Chapter 6

Tidal power

By David Elliott

6.1 Introduction

The rise and fall of the seas represents a vast, and as King Canute demonstrated, relentless natural phenomenon. The use of the tides to provide energy has a long history: small tidal mills on rivers were used for grinding corn in Britain and France in the Middle Ages. Subsequently, the idea of using tidal energy on a much larger scale to generate electricity emerged, using turbines mounted in large **barrages** – essentially low dams – built across suitable estuaries. More recently interest has grown in putting free-standing turbines into tidal currents.

Figure 6.1 A view of La Rance tidal power station

This chapter looks at some examples of these tidal technologies and at their potential and limitations. It is, as yet, still a relatively undeveloped field, although a number of projects do exist. A medium-scale 240 MW tidal barrage scheme has been built at the Rance Estuary in France (Figure 6.1) and, at the time of writing, a similar scale scheme is being implemented in South Korea. Around the world, a number of smaller tidal barrages have been built, and at the other end of the scale there have been proposals for large-scale developments at several sites. For example, Figure 6.2 shows

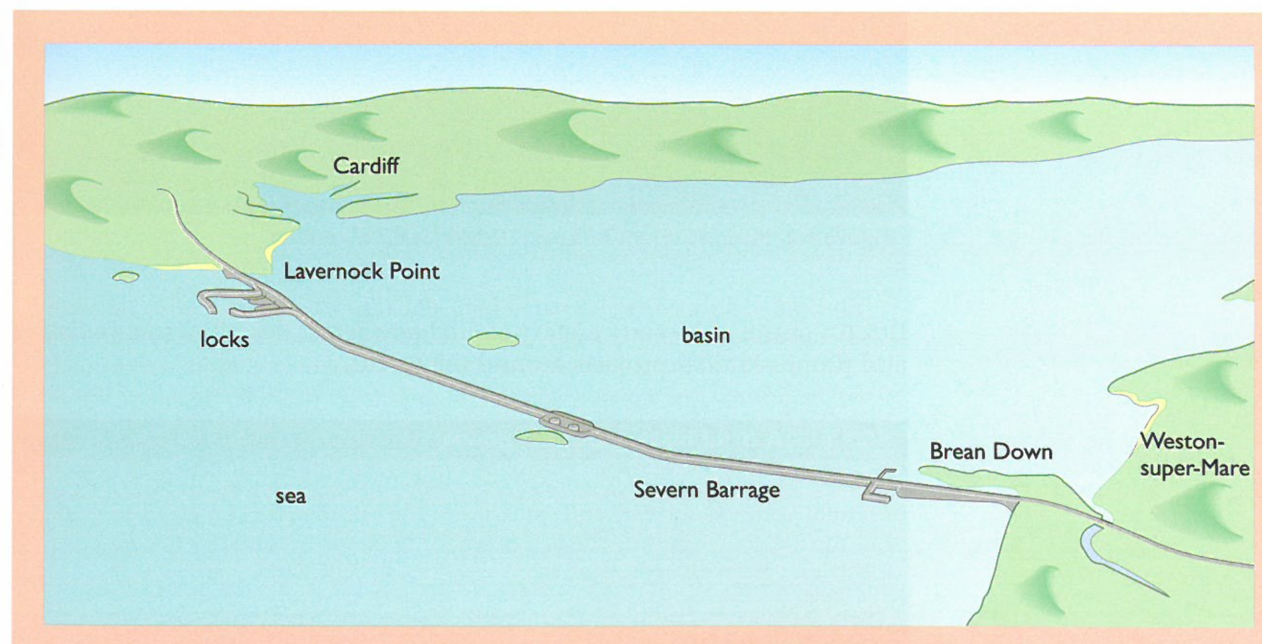


Figure 6.2 Artist's impression of the proposed Cardiff to Weston Severn Barrage

an artist's impression of the proposed 8.6 GW Severn Barrage, stretching 16 kilometres across the Severn Estuary in the UK. If built, this would generate 17 TWh per year, the equivalent of about 4.5% of the electricity generated in the UK in 2010. However, in recent years much of the emphasis has been on free-standing tidal current turbines – a range of devices are being developed, and some have already been deployed at full scale (Figure 6.3).

Figure 6.3 Marine Current Turbines' 1.2 MW 'SeaGen' concept

Box 6.1 outlines the early history of tidal power and describes some existing and proposed tidal projects around the world.

BOX 6.1 A brief history of tidal power

Small tidal mills, not unlike traditional watermills, were used quite widely on tidal sections of rivers and estuaries in the Middle Ages for grinding corn, but the idea of exploiting the full power of the tides in estuaries to generate electricity is relatively recent.

There have been a number of proposals for various types of barrage across the Severn, the UK's largest estuary, with the world's largest low- to high-tide range, but so far none have been taken forward. For example, a barrage

concept (albeit with no provision for electricity generation) attributed to Thomas Telford was put forward in 1849. The first serious proposal involving electricity production came in 1920 from the Ministry of Transport. This was followed by a major study by the Brabazon Commission, which was set up in 1925. Its 1933 report focused on a barrage crossing the estuary along the 'English Stones line', not far from the modern Severn Bridges. It was to have 72 turbines with a total installed capacity of 804 MW and to incorporate road and rail crossings. The scheme was not taken up. It was reassessed in 1944, but, again, not implemented.

During the 1960s and 1970s a number of schemes were proposed, each crossing along different lines. These proposals culminated in another government-supported study by the Severn Barrage Committee, which was set up in 1978 under Professor Sir Hermann Bondi. The Committee reported in 1981 (Department of Energy, 1981), concluding that it was 'technically feasible to enclose the estuary by a barrage located in any position east of a line drawn from Porlock due North to the Welsh Coast'. Of all the possible crossing lines, three were favoured, the most ambitious being from Minehead to Aberthaw, which, it was estimated, could generate 20 TWh per year from 12 GW of installed capacity.

Subsequently, the less ambitious, but still very large, so-called 'inner barrage', on a line (first proposed by E. M. Wilson in 1966) from Brean Down, Weston-super-Mare to Lavernock Point near Cardiff, became the favourite, and was pursued by the Severn Tidal Power Group (STPG) industrial consortium in the 1980s. It was initially conceived as generating approximately 13 TWh per year from 7 GW installed, although this was later upgraded to 17 TWh per year from 8.64 GW installed.

Enthusiasm for tidal schemes was fuelled in part by the success of the French scheme on the Rance Estuary in Brittany, near St Malo (Figure 6.1). This was constructed between 1961 and 1967 and the first output from its 240 MW turbine capacity was achieved in 1966. The structure includes a road crossing. Apart from a problem with the generator mountings in 1975, it has operated very successfully. Subsequently, a much larger 15 GW scheme was proposed, to enclose a vast area of sea from St Malo in the south to Cap de Carterel in the north, the so-called 'Île de Chausey Project'. This has not been implemented.

Although large-scale schemes have also been proposed for the Bay of Fundy in Canada and at various sites in Northern Russia, the only significant tidal plants to be built to date, other than La Rance, are an 18 MW single unit, using a 'rim generator' (see Figure 6.15), at Annapolis Royal in Nova Scotia, Canada, completed in 1984; a 400 kW unit in the Bay of Kislaya, 100 km from Murmansk in Russia, completed in 1968; and a 500 kW unit at Jangxia Creek in the East China Sea.

However, at the time of writing, some medium-scale projects are being built in South Korea (including a 254 MW barrage), and a number of other barrage schemes have been considered both there and elsewhere around the world. Interest in the much larger Severn 'inner barrage' concept has continued, but there are economic and environmental challenges.

Instead, the emphasis in the UK and many other countries has moved on to smaller-scale modular tidal current turbines, operating on (horizontal) tidal flows rather than on (vertical) tidal height ranges. The world's first commercial-scale grid-linked tidal current turbine, a 1.2 MW two-bladed unit (see Figures 6.3 and 6.32) has been operating successfully in Strangford Narrows, Northern Ireland, since 2008. Dozens of other tidal current devices of various designs are under development in the UK and elsewhere and this area of activity seems likely to expand (see Sections 6.9 and 6.10).

The nature of the resource

It is important at the outset to distinguish *tidal* power from *hydro* power. As we saw in Chapter 5, *hydro* power is derived from the hydrological cycle (which is driven by solar energy) and is usually harnessed via hydroelectric dams. In contrast, *tidal* power is the result of the interaction of the gravitational pull of the Moon and, to a lesser extent, the Sun, on the seas. Schemes that use tidal energy rely on the twice-daily tides, and the consequent upstream flows and downstream ebbs in estuaries and the lower reaches of some rivers, as well as, in some cases, tidal movements out at sea.

Equally, we must distinguish between tidal energy and the energy in waves. Ordinary waves are caused by the action of wind over water, the wind in turn being the result of the differential solar heating of air over land and sea (see Chapter 8). If we consider wave energy, like hydroelectric energy, to be a form of solar energy, tidal energy could be called 'lunar energy'. Such distinctions are, unfortunately, not helped by the terminology which is often used – for example, the term 'tidal wave' is sometimes used to describe what are these days more usually called tsunami, the occasionally dramatic surges of water (which are neither wind-driven waves nor lunar-driven tides!) that can be produced by undersea earthquakes. There are also large climate-driven water flows in the oceans, such as the Gulf Stream, which are ultimately the result of solar heating. For the sake of completeness, we should also note that the gravitational pull of the Sun and the Moon also cause tidal phenomena in the atmosphere and in the Earth.

The energy in these various movements of water can, in principle at least, be tapped. The rise and fall of the tides can be exploited without the use of dams across estuaries, as was done in the traditional **tidal mills** on the tidal sections of rivers, as mentioned earlier. A small pond or pool is simply topped up and closed off at high tide and then, at low tide, the trapped water is used to drive a waterwheel, as with traditional watermills.

There is also the possibility of using turbines mounted independently in **tidal streams** (also called **tidal currents** – both terms are used, often interchangeably), that is *horizontal* tidal flows. Indeed, in the Middle Ages there were some floating 'undershot' waterwheels running on tidal currents. These flows of *kinetic energy* can be enhanced in some locations due to the effects of concentration in narrow channels, for example between islands or other constrictions, or around headlands.

In addition, it may be possible to harness some of the energy in large-scale ocean streams such as the Gulf Stream. Some recent developments in the tidal current and ocean stream areas are discussed below, from Section 6.8 onwards. As noted in Box 6.1, tidal current projects are now emerging as a leading tidal option, not least since, unlike large estuary-wide barrages, they are modular and can be developed incrementally.

Before looking at tidal current systems, the initial sections of this chapter focus on tidal barrages across estuaries. The vertical difference between the water level at low tide and high tide is usually called the **tidal range**. In most *tidal range energy generation systems*, the water carried upstream by the **tidal flow** – usually called the **flood tide** – is trapped behind a barrage across the estuary. As the tide ebbs, the water level on the downstream side of the barrage reduces and a head of water develops across the barrage. The head is used to drive the water through turbine generators and the barrage scheme operates like a low-head hydro plant (see Chapter 5). Thus the barrage can be used to harness the *potential energy* provided by the *vertical* difference between tides. The main difference from hydro, apart from the salt-water environment, is that the power-generating turbines in tidal barrages have to deal with regularly varying heads of water.

A variant of the barrage concept is the tidal lagoon, which depends on a containment structure being built *within* the estuary to retain a small proportion of water in the estuary (in contrast to a barrage that acts on the whole estuary). However the mode of operation is similar – the tidal range is used to create a head of water within the containment structure. Tidal barrages and tidal lagoons are therefore often collectively labelled **tidal range systems**, to distinguish them from systems using tidal currents.

Before looking at the details of, in turn, barrages, lagoons and tidal current schemes it is instructive to consider the physics behind tides and to appreciate what factors are involved in locating tidal energy systems.

The physics of tidal energy

The existence of tides is due primarily to gravitational interaction between the Earth and the Moon. This gravitational force, combined with the rotation of the Earth, produces, at any particular point on the globe, a twice-daily rise and fall in sea level, this being modified in height by the gravitational pull of the Sun and by the topography of land masses and ocean beds. A detailed analysis of this interaction between Earth, Moon and Sun is quite complex, but we will attempt to describe it in simple terms.

The first part of the explanation is relatively straightforward. Starting first with just the Earth and the Moon, the gravitational pull of the Moon draws the seas on the side of the Earth *nearest* to the Moon into a bulge *towards* the Moon. That gives us one tide per day at any one point, as the planet rotates through the bulge. But what about the second tide each day? This is more difficult to explain. Sometimes it is explained in simple terms by saying that the waters that make up the bulge facing the Moon are drawn from the seas at each side of the Earth, but the water at the far side is 'left behind', at its original level. However that does not really explain the fact that the second tide is roughly the same height as the first. Neither does the fact that the water in the seas *furthest* from the Moon experiences slightly less of the lunar pull, being further away, although it may be part of the explanation.

The full explanation of the bulge that forms on the side of the Earth away from the Moon depends on a more complicated analysis, based on understanding the effect of the relative movements of the Earth and Moon (see Box 6.2).

The basic pattern described in Box 6.2 is also modified by the pull of the Sun. Although the Sun is much larger than the Moon, its distance from the Earth is much greater, and the Moon's gravitational influence on the seas is therefore approximately twice that of the Sun. The final impact depends on their relative orientation.

X 6.2 The Earth and the Moon

ıseful mathematical analysis of the generation of tides is given in *newable Energy Resources* (Twidell and Weir, 2006). This identifies *two* ɔcesses at work in relation to the Earth and the Moon: a rotational effect as ll as a gravitational effect.

e first process, the rotational effect, is the result of the fact that the Earth and Moon rotate around each other, somewhat like a 'dumb-bell' being twirled. is rotation gives rise to an outward force, sometimes (rather loosely) called entrifugal force, which acts on the water in the seas. However, this giant mb-bell does not rotate around the halfway point between the Earth and Moon. Since the Earth is much larger than the Moon, their common centre rotation is close to the Earth; in fact it is just below its surface (Figure 6.4). e mutual rotation around this point produces a relatively large *outward* ıtrifugal force acting on the seas on the side of the Earth *furthest* from the ɔon, bunching them up into a bulge. There is also a much smaller centrifugal ce, directed *towards* the Moon, that acts on the seas *facing* the Moon. (This ce is smaller since here the distance from the Earth's surface to the common ation point, just below the surface, is smaller.)

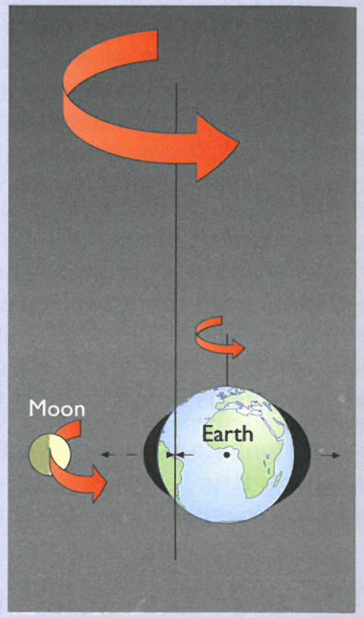


Figure 6.4 Relative rotation of the Earth and the Moon (not to scale)

e second process, the gravitational effect, is more familiar and relates to the vitational pull of the Moon, which draws the seas on the side of the Earth *ırest* to the Moon into a bulge *towards* the Moon, whilst the seas *furthest* m the Moon, being slightly further away, experience a reduced lunar pull vards the Moon.

ere is thus, to summarize, a small centrifugal force l an increased lunar pull acting on the seas facing Moon, and a larger centrifugal force and a decreased ıar pull acting on the seas on the other side of the th. The end result, on the basis of this analysis, ssentially a rough symmetry of forces, small and ʒe, on each side of the Earth, producing tidal bulges oughly the same size on each side of the Earth. In ıctice, the bulges may differ significantly, due, for ımple, to the tilt of the Earth's axis in relation to the it of the Moon and to local topographic effects.

As the Earth rotates on its axis, the lunar pull will maintain the high-tide patterns, as it were 'under' the Moon. That is, the two high-tide configurations will in effect be drawn around the globe as the Earth rotates, giving, at any particular point, *two* tides per day (or, more accurately, two tides in every 24.8 hour period), occurring approximately 12.4 hours apart. Since the Moon is also moving in orbit around the Earth, the timing of these high tides at any particular point will vary, occurring approximately 50 minutes later each day.

When the Sun and the Moon pull together (in line), whether both pulling on the same side of the Earth or each on opposite sides, the result is the very high **spring tides**; when the Sun and Moon are at 90° to each other (relative to the Earth), the result is the lower **neap tides**. The period between neap and spring tides is approximately 7 days – that is, a quarter of the 29.5-day lunar cycle (Figure 6.5). The ratio of output from a tidal range plant at the maximum spring tide to the output at a minimum neap tide can be more than two to one (Figure 6.6).

