world	431	Rest of world	1 982
Total	**9 633**	**Total**	**1 028**	**Total**	**5 066**

Table 3 Electricity derived from solid fuels, oil and natural gas
Source: International Energy Agency

2.3 Electrical energy from water

Chapters 4 to 8 consider energy, almost exclusively electrical energy, derived from water in various ways. However, it is useful in this chapter to establish the current worldwide situation. Which countries are the major producers of electrical energy derived from water? Which countries are very reliant upon electrical energy derived from water?

In 2013 the energy derived from water, largely through hydroelectric schemes, was 3 874 TWh. The major producing countries are shown in Figure 5. To a large extent these figures reflect the geographical nature and the climate of the countries concerned. Major rivers and mountainous terrain combined with abundant precipitation favour the use of water to provide power. China, Brazil, Canada, the United States and Russia are good examples of the areas of the world where the exploitation of water power is attractive.

Figure 5 shows the major producers of energy from water.

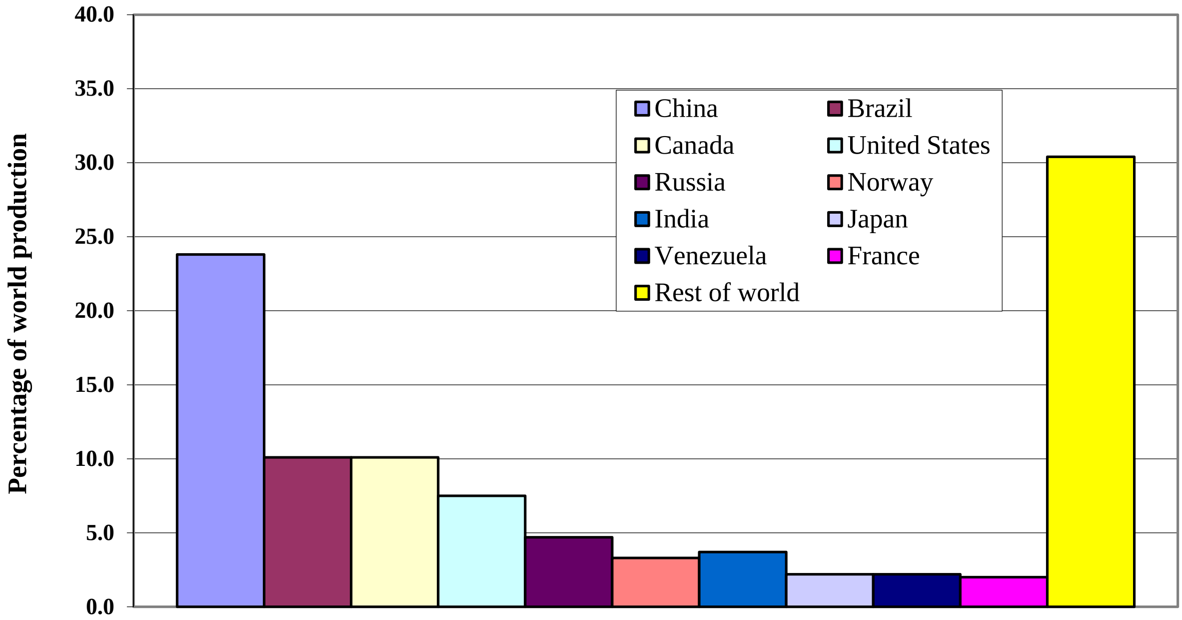


Figure 5 Major producers of energy from hydropower
Source: International Energy Agency

It is also interesting to note those countries which are heavily dependent upon electrical energy derived from water. Here four countries stand apart from the rest of the world, Norway, Brazil, Venezuela and Canada. See Figure 6 for details.

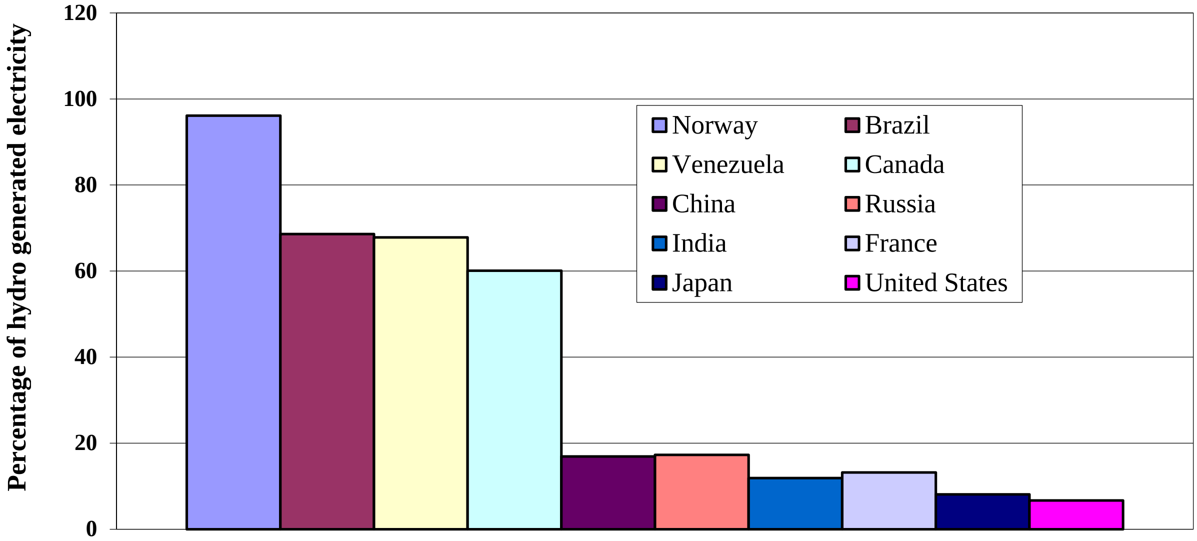


Figure 6 Countries heavily dependent upon hydroelectricity
Source: International Energy Agency

3 Energy consumption in the United Kingdom

Data for energy consumption in the United Kingdom is quoted by the Department of Energy and Climate Change, ***see Department of Energy and Climate Change (DECC), 2014.*** in terms of primary energy and final energy. Primary energy consumption concerns basic fuel sources such as solid fuels, oil, gas, biofuels, wind, waves etc.. Some of these basic fuels are converted into other forms of energy before use. For example, many power stations use gas or solid fuels to generate electrical energy which is a convenient form of energy for transmission and usage. Electrical energy generated in this way features in the final energy balance and the basic fuels used to generate the electrical energy are removed from the final energy balance.

3.1 Primary energy consumption

The data for primary energy consumption is presented in Figure 7. There has been a significant change in the fuel mix used in the United Kingdom since 1970 in terms of these primary fuels. The change broadly reflects:

- The replacement of solid fuels by natural gas
- A steady rise in the use of electricity from renewable sources
- A steady rise in the use of biofuels
- A steady fall in the use of oil products.

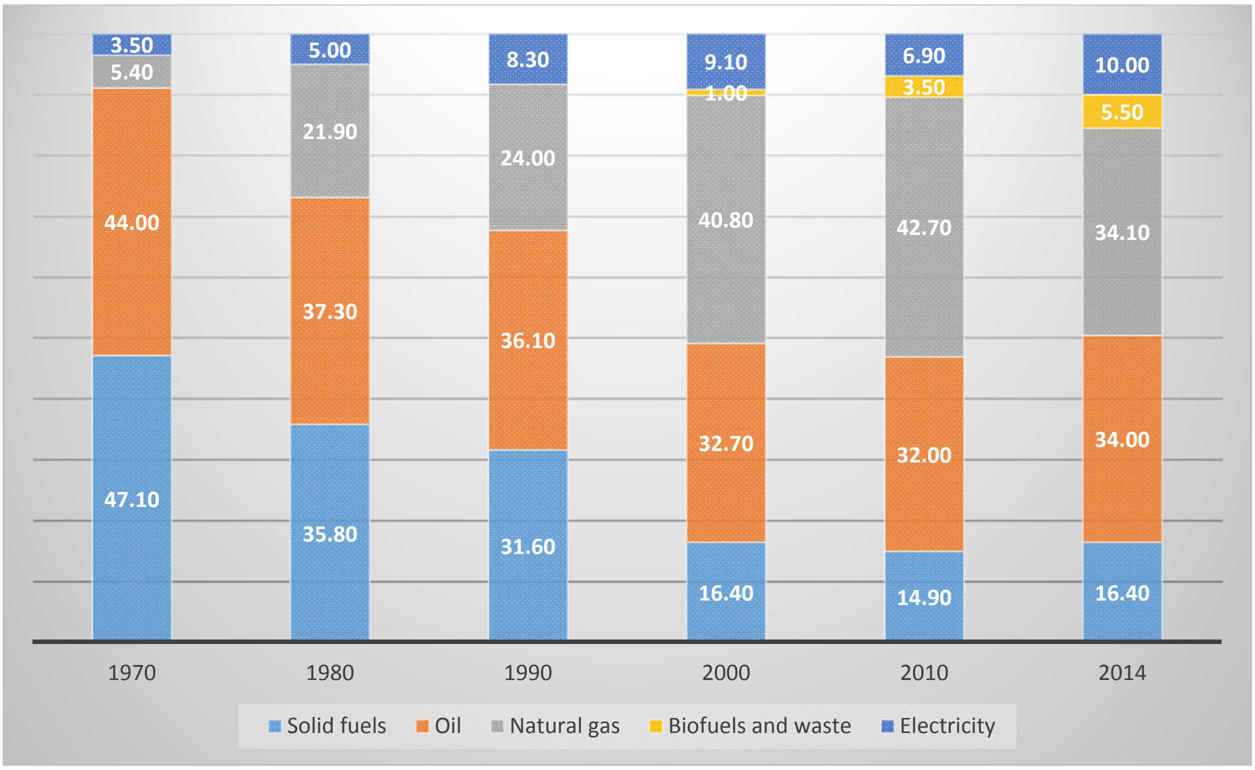


Figure 7 United Kingdom: primary energy consumption by fuel
Source: Department of Energy and Climate Change

3.2 Final energy consumption

In 1970 the actual United Kingdom consumption of energy from fuels derived from natural sources was 1 700 TWh, 2.4 per cent of the worldwide total as reported by the Department of Energy and Climate Change. Total consumption in the United Kingdom has varied from year to year but with no systematic, ongoing trend. Around the year 2000 it reached a peak of 1 800 TWh but the latest data shows a total consumption falling back to the 1970 level.

The data is shown graphically in Figure 8. This figure shows consumption by final users. In particular, the energy used in conventional power stations to generate electricity has been deducted from the primary figures for solid fuels and natural gas.