However, it is not simply a matter of the Earth's oceans rising and falling under gravitational forces. The pull of the Moon sets the whole sea into a state of oscillation, much as water might slop to and fro in a shallow dish if slightly shaken. The scale and frequency of these oscillations is influenced by the shape and size of the area of water, as defined by the surrounding land masses. The effect is somewhat like the resonance that occurs in musical instruments at various frequencies and volumes. Tidal resonances

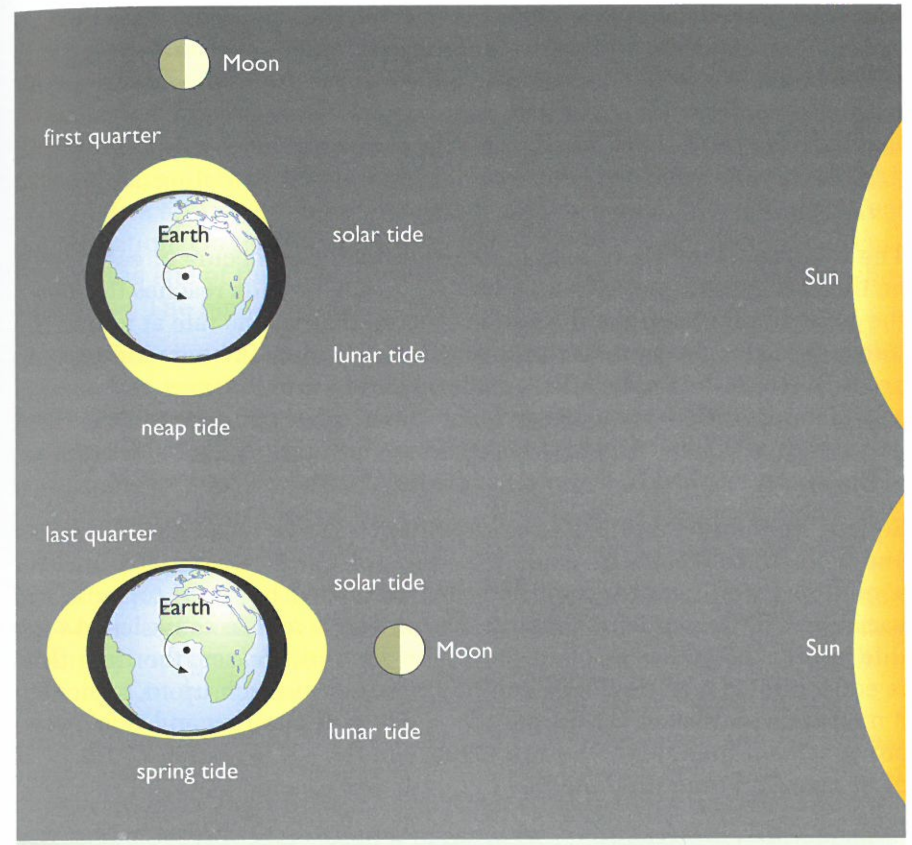


Figure 6.5 Influence of the Sun and the Moon on tidal range (not to scale)

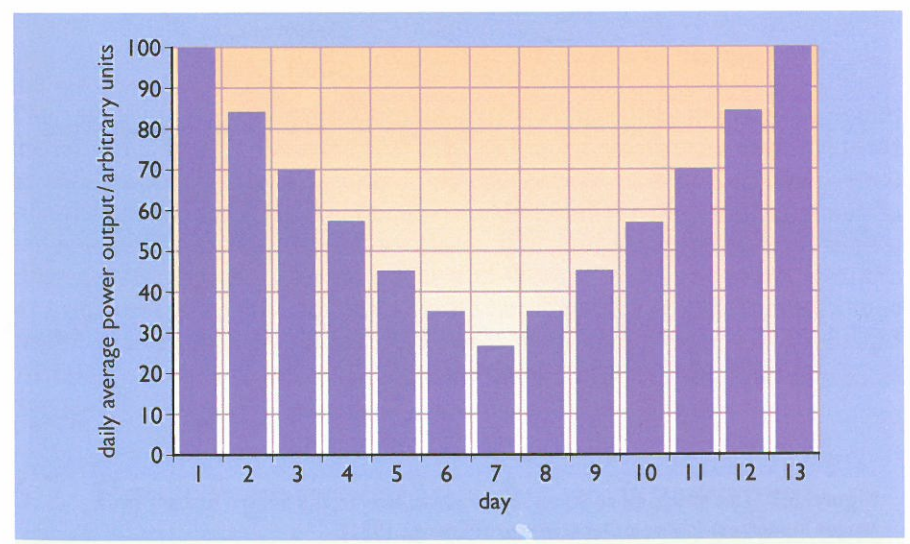


Figure 6.6 Typical variation in daily average output from a tidal range power plant over the spring–neap cycle (source: adapted from SDC, 2007)

can occur in well defined estuaries but can also be significant across entire oceans. For example, while the tidal range in open sea in mid-Atlantic is about 0.5 metres, at the coasts it can be enhanced to about 3 metres. In the case of the much wider Pacific the resonance effects are much smaller, so that the tides can be very small. In addition, the Earth's rotation causes the tidal flows to be deflected slightly, which can create a swirling pattern – in the North Atlantic there is a slow anticlockwise motion.

The rotation of the Earth also means that high tide occurs at each point on the Earth at a different time. Moreover, when the tide reaches the coast, the general topography of the landmass then defines the rate at which the tide moves along a coast. For example it takes about six hours for a tide to progress down the English Channel from Land's End to Dover and there is several hours difference between high tides at other points around the east and west coast of the UK. This has important implications for the integration of the output of tidal power plants into an electricity grid.

Equally important for tidal power generation is the fact that the tidal ranges and tidal stream velocities experienced in practice at coastal sites are also sometimes significantly modified and amplified by *local* topographic variations, for example in shallow coastal waters and in estuaries. As the tide approaches the shore and the water depth decreases, the tidal flow is concentrated and the range can be increased to reach up to, typically, 3 metres. Examples of coastlines giving rise to funnelling and tidal range enhancement include the Severn Estuary in the UK (Figure 6.7), the Gulf of St Malo in France and the Bay of Fundy in Canada.

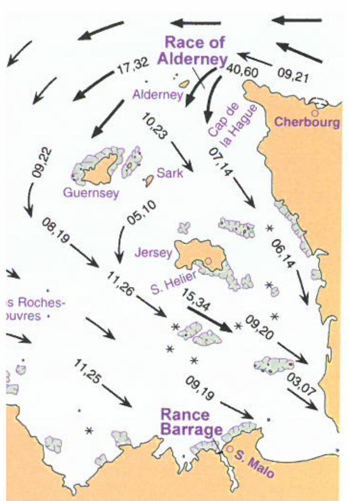


Figure 6.8 Tidal stream map for the Race of Alderney and La Rance Barrage 4 hours after high water at Dover; tidal stream rate in tenths of a knot expressed in the form: neap tide, spring tide (i.e. 10,23 means on a neap tide the stream runs at 1.0 knots and on a spring tide 2.3 knots). Note: 1 knot = 0.51 m s^{-1} (source: adapted from *Admiralty Tidal Stream Atlas: The English Channel NP250*, 1992)

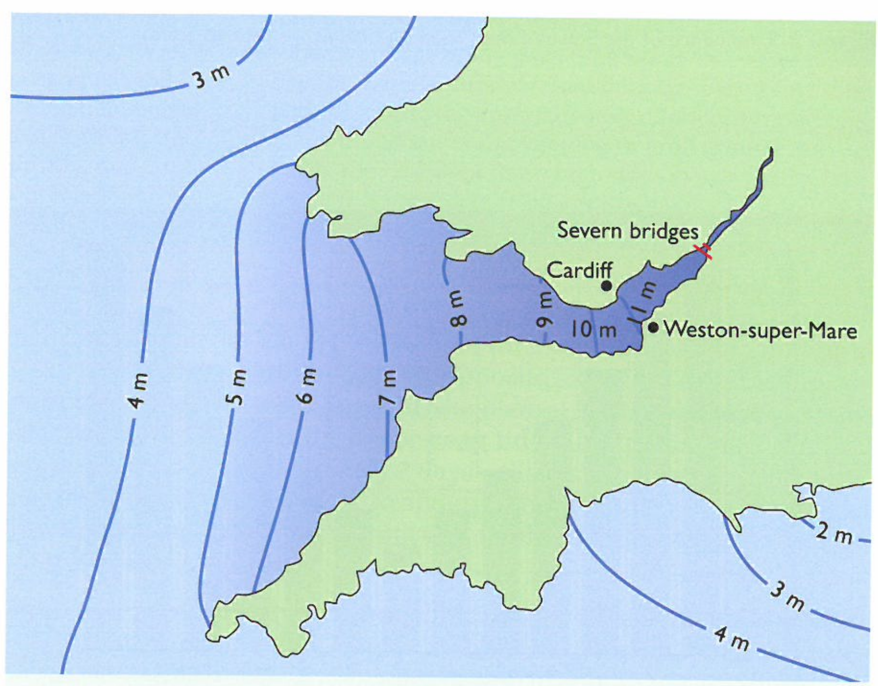


Figure 6.7 The effects of concentration of tidal flow in the Severn Estuary (tidal ranges in metres) (source: Department of Energy, 1981)

The tidal stream velocity can also be amplified if the tidal flow is constrained, for example in the Race of Alderney between the island of Alderney and the French mainland (Figure 6.8).

However, there are also frictional effects to take into account. For example, energy is lost as the tidal flow moves over differing estuary bed materials. Thus, the extent to which the tidal range is magnified at any point depends on the balance between the energy losses and the concentration of the tidal flow by the topography. The frictional effects will usually begin to outweigh the concentration gains at some point upstream when the funnel-like layout of an estuary gives way to a more parallel-sided, flat-bottomed river configuration. On the Severn, this 'natural' optimal point normally occurs around the site of the (first) Severn Bridge, where the tidal range reaches 11 metres. The range decreases further upstream, as do flow rates.

Occasionally, in some long estuaries, dramatic tidal effects can occur upstream. For example, rather than producing a relatively slow rise, as normally happens in the main part of the Severn Estuary, the upstream tidal flow further up the Severn can be concentrated so abruptly that it rises into an almost vertical step or wave: the so-called Severn Bore. A similar effect occurs on other long estuaries, including the Humber in the UK and the Hoogly near Calcutta in India.

The water level actually experienced at a given location is also influenced by the weather – so-called **surge tides** are generated by storms rather than the Moon and Sun. Their effects can also be amplified with devastating effects by topographic features and tidal power plants have to be built to withstand such extreme phenomena.

So, even leaving aside freak effects like the Severn Bore and occasional surge tides, there is a complex range of tidal phenomena. Fortunately for the designers of tidal barrages and other tidal devices, the end results – that is, the normal tidal patterns in estuaries – although very site specific, are predictable and reliable. The tides will continue to ebb and flow, on schedule, indefinitely.

But is the energy in the tides *really* 'renewable'? As we have seen, the primary mechanism in tide generation is the gravitational interaction between the Earth and the Moon, and the forces produced by their relative orbital movements. These forces create bulges of water. The rotation of the Earth draws these resulting tidal bulges across the seas, or, more precisely, the water in the seas rise into a bulge as the water rotates with the planet. The result is that there are horizontal tidal flows, as water is drawn into the moving bulge. The rotation of the Earth is being very gradually slowed by tidal processes (by approximately one-fiftieth of a second every 1000 years), because of frictional effects – it takes energy to drag the water along, especially through areas where there are topographical constrictions. However, the extra frictional effect that would be produced by even the widespread use of tidal barrages would be extremely small. The influence on the Moon's orbital velocity (which is also being very slowly reduced by the tidal interaction) would be even smaller. So overall, tidal energy is renewable on any reasonable interpretation of the concept.

6.2 Power generation from barrages

The basic physics and engineering of tidal barrage power generation are relatively straightforward.

Tidal barrages, built across suitable estuaries, are designed to extract energy from the rise and fall of the tides, using turbines located in water passages in the barrages. The potential energy, due to the difference in water levels across the barrage, is converted into kinetic energy in the form of fast-moving water which passes through the turbines – the spinning turbines then drive generators to produce electricity.

The *average* power output from a tidal barrage is roughly proportional to the square of the tidal range. The mathematical derivation of this is fairly simple, as is demonstrated by the analysis in Box 6.3.

BOX 6.3 Calculation of power output from a tidal barrage

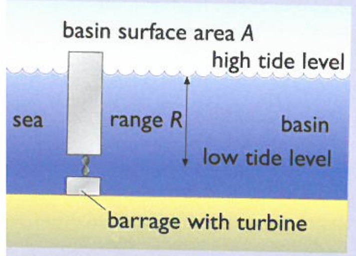


Figure 6.9 Power generation from tides (source: Twidell and Weir, 2006)

Let us assume that we have a rectangular basin with a constant surface area A, behind a barrage, and a high-to-low tidal range R (Figure 6.9). In conventional ebb generation, when the tide comes in, it is freely allowed to flow into the basin, but when the tide goes out, the water in the basin is held there, at the high-tide level. When the sea has retreated to its low-tide level, the surface of the water held behind the barrage will be at a height R above the sea.

Given a rectangular basin, the centre of gravity of the usable mass of water will be at a height $R/2$ above the low-tide level. The total volume of water in the basin will be AR and, if the density of the water is ρ it will have a mass ρAR, i.e. ρ multiplied by the volume of water (A times R). This water could all now be allowed to flow out of the barrage through a turbine to the low-tide level. The maximum potential energy E available per tide if all the water falls through a height of $R/2$ is therefore given by the mass of water (ρAR) times the height ($R/2$) times the acceleration due to gravity (g); that is, $E = \rho ARg(R/2)$. The basin could then be allowed to fill on the next incoming tide and the cycle repeated again and again. If the tidal period is T, then the average potential power that could be extracted becomes E/T or $\rho AR^2g/2T$.

Clearly, even small differences in tidal range, however caused, can make a significant difference to the viability and economics of a barrage. A mean tidal range of at least 5 metres is usually considered to be the minimum for viable power generation, depending on the economic criteria used. As the analysis in Box 6.3 indicates, the energy output is also roughly proportional to the area of the water trapped behind the barrage, so the geography of the site is very important. All of this means that the siting of barrages is a crucial element in their viability.

Many studies have been carried out on tidal power in the UK, dating from the early 1900s onwards (see Box 6.1). This is hardly surprising, as the UK holds about half the total European potential for tidal barrage energy, including one of the world's best potential sites, the Severn Estuary. There is also a range of possible medium- and small-scale sites, including locations on the Mersey and Solway Firth (further details are in Section 6.6). The total UK tidal barrage resource potential has been put at around 53 TWh per year (ETSU, 1990) which was about 14% of UK electricity generation in 2010. In practice, the contribution to electricity consumption that could be achieved in the UK and elsewhere would depend on a range of *technical*, *environmental* and *economic* factors. Although these factors interact, we can explore each in turn before attempting a synthesis.

Barrage designs

The input energy source for a barrage, the rise and fall of the tides, follows a roughly sinusoidal pattern (see the sea-level curves in Figures 6.10–6.12). The tides have a 12.4 hour cycle, with the actual tidal range varying from site to site as a result of complex resonance and funnelling effects as mentioned earlier.

Given the complexity of estuary configurations, the actual resonances and funnelling effects are very difficult to model accurately, with variations in depth, width and friction over differing estuary bed materials introducing many local variations.

However, it is well worth the effort required to analyse these effects when deciding on the precise siting and orientation of a barrage, since they will have a major effect on its output. Indeed, it may be possible to locate and/or operate a barrage so as to 'tune' the barrage to the estuary tidal pattern, and thus to increase energy output. Certainly, any disturbance that might reduce existing resonance effects should be avoided.

In addition to the basic issues of location and orientation, a second set of factors that influences the likely energy output of a barrage relates to its *operational pattern*.

Energy can be generated from a barrage in three main ways. The most commonly used method is **ebb generation**. Here the incoming tide is allowed to pass through the barrage sluice gates. The water is trapped behind the barrage at high-tide level by closing the sluices. The head of water then passes back through the turbines on the *outgoing* ebb tide in order to generate energy (Figure 6.10). Alternatively, **flood generation** uses the *incoming* tide to generate electricity as it passes through the turbines mounted in the barrage (Figure 6.11). In each case, two bursts of energy are produced in every 24.8 hour period. **Two-way operation**, on the ebb *and* the flood, is also possible (Figure 6.12).

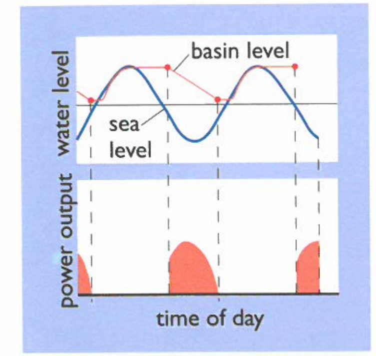


Figure 6.10 Schematic diagram of water levels and power outputs for an ebb generation scheme (source: Department of Energy, 1981)

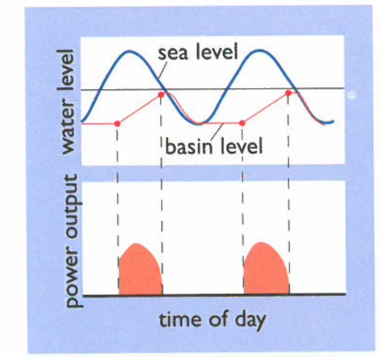


Figure 6.11 Schematic diagram of water levels and power outputs for a flood generation scheme (source: Department of Energy, 1981)

The basic technology for power production is well developed, having much in common with conventional low-head hydro systems (see Chapter 5). Figure 6.13 is an artist's impression of the typical layout of a power generation scheme.

A number of different turbine configurations are possible. At La Rance, a so-called **bulb** system is used, with the turbine generator sealed in a bulb-shaped enclosure mounted in the flow (Figure 6.14). As the water has to flow around the large bulb, access (for maintenance) to the generator involves cutting off the flow of water.

These problems are reduced in the **Straflo** or **rim generator** turbine (as used at Annapolis Royal in Canada), with the generator mounted radially around the rim and only the runner (that is, the turbine blades) in the flow (Figure 6.15). Although it is more efficient than the bulb design, because the water flow is not so constricted, this design introduces extra problems with the sealing between the runner blades and the radial generator.