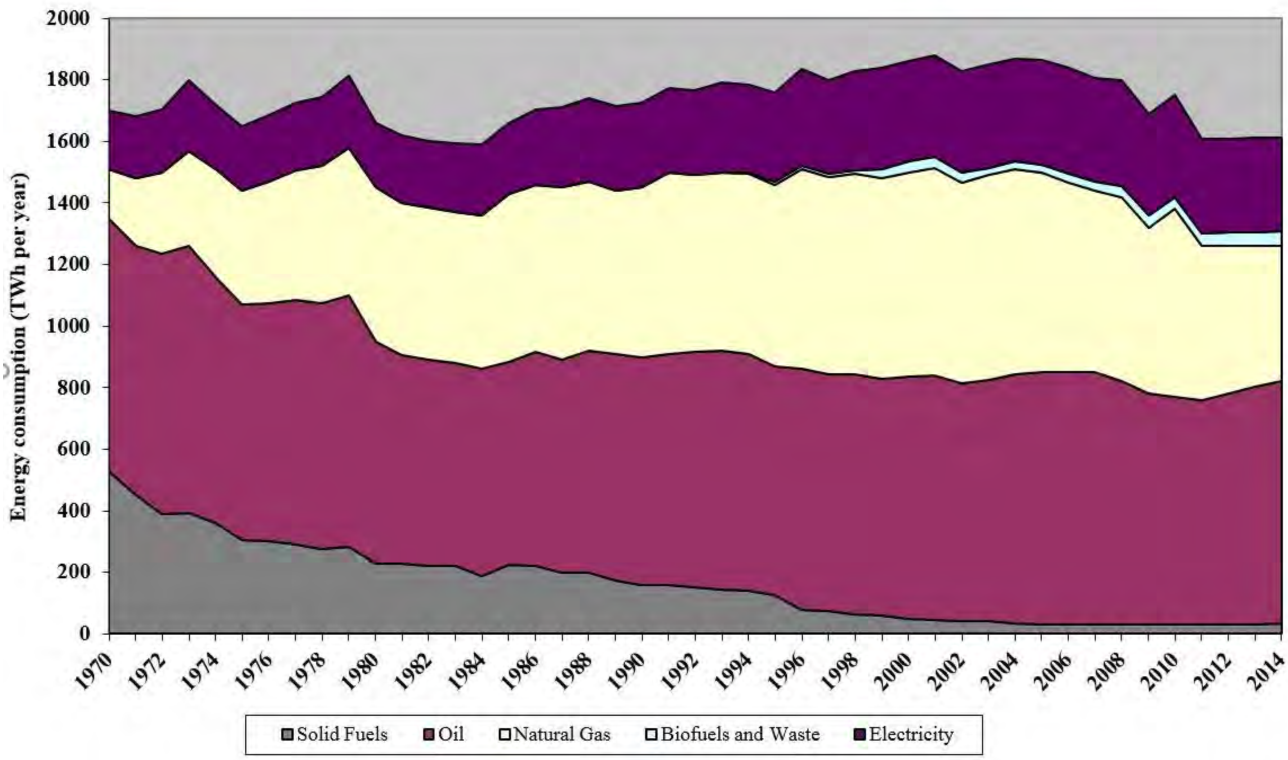


Figure 8 United Kingdom: final energy consumption by fuel
Source: Department of Energy and Climate Change

Comparing Figure 8 with Figure 4 in Chapter 2 it is clear that the worldwide increase in fuel consumption since 1970 is not reflected in the United Kingdom data.

In the UK the use of solid fuels, excluding that which is used in power stations, has fallen from 540 TWh in 1970 to 33 TWh in 2014, largely replaced by natural gas which rose from 170 TWh to 439 TWh. The consumption of electricity increased by

60 per cent over this period from 190 TWh to 303 TWh. Energy from biofuels and waste became significant in the 1980s and rose to 47 TWh by 2014.

3.3 Renewable resources

The United Kingdom is committed to increasing the use of energy from renewable resources. This section gives information on progress in the last decade.

Renewable resources include:

- Wind, including offshore and onshore
- Shoreline waves and tidal currents
- Solar photovoltaics
- Hydroelectric, small and large
- Bioenergy, including landfill gas, sewage sludge digestion, municipal solid waste combustion, animal biomass, anaerobic digestion and plant biomass.

The EU Directive 2009/28/EC promotes the use of energy from renewable sources and sets targets up to the year 2020 for individual Member States. The UK performance against the EU target is shown in Figure 9.

Figure 9 UK progress with renewables against EU targets
Source: Department of Energy and Climate Change

It is not clear what happens beyond 2020. However, the UK Government has aspirations for an 80 per cent cut in carbon emissions by 2050, ***see Department of Energy and Climate Change, 2011***.

Renewables are used in three main sectors:

- Generation of heat
- Vehicular transport
- Generation of electricity

Figure 10 shows the main applications of the various renewable categories as currently defined by the Department of Energy and Climate Change. Biodiesel and bioethanol are used exclusively by the transport industry. Bioenergy, wind, hydro and solar are used mainly in the generation of electricity.

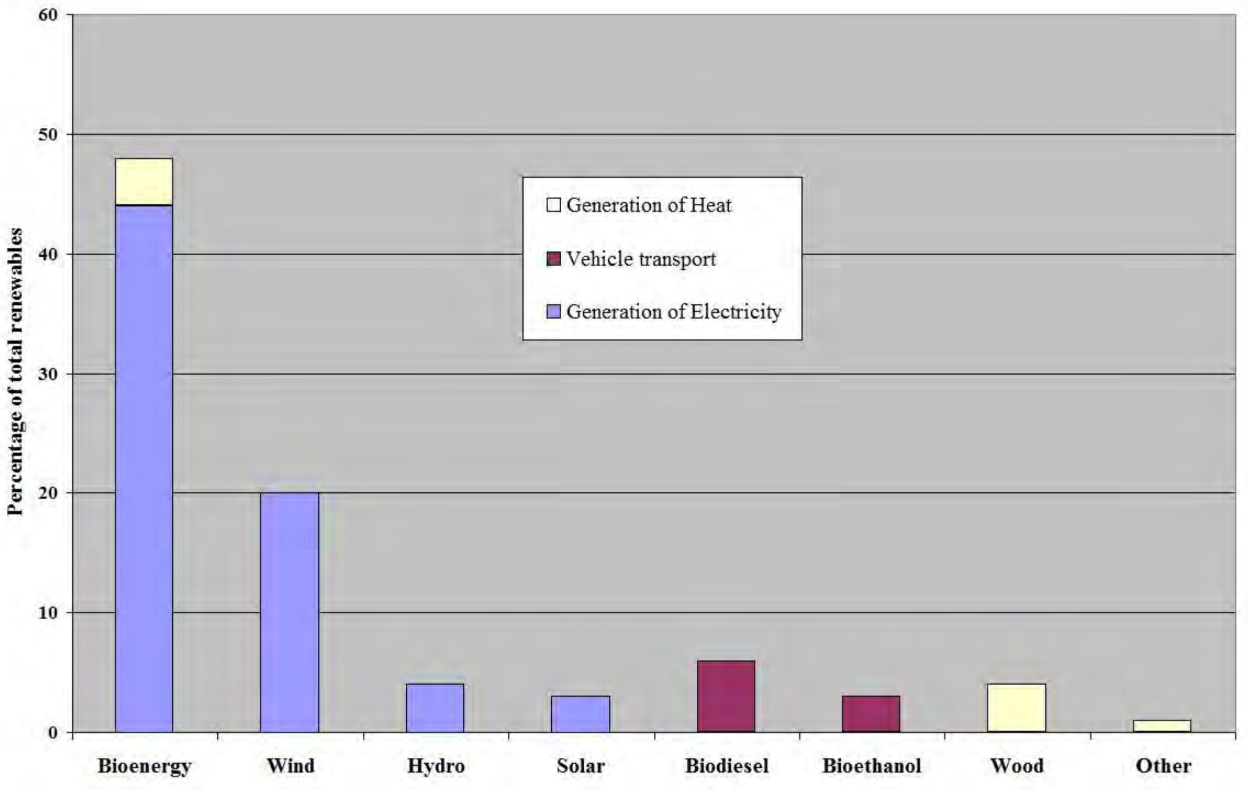


Figure 10 Applications of UK renewable energy sources, 2014
Source: Department of Energy and Climate Change

Figure 11 shows the increase in capacity in recent years which mainly comes from wind farms and bioenergy. The capacity in onshore wind farms currently exceeds the capacity in offshore wind farms.

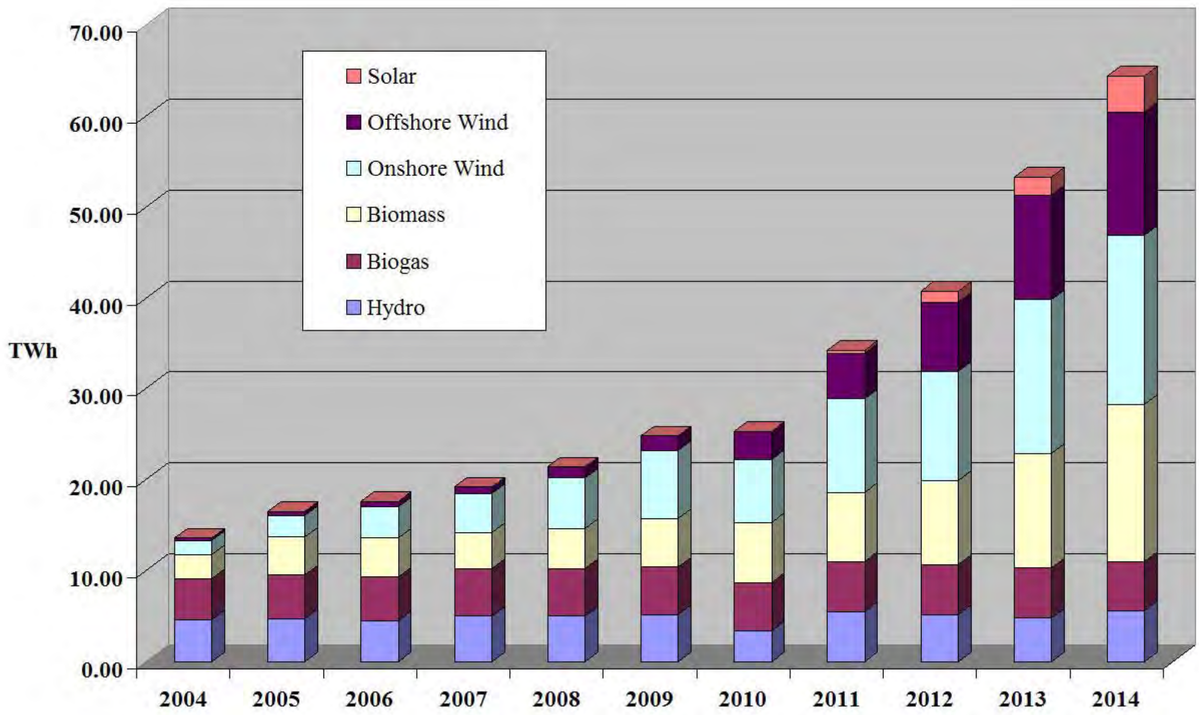


Figure 11 United Kingdom: installed capacity in renewable resources
Source: Department of Energy and Climate Change

Generation of electricity from all renewable resources in 2014 reached 64.4 TWh. The trend since 2004 is shown in Figure 11.