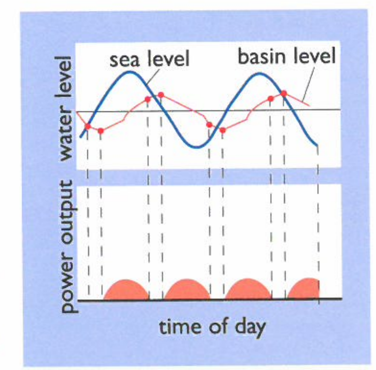


Figure 6.12 Schematic diagram of water levels and power outputs for a two-way generation scheme (source: Department of Energy, 1981)

Alternatively, there is the **tubular** turbine configuration, with the runner set at an angle so that a long (tubular) shaft can take rotational energy out to an external generator (Figure 6.16). This design also avoids constricting

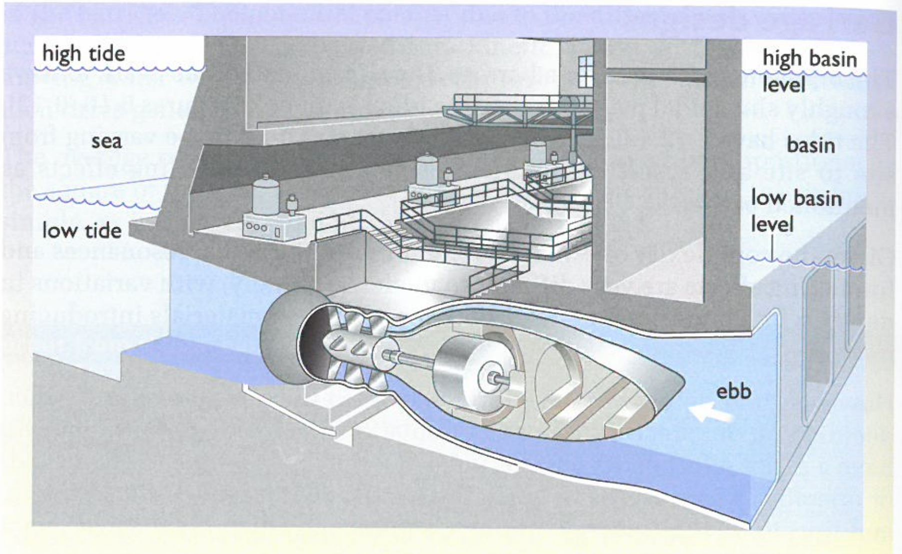


Figure 6.13 Artist's impression of the typical layout of a power generation scheme

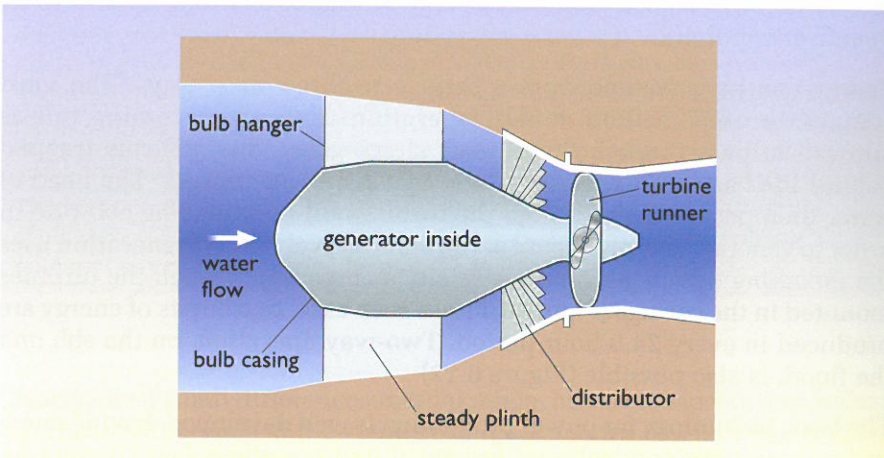


Figure 6.14 Bulb turbine as used at La Rance

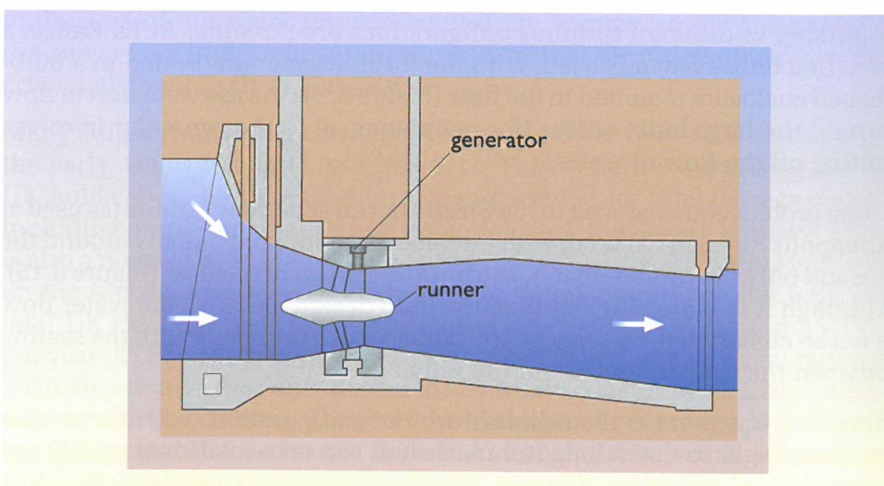


Figure 6.15 Straflo or rim generator turbine as used at Annapolis Royal

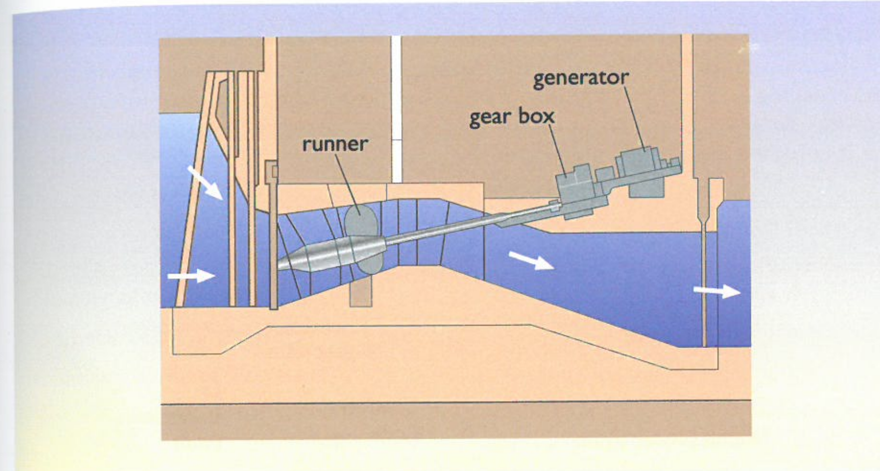


Figure 6.16 Tubular turbine

the flow of the water and, since the generator is not in a confined space, there is room for a gearbox, which can allow for efficient matching to the higher speed generators usually used with hydro plants. Several such units have been used in hydro power plants in the USA, the largest being rated at 25 MW. However, there have been vibration problems in the long drive shaft and, so far, bulb turbines have proved to be the most popular with barrage designers.

As mentioned above, the rotational speeds of the turbines in tidal barrages tend to be lower than those for turbines in hydro plants (50–100 revolutions per minute, in comparison to 200–450 revolutions per minute for hydro generators) and therefore wear is also reduced. Since large volumes of water have to pass through the barrage in a relatively short time, large numbers of turbines are required in a large-scale barrage (see Boxes 6.4 and 6.5 for details of La Rance and the proposed Severn Barrage).

In simple ebb or flood generation, this large installed capacity is used only for a relatively short period (three to six hours at most) in each tidal cycle, producing a large but short burst of power, which may not match the demand for electricity. However, using reversible-pitch turbines it is possible to operate on both the ebb and the flood in a two-way operation. Reversible-pitch turbines are more complex and costly than standard turbines and, although the output will be more evenly distributed over time, there will be a net decrease in electricity output for each phase compared with a simple ebb generation scheme. This is because, in order to be ready for the next cycle, neither the ebb nor the flow generation phases can be taken to completion: it is necessary to open the sluices and reduce water levels ready for the next flood cycle, and vice versa for ebb generation (see Figure 6.12).

Flood pumping is another option for electricity generation. Here, the turbine generators are run in reverse and act as motor-pump sets, powered by electricity from the grid. Additional water is pumped behind the barrage into the basin at around high tide, when there is a low head difference across the barrage. This provides extra water for the subsequent ebb generation phase when there is a high head difference. This is, in effect, a way to store excess off-peak power from the grid, but with a net energy gain.

BOX 6.4 La Rance

The 740-metre long Rance Barrage was constructed between 1961 and 1967. It has a road crossing and a ship lock (Figure 6.17) and was designed for maximum operational flexibility. It contains 24 reversible (that is, two-way) turbines, each of 10 MW capacity, operating in a tidal range of up to 12 metres, with a typical head of approximately 5 metres.

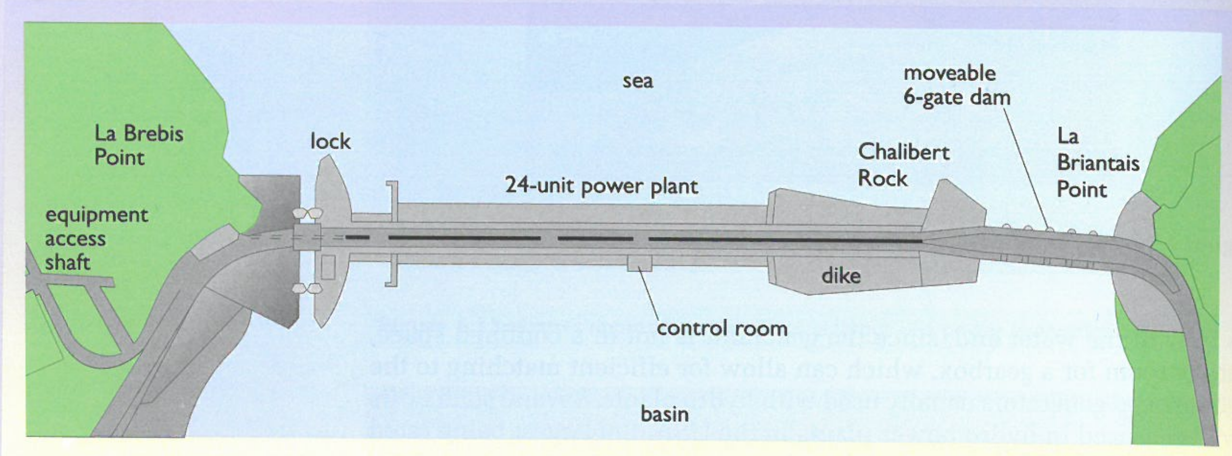


Figure 6.17 Layout of the Rance Barrage (source: Department of Energy, 1981)

The operational pattern initially adopted at La Rance was to optimize the uniformity of the power output by using a combination of two-way generation (which meant running the turbines at less than the maximum possible head of water) and incorporating an element of pumped storage. For spring tides, two-way generation was favoured; for neap tides and some intermediate tides, direct pumping from sea to basin was sometimes carried out to supplement generation on the ebb.

Although some mechanical problems were encountered in 1975, which subsequently led to two-way operation mostly being avoided, overall the barrage has been very successful. Typically the plant has been functional and available for use more than 90% of the time, and net output has been approximately 480 GWh y^{-1} with, in some years, significant energy gains from pumping.

The construction of the barrage involved building two temporary coffer-dams, with the water then being pumped out of the space in between, to allow work to be carried out in dry conditions (see Figure 6.18). River water was allowed to pass via sluices, but the reduced ebb and flow resulted in effective stagnation of the estuary and the subsequent partial collapse of the ecosystem within it. Since construction, exchange of water between the open sea and the estuary has restored the estuarine ecosystem, but because there was no monitoring it is difficult to establish what changes the barrage caused to the original environment in the estuary.

Figure 6.18 La Rance coffer-dam during construction of the barrage

BOX 6.5 The Proposed Severn Barrage

Basic data for the Cardiff to Weston Barrage is given below (Department of Energy, 1989). The same design specifications were used for the assessment carried out by the Sustainable Development Commission in 2007 (SDC, 2007) and in the Department of Energy and Climate Change/Welsh Assembly Government/SWRDA study in 2010 (DECC, 2010a).

Number of turbine generators		216
Diameter of turbines		9.0 metres
Operating speed of turbines		50 rpm
Turbine generator rating		40 MW
Installed capacity		8640 MW
Number of sluices, various sizes		166
Total clear area of sluice passages		35 000 m^2
Average annual energy output		17 TWh
Operational mode		ebb generation with flood pumping
Length of barrage:		
total		15.9 km
including:	powerhouse caissons	4.3 km
	sluice caissons	4.1 km
	other caissons	3.9 km
	embankments	3.6 km
Area of enclosed basin at mean sea level		480 km^2

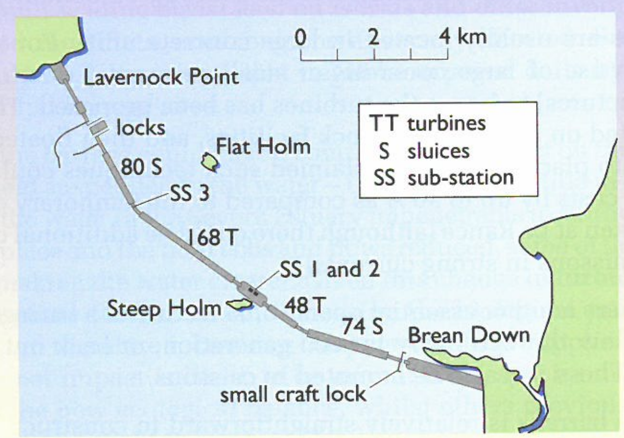


Figure 6.19 Layout of the proposed Cardiff to Weston Severn Barrage (source: adapted from Department of Energy, 1989)

In addition, as will be discussed in more detail later, many different types of **double-basin** system have been proposed (see, for example, Figure 6.20), often using pumping between the basins. During periods of low demand, excess electricity generated by the turbines of the first basin can be used to pump water into the second basin, ready for the latter to use for generation when power is required.

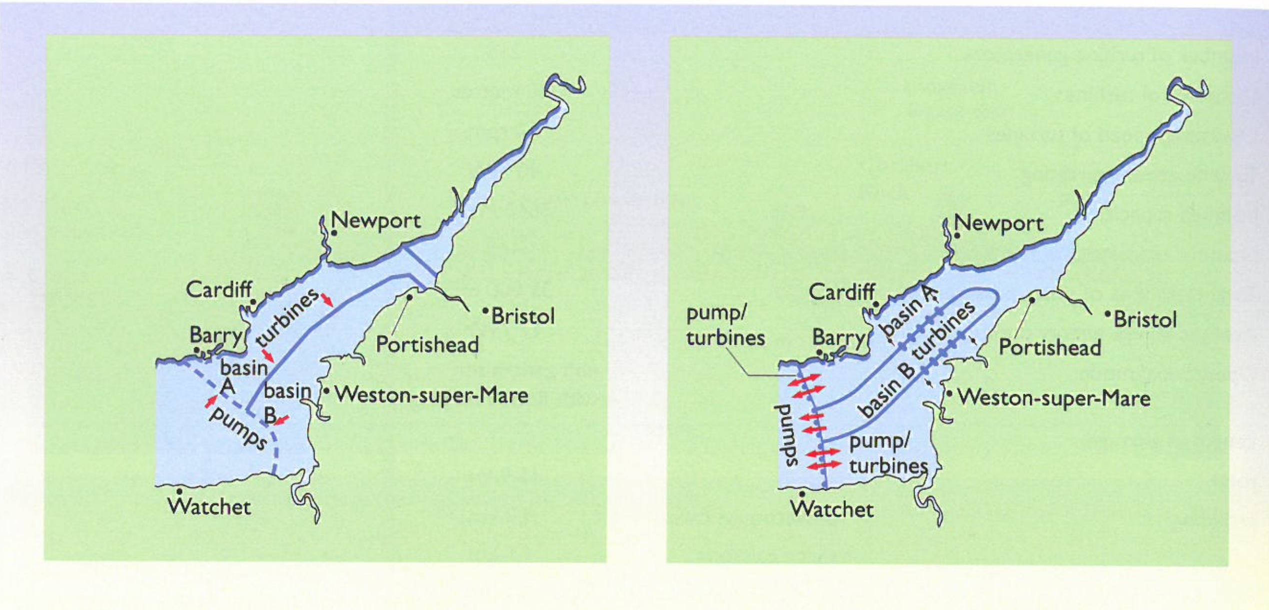


Figure 6.20 Severn Estuary with possible double-basin schemes (source: adapted from Department of Energy, 1981)

Whatever the precise configuration chosen for a barrage, the basic components are the same: *turbines*, *sluice gates* and, usually, *ship locks*, to allow passage of ships, all linked to the shore by *embankments*.

The turbines are usually located in large concrete units. For the Severn Barrage, the use of large concrete, or steel, caissons (containment and support structures) to house the turbines has been proposed. These could be constructed on shore, in dry dock facilities, and then floated onto site and sunk into place. It has been claimed such techniques could cut civil engineering costs by up to 30% as compared to the temporary coffer-dam approach taken at La Rance (although there could be additional difficulties in placing caissons in strong currents).

Sluice gates are another essential operational feature of a barrage, to allow the tide to flow through ready for ebb generation, or back out after flow generation. These can also be mounted in caissons.

The rest of a barrage is relatively straightforward to construct. La Rance, for example, has a rock-filled embankment, whilst one design proposed for the Severn used sand-filled embankments faced with suitable concrete or rock protection.

6.3 Environmental considerations for tidal barrages

The construction of a large barrier across an estuary will clearly have a significant effect on the local ecosystem. Some of the effects will be negative, and some will be positive. The negative local impacts have to be weighed up against the role that barrages could play in helping to resolve some global environmental and energy problems (such as global warming caused by CO_2 emissions from the burning of fossil fuels), and in offering improved energy security through decreased reliance on imported fuel.

In the UK, much research has gone into trying to ascertain the probable final balance of positive and negative impacts, and the overall cost effectiveness, focusing mainly on the proposed Severn Tidal Barrage (Department of Energy, 1989). The most recent review was carried out as part of the UK government's Severn Tidal Power Feasibility Study (DECC, 2010a). This looked at a number of tidal range projects for the Severn, including the Cardiff–Weston Barrage and some smaller barrages and tidal lagoons, and concluded that of all the schemes studied, the Cardiff–Weston Barrage would 'have the greatest impact on habitats and bird populations and the estuary ports', as well as very high capital costs.