The data in Figure 11 shows variations away from the smooth increase from year to year. The reason is that the load factors for wind and hydro, in particular, vary with weather conditions from year to year.

4 Large scale hydroelectric schemes

Hydroelectricity is the term used to describe electricity generated by hydropower, the production of electrical energy through the use of falling, flowing water. Hydroelectricity accounted for 16 per cent of global electricity consumption in 2010 and production reached over 3 900 TWh in 2013. Comprehensive information about the design, performance and worldwide usage of large scale hydroelectric schemes is provided by the International Commission on Large Dams, ***see International Commission on Large Dams (ICOLD), 2011***.

Hydropower is used in more than 150 countries. The largest concentration of schemes is in the Asia-Pacific region which generates 30 per cent of the global total. Hydroelectric schemes have increased in size as the technology has developed and there are now three schemes with an installed capacity of more than 10 GW:

- Three Gorges hydroelectric scheme in China
- Itaipu hydroelectric scheme in Brazil
- Guri hydroelectric scheme in Venezuela.

Plate 1 The Three Gorges hydroelectric scheme, Yangtze River, China
Source: https://pages.vassar.edu/

The Three Gorges Dam is a hydroelectric scheme which spans the Yangtze River. It has the world's largest power station in terms of installed capacity at 22,500 MW. In 2014 the dam generated 98.8 TWh of electricity, setting a new world record by 0.17 TWh previously held by the Itaipu scheme on the Brazil/Paraguay border in 2013 of 98.63 But in 2015, the Itaipu power plant produced 89.5 TWh, while production by the Three Gorges scheme was 87 TWh.

Plate 2 Itaipu hydroelectric scheme, Rio Parana, Brazil / Paraguay
Source: http://www.aboutcivil.org/

Itaipu dam is the largest operating hydroelectric facility in the world in terms of annual energy generation. It generated 94.7 TWh in 2008 and 91.6 TWh in 2009. The scheme has an installed capacity of 14 000 MW and operates at a design head of 118 m. It supples around 90 per cent of Paraguay's, and 20 per cent of Brazil's electricity.

The electrical energy available at any particular hydroelectric scheme is a function of the head on the turbines, the flow through the turbines and the duration of operation of the turbines. Hence the higher the dam and the larger the reservoir capacity (or replenishing flow), the higher the anticipated output. Examples of recent schemes showing the ten highest dams and the ten largest reservoirs in the world are given in Tables 4 and 5.

Dam	Date commissioned	Height (m)	Location
Rogun	UC	335	Vakhsh, Tajikistan
Jinping	2013	305	Yaling, China
Nurek	1980	300	Vakhsh, Tajikistan
Xiaowan	2010	292	Lancang, China
Xiluodu	2013	286	Jinsha, China
Grande Dixence	1965	285	Dixence, Switzerland
Enguri	1987	272	Enguri, Georgia
Vajont	1959	262	Vajont, Italy
Nuozhadu	2012	262	Lancang, China
Manuel M. Torres	1981	261	Grijalva, Mexico
Tehri	2006	261	Bhagirathi, India

Table 4 The ten highest dams
Source: International Commission on Large Dams

Reservoir	Date commissioned	Reservoir capacity (km^3)	Country
Kariba	1959	181	Zambezi, Zimbabwe / Zambia
Bratsk	1964	169	Angara, Russia
Volta	1965	150	Volta, Ghana
Manicouagan	1968	142	Manicouagan, Canada
Guri	1986	135	Caroni, Venezuela
Nasser	1971	132	Nile, Egypt
Williston	1967	74	Peace, Canada
Krasnoyarsk	1967	73	Yenisei, Russia
Zeya	1978	68	Zeya, Russia
Robert-Bourassa	1981	62	La Grande, Canada

Table 5 The ten largest reservoirs by volume
Source: International Commission on Large Dams

The design of large dams is a long and complex process. Suitable dam sites are not unlimited and the choice of site depends on the economic and other benefits which may accrue from a particular scheme and the cost to develop and build the scheme. At an early stage extensive modelling exercises are carried out in order to evaluate the problems which may occur during and after construction. These models also help with the detailed design of the scheme.

Numerical (computer) models are used to evaluate:

- Hydrological aspects of the catchment
- Water storage within the reservoir
- Sedimentation within the reservoir
- Flood attenuation benefits to the downstream community
- Simulation of annual power outputs from the proposed scheme
- Simulation of irrigation or water supply outputs from the proposed scheme.

Physical models are used to evaluate specific aspects of the proposed scheme:

- Flow bypass arrangements during construction
- Configuration and design details of spillways
- Control of erosion immediately downstream of the dam.

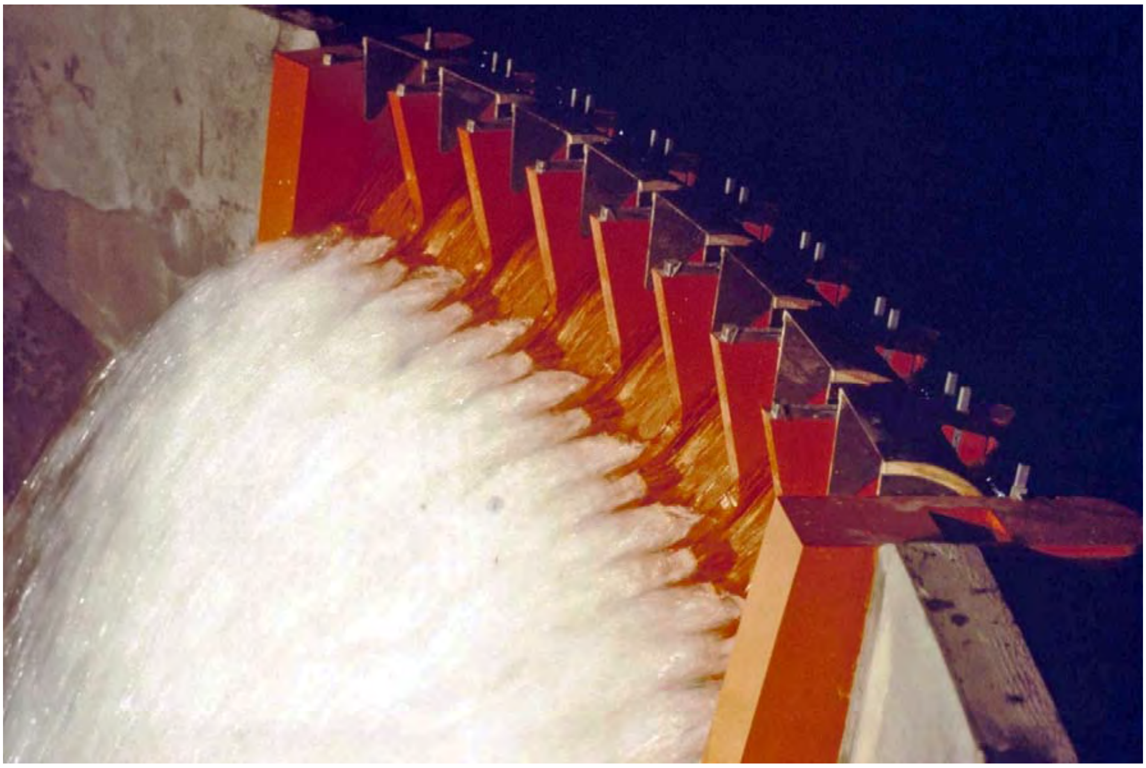


Plate 3 Spillway model for Victoria Dam, Mahaweli River, Sri Lanka
Source: HR Wallingford

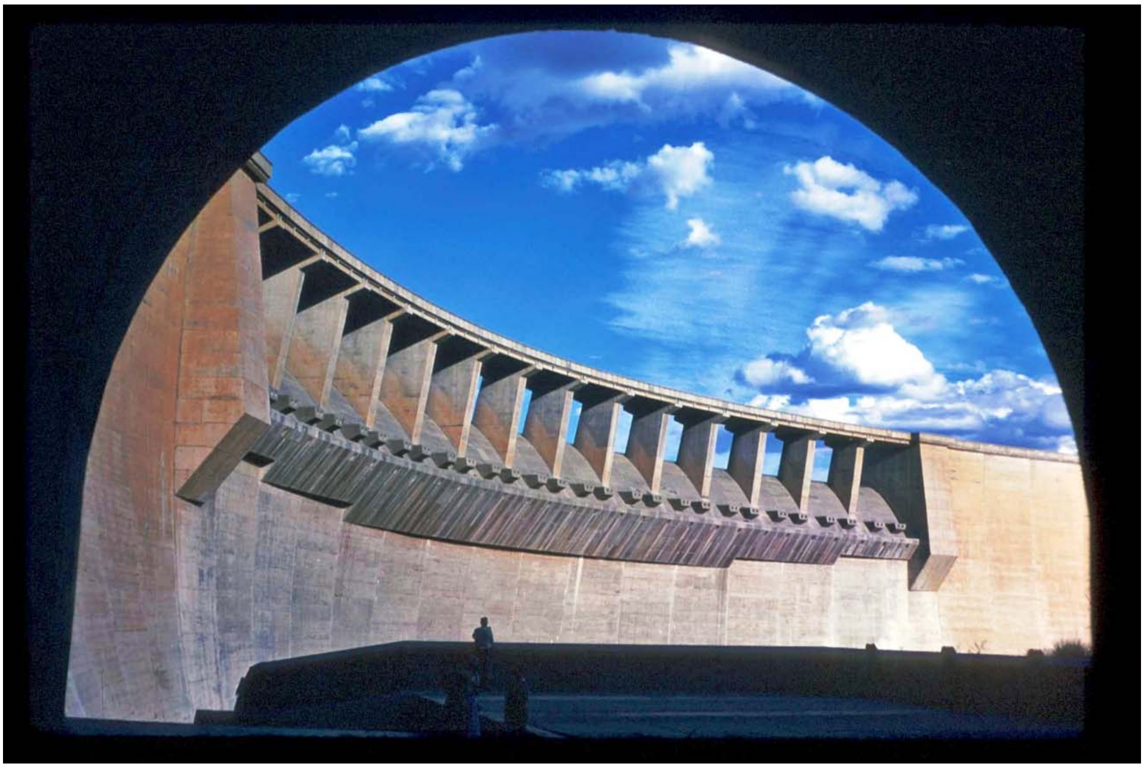


Plate 4 Spillway of Victoria Dam, Mahaweli River, Sri Lanka
Source: W R White

Plate 5 Spillway model for El Chocon Dam, Rio Limay, Argentina
Source: HR Wallingford

Plate 6 Spillway of El Chocon Dam, Rio Limay, Argentina
Source: W R White

The basic principle behind hydroelectric power is to store water at a high elevation and then to use that potential energy to drive turbines at a lower elevation. The type of turbine depends upon the head difference between the stored water and the turbine. As an example, Pelton Wheel turbines are suitable for high heads whereas Kaplan turbines become the more efficient solution at modest heads. In all cases the turbines are connected to generators to produce the electrical output.

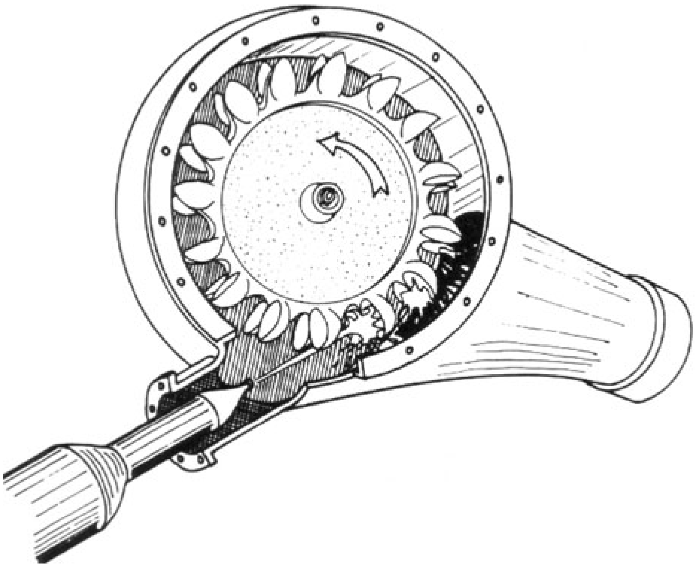


Plate 7 Pelton wheel turbine
Source: www.hydrogenappliances.com

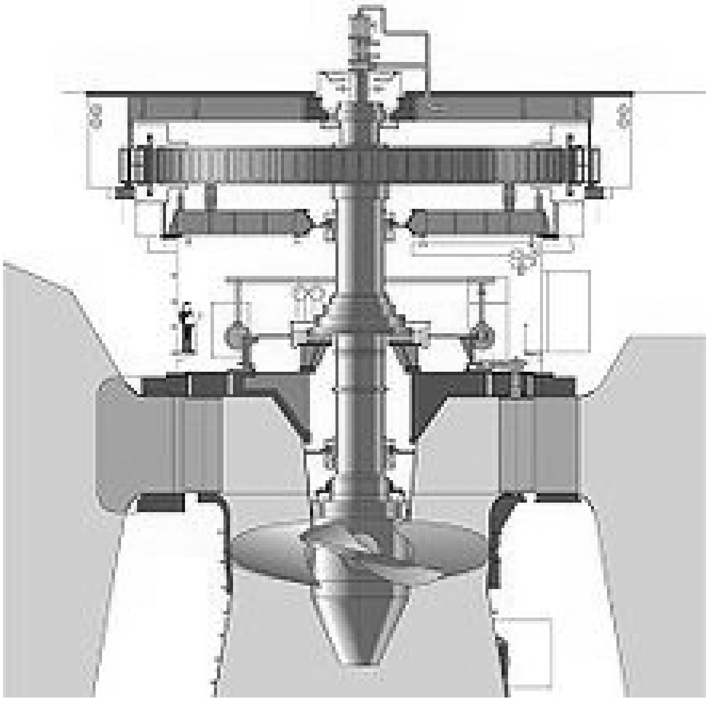


Plate 8 Kaplan turbine and generator
Source: https://en.wikipedia.org/

Large scale hydroelectric schemes have advantages as follows:

- The power available can be predicted with some certainty at the design stage where long hydrological records are available.

- The power generated is renewable and only depends upon natural precipitation.
- The cost of hydroelectricity is relatively low because it uses proven and efficient technologies.
- Power output is flexible because the plant can be regulated easily to match demand.
- Once constructed, hydroelectric schemes produce little waste, and greenhouse gas emissions are negligible compared with energy plants powered by fossil fuels.
- Many schemes also provide regulated water supplies for irrigation.

Large scale hydroelectric schemes have disadvantages as follows:

- Hydroelectric schemes can change river flow characteristics downstream and can affect local ecosystems.
- The construction of hydroelectric schemes, involving dams and large reservoirs, often involves the displacement of people and wildlife.
- Siltation in reservoirs can reduce available water but there are operational and maintenance procedures which can minimise this effect, ***see White W R, 2001 and Palmieri A, Shah F, Annandale G W and Dinar A, 2003***.

5 Run of the river hydroelectric schemes

The difference between run of the river and traditional hydro power generation is that a run of the river scheme does not require a large reservoir and tends to be on a smaller scale than the reservoir based schemes. Run of the river schemes have a limited amount of storage within the river channel upstream of a weir or dam structure and are ideally built on rivers with a consistent and steady flow regime. The limited amount of storage is usually referred to as "pondage". Once constructed, these schemes produce negligible greenhouse gas emissions and they run using a renewable, non-depleting resource.

Within this concept there are a range of options:

1. Schemes on major rivers where enough pondage can be provided within the upstream river banks.
2. Off-line schemes which extract a proportion of the river flow and transmit the extracted flow to a power station lower down the catchment, usually through pressurised pipework but occasionally in open channels which broadly follow the contours of the valley.
3. Small schemes which generate some electricity for local use.

This chapter gives some information about these three options, with examples.

Factors which favour run of the river hydroelectric schemes depend upon the option chosen and may include:

Relatively low environmental impacts
Run of the river schemes are considered to provide ‘green energy’ with less environmental impact than large scale schemes because they do not require large dams and large reservoirs. This reduces the area affected by the scheme and hence the interference with wildlife, plant and human populations. This factor applies to all three options.

River morphology
Run of the river schemes can be designed to take only a small percentage of the total river flow, thus having little impact upon the natural movement of river sediments and fish migration within the river system. However, a balance needs to be struck between energy extraction, which increases with the proportion of the water taken from the river, and detrimental environmental consequences which increase at the same time. This factor applies to options 2 and 3 but may not apply to option 1.

Factors which count against run of the river hydroelectric schemes include:

Continuity of supply
Run of the river hydroelectic schemes cannot be relied upon to meet demand at all times because they have little or no capacity for storing energy. They provide more electrical energy during times when seasonal river flows are high, and less during extended dry periods. This may not apply to options 2 and 3 where water used for hydroelectric purposes is only a small proportion of the natural river flow.

Some environmental impacts
The effects on the natural habitat can be a concern with run of the river schemes. Reduction of natural river flows, which may change water temperature, depth, velocity and the growth of vegetation, can change the quality of the habitat for fish and other organisms. This applies particularly to option 2 schemes where water taken for hydroelectric purposes may be a high proportion of the natural river flow.

5.1 Schemes on major rivers

Table 6 lists some large run of the river hydroelectric schemes on a worldwide basis, showing installed power, the river on which they are situated and the location by country. Also shown are the date of commissioning and the head on the turbines.

Although these schemes are listed as run of the river, some of the larger schemes have long, named, "lakes" upstream of the control structure which are contained mainly within steep valleys. These are marked with an asterisk in Table 6.

Station	Installed capacity (MW)	River	Country	Date commissioned	Head (m)
Beauharnois	1 903	St Lawrence	Canada	1961	24
Chief Joseph *	2 620	Columbia	United States	1979	72
The Dalles *	1 779	Columbia	United States	1952	79
Jean-Lesage	1 145	Manicouagan	Canada	1967	94
Jinping-II	4 800	Yalong	China	2014	37
Jirau	3 300	Madeira	Brazil	2012	15
John Day *	2 160	Columbia	United States	1971	56
Karcham Wangtoo	1 000	Sutlej	India	2011	98
Kettle	1 220	Nelson	Canada	1973	30
La Grande-1	1 436	La grande	Canada	1995	28
Limestone	1 340	Nelson	Canada	1992	28
Outardes-3	1 026	Outardes	Canada	1969	76
Santo Antonio	3 150	Madeira	Brazil	2011	14
Tala	1 020	Wangchu	Bhutan	2007	92

Table 6 Some large run of the river hydroelectric schemes
Source: International Energy Agency

Plate 9 John Day Dam, Columbia River, United States
Source: Google Earth

The John Day Dam is a concrete gravity run of the river dam spanning the Columbia river in the north western United States. It is located 45 km east of the city of The Dalles, Oregon.

5.2 Off-line schemes which extract a proportion of the river flow

These smaller run of the river schemes are usually defined as ones with no more than 48 hours of water supply. The main river structure is a weir with a small head pond which delivers water through a delivery pipe or penstock. The pressurised delivery pipe connects the head pond to the power station which is at a much lower level. The energy extracted from the water depends on the flow rate and on the difference in height between the source and the water's outflow.