Certainly the most obvious potential impact of any barrage would be on local wildlife, that is, fish and birds, many of the latter being migratory. The UK's estuaries play host to approximately 28% of European swans and ducks and to 47% of European geese. There are also large populations of fish: the Severn, for example, is well known for its salmon and eels (elvers). Many of these species rely on the estuaries for food, and access to that supply might be affected by a tidal barrage (Department of Energy, 1989).

The proposed Severn Barrage would decrease a large area (200 km^2 or more) of mud flats exposed each day, since the water level variations behind the barrage would be significantly reduced (Figure 6.21). Some species (for example, mud-wading birds) feed on worms and other invertebrates from the exposed mud flats, and could be adversely affected. Similar issues would apply for salt marshes that might be exposed daily by the tides at other potential barrage sites.

However, the barrage could have a compensating impact on the level of silt and sediment suspended in the water – the action of the tide in churning up silt makes the water in the Severn Estuary impenetrable to sunlight. With the barrage in place and the tidal ebbs and flows reduced, some of this silt would drop out, making the water clearer. Given this change in **turbidity** sunlight would penetrate further down, increasing the biological productivity of the water and therefore increasing the potential food supplies for fish and birds. The net impact is likely to be mixed: some species might not find a niche in the new ecological balance, whilst others previously excluded from the estuary might become established.

This rather simplified example illustrates the general point that there are complex interactions at work making it difficult to predict the outcome.

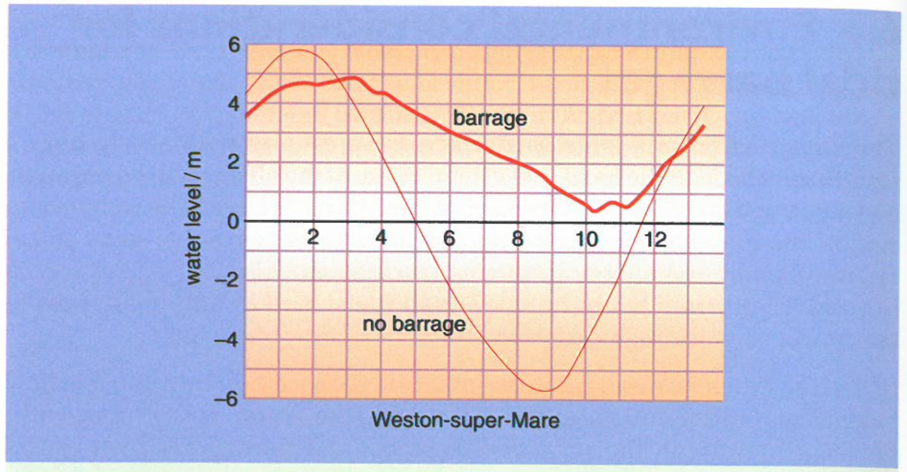


Figure 6.21 Variation in tide levels with and without the Severn Barrage over a 12 hour period (source: Department of Energy, 1989)

Similar interactions and trade-offs occur in relation to other ways in which barrages can impact on their surroundings. Clearly, the construction of a barrage across an estuary will impede any shipping, even though ship locks are likely to be included. The fact that the sea level behind the barrage would, on average, be higher could improve navigational access to ports, the net effect depending on tidal cycles and the precise location of the barrage and of any ports.

Visually, barrages present fewer problems than comparable hydro schemes. Even at low tide, the flank exposed would not be much higher than the maximum tidal range. From a distance, all that would be seen would be a line on the water.

Barrages could also play a useful role in providing protection against floods and storm damage, since they could be operated to control very high tidal surges and limit local wave generation. Conversely, for some sites, due to the change in tidal patterns (with the tide upstream staying above mid-level for longer periods), there might be a need for improved land drainage upstream.

A barrage would have some effect on the local economy both during the construction phase and subsequently, in terms of employment generation and local spending, tourism and, in particular, enhanced opportunities for water sports. Depending on the scale and the site, there could also be the option of providing a new road or rail crossing, as with the Rance Barrage. The incorporation of a public road was part of the plans proposed for the Severn barrage.

Whether these local infrastructural improvement options represent environmental benefits or costs depends on your views on industrial and commercial development (some conservation and wildlife groups, for example, baulk at the prospect of increased tourism), but many people would be likely to welcome local economic growth. Indeed, that was the message from local populations faced with barrage proposals. Local commercial and civic interests and the wider public have on the whole been supportive of such plans while other special interest groups have opposed

barrages. For example the Royal Society for the Protection of Birds (RSPB) sees barrages as inherently damaging, reducing habitats for key species, particularly migrant birds. This problem could clearly be compounded if several barrages were to be built. In 2008, when the Severn Barrage idea was moving up the UK political agenda, the National Trust, RSPB and World Wide Fund for Nature (WWF), in a coalition with other groups, came out strongly against the barrage.

6.4 Integration of electrical power from tidal barrages

The electricity produced by barrages must usually be integrated with the electricity produced by the other power plants that feed into a national grid power transmission network.

The key problem in feeding power from a tidal barrage into national grid networks is that with conventional ebb or flood generation schemes the tidal energy inputs come in relatively short bursts at approximately twelve-hour intervals. Typically, power can be produced for five to six hours during spring tides and three hours during neap tides, within a tidal cycle lasting 12.4 hours (Figure 6.22).

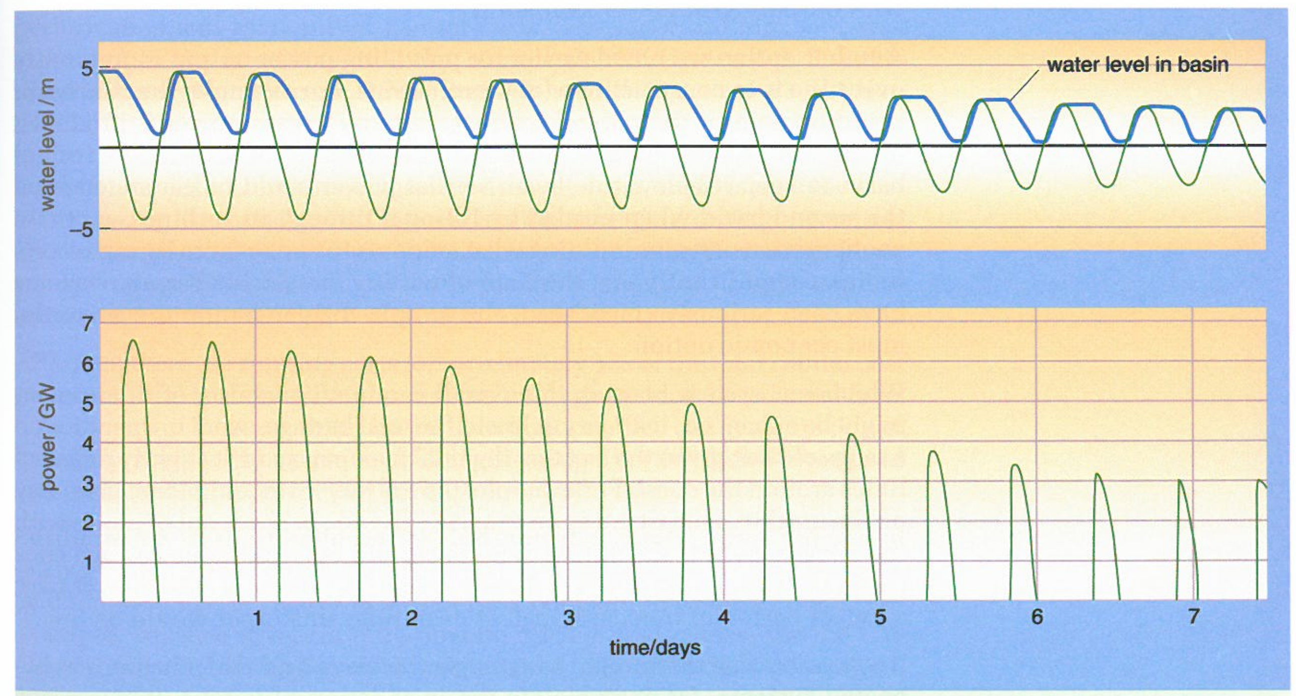


Figure 6.22 Water level and power output of the proposed Severn Barrage over a spring–neap tide cycle (source: Laughton, 1990)

Clearly, such availability of power from a barrage will not always match the pattern of demand for power on the grid. With a large, well-developed grid, as in the UK, with a large load and many other types of power plant connected into it, this problem might not be too severe, depending on the size of the barrage output. The two daily bursts of tidal power could be used to reduce the load on older, less efficient and/or more expensive plants such as older coal-fired plants. The barrage would thus be operating in a 'fuel-saving' mode, the predictability of the tides allowing for the process of substitution to be planned well in advance. Even so, with a barrage the size of that proposed for the Severn, absorbing all the power would clearly represent a significant task. At its peak, it would be generating over 8 GW of power, which represents a sizeable proportion of the UK's peak electricity demand of almost 60 GW (in 2010), and an even larger proportion of the minimum demand level during summer nights (around 20 GW – see Figure 10.13).

Two-way generation, on the incoming flood as well as the ebb, might offer some advantages since that would give *four* bursts of power for each 24 hour cycle, but as noted earlier the more complex turbines required add to the cost. There is also the option of using modified turbines as pumps, running on grid power (e.g. during off-peak periods), to pump extra water behind a barrage during the flood phase. Typically, between 5% and 15% extra output can be gained, with little additional capital cost and with no loss of generating efficiency. This has been the favoured option for all the barrage schemes proposed in the UK. That said, the overall *economic* advantages of pumping may be fairly small (the electricity used has to be paid for), and they depend crucially on tidal timing, which will not necessarily coincide with off-peak grid power availability.

Another option we noted earlier for providing power output more evenly over time is to construct two (or more) basins. For example, the first basin could operate in the normal manner, but any excess power it produced during low-demand periods, could be used to pump water out of the second basin to keep it below tide level, so that power could be generated from the second basin when needed by filling it through its turbines. As these configurations involve building what amounts to two or more barrages costs increase significantly – at the time of writing, no double-barrage systems have been seriously considered, and simple ebb generation is seen as the most economic option.

Whichever system is used, the overall economic viability of tidal power might be enhanced, in theory at least, if several barrages were in operation in a range of sites, given the fact that the tidal maxima occur at slightly different times around the coast. For example, the Solway Firth and Morecambe Bay on the northwest coast are approximately five to six hours out of phase with the Severn, so that the output from these and other possible barrage sites could be fed into the grid to provide a contribution from tidal power over a longer period of time, although at neap tides this input would be low.

It is possible that there might be synergies between tidal and other renewable energy systems, for example via the installation of wind turbines along barrages in the same way as some wind farms have been constructed on causeways in harbours. The wind plant might even be used at times for pumping water behind the barrage, although the energy contribution that could be made, even if wind turbines were located regularly along the entire length of a barrage, would be relatively small compared with the output of a large barrage. For example, if, say, thirty 2 MW wind turbines were installed along parts of the 16 km long proposed Severn Barrage, their total annual electricity output would be just over 1% of that from the barrage.

Finally, the linking of power from barrages to the national grid could present some practical problems. As with many other types of large, new, power plant, extra grid connections would have to be made, and in some circumstances existing local grid lines strengthened to carry the extra power. Fortunately, most potential barrage sites in the UK are reasonably near to existing power lines, so the problems such as those of harnessing deep-sea wave power (much of which would have to be transmitted from the north of Scotland; see Chapter 8) would be avoided. In the case of the proposed Severn Barrage new power lines, perhaps stretching to the major loads in the Midlands, would probably be required. It has been estimated that these grid connections might add 10% to the capital costs of the barrage.

In summary, the key issue to integration is cost, whether this is for additional grid linkages or for systems that allow power to be produced on a more nearly continuous basis. We now move on to look at economic factors more generally.

6.5 The economics of tidal barrages

The overall economics of tidal barrages depends both on their operational performance and their initial capital costs. The latter are high – it was estimated in the late 2000s that the 10 mile Cardiff (Lavernock Point) – Weston-super-Mare (Brean Down) barrage would cost over £30 billion (DECC, 2010a). The civil engineering works are the single largest element in the total cost, closely followed by turbine manufacture and installation. In addition to the construction and equipment costs, there is also the cost of borrowing the money, with interest having to be paid during the course of construction, when of course there is no income since the barrage is not yet operating. This raises a key issue for the economics of large capital-intensive projects like this with long construction times.

Although there are running costs (approximately 1% of the total capital cost per year), tidal barrages, like all renewable energy systems based on natural flows, have no fuel cost. After initial construction, they can generate power for many years without major civil engineering effort with the low-speed turbines needing replacement perhaps every 30 years.

Furthermore, in addition to the significant initial capital costs, the period during which power can be produced, at least for simple single-basin ebb or flood systems, is clearly less than for a conventional power plant. For example, because it would only operate during tidal cycles, the 8.6 GW turbine capacity of the Severn Barrage could only offer the same output, averaged out over a year, as a conventional plant with around 2 GW of generating capacity. In other words, the barrage requires a large investment in expensive capacity which is only used intermittently and can therefore only replace a limited amount of conventional plant output. The value of a barrage as a replacement for conventional plant(s) will depend in practice on the scale and timing of the outputs of the plants they can replace, not all of which will be able to generate continuously either.

As explained in Chapters 1 and 5, a convenient way to compare systems is in terms of their capacity factors (the ratio of a plant's actual energy output over a given period to the theoretical output if the plant operated at its full-rated capacity). The annual capacity factor for the proposed Severn Barrage is estimated at around 23%. By comparison, in typical UK conditions the average annual plant capacity factor for nuclear stations has in recent years been around 77%, and for combined cycle gas turbine power plants around 84%.

Thus, compared with most other types of power plant, tidal projects have a relatively high capital cost in relation to the energy output with, consequently, long capital payback times and low rates of return on the capital invested, the precise figures depending on the price that can be charged for the electricity.

In the 1980s, when the Severn Tidal Power Group analysed the economics of a Severn Barrage, the UK electricity industry was state-owned. As such it was expected to make a return on investment of about 5% per annum. However, the policy of the Conservative government of the time was to privatise the industry (which eventually happened in 1989). Any barrage project would thus be expected to be competitive with existing coal-fired and nuclear plant. It would also be privately financed and required to make commercial rates of return (10–15%). This would require a high electricity price to cover the interest on the large capital outlay. The Severn Barrage was not considered to be economic under these conditions (STPG, 1986). That was one reason why the project was not supported at that particular time.

Although fuel prices have increased dramatically and concerns about climate change have grown, the basic economic assessment has not changed significantly since then. It has, however, been argued that, given wider strategic concerns, such as climate change and security of energy supplies, it might be justifiable to accept a lower rate of return, similar to that used for public projects.

In its 2003 Green Book, the UK Treasury suggests that public sector organizations should make a real return of 6% on investments, though this point is qualified with a long discussion on the proper evaluation of risk and 'optimism bias' (HM Treasury, 2003).

In its 2007 study of tidal options for the Severn, the UK government's Sustainable Development Commission (SDC) noted that 'The high capital cost of a barrage project leads to a very high sensitivity to the discount rate used' (a truism for all projects with significant initial capital expenditure, as exemplified in Chapter 5 where a cost comparison of CCGT and hydro plants was made). At a low discount rate of 2%, which it argued could be justified for a climate change mitigation project, the cost of electricity output 'is highly competitive with other forms of generation'. On that basis they felt that the project should be financed as a public project (SDC, 2007).

In contrast they noted that, at a more 'commercial' discount rate of 8% or more, costs escalated significantly, making private sector investment unlikely without significant market intervention by government. For example they calculated that at a 2% discount rate the Cardiff–Weston Barrage would generate at between 2.27 and 2.31p per kWh depending on

how long it took to build, whereas at 10% discount rate the cost would rise to 11.18–12.37p per kWh. These costs were expressed in the money of the day, i.e. £(2006).

In its 2010 study of Severn tidal schemes the UK government compared the impact of 3.5% public sector 'social' discount rates with 10% commercial 'investor' discount rates (see Chapter 10 and Appendix B for a further discussion of discount rates). Table 6.1 illustrates the dramatic difference in energy costs and also the different levels of environmental impact of different options. Table 6.1 also compares the costs of large and smaller barrage schemes on the Severn. It might be expected that the smaller schemes further upstream would be more attractive financially, because they can be built more rapidly – but this is evidently not the case, in part due to the lower energy output from the smaller tidal ranges at these sites. So whether under 'investor' or 'social' financial frameworks, smaller barrages on the Severn are less attractive in terms of the cost of electricity produced. Although in the case of the Severn this seems clear-cut, small barrages in other estuaries, in locations with higher tidal ranges, might do better.

Table 6.1 Comparison of costs and impacts of large and small barrages on the Severn

Scheme	Installed capacity /MW	Annual energy generated /TWh y^{-1}	Levelized energy cost/£ MWh^{-1}		Inter-tidal habitat loss/km^2
			Investor (10% discount rate)	Social (3.5% discount rate)	
Cardiff–Weston Barrage	8640	15.6	312	108	160
Shoots Barrage	1050	2.7	335	121	33
Beachley Barrage	625	1.2	419	151	27

Source: DECC, 2010a

Given the lifetime of the low-speed turbines (replacement needed perhaps only every 30 years), low running costs (approximately 1% of the total capital cost per year) and zero fuel cost, it has been argued that, like hydro projects, barrages make a very good long-term investment. This is unfortunately not reflected in contemporary financial approaches, with the emphasis usually being on short-term returns.