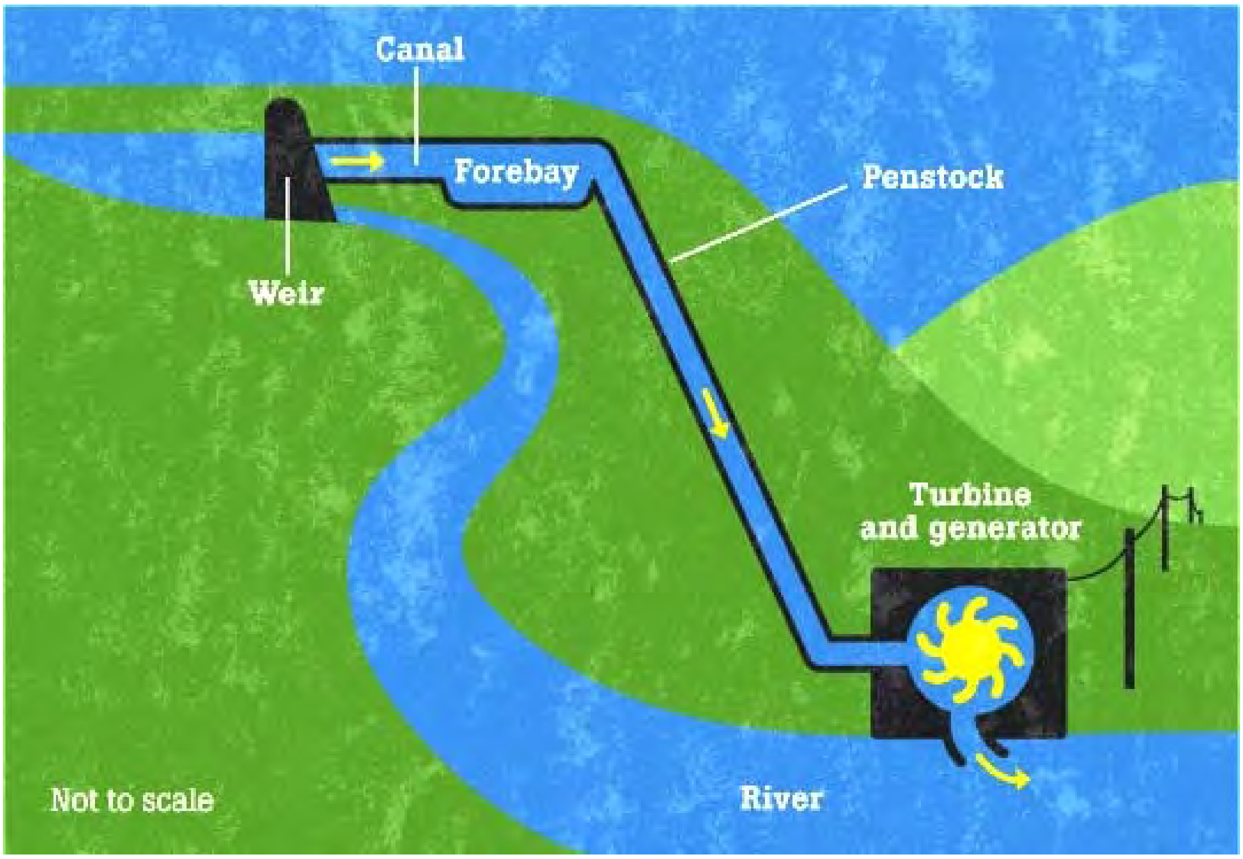


Plate 10 Typical arrangement for off-line run of the river schemes
Source: www.ashden.org

An intake weir, usually a gated structure, provides a head pond from which water is extracted. A pressurised pipe or, in some cases an open channel, conveys water to the location of the power house, which contains turbines and generators. A tailrace channel, or pipe, returns the diverted water to the river.

Table 7 lists some of the larger off-line run of the river hydroelectric schemes of this type on a worldwide basis, showing installed power, the river on which they are situated and the location by country. Also shown are the date of commissioning and the head on the turbines, where available.

Station	Installed capacity (MW)	River	Country	Date commissioned	Head (m)
Nathpa Jhakri	1 500	Satluj	India	2004	428
Ghazi Barotha	1 450	Indus	Pakistan	2002	76
Tianshengqiao II	1 320	Nanpan	China	1997	59
Pandoh	990	Beas	India	1977	335
Neelum - Jhelum	969	Neelum	Pakistan	2012	420
Gilgel Gibe II	420	Gilgel Gibe	Ethiopia	2010	500
Ranganadi	405	Ranganadi	India	2001	68

Table 7 Some large off-line run of the river hydroelectric schemes
Source: International Energy Agency

The Ghazi Barotha scheme is a good example of one of these larger run of the river schemes and is shown in the satellite image below. Water is extracted from the Indus at a control structure near the village of Ghazi, a few kilometres downstream of Tarbela dam. This structure is seen towards the left of the image. Flow is then taken through an open channel to a head pond immediately upstream of the power station at Barotha where the flow is returned to the Indus through the power station.

Plate 11 Ghazi Barotha hydroelectric scheme, Pakistan
Source: Google Earth

Water is diverted from the Indus river near the town of Ghazi about 7 km downstream of Tarbela dam. It then runs through a 100 metre wide and 9 metre deep open power channel down to the village of Barotha where the power complex is located. In the reach from Ghazi to Barotha, the Indus River falls by 76 meters over a distance of 63 km. After passing through the powerhouse, the water is returned to the Indus.

Whereas these larger run of the river schemes are often designed to take a high proportion of river flows, subject to the availability of water and the requirements of maintaining stipulated compensation flows to the downstream reach, there are a multitude of schemes of a much lower capacity used throughout the world for specific purposes. For example, a railway company may develop a modest scheme simply to supply power for its own requirements.

A typical small-scale scheme might have installed power of 10 MW to 15 MW. This compares with some large scale hydroelectric schemes with installed capacities in excess of 10 GW, see Chapter 4.

5.3 Small schemes which generate some electricity for local use

Existing river structures have been built for various purposes including:

- measurement of river flows to provide hydrometric data used in the assessment of water resources and/or flood frequencies
- control of upstream water levels for water offtakes
- creation of a head loss to provide energy for mills, etc.
- creation of navigable depths for river traffic.

These structures are commonly found in developed countries but less so elsewhere. In the UK there is an interest in harnessing this potential source of energy to provide electrical power for local communities. Certain types of low head turbine have gained approval from an environmental point of view including traditional water wheels of various types, propeller turbines and Archimedean screw turbines.

These small schemes vary in output depending upon the available flow and the difference between upstream and downstream water levels. One classification of these schemes is as follows:

Mini-hydro

- Power output between 100 kW and 1 MW
- Most often connected to the national grid
- An estimated 100 to 150 potential sites in the UK

Micro-hydro

- Power output between 5 kW and 100 kW
- Usually providing power for small communities or commercial enterprises. Some are connected to the national grid
- A large number of potential sites in the UK

The British Hydro Association provides information on current operational schemes and lists forty installations rated between 50 kW to 100 kW.

These schemes are of a modest size and are, as yet, of unproven reliability. They do provide a green and reliable source of energy but their contribution is small when judged within the context of the total UK power requirements.

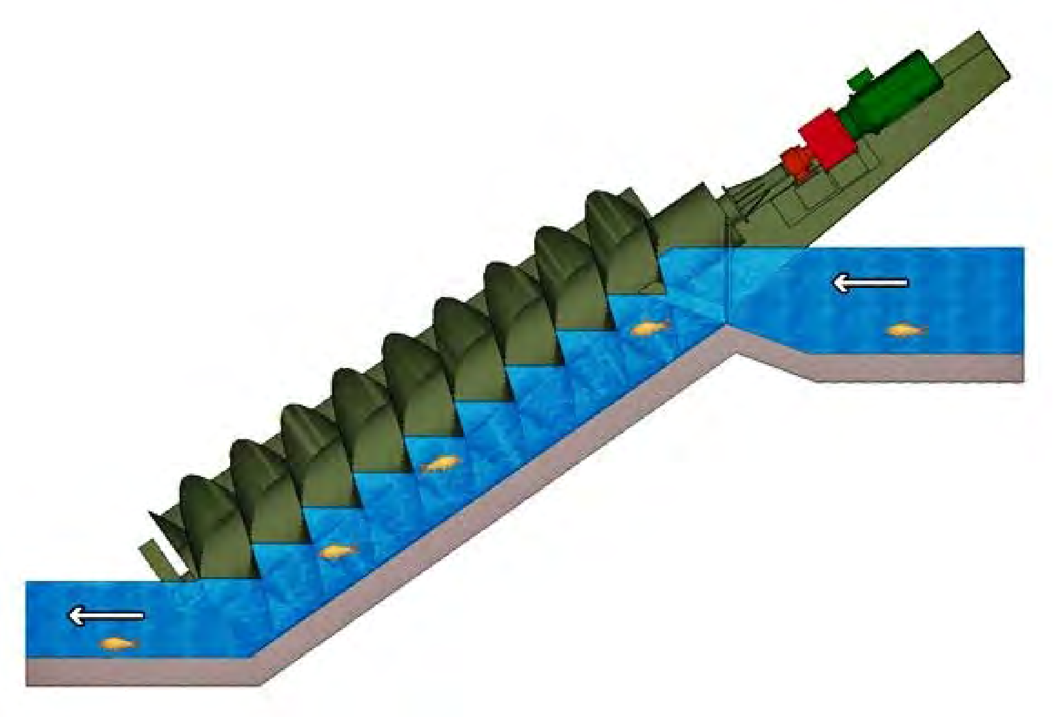


Plate 12 Archimedes screw
Source: www.archimedeshydroscrew.com

The Archimedes screw has been used for many years to lift water from one level to another, being driven by an electric motor. However, the device can be used "in reverse" to generate power.

6 Pumped storage schemes

Pumped storage hydroelectric schemes help to balance supply and demand over a period of fluctuating load. It is not possible to store large quantities of electricity per se and pumped storage schemes utilise water stored at a high elevation as potential electrical energy. Water is pumped from a lower elevation reservoir to a higher elevation during periods of low demand for electricity, usually during the night. During periods of high electrical demand, the stored water is released through turbines to produce electricity, thereby augmenting power from base load stations. Pumped storage schemes are net users of electricity because more energy is consumed in the pumping process than is later generated from the turbines.

Pumped storage is the only practical way of storing large quantities of (potential) electrical energy. The principles are shown in the illustration below.

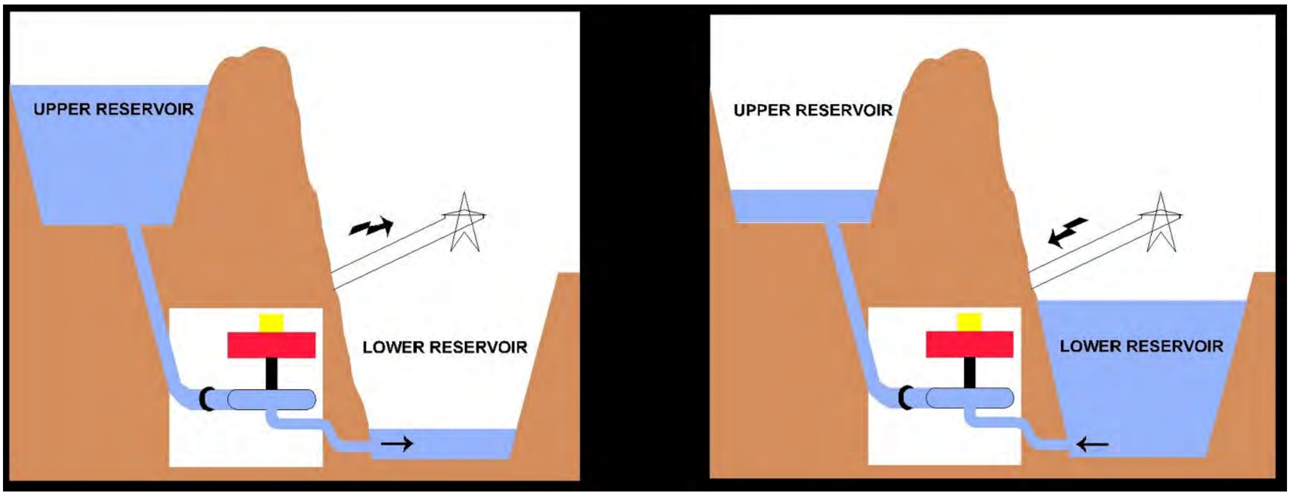


Plate 13 Pumped storage hydroelectric scheme
Source: www.eskom.co.za

Pumped storage schemes store potential energy during periods of low electrical demand and release energy during periods of high electrical demand, thereby helping to satisfy demands which fluctuate on a daily basis.