Quite apart from the problems of funding and the vagaries of finance capital, interest rates, etc., on the 'supply' side, there are technical and environmental uncertainties, with trade-offs between operational efficiency and likely impact. To these uncertainties must be added the 'demand side' uncertainties, with the price that can be charged for tidal electricity having to be estimated over the very long term and compared with conventional fuel prices.

At £30 billion or so for cyclically varying power, the Severn barrage might not be the best use of any money available. Indeed a study by Frontier Economics for the National Trust, RSPB, WWF and other environmental groups opposed to the Severn barrage, suggested that large barrages were significantly more expensive on a £ per MWh basis than any other major energy generation option (Frontier Economics, 2008; see Figure 6.23). On this basis, it would seem that other options are likely to be more attractive, a view that now seems to be shared by the government, which in its 2010 study of the Severn tidal options commented: 'The Government believes that other options, such as the expansion of wind energy, carbon capture and storage (CCS) and nuclear power without public subsidy, represent a better deal for taxpayers and consumers at this time' (DECC, 2010a).

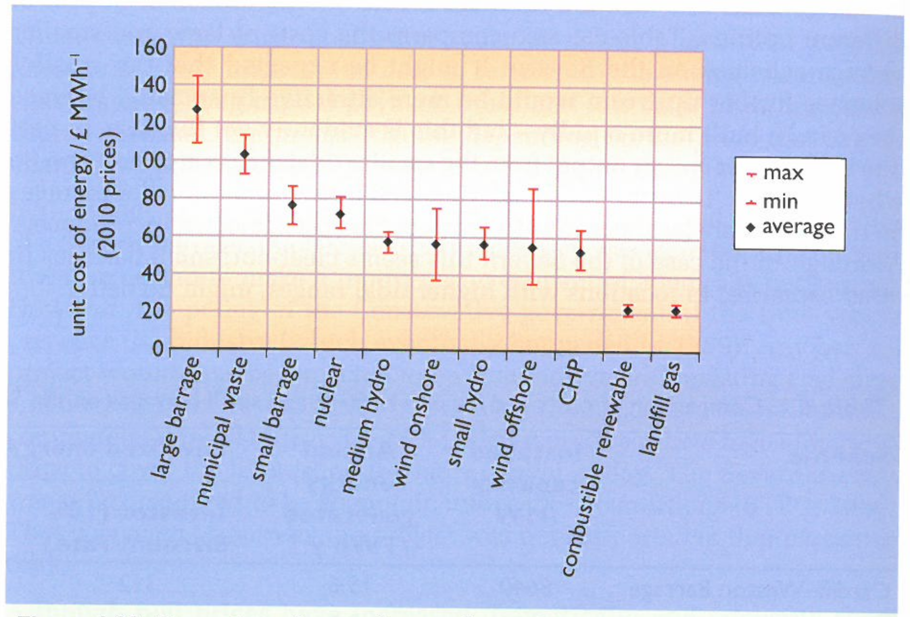


Figure 6.23 Comparison of costs of energy from tidal and other renewable energy projects, at 7% discount rate (source: adapted from Frontier Economics, 2008)

Although it seems likely that fossil fuel (and possibly nuclear) electricity prices will increase over time, so that tidal barrage projects will become more attractive, under the conditions present at the time of writing tidal barrages appear to be relatively unattractive commercial investment options. Nevertheless, with concerns about climate change and energy security, interest in the concept might revive, in part because of the large amount of renewable energy that could be generated.

In carbon balance terms, barrages do not generate CO_2 during their operation, but building them inevitably does. The UK SDC estimated that the carbon dioxide that would be produced by making the materials for and constructing the Cardiff–Weston barrage effectively amounted to 2.42 gCO_2 per kWh generated. This translates into a carbon payback time (based on how long it would take to recoup those emissions by the use of the barrage rather than a fossil-fuelled plant) of around 5–8 months (SDC, 2007).

Once built, a barrage could be seen as either displacing the output of existing fossil plant, or displacing the need for some other form of new capacity, and the associated emissions. The SDC decided to focus on the latter and assume that a Severn barrage would displace the need for new gas-fired combined cycle gas turbine (CCGT) plant, since 'a Severn barrage is unlikely to be operational for at least 10 years, during which time much of the UK's coal capacity will be taken out of service' (SDC, 2007).

On this basis, SDC calculated that the Cardiff–Weston Barrage would avoid the emission of 5.5 $MtCO_2$ per year compared to alternative CCGT gas-fuelled electricity generation, which represents a 0.92% reduction in UK carbon emissions compared to the 1990 baseline level used by the government. That might be seen as a relatively small saving for an estimated outlay of £30 billion or more.

6.6 Tidal barrages: potential projects

United Kingdom

The UK has some of the largest, and most studied, tidal energy resources in the world. In general, the best potential tidal barrage sites in the UK are on the west coasts of England and Wales, where the highest tidal ranges are to be found. Despite its indented coastline, the tidal energy potential of Scotland is very small (1–2 TWh y^{-1}) due to its generally low tidal range.

As we have seen, the practical potential of tidal power depends crucially on economics, as well as on environmental factors. In theory, the exploitable potential, assuming that every practical UK scheme was developed, could rise to approximately 53 TWh per year, or around 14% of UK electricity generation in 2010. Approximately 90% of this potential (48 TWh y^{-1}) lies in eight large sites, each offering between 1 TWh y^{-1} and 17 TWh y^{-1}, while the remaining 10% relates to 34 small sites, each providing somewhere in the range 20–150 GWh y^{-1} (ETSU, 1990).

The Cardiff–Weston Barrage, if built, would make the largest contribution, approximately 17 TWh y^{-1}, but initial estimates have suggested that the Wash, the Mersey, the Solway Firth, Morecambe Bay and possibly the Humber, amongst others, could also make significant contributions (Figure 6.24).

In addition to these larger sites, there are many smaller estuaries and rivers that could be used. Feasibility studies were carried out in the 1980s on the Loughor Estuary (8 MW) and Conwy Estuary (33 MW) in Wales, the Wyre (64 MW) in Lancashire, and the Duddon (100 MW) in Cumbria.

Overall, the total UK potential for small tidal schemes (that is, schemes of up to 300 MW capacity), has been estimated at nearly 2% of UK electricity requirements.

Studies have continued on some of these smaller sites, for example on the Duddon and there have also been proposals for larger schemes, including a 1 GW rated £2 billion barrage 11 miles across the Wash, and a 4.75 km² tidal lagoon in the Thames estuary, coupled, in a £2 – £4 billion project, with a tunnel crossing and tidal surge barrier between Medway and Canvey Island.

In addition there is continuing interest in other locations, where some even larger schemes might be possible. For example, a study led by the North West Regional Development Agency looked at tidal energy options for the Solway Firth, the UK's third largest estuary, on the border of England and Scotland. It identified nine main options including four tidal barrages, the largest scheme running from Workington to Abbey Head.

Figure 6.24 Some potential locations for tidal barrages in the UK

The schemes were compared on the basis of their likely environmental impact and the levelized cost of energy generated. The conclusions for the barrage projects were as follows.

- Workington to Abbey Head: £16 billion cost and large environmental impact; 5.9 GW installed, delivering 11.5 GWh y^{-1} – this scheme had a CoE of £183 per MWh (18.3p/kWh).
- Southerness Point to Beckfoot: £6.1 billion cost and substantial environmental impact; 2.7 GW installed – this had the lowest CoE of all the Solway schemes studied at £175 per MWh (17.5 p/kWh).
- Bowness to Annan: £1.2 billion cost; 316 MW installed delivering 320 GWh y^{-1} – CoE of £389 per MWh (38.9p/kWh).
- Morecambe Bay barrage (located out of the main estuary to reduce ecological impact): 113 MW installed delivering 120 GWh y^{-1} – CoE of £553 per MWh (55.3p/kWh).
- For comparison, the 8.6 GW Cardiff–Weston Severn Barrage (using an 8% rate of return, not the 10% discount rate in Table 6.1) was estimated to give a CoE of £160 per MWh (16.0 p/kWh).

The non-barrage tidal projects examined (including lagoons and tidal flow turbine systems) all had similarly high CoEs, but lower environmental impacts (Halcrow Group Ltd et al., 2009).

A 2010 study by the North West Regional Development Agency and renewable energy developer Peel Energy looked at a range of tidal options for the Mersey, including barrages of various sizes but also tidal lagoons and a variety of tidal current turbine concepts. The study reviewed an earlier 700 MW barrage proposal by the Mersey Barrage Company, but suggested that, although viable, the impacts of a barrage on shipping, sedimentation, water quality and the local ecology would need to be very carefully assessed. A smaller 500 MW barrage was also seen as viable, delivering 900 GWh y^{-1}. Moreover, it also found that some the other tidal options, although producing less energy, might have significantly lower environmental impacts (Peel Energy/NWRDA, 2010).

World

The total power in the tides globally is very large – of the order of 3000 GW.

In practice, since there are geographical access and location constraints on siting barrages or other means of extracting tidal energy, and they also have to be reasonably near to major lines of a national grid, the realistically available resource is much smaller. Jackson (1992) has put the realistically recoverable resource at 100 GW. Although that is under 12% of the existing global hydroelectric capacity, it still represents a significant resource. As Table 6.2 indicates, there are a number of potential large-scale sites for tidal barrages around the world, in Russia, Canada, the USA, Argentina, Korea, Australia, France, China and India, with an estimated total potential of perhaps as much as 300 TWh y^{-1}. There are some locations where some very large projects might be possible, (e.g. the potential 87 GW scheme at Penzhinsk in Russia) as well as many smaller ones.

So far, only a few of these potential sites have been exploited, notably, some small projects in Canada, Russia and the medium-scale project of La Rance in France. However, South Korea has a significant tidal barrage programme, which is developing some sites in addition to those identified by the World Energy Council in 2001 (see Table 6.2).

A 2006 study (Lee, 2006) estimated that South Korea had around 2400 MW of barrage potential, including possibly 700–1000 MW at Incheon, 600–800 MW at Cheonsu, and 480–520 MW at Garolim (this estimate being an increase on the 400 MW shown in Table 6.2). A 2008 study reported that a new 430 MW barrage project was planned near a dam at Saemangeum, along with a 520 MW project at Garolim and that an 812 MW Gangwha/Incheon project was planned to be completed in 2014 (Jo, 2008) At the time of writing a 254 MW tidal range project is being completed at Sihwa, in Gyeonggi province, bordering the West Sea. This is designed to generate power from a tidal rise of 5.64 metres and when fully operational will become the world's largest tidal power plant.

There have also been some very ambitious (if very speculative) proposals for very large barrages, such as huge barrages across the Bering Straits and the Irish Sea although the latter proposal would be considered by many engineers to be technologically unrealistic, as well as economically and politically challenging.

ıble 6.2 Potential non-UK tidal power sites

›untry	Mean tidal range/m	Basin area/km²	Installed capacity/MW	Approx annual output/TWh	Annual plant capacity factor/%
gentina					
ı José	5.8	778	5040	9.4	21
·lfo Nuevo	3.7	2376	6570	16.8	29
› Deseado	3.6	73	180	0.45	28
ıta Cruz	7.5	222	2420	6.1	29
› Gallegos	7.5	177	1900	4.8	29
stralia					
ure Bay	7.0	140	1480	2.9	22
lcott Inlet	7.0	260	2800	5.4	22
nada					
bequid	12.4	240	5338	14.0	30
nberland	10.9	90	1400	3.4	28
pody	10.0	115	1800	4.8	30
ia					
f of Kutch	5.0	170	900	1.6	22
f of Khambat	7.0	1970	7000	15.0	24
ıth Korea[1]					
·olim	4.7	100	400	0.836	24
›onsu	4.5	–	–	1.2	–
xico					
Colorado	6–7	–	–	5.4	–
A					
ımquoddy	5.5	–	–	–	–
‹ Arm	7.5	–	2900	7.4	29
ıagain Arm	7.5	–	6500	16.6	29
sian					
eration					
en	6.7	2640	15 000	45	34
ır[2]	6.8	1080	7800	16.2	24
:hinsk	11.4	20 530	87 400	190	25

e text for more recent additions/updates
00 MW variant also studied
rce: WEC, 2001

6.7 Tidal lagoons

Somewhat less ambitiously but still speculatively, in addition to large barrages, there have also been proposals for offshore 'bounded reservoir' or 'tidal lagoon' systems, consisting of circular low-head dams in open water, trapping water at high tide, with the water then being released to drive turbines in the usual way (Figure 6.25).

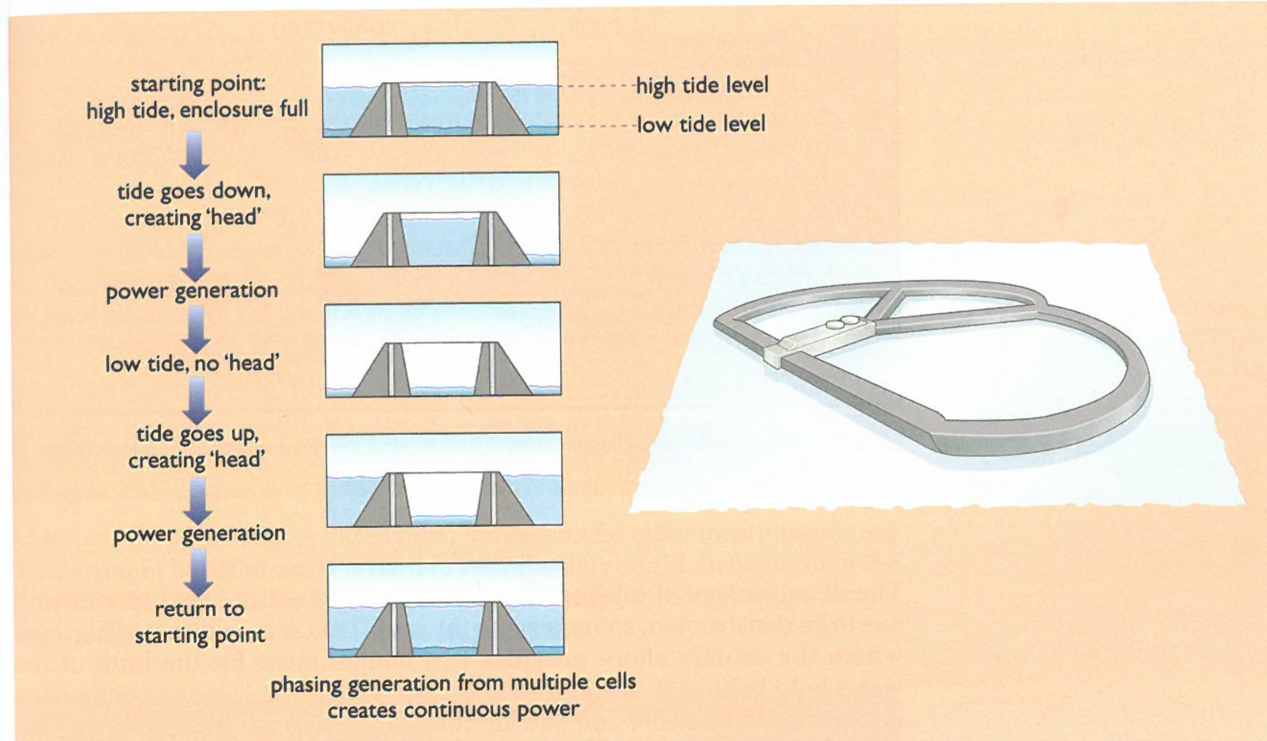


Figure 6.25 Tidal Electric's 'bounded' reservoir proposal

Lagoons would be in relatively shallow water and would be constructed like causeways with rock infill. Lagoons have the key advantage that although, as with conventional barrages, they would involve the creation of a head of water, they would not involve blocking off an estuary and so should have a lower environmental impact and avoid interfering with the passage of ships.

As well as generating power directly for the grid, lagoons might also be used as a low-head offshore pumped storage facility (see Chapter 5). Moreover, as with the double barrage idea, segmented lagoons could enable phased operation and pumping between segments.

The US company Tidal Electric has been investigating potential sites for tidal lagoons in Alaska, Africa, Mexico, India and China. At the time of writing a 1000 MW project is being considered in India and the company has also been in discussion with the Chinese government, which, it says, has expressed interest in a 300 MW offshore tidal lagoon to be built near the mouth of the Yalu River. Three sites are also under consideration in the UK, off the coast of Wales, including a 60 MW lagoon off Swansea. As illustrated in Figure 6.26 many other locations in that area have also been seen as possible lagoon sites.

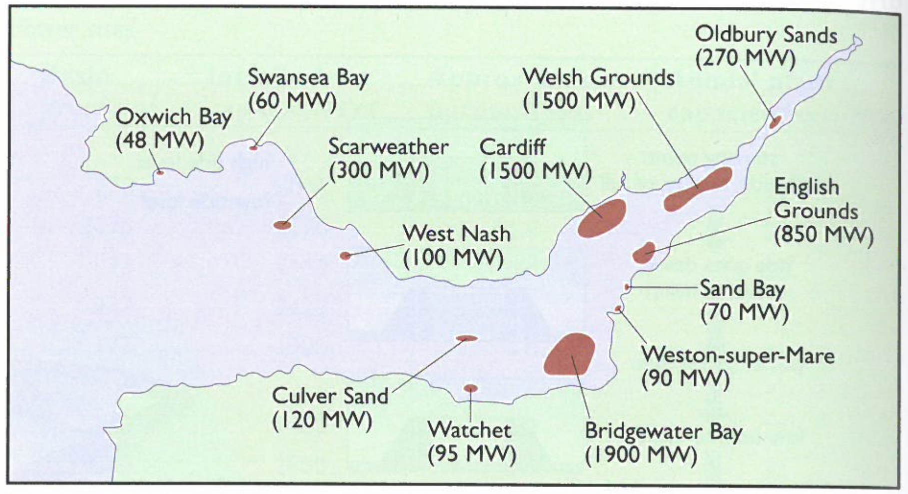


Figure 6.26 Possible tidal lagoon sites in and around the Severn estuary (source: Salter and Walker, 2010)

The disadvantage of offshore lagoons is that the entire containment wall has to be constructed, so increasing the cost. This is in contrast to barrages where the estuary shore provides free containment for the bulk of the water held behind it at high tide. Even so, given that lagoon construction is expected to be easier and quicker than for barrages, it is claimed that the cost of power from offshore lagoons can be competitive (Atkins Consultants Ltd, 2004).