6.1 Worldwide

Estimates of the worldwide generating capacity of pumped storage schemes vary with source but the figure was between 100 GW and 130 GW as of 2010. It has been estimated that the energy produced by these schemes worldwide is around 5 500 GWh per year.

The five largest operational pumped storage schemes are given in Table 8.

Station	Country	Capacity (MW)
Bath County	United States	3 000
Guangdong	China	2 400
Huizhou	China	2 400
Okutataragi	Japan	1 930
Ludington	United States	1 870

Table 8 Five large pumped storage schemes
Source: www.wikipedia.org

6.2 United Kingdom

The best known pumped storage scheme in the United Kingdom is at Dinorwig, near Llanberis in North Wales. It was the largest pumped storage scheme in Europe when completed in 1984. The upper reservoir used is Marchlyn Mawr, a natural lake the capacity of which was increased by the building of a rockfill dam with asphaltic concrete on its face. The station's machinery is housed in nine man-made caverns, the largest of which is 180 m long, 24 m wide and 60 m high. There are other shafts and galleries for control equipment, and 16 km of tunnels. Great care was taken not to disturb the local environment. The outgoing transmission cables are buried underground for the first 6 miles. Stone and debris from the works was tipped into old quarries and into Llyn Peris. The installed capacity is 1 800 MW.

The illustration below shows the upper and lower lakes used at Dinorwig.

Plate 14 Dinorwig pumped storage scheme, United Kingdom
Source: Google Earth

The pumped storage scheme at Dinorwig in North Wales has been in operation for almost 30 years. It provides a valuable balancing element within the national grid of the United Kingdom.

7 Tidal barrage schemes

A tidal barrage is a dam-like structure used to capture the energy from water, moving in and out of a river or estuary, from tidal flows. Instead of damming water on one side like a conventional dam, a tidal barrage first allows water to flow into a river or estuary during rising tides, and releases the water back during falling tides. Flows are controlled by sluice gates within the barrage structure. Turbines are placed adjacent to the sluices and these capture the energy as the water flows in and out. Generators connected to the turbines provide the electrical output.

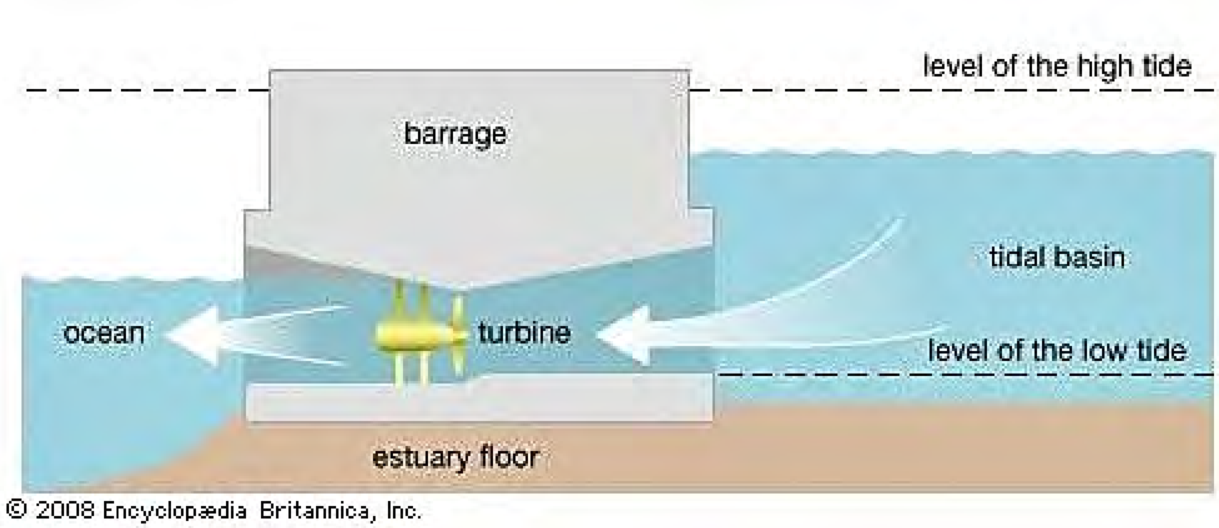


Plate 15 Tidal barrage schematic, ebb generation
Source: Encyclopaedia Britannica

Tidal barrage schemes provide a means of harnessing tidal energy, a renewable and predictable source, in estuaries and tidal rivers. They are most attractive where there is a large tidal range and where significant upstream storage is available.

A tidal barrage scheme involves a structure which creates a reservoir on the upstream side. Typically this will include caissons, which house sluices and turbines to control water flows and power generation, and solid embankments elsewhere. If shipping through the barrage is required then a ship lock will be provided.

Only a few such plants exist. The first was La Rance Tidal Power Station, in France, which has been operating since 1966, and has a capacity of 240 MW. A larger 254 MW plant began operation at Sihwa Lake, Korea, in 2011. Smaller plants include one on the Bay of Fundy, and another across a small inlet in Kislaya Guba, Russia. A number of proposals have been considered for a barrage across the River Severn estuary, from Brean Down in England to Lavernock Point near Cardiff in Wales.

Barrage systems may involve high civil infrastructure costs associated with extensive works in estuaries. Environmental issues need careful attention both during construction and after commissioning.

There are a range of methods of generating electricity from tidal barrages:

- ebb generation where the upstream basin is filled through sluices during the in-coming tide and the turbines operate as the basin empties on the falling tide
- flood generation where the turbines operate during the in-coming tide
- a combination, with some generation on both the ebb and flood tides.

The construction of a tidal barrage changes the environment of the estuary:

- the flow of salt water in and out of the estuary is affected
- tidal levels and sequences upstream of the barrage are affected
- marine mammals may be affected by changes in salinity and levels upstream of the barrage
- during construction the flora and fauna, mainly around the upstream basin, may be affected
- the changes in salinity and levels may affect the turbidity of the water and the settlement and re-suspension of fine sediments.

Whilst the above list of environmental effects seems a long one, those schemes which are currently in operation have shown that disruption to the ecosystems is relatively modest once the scheme has been running for a decade or so.

7.1 European experience

La Rance Barrage is the world's first tidal power station. The facility is located on the estuary of the Rance river, in Brittany, France. Opened on the 26th November 1966, it is currently operated by Électricité de France (EDF), and is one of the largest tidal power stations in the world, in terms of installed capacity. With a peak rating of 240 MW, generated by its 24 turbines, it has an annual output of approximately 600 GWh. The development costs were high but these have now been recovered and electricity production costs are lower than that of nuclear power generation.

The tidal plant produces a source of energy that is clean, renewable and sustainable. It has no impact on climate because it does not emit any greenhouse gases. The pattern of the tides is preserved so that the impact on species living in the estuary is minimal. The operator monitors the tides and weather forecasts to program the barrage operations on a weekly basis.

A canal lock in the west end of the dam permits the passage of 20 000 vessels each year between the English Channel and the estuary. The highway on the barrage linking Dinard and La Rance is used by 26 000 vehicles each day. The facility attracts approximately 70 000 visitors per year. The mean water level in the lagoon is higher than it was before the construction, which has promoted an increase in boating and sailing activities.

Since the construction of the barrage a new ecological equilibrium has been established in the estuary and there is an abundance of fish, bird and other wild life. The barrage has caused limited siltation of the Rance estuary but this has been manageable. The tides still flow in the estuary and the operator adjusts the tidal levels to minimize the biological impact. Sand-eels and plaice have reduced in numbers but sea bass and cuttlefish have returned to the river.

Plate 16 La Rance tidal barrage, France
Source: https://www.betterworldsolutions.eu/

The tidal barrage at La Rance has been in operation for 46 years. The initial capital cost has been shown to be worthwhile and environmental issues have not overshadowed the scheme.

8 Energy from waves and tidal currents

This chapter describes, in general terms, ongoing research and development into ways of capturing energy from waves and tidal currents. This is a relatively new field and is also commercially sensitive because there are many competing companies seeking to develop better and more efficient devices for capturing energy from the sea.

The research and development work in progress involves several aspects of the subject including answers to the following water related questions:

- how much energy can be extracted from waves?
- how much energy can be extracted from tidal currents?
- what technologies need to be developed to tap these sources of energy?

8.1 Energy from waves

Waves are formed by winds blowing over the water surface. The size of waves generated depends mainly upon:

- wind speed
- duration of the event
- length of water over which the wind blows, known as the fetch
- contours of the sea bed which can focus or disperse the energy.

Waves have the potential to provide a sustainable source of energy and are greatest in areas where there is a long fetch and where storm conditions are prevalent. Wave energy is greatest well offshore because friction on the sea bed in shallow water tends to dissipate wave energy. In Europe the optimum conditions occur along western coasts which are exposed to the Atlantic Ocean.

Wave energy is statistically predictable based on long term records of wave heights at particular locations. However, waves do not provide firm, guaranteed, power at any particular time because of the random nature of weather conditions. During storm conditions the amount of natural wave energy is large and the amount converted to electrical energy by wave devices is unlikely ever to make material changes to the wave climate.

8.2 Energy from tidal currents

Tides are generated by the gravitation pull of the sun and the moon on the oceans of the world. They change from day to day and from season to season. Tides are predictable and represent a reliable and renewable source of energy.

Tidal current resources are generally largest in areas where a good tidal range exists, and where the current velocity is amplified by the shape of the local coastline and the contours of the seabed. Typical examples of appropriate sites would be in narrow straits and inlets, around headlands, and in channels between islands.