While Tidal Electric have focused on fully offshore lagoons, a compromise option, to reduce cost further, would be to site the lagoon near to the shore, with part of the containment being the shore line. However inshore lagoons of this type are more likely to impact on mud flats, and the wildlife that uses them, than fully offshore schemes.

A 2010 DECC review of Severn tidal options (DECC, 2010a) concluded that although the cost of energy was relatively high, a near-shore lagoon at Bridgwater Bay on the English side could be feasible, with 'lower environmental impacts than barrage options', but that the Welsh Grounds near-shore lagoon was not viable (see Table 6.3). Tidal Electric's fully offshore scheme for Swansea Bay was not reviewed, being deemed to be outside of the geographical area of the study.

Lagoon proposals have also emerged for other locations around the UK, notably the Solway Firth and the Mersey estuary (see Section 6.6 above), but, so far, none have gone ahead.

Table 6.3 Comparison of costs and impacts of lagoons in the Severn (see Table 6.1 for the equivalent information for barrages)

Scheme	Installed capacity /MW	Annual energy generated /TWh y^{-1}	Levelized energy cost/£ MWh^{-1}		Inter-tidal habitat loss/km^2
			Investor (10% discount rate)	Social (3.5% discount rate)	
Welsh Grounds Lagoon	1000	2.1	515	169	73
Bridgewater Bay Lagoon	3600	6.2	349	126	25

Source: DECC, 2010a

No doubt the debate over the relative merits of barrages, large and small, and lagoons near shore and offshore, will continue. The combined resource is certainly not insignificant – an assessment of the energy resource offered by tidal range projects in the UK carried out in 2010 suggested that, assuming a maximum credible expansion programme, 20 GW of tidal range capacity might be expected by 2050 delivering 40 TWh per year. That included contributions from tidal lagoons, as well as barrages on the Severn, Mersey and Solway (DECC, 2010b).

The 2010 DECC Severn Tidal Feasibility Study concluded that the over £30 billion cost of the Cardiff–Weston Barrage made it high cost and high risk in comparison to other methods of generating electricity and the smaller barrages and lagoons were even less attractive economically (Figure 6.27).

Although the DECC report did say that the results for other locations around the UK might be different, it is hard to see how they could do better than the Severn – the best site by far in terms of tidal range, although other factors may in the future prove to be more important.

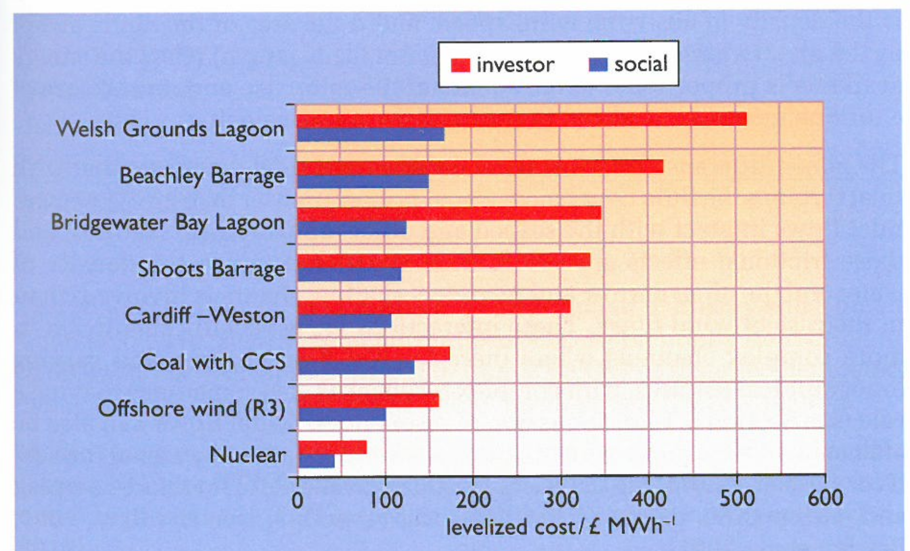


Figure 6.27 DECC estimates of Severn barrage and lagoon electricity prices compared to other options at 'investor' (10%) and 'social' (3.5%) discount rates (source: DECC, 2010a)

6.8 Tidal streams/currents

As noted in the introduction to this chapter, the use of tidal streams or currents is being followed up with some enthusiasm. Instead of using costly and potentially invasive barrages located in estuaries to exploit the *vertical* rise and fall of tides, and the *potential* energy of heads of water trapped behind dams or lagoons, it is possible to harness the energy in the *horizontal* movement of the tides – that is, the *kinetic* energy of the tidal ebbs and flows.

In open sea, the speed of the tidal ebbs and flows is relatively low, but it can be much higher when the tidal movements are concentrated by passing through narrow channels or around islands, headlands, or other topographical constraints. The enhanced velocity of the tidal streams or currents in such locations enables maximum energy extraction, for example by using relatively simple, submerged, wind turbine-like rotors (Figure 6.3).

As was noted in Section 6.1, the terms 'tidal current' and 'tidal stream' are often used interchangeably, and to confuse matters more not all the water flows in oceans are actually 'tidal' in the sense of being driven by the Moon. Some of these flows, especially the larger offshore ones, such as the Gulf Stream, are the result of complex interactions between warm and cold layers of water in the oceans around the world, and the associated effects of varying salinity – they are, in effect, solar-driven. Strictly speaking the correct terms to use for such non-tidal flows are **ocean currents** or **ocean streams**. We will be looking at some projects aiming to tap this energy in a later section.

Whatever type of flow is used, the basic physics of power extraction via turbines is similar to that for wind turbines. As Chapter 7 will explain, the power P in the wind is given by the formula $P = 0.5\ \rho a v^3$, where ρ is the density of air, v the wind speed, and a the area of the circle swept by the rotor (which is πr^2, where r is the rotor blade length). Thus the energy available is proportional to the square of the rotor size and, in the case of a turbine mounted in water, the cube of the water velocity.

The major difference between wind turbines and tidal devices is that with tidal turbines the fluid concerned, water, is much denser than air. Moreover, tidal flows interact with the seabed and other topographical features, and these frictional effects are much more significant (given the density of water and the often narrow and relatively shallow channels involved) than in the case of wind flows. These interactions are especially significant in more complex channels where there are direction changes and varying topographical features, with complex resonances also sometimes playing a role (see Section 6.1 for discussion of resonances). Tidal flows will also be affected by interactions with the interface between air and water at the sea/river surface. Estimating the energy resource available is therefore complex and site specific, requiring detailed local modelling (see Hardisty, 2007; Bryden et al., 2007).

So, while areas where there are high tidal ranges are important (see Figure 6.24), the local topography is crucial in determining whether tidal currents/streams can be utilized effectively – flow rates can sometimes be low at sites with a high tidal range and vice versa.

The resource and its location

Although tidal current resources are site specific, there is a lot of energy in the enhanced tidal currents in appropriate locations. For example, it has been estimated that the power flowing through the north channel of the Irish Sea is equivalent to 3.6 GW, while the flow through Pentland Firth in Scotland is the equivalent of 6.1 GW.

Mean peak spring tidal currents of at least 2–2.5 m s^{-1} (~4–5 knots) and a depth of between 20 and 35 metres are seen as necessary for economic exploitation. On this basis, the UK has some of the world's best sites for producing energy from tidal streams, as shown (see Figure 6.28). Table 6.4 gives details of the expected energy outputs in some of these sites.

Figure 6.28 Possible tidal current sites around and near the British Isles

Table 6.4 Some major tidal current sites in the vicinity of the British Isles and their associated resource potential

Site name	Location	TWh y^{-1}
Pentland Skerries	Pentland Firth	3.9
Strøm	Pentland Firth	2.8
Duncansby Head	Pentland Firth	2.0
Casquets	Alderney	1.7
South Ronaldsay	Pentland Firth	1.5
Hoy	Pentland Firth	1.4
Race of Alderney	Alderney	1.4
South Ronaldsay	Pentland Firth	1.1
Rathlin Island	North Channel	0.9
Mull of Galloway	North Channel	0.8

Source: SDC, 2007

The 2050 Pathways report produced by Department of Energy and Climate Change in 2010 saw UK tidal current projects as potentially delivering up to 69 TWh per year in total by 2050, from 21.3 GW of installed generating capacity, assuming maximum possible development (DECC, 2010b).

Moreover, a study by an industry group led by the Public Information Research Centre (PIRC), put the practical resource potential for tidal currents much higher, at 116 TWh per year, from 33 GW installed capacity (OVG, 2010).

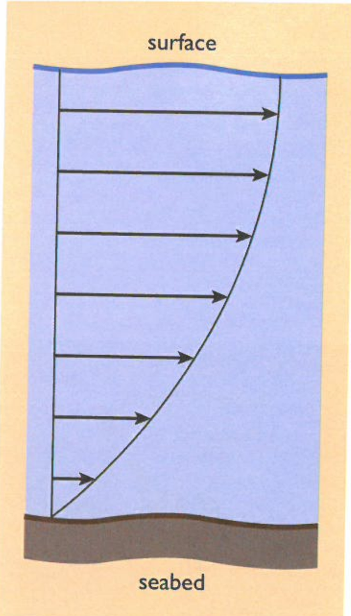


Figure 6.29 The shear effect – water speed (as indicated by arrow length) reduces with depth

Tidal current turbine design constraints

When considering device design and location it is crucial to note that friction with the seabed produces a vertical 'shear' effect in the current: surface water moves fastest, with the flow being slower lower down. Around 75% of the energy in the flow is contained in the top half of the water (Figure 6.29), but since the rotors have to be fully submerged, and to be efficient and avoid breaking the surface, a mid-depth location can make sense, with the size of the device being limited by the water depth. Given that most sites with high velocity water flow are relatively shallow (below 40–50 metres), tidal devices thus have a size constraint that does not apply to wind turbines.

Since the available energy is proportional to the square of the rotor blade length and the cube of the water velocity, even a small increase in blade size or water speed will yield a significantly increased amount of energy production. Figure 6.30 shows how the relationship works out in practice – the faster the flow and the larger rotor (subject to practical considerations) the better.

Submerged free-standing tidal rotors can operate at lower rotational speeds than wind turbines, the rotor speed in both cases being proportional to the flow velocity, with typical sea current velocities only being approximately 3 m s^{-1} compared with, say, 5–15 m s^{-1} for wind machines. Given that the density of the working fluid is much higher, the power output for a tidal stream machine is much larger than for a wind machine of equivalent rotor diameter.

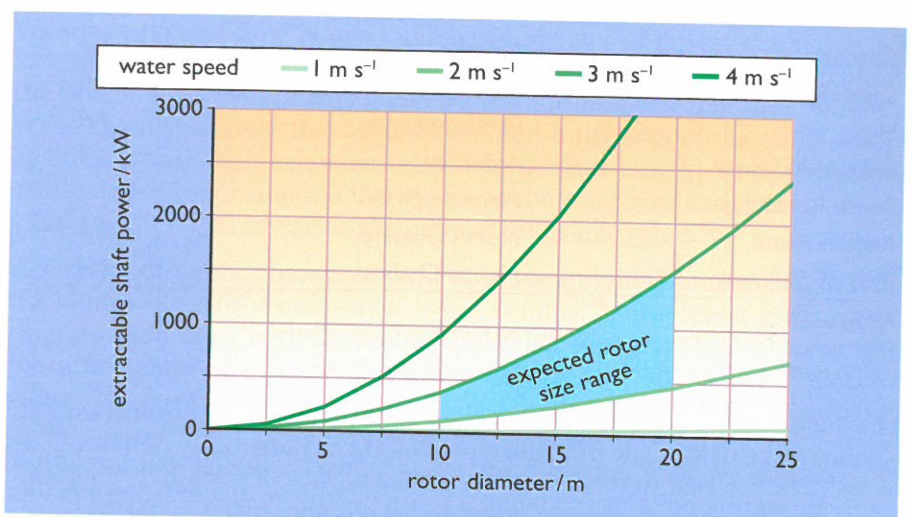


Figure 6.30 Relationship between rotor diameter, water speed and extractable power (source: adapted from Marine Current Turbines, 2010)

In comparison to barrage systems, the output from a tidal stream turbine is likely to be lower than that from an equivalent-sized conventional turbine in a barrage, which has the advantage of the funnelling effect of the barrage and the creation of an enhanced head of water. However, free-standing tidal current systems can have much larger rotors than is practical in barrage-mounted turbines.

An advantage of tidal current devices over simple ebb or flood tidal barrages is that they can operate on both ebb and flood tides and thereby attain a much higher capacity factor. Other advantages are that individual units can be constructed on a modular basis and installed incrementally in gradually expanding arrays giving both economies of scale and a much shorter lead time between investment and gaining revenue.

As with wave energy systems (see Chapter 8) there may be problems of fouling (for example, by seaweed, lost fishing nets, etc.), tethering and power take-off to overcome, but on the other hand, expensive and environmentally intrusive barrages are not required. There will be little visual impact, as in most designs all of the device would be under water, and there is virtually no noise.

There is a range of possible device configurations. Energy in tidal and ocean streams/currents can be captured using wind turbine-like horizontal or vertical axis rotors, supported under floating pontoons tethered to the seabed, fixed directly on the seabed, or mounted on towers. Ducts can be used to accelerate the water flow through the turbine. Alternatively, use can be made of hydroplane arrangements, involving seabed mounted hydrofoils oscillating up and down in the tidal flows. The following sections look at some examples of each approach and at the status, at the time of writing, of development in the UK and elsewhere.

Some of the projects reviewed below are well established, having been fully tested at sea, and some have been deployed at full scale. However, it should be stressed that many of the projects being discussed are at a relatively early stage of development, with the claims about potential energy outputs and generation capacities still unproven – indeed some descriptions are of currently speculative design concepts and proposals. When examining novel proposals, care has to be taken to assess the credibility of the claims being made. For example, generation capacities are sometimes claimed which could only be achieved, given the size of the device, at very high water speeds. While many of the devices and proposals described in the sections below may not eventually prove successful, a wide sample of projects has been included here, to give a feel for the range and vitality of the innovative and experimental processes underway in this field.

6.9 An overview of projects and innovative tidal stream concepts in the UK

Tidal current/stream development has only begun to be developed on a significant scale in the UK relatively recently, partly because it was previously thought that the cost of generating electricity via such technologies was likely to be high. Such cost considerations meant that work on tidal stream technology was given a low priority in the renewable energy development strategy adopted in the early 1990s by the (then) Department of Trade and Industry (ETSU, 1993).

Subsequently, following a review by the Marine Foresight panel set up by the Office of Science and Technology, support for tidal stream projects has grown, partly because the report argued that economies of scale via the production of large numbers of turbines (albeit only after a substantial development programme) could reduce these costs (OST, 1999) and also because novel devices have begun to emerge.

In 1994, in a pioneering project, a prototype two-bladed 10 kW tidal current turbine was tested in the Corran Narrows in Loch Linnhe, near Fort William in Scotland, by a consortium involving IT Power, the National Engineering Laboratory and Scottish Nuclear. This was the world's first tidal current turbine. The tests involved a rotor of 3.9 metres in diameter submerged under a small catamaran pontoon in the sea at a depth of 5 metres. In a fully operational system it was proposed that the rotor unit would be supported by a cable attached to a floating buoy and also tethered to the seabed. It could therefore swivel around on the change of the tide to absorb power from tidal currents in either direction (Figure 6.31).

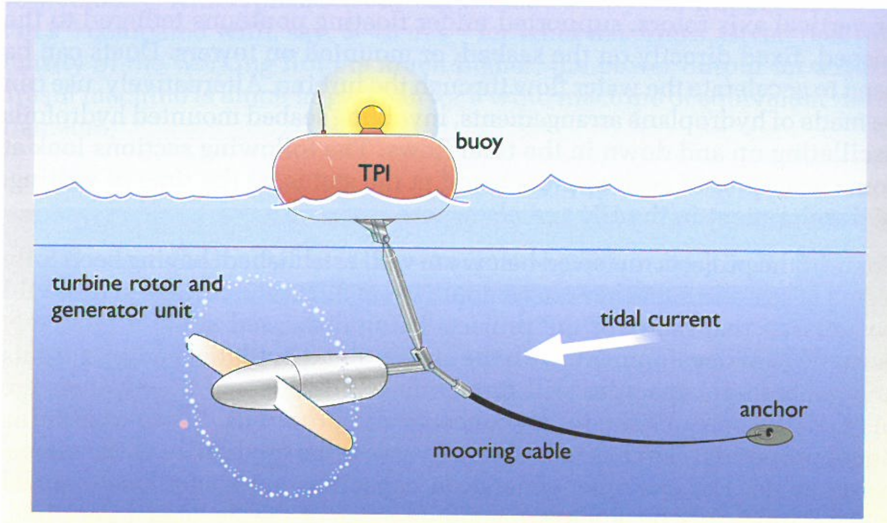


Figure 6.31 The IT Power tidal current turbine concept, developed and tested at Loch Linnhe, Scotland (source: adapted from Marine Current Turbines, 2010)

This free-floating, mid-depth swivelling system concept might in some locations have cost advantages over fixed bottom-mounted devices, e.g. in places where there is sufficient room for the structure to swing around. However, the need for flexible marine cable power take-off arrangements could add to the overall cost, and Marine Current Turbines (MCT) (an offshoot of IT Power) went on to develop a system with a rotor mounted on a fixed steel pile driven into the seabed.

Subsequently, MCT implemented this approach in a two-bladed 300 kW experimental prototype named SeaFlow which was tested 1 km off the

coast of north Devon near Lynmouth between 2003 and 2006 before being decommissioned in 2009 after testing had finished.

MCT then developed a larger two-bladed twin-rotor design of 1.2 MW capacity (at 2.4 m s^{-1}), called SeaGen, which they installed in Strangford Narrows, Northern Ireland in 2008 (Figure 6.32). The rotors of the first prototype are 16 metres in diameter and their pitch can be rotated through 180 degrees, to re-orient them to the tide when it changes direction, thus allowing efficient operation on both the ebb and the flood. They can be

Figure 6.32 MCT 1.2 MW SeaGen in Strangford Narrows with the rotor blades raised out of the water for access

raised out of the water for easy access. Although the prototype is rated at a relatively low power level its successors are expected to be capable of up to 2 MW, using rotors of up to 20 m diameter.

SeaGen has proved very successful, delivering power to the grid and, from 2009 onwards, earning Renewable Obligation Certificates for the electricity supplied, under the UK Renewable Obligation scheme – it was the first tidal project to obtain support from this scheme. Following this project, the aim is to build a 10 MW 'tidal farm' array, using several machines off the coast of Wales near Anglesey, with a similar project planned for Kyle Rhea off the Isle of Skye in Scotland. In addition MCT and ESB International are developing the initial phase of a 100 MW project off the Antrim coast, in Northern Ireland, the initial 50 MW phase of which could be in operation by 2018. MCT also has plans for a 100 MW project off the Orkney Islands with a 2020 completion date.

A new development of SeaGen has multiple rotors (3 to 6) to gain further economies of scale. It operates completely submerged but has the facility to be automatically surfaced by remote control to enable safer and easier maintenance; the prototype, a 2 MW triple rotor device, is intended to be installed in 2012 in the Bay of Fundy in Canada.

Conventional axial flow or 'propeller-type' designs like MCT's SeaGen seem the most obvious way forward: they mimic the successful approach used by the wind industry. Although not yet fully developed tested or deployed like MCTs systems, there have been several similar designs, like Swanturbine's seabed mounted Cignet, developed at Swansea University, and Tidal Energy's DeltaStream triangular frame seabed-mounted system, being tested off Wales – although both of these use three-bladed turbines, rather than two-bladed ones as in SeaGen. A double rotor system, with two triple-bladed contra-rotating rotors mounted on a common shaft, has also been developed by Strathclyde University and a 500 kW version has been tested by spin-off company Nautricity.

Novel designs

The turbines we have looked at so far may look like aircraft or ship propellers, but of course they do not propel anything – they absorb energy from the tidal flow. Propeller-type configurations have certainly been popular, but they are not the only option and the tidal turbine field is currently at the innovative stage where many different concepts are being proposed and tested. For example the Engineering Business group developed a novel design - the **Stingray** - with a set of totally submerged hydroplanes, oscillating up and down in the tidal flows and driving a generator mounted on the seabed (Figure 6.33). A 150 kW prototype was installed and tested in 2002 and

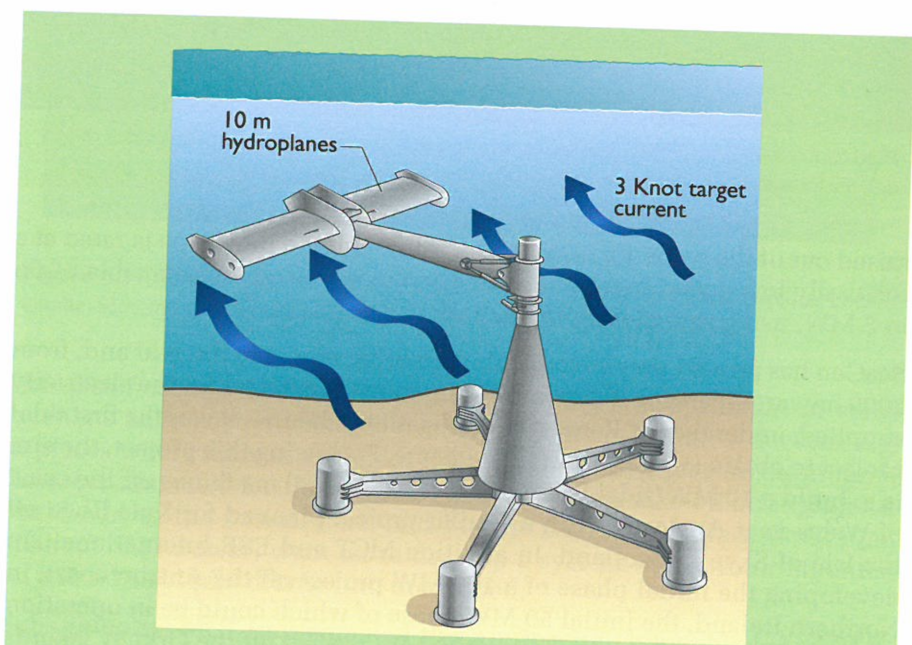


Figure 6.33 Stingray tidal generator

again 2003, in Yell Sound in the Shetlands. However it proved to be very inefficient and was subsequently abandoned.

It seems the energy conversion efficiency was low (around 9.5%) due in part to the relatively slow oscillation rate, but a derivative, with two sets of hydrofoils on a 'see-saw' arrangement oscillating much more rapidly, was subsequently developed by Pulse Tidal. In 2009, a 100 kW test rig was tested in the Humber estuary, with power being delivered to shore. The company has been looking in particular at Kyle Rhea as a possible site for a 1.2 MW unit, possibly to be followed by linking eight tidal power devices together in a 9.6 MW tidal fence (Figure 6.34).

Given the relatively shallow depth of most tidal channels, hydroplane type designs are claimed to have an advantage over propeller-like designs in that they can operate in shallower water, with the blades able to traverse a larger cross-sectional area of tidal flow than the circular area defined by the rotating blades of propeller-like devices. This comparison does need to be treated with some caution, since reciprocating devices operate most efficiently in mid-stroke and lose energy as they slow at the end of each stroke.

Many other designs have been proposed. One approach has been to enhance/accelerate the tidal flow using an annular duct surrounding a conventional horizontal-axis rotor (Figure 6.35).

A very different approach to ducting has been adopted by Neptune Renewable Energy. Their Proteus system has a vertical-axis rotor mounted in a duct system submerged under a floating pontoon (Figure 6.36). The system was tested at the University of Hull and a 150 tonne prototype was then built and installed in the Humber Estuary, the aim being to use the electricity generated to power The Deep, an aquarium centre in Hull.

An issue with ducting is whether the enhancement of the flow justifies the extra cost of the duct. With wind turbines, this does not seem to be the case, especially since wind directions vary, but tidal flows always follow fixed paths, back and forth, so fixed ducting might be economically viable.

One of the most novel designs is the 'open-centred' turbine developed by Irish company OpenHydro, which has rotors mounted around the inner rim of a sealed circular generator system, which also acts as a duct (Figure 6.37). Following tests of a 250 kW rated prototype at the

Figure 6.34 Pulse Tidal's two hydrofoils mounted on a see-saw concept

Figure 6.35 Example of a ducted rotor being developed by Rotech

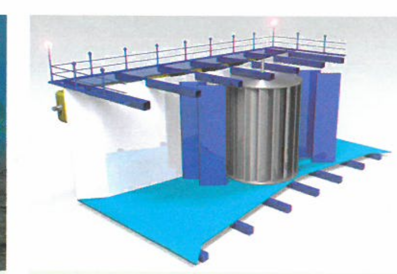


Figure 6.36 Neptune's Proteus – a vertical-axis ducted rotor

European Marine Energy Centre (EMEC), a 1 MW version was developed and installed for testing in the Bay of Fundy, Canada in 2008, and, in 2010, a 200 MW project was given a site in the Pentland Firth off the northern coast of Scotland. In addition there are plans for a 284 MW project off Alderney.

BOX 6.6 A European test centre

The European Marine Energy Centre (EMEC) in Stromness in the Orkney Islands, provides support for development in tidal and wave power with a site at the Fall of Warness off the island of Eday supporting tidal power research and a site at Billia Croo (Mainland) where wave power devices may be tested.

Apart from offering sites that allow developmental systems to be deployed in the open sea and connected to a grid, EMEC has expertise in device monitoring and with its links to different developers can support best practice throughout this part of the renewables industry. The site is not just restricted to UK devices as the centre is being used by developers from across the world.

One of the key factors in tidal turbine design, as with wave energy devices, is accessibility for maintenance and repair, since this is likely to be a dominant factor in the running costs. Many devices are designed so that the rotor unit and/or generator can be winched to the surface by a boat. Alternatively some have in-built mechanisms for raising the turbine assembly out of the water, as shown in Figure 6.32 in the case of MCT's SeaGen. In a similar vein, TidalStream's Triton design has a series of propeller-type units on a hinged structure fixed to the seabed which can be tilted up so that the turbines are on the surface (Figure 6.38). A one-tenth scale prototype has been tested in the Thames. MCT have also proposed something similar for

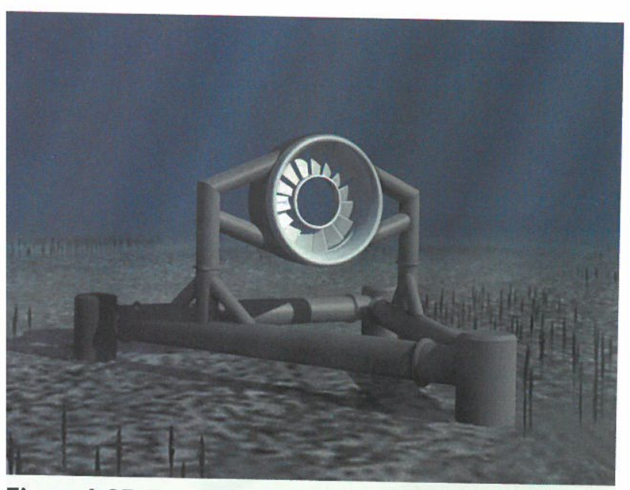


Figure 6.37 The OpenHydro open-centred turbine

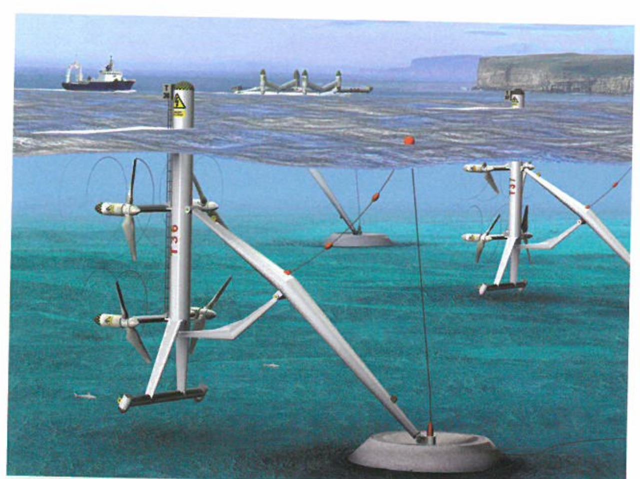
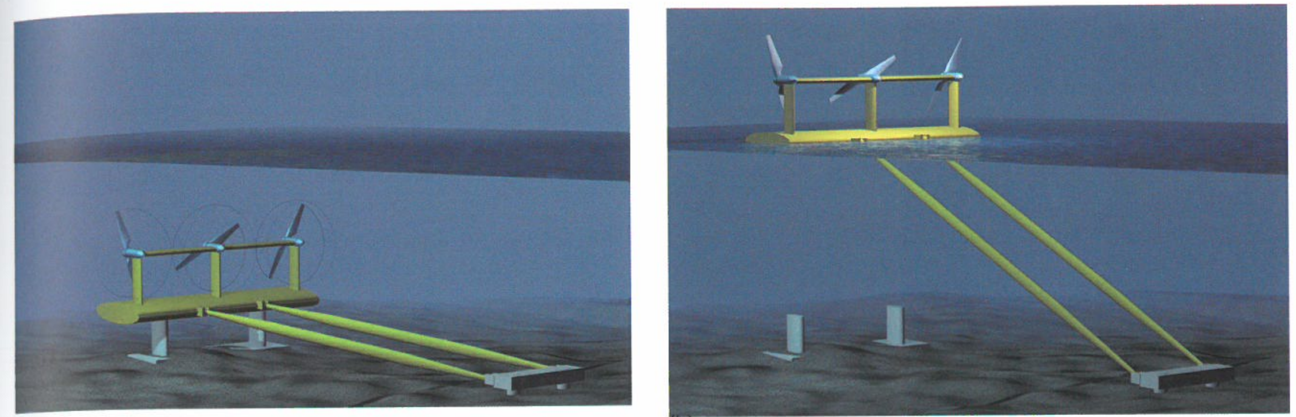


Figure 6.38 TidalStream's Triton



(a) (b)

Figure 6.39 MCT's next generation SeaGen – the seabed-mounted array can be raised to the surface for access

the follow-up SeaGen deployments – a hinged frame fixed to the seabed (Figure 6.39).

Most of the tidal current schemes and designs discussed above involve single machines or groups of machines in free-standing 'tidal farm' arrays, but there are also proposals for more integrated schemes, with devices mounted in structures such as permeable 'tidal fences' across estuaries (see Box 6.7).

BOX 6.7 Integrated tidal current turbine structures for the Severn

Although some integrated schemes were looked at, along with barrages and lagoons, in the first round of the UK government's Severn Tidal Feasibility Study, they were not included on the final shortlist. An ancillary DECC-supported assessment programme, the Severn Embryonic Technology Scheme (SETS), which started in 2008, followed up some of the ideas described here.

Tidal Fence

As an alternative to the Severn Tidal Barrage, the Severn Tidal Fence group (STF) proposed a 1.3 GW permeable tidal fence in the same location, with a row of large-diameter ducted tidal current turbines, which STF said would be less environmentally invasive than a barrage – since it was not trying to create a head of water, it would not have to block the entire estuary (Figure 6.40).

Figure 6.40 The STF Tidal Fence Proposal

Tidal Reef

The Tidal Reef concept, developed by Evans Engineering, is something of a compromise between a full barrage and the tidal fence, designed to minimize environmental impact. It would be a 15 mile long causeway from Minehead to Aberthaw in Wales, with, in one version, vertical-axis tidal turbines running on both ebb and flood tides, mounted in floating caissons, which would rise, from the supporting causeway, with the tides. The project would comprise over 1000 5 MW turbines of 10 m diameter with an annual generation of around 20 TWh. This compares to the 17 GWh expected from the Cardiff–Weston Barrage.

The basic concept was for the reef to be very permeable, so, unlike the Cardiff–Weston Barrage it would not hold back the full height of the tide or create a large head of water – the low-speed turbines would run on only about a 2 m head, so that the environmental impact should be lower.

Atkins and Rolls Royce subsequently developed a new version of the idea (the Rolls Royce/Atkins Tidal Bar) which was chosen, along with STF's Tidal Fence, for further assessment funded by the government's SETS scheme.

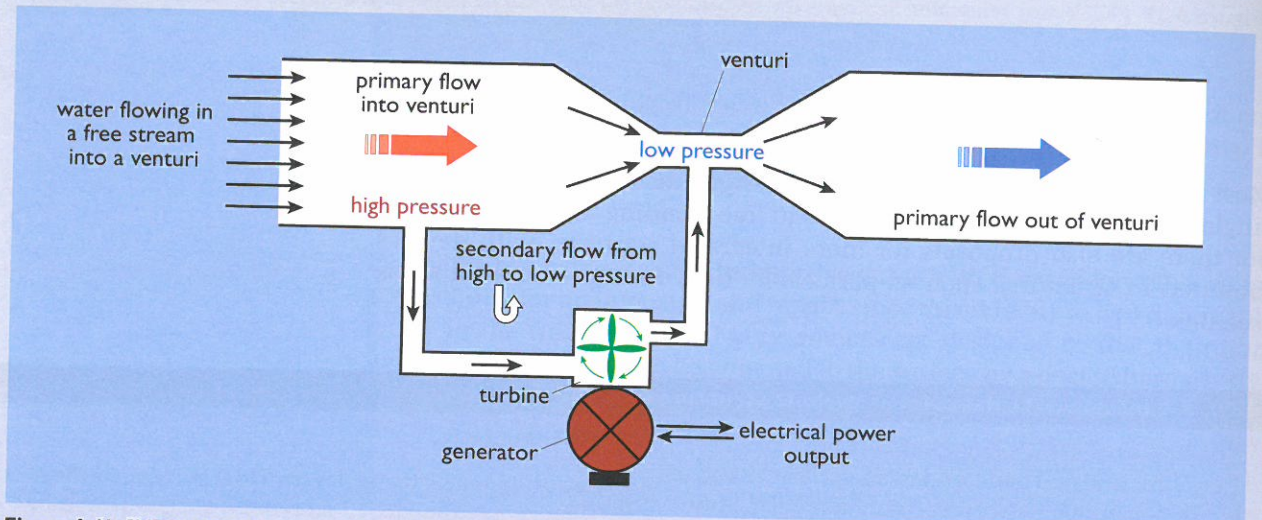


Figure 6.41 SMEC 'venturi' concept – basic principles (source: adapted from VerdErg, 2009)

Spectral Marine Energy Converter (SMEC)

A third project looked at under SETS was the Spectral Marine Energy Converter (SMEC), a novel device being developed by VerdErg using the venturi effect – the reduction in fluid pressure that results when a fluid flows out through a constriction. In this system the tidal flow passes through vanes, creating a pressure drop which is used to drive a turbine and generator via a secondary water flow. The secondary flow will have a higher velocity than the primary flow (Figure 6.41). Furthermore this secondary flow can power a turbine and generator located more conveniently out of the water.