8.3 Fundamental research into the amount of energy available from tidal currents

The extraction of wave power is unlikely to be developed to the point where there is a risk of any significant reduction in the available wave energy. However, this may not be the case as the extraction of energy from tidal currents is developed and the effects could be far reaching under certain circumstances, ***see Garrett C and Cummins P, 2005, 2008***.

Energy from tidal currents is most commonly discussed in terms of exploiting the currents entering and/or leaving a tidal inlet. However, there are some limitations to this approach and the alternative of exploiting tidal streams in areas of open water is also being explored, ***see United Kingdom Parliament Select Committee on Science and Technology, 2001***.

When energy is extracted at the entrance to a tidal inlet there is a limit to the amount of energy available. A small number of turbines provide little power but do not change significantly the tidal regime. The tidal currents and the level variations within the inlet remain largely unchanged. Too many turbines could effectively block the flow and change both tidal currents into, and levels within, the inlet. In between these two extremes there is a particular number and size of turbines which optimize the amount of energy available. The average energy produced is not necessarily much less than would be obtained from the construction of a conventional tidal barrage scheme.

When energy is extracted in more open waters, typically between islands, there is less likelihood of tidal levels and flows being affected. However, in extremis, the same principles apply and the deployment of too many turbines affects tidal propagation. In typical cases, the maximum average energy which can be extracted from a tidal stream has been found to be considerably less than the average kinetic energy flux in the natural tidal flows. The computation of these estimates is extremely complex and is beyond the scope of this ROCK.

8.4 Types of device used to extract energy

Aquatic Renewable Energy Technologies (Aqua-RET) provides information which promotes aquatic renewable technologies. This project is funded with support from the European Commission. The outputs show, in general terms, how the new technologies work and their potential benefits. Illustrations, some of which are given below, may be freely downloaded from the Aqua-RET website (www.aquaret.com)

Wave energy devices

Devices which exploit wave energy take many different forms. Aqua-RET has identified several type of wave energy devices, in general terms:

- attenuators
- point absorbers
- oscillating wave surge devices
- oscillating water column devices
- overtopping / terminator devices
- submerged pressure differential devices
- bulge wave devices
- rotating mass devices.

The principles of some of these devices are shown below.

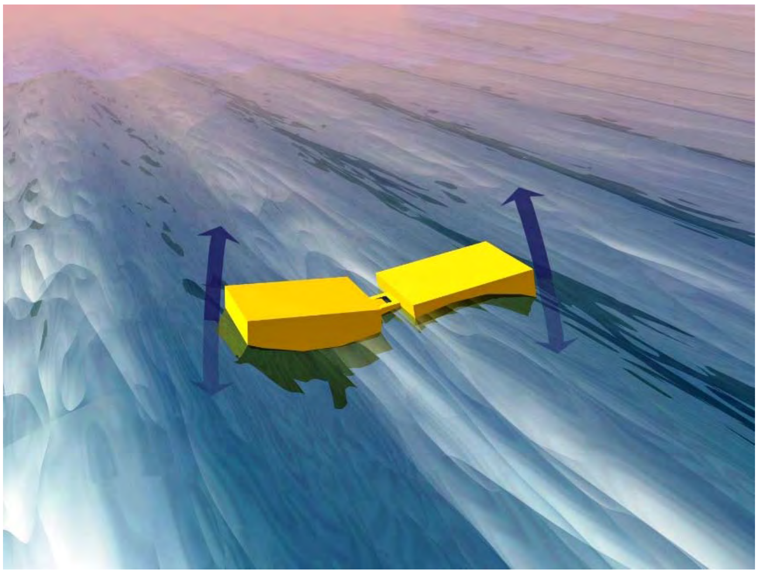


Plate 17 Attenuator

Source: Aquatic Renewable Energy Technologies

An attenuator is a floating device which operates parallel to the wave direction and effectively rides the waves. These devices capture energy from the relative motion of the two arms as the wave passes them.

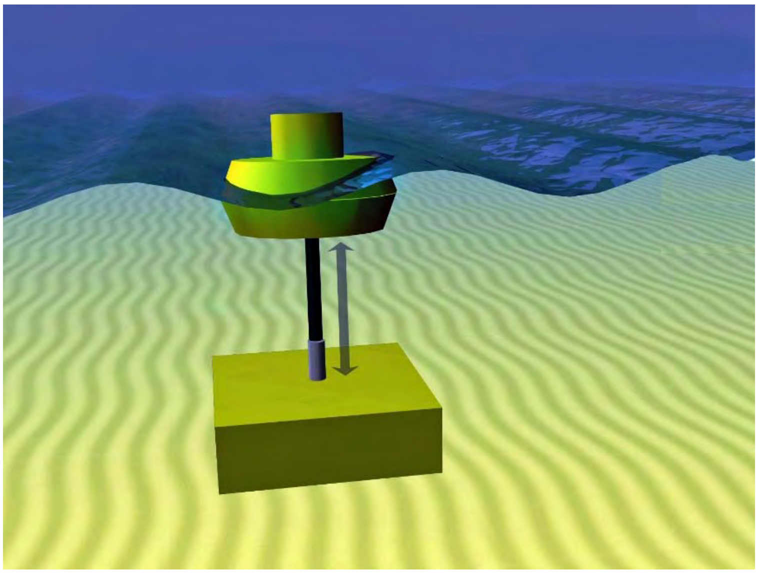


Plate 18 Point absorber
Source: Aquatic Renewable Energy Technologies

A point absorber is a floating structure which absorbs energy from all directions through its movements at or near the water surface. It converts the motion of the buoyant top relative to the base into electrical power. The power take-off system may take a number of forms, depending on the configuration of displacers or reactors.

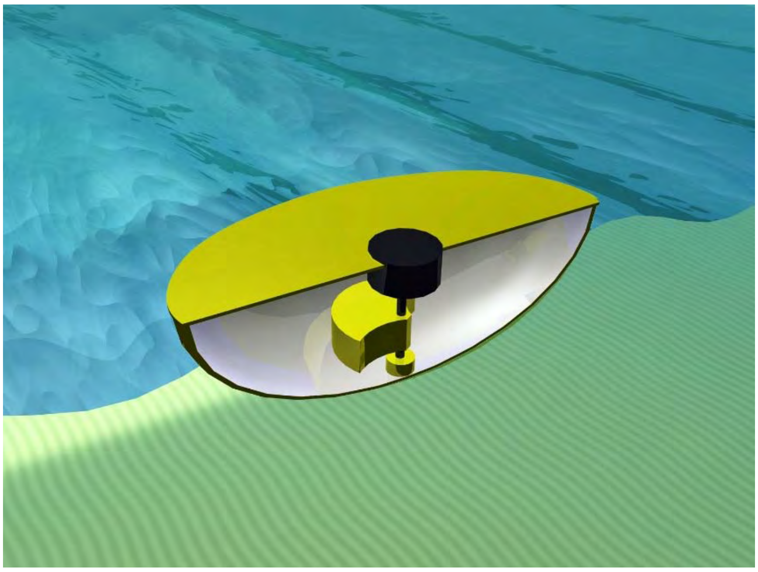


Plate 19 Rotating mass
Source: Aquatic Renewable Energy Technologies

Two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope which causes precession. In both cases the movement is attached to an electric generator inside the device.

Tidal energy devices

Devices which exploit tidal currents take the form of specialized submerged turbines. Aqua-RET has identified several types of tidal current devices, again in general terms:

- horizontal axis turbines
- vertical axis turbines
- oscillating hydrofoils
- enclosed Venturi turbines
- Archimedes screws
- tidal kites.

The principles of some of these devices are shown below.

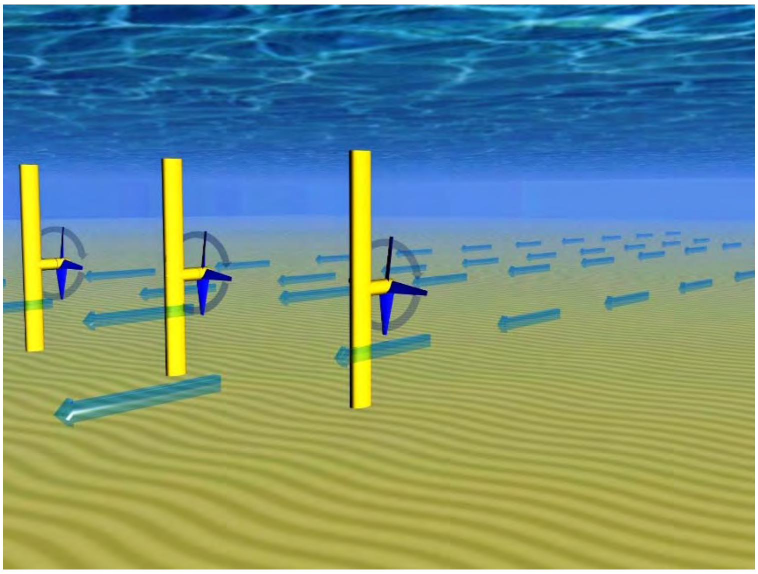


Plate 20 Horizontal axis turbine
Source: Aquatic Renewable Energy Technologies

Horizontal axis turbines extract energy from moving water in much the same way as wind turbines extract energy from moving air. The tidal stream causes the impellers to rotate around the horizontal axis and generate power.

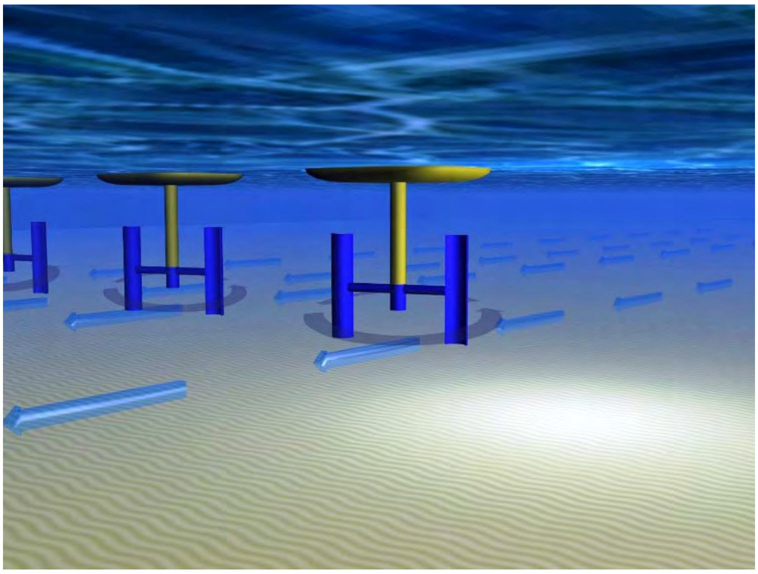


Plate 21 Vertical axis turbine
Source: Aquatic Renewable Energy Technologies

Vertical axis turbines extract energy from the tides in a similar manner to that above, however the turbine is mounted on a vertical axis. The tidal stream causes the impellers to rotate around the vertical axis and generate power.

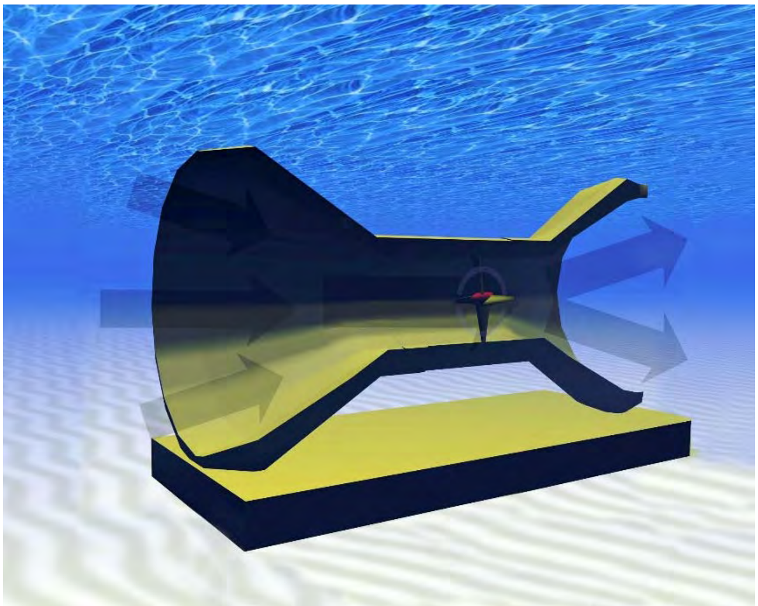


Plate 22 Enclosed Venturi turbine
Source: Aquatic Renewable Energy Technologies

Venturi effect devices house the impeller in a duct which concentrates the tidal flow. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine.

8.5 Prototype development of devices to extract wave and tidal energy

The waters around the United Kingdom provide some of the best locations for harnessing energy from the sea. The Severn Estuary has the second highest tidal range in the world after the Bay of Fundy in Canada and could provide energy using a conventional tidal barrage scheme. In addition, exposure to the Atlantic provides good conditions for extracting wave and tidal energy along the western and northern coasts of the United Kingdom.

One initiative which aims to further develop opportunities for the extraction of energy from waves and tidal currents is based in the Pentland Firth between Scotland and the Orkney Islands. It involves scientists and developers from around the world and was launched as "The Pentland Firth and Orkney Waters Marine Energy Park" by the Department of Energy and Climate Change in 2012. It incorporates the European Marine Energy Centre (EMEC) which was set up in 2003 and is based in Stromness, Orkney Islands. The role of the company is to provide developers of both wave and tidal energy devices with purpose built and accredited open sea and laboratory testing facilities. The company operates on a worldwide basis and plays a key role in research and development in this field.

The interest in the development of wave and tidal devices is considerable. A database compiled by the European Marine Energy Centre suggests there are more than 160 developers of wave devices, with the USA and the UK taking the lead, and more than 80 developers of tidal current devices. The Department of Energy and Climate Change estimates that the installed capacity of devices extracting energy from waves and tidal currents in United Kingdom coastal waters could reach 27 GW by 2050, equivalent to the installed capacity of eight coal fired power stations.

The location of this initiative, together with examples of prototypes wave and tidal current devices, are shown in Plates 23, 24 and 25.

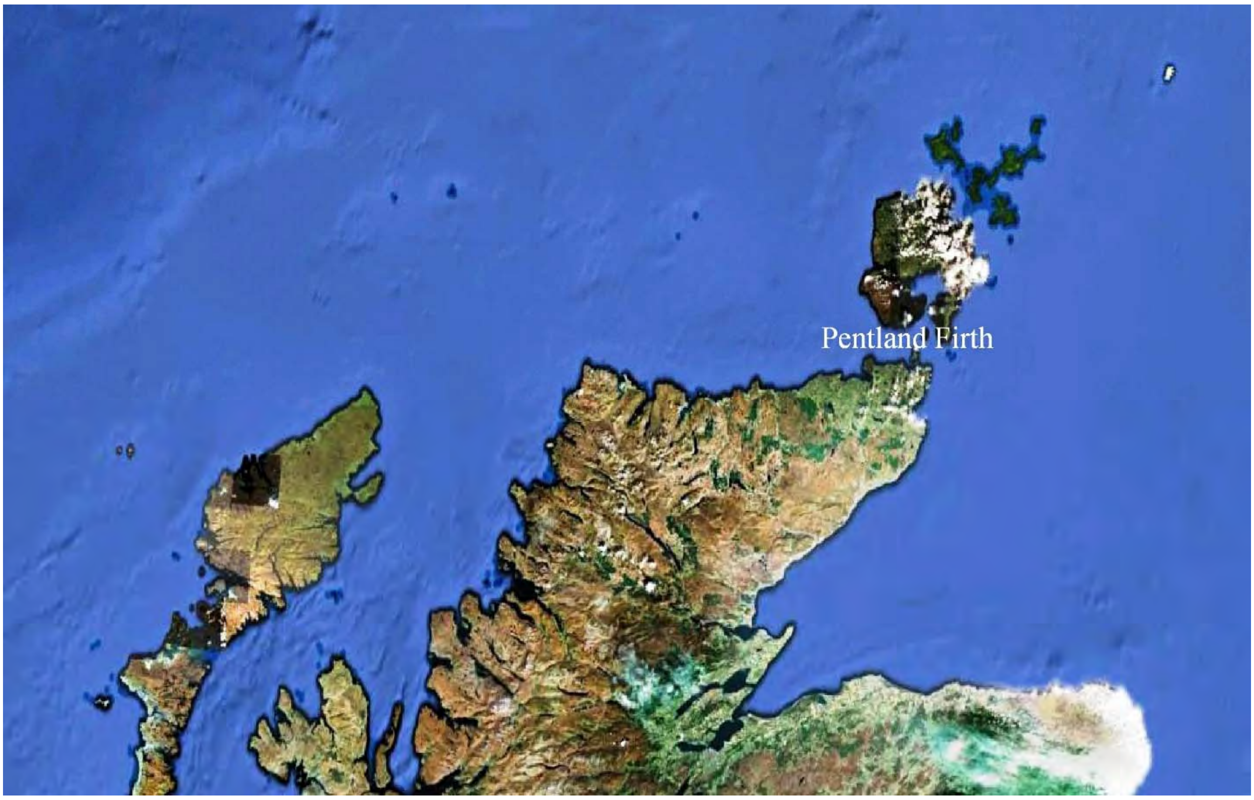


Plate 23 Pentland Firth, United Kingdom
Source: Google Earth

24 Plate Prototype wave device
Source: http://energy-alaska.wikidot.com/

Plate 25 Prototype tidal current device
Source: www.newenergyandfuel.com

The current field testing of wave and current devices is ongoing and is helping to define optimum design parameters for these units. The strategic positioning of several "production" units at the entrance to a tidal inlet, or in offshore tidal waters, will need careful consideration at a later date.

One fully developed scheme for harnessing tidal currents was installed in the Bluemull Sound between the islands of Unst and Yell in the north of Shetland in 2016. This installation comprises an array of five turbines, each with a capacity of 100 kW. The Shetlands are not connected to the UK national grid and historically the islanders have obtained power from a diesel-fuelled power station. The new tidal current scheme will reduce reliance on this old technology.

References

Aquatic Renewable Energy Technologies (Aqua-RET). European Union Lifelong Learning Programme, Agreement no LLP/LdV/TOI/2009/IRL – 515. www.aquaret.com

Department of Energy and Climate Change (DECC), 2011. *UK Renewable Energy Roadmap.*

Department of Energy and Climate Change (DECC), 2014. *Energy consumption in the United Kingdom.*

EU Directive 2009/28/EC, 2009. *Promotion of the use of energy from renewable sources.*

European Marine Energy Centre (EMEC). www.emec.org.uk

Garrett C and Cummins P, 2005. The power potential of tidal currents in channels. *Proceedings of the Royal Society* A (2005) **461**, 2563-2572. www.rspa.royalsocietypublishing.org

Garrett C and Cummins P, 2008 Limits of tidal current power. *Renewable Energy 33* 2485–2490. Elsevier. www.elsevier.com/locate/renene

International Commission on Large Dams (ICOLD), 2011. *Dams and the World's Water*. Copyright CIGB-ICOLD. Available for purchase on-line at: www.icold-cigb.net.

International Energy Agency (IEA), 2015. *Key world energy statistics.* www.iea.org

Palmieri A, Shah F, Annandale G W and Dinar A, 2003. *Reservoir Conservation: Volume 1 The RESCON Approach, Volume 2 RESCON Model and User Manual.* The International Bank for Reconstruction and Development / The World Bank, Washington D.C.

United Kingdom Parliament Select Committee on Science and Technology, 2001. *Wave and Tidal Energy*. Seventh report. www.publications.parliament.uk/pa/cm200001/cmselect/cmsctech/291/29102.htm.

White W R, 2001. *Evacuation of sediments from reservoirs.* Thomas Telford Publishing. London. ISBN 0 7277 2953 5

Appendix

Conversion factors for energy units

The energy inherent in various fuels such as oil, gas, and electricity is often quoted in different units. However, to compare different fuels it is necessary to convert to a single measure. For the purpose of this ROCK the unit used throughout is the electrical unit of watt hours (Wh). However, to compare with other publications, particularly those dealing with the oil industry, the electrical unit can be converted fairly precisely to the equivalent mass of oil as follows:

Electrical power is measured in:

Watts (W)
Kilowatts (kW = 10^3 W)
Megawatts (MW = 10^6 W)
Gigawatts (GW = 10^9 W)
Terawatts (TW = 10^{12} W)
Petawatts (PW = 10^{15} W)

Electrical energy is the product of power and duration of consumption of that power:

Watt hours (Wh)
Kilowatt hours (kWh = 10^3 Wh)
Megawatt hours (MWh = 10^6 Wh)
Gigawatt hours (GWh = 10^9 Wh)
Terawatt hours (TWh = 10^{12} Wh)
Petawatt hours (PWh = 10^{15} Wh)

Energy from oil is measured in:

Tonnes of oil equivalent (toe)
Megatonnes of oil equivalent (Mtoe = 10^6 toe)

Conversion between electrical energy and oil equivalents

The conversion between these two sets of units is assumed by the International Energy Agency, to be as follows:

1.0 toe = 11 630 kWh
and
1.0 Mtoe = 11 630 GWh = 11.63 TWh