The SMEC concept could be used at a variety of scales – in free-standing mid-stream locations in rivers, or across whole estuaries in a permeable fence-like structure. Vertical vanes would be used in the latter case to produce the pressure drop, horizontal vanes for shallow mid-channel use in rivers (see Figure 6.42). An estuary-wide tidal fence version (Figure 6.43), would, VerdErg claims, produce nearly as much electrical power as a full conventional barrage, but at two thirds of the cost and with much less environmental impact.

Reporting on the outcome of the SETS project in 2010, DECC's Severn Tidal Feasibility Study noted that the tidal bar/reef and the Spectral Marine Energy Converter 'showed promise for future deployment within the Severn estuary – with potentially lower costs and environmental impacts than either lagoons or barrages.' However they added 'these proposals are a long way from technical maturity and have much higher risks than the more conventional schemes the study has considered. Much more work would be required to develop them to the point where they could be properly assessed.' (DECC, 2010a).

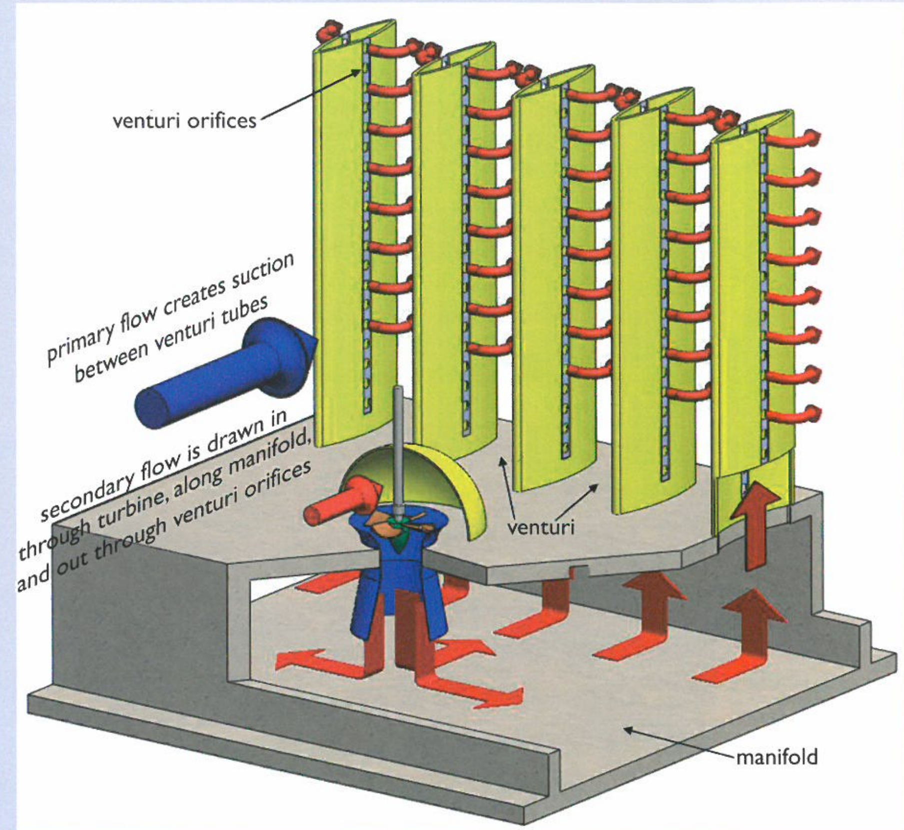


Figure 6.42 Proposed SMEC tidal system for a river

Figure 6.43 Proposed SMEC tidal fence system for an estuary.

The devices looked at in the Severn Embryonic Technology Scheme (SETS) are all at very early stages in their development, as are some of the other devices mentioned above, with only a handful having been tested. There are also many other novel designs emerging. Clearly not all of the designs discussed will prove successful, although MCTs SeaGen has broken through to commercial-scale deployment, and several others seem likely to do so.

In 2010 The Crown Estate announced successful bidders for 10 tidal current and wave energy projects on sites in Scotland's Pentland Firth and Orkney waters. Projects totalling 1.2 GW of installed capacity, 600 MW each from wave and tidal project bids, were given the go-ahead for development, with the target completion date being 2020.

The successful tidal bids included a 100 MW project from MCT, a 200 MW OpenHydro project, a 200 MW project at Westray South led by SSE Renewables Developments (UK); and a 100 MW project led by Scottish Power Renewables UK, using a 1 MW turbine being developed by Norwegian company Hammerfest Strøm (see Figure 6.44).

Figure 6.44 The Hammerfest Strøm tidal turbine

Subsequently the go ahead was also given for a 400 MW project in the Inner Sound area of Pentland Firth, involving the Atlantis Resources Corporation, a Singapore based company that has developed a 1 MW double rotor turbine (see Figure 6.45). In this device one rotor runs on the ebb tide and the other runs on the flood tide (on each tide the non-functioning rotor is fixed).

Figure 6.45 Atlantis AK-1000 1MW double rotor tidal turbine

In all, 1 GW of tidal current projects are now planned for the area and, as there are also plans for other projects elsewhere off the UK coast, in total perhaps 1.2 GW capacity may be in place around the UK by around 2020.

6.10 Tidal current projects and concepts around the world

The idea of using tidal currents is also being explored around the world, although, since UK tidal current resources are amongst the best globally, some of the devices being developed by non-UK companies are being tested in UK waters, with some subsequently being designated for full scale deployment in UK waters, sometimes as joint projects with UK companies. As noted in the previous section both the Norwegian Hammerfest Strøm (see Figure 6.44) and the Singaporean Atlantis Resources Corporation (see Figure 6.45) are deploying devices into UK waters.

Tidal current projects – a world overview

A wide variety of concepts are being developed and tested around the world, for example in Europe (including most notably Norway, but also France, the Netherlands, Germany and Italy), and in the USA, Canada, New Zealand and Australia. In this section a sample of the larger projects underway at the time of writing will be outlined starting with South Korea, which has several medium-scale projects underway.

South Korea

Following tests with a 100 kW tidal current power facility installed in 2003 in Uldolmog on the South coast, in a narrow channel with a 5.5 m s^{-1}

current speed, a 1 MW rated facility is being built and there are plans for a larger project in Daebang Strait, of up to 20 MW. There are also plans for an ocean current power farm in the Sihwa area where there is already a tidal barrage nearing completion . The largest tidal stream project so far is at Wando, where there are plans to have 300 MW of tidal current turbines installed by 2015. Here Voith Hydro is to install up to 600 of its 1 MW Seaturtle tidal current turbines.

Voith have also developed a three-bladed 1 MW seabed mounted propellor-type system, which they plan to test at EMEC, and then to install in an array of 100 MW capacity at Jindo, Jeollanamdo Province. A unique feature is that it has unsealed sea-water compatible bearings, which it is claimed reduce maintenance requirements (Figure 6.46).

Figure 6.46 Voith 1 MW turbine

Norway

In addition to the Hammerfest Strøm project already mentioned, Hydra Tidal are developing a multi-rotor floating propeller-type device with laminated wood composite blades. A 1.5 MW four-rotor two-bladed version, Morild II, with 23m diameter blades, was officially opened offshore from Lofoten, northern Norway, in 2010, with grid links planned.

USA

Six of Verdant Power's small (35 kW) three bladed propeller-type tidal turbines have been tested in New York City's East River near Roosevelt Island. By 2008 they claimed to have clocked up 9000 turbine-hours of operation (Figure 6.47). There are plans for expanding the project to 30 turbines, possibly feeding power to the United Nations building nearby. In addition, the Massachusetts Tidal Energy Company has been looking at the possibility of installing up to 150 2 MW devices at Vineyard Sound on the New England coast.

Meanwhile, following tests with a prototype, the UEK Corporation, based in Annapolis, has plans for a project at the mouth of the river Delaware, using a series of its two-way 45 kW Underwater Electric Kite ducted turbines.

In addition, the Ocean Renewable Power Company (ORPC) is deploying its cross-flow tidal turbine in Eastport, Maine and in 2010 reportedly landed power from its 60 kW prototype (Figure 6.48). The device has a helical turbine design similar to that developed by Gorlov (see below). The company is also looking at sites in Alaska, which has some of the USA's largest tidal resources.

On the US West coast, the Pacific Gas & Electric Company has signed an agreement with the City and the County of San Francisco, as well as the Golden Gate Energy Company, to assess possibilities for harnessing the tides in San Francisco Bay. UK developer Hydroventuri has also been looking at

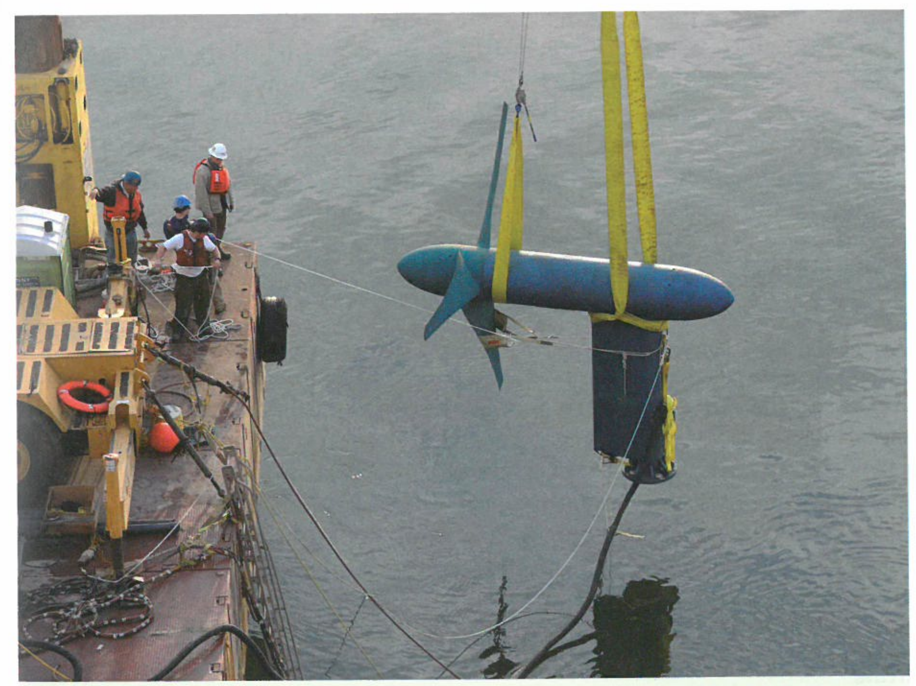


Figure 6.47 Verdant Power's turbine being lowered into East River, New York City in 2007

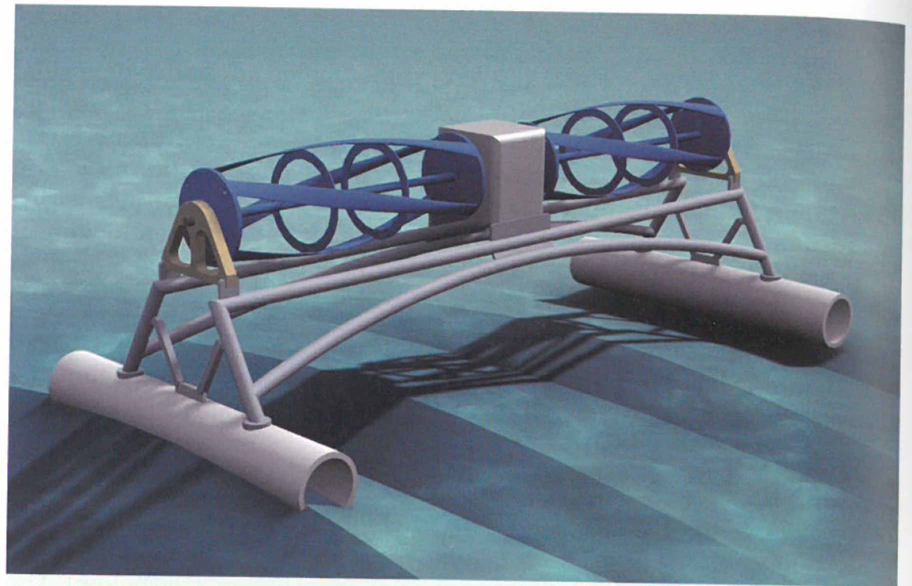


Figure 6.48 ORPC cross-flow turbine: a 250 kW version is planned

the possibility of using its innovative venturi turbine device (see Box 6.7) in that location.

Canada

Canada has had a long involvement with tidal barrage technology and is now also looking at tidal current systems. For example the Atlantic Tidal Energy Consortium has outlined plans to install up to 600 MW of tidal systems in the Bay of Fundy. Canadian company Clean Current has developed a version of the ducted rotor design and plans to test it in the Bay of Fundy. In addition, Canada's Minas Basin Pulp and Power Company has an agreement with the UK's MCT to install a 2 MW SeaGen device in the Bay of Fundy and the OpenHydro turbine has also been tested there (a 1 MW device was installed in 2008, although it suffered blade failure).

Australia and New Zealand

In Australia, Tenax Energy has plans for a 200 MW tidal project in fast-flowing waters in Clarence Strait between northern Australia and the Tiwi Islands, while in New Zealand Neptune Power is planning an array of 1 MW floating sub-sea turbines in the tidal currents off the Cook Strait between the North and South Islands, and CREST Energy have plans for a major $400m 300 MW project at Kaipara Harbour near Auckland.

India

The Atlantis Resources Corporation is planning to install a 50 MW tidal farm in the Gulf of Kutch in Gujarat, western India, to be followed up by a 250 MW project if all goes well.

Other novel projects and devices

An EU-funded study has been made of the potential for tidal current generation in the Strait of Messina, between Sicily and mainland Italy. This involves installing 100 vertical-axis turbines on the seabed at a depth of 100 metres (Figure 6.49). In preparation for this, the EU-backed Enemar project has tested a novel vertical-axis turbine in the Strait of Messina. Interest has been shown in this system by China, which is looking at a possible project in the Jintang Strait in the Zhoushan Archipelago.

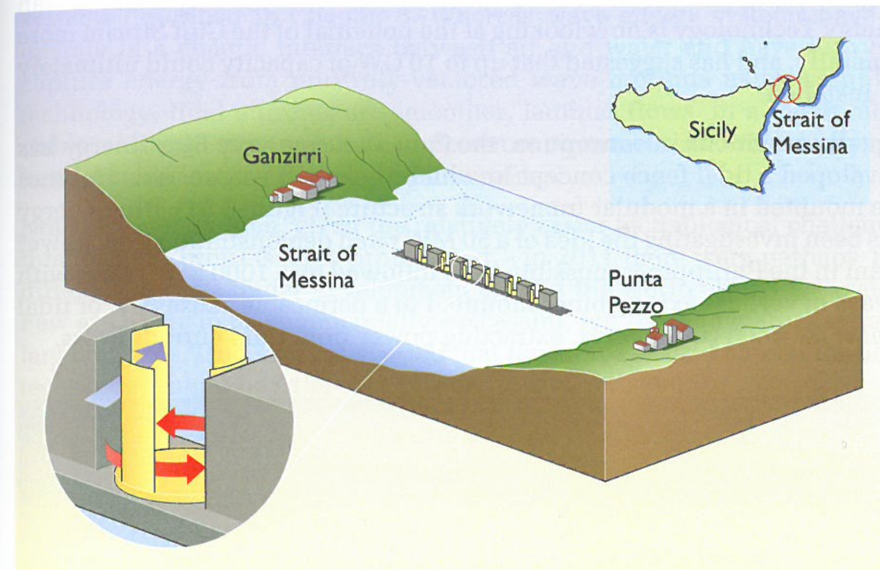


Figure 6.49 The Strait of Messina project

There are many other novel projects under development around the world, some of which are quite exotic, for example:

- tidal kites (aerofoil wings carrying a lightweight rotor and generator that are tethered to the seabed but effectively 'fly' in tidal currents)
- tidal sails (current driven 'sails' mounted on an underwater 'ski-lift' like arrangement).

Some devices are designed for slower water speeds and for use in rivers with smaller rotors: although the basic physics is against them (to get the same output as from fast-moving water, you would need much larger rotors). Although, in general, big is best there may be locations where useful and commercially viable energy can be obtained from such systems.

Large tidal projects and ocean current schemes

While small projects may have a place, there are also proposals for some very large projects. For example, Dr Alexander Gorlov, Professor of Mechanical Engineering at Northeastern University in Boston, has been developing ideas for turbine devices for use with *ocean* currents further out to sea. Dr Gorlov is the inventor and patent holder of the Gorlov Helical Turbine (Figure 6.50) – a variant of the Darrieus vertical-axis wind turbine design

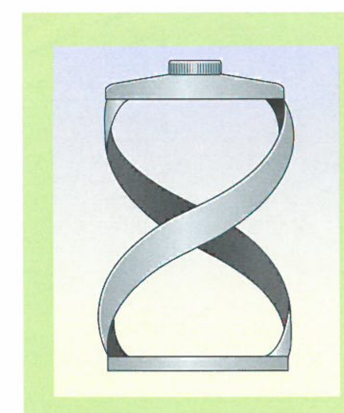


Figure 6.50 Gorlov's helical turbine

(see Chapter 7). Small prototypes have been tested and Gorlov is proposing large-scale applications in offshore locations – in particular, the Gulf Stream. He has noted that the total power of the kinetic energy of the Gulf Stream near Florida is equivalent to approximately 65 000 MW.

Clearly, there exists a large potential energy resource and Gorlov has ambitious plans for exploiting it. His aim is to construct a very large tidal farm of one hundred power modules each with hundreds of triple-helix Gorlov turbines mounted in columns in a lattice array.

Although Gorlov's scheme is still highly-speculative, interest in tidal power is growing in the USA. Florida Atlantic University's Center for Ocean Energy Technology is now looking at the potential of the Gulf Stream more generally, and has suggested that up to 10 GW of capacity could ultimately be installed.

Equally ambitious in conception, the Canadian company Blue Energy has developed a tidal fence concept in which H-shaped vertical-axis turbines are mounted in a modular framework structure (Figure 6.51). Blue Energy has been investigating the idea of a 50 MW rated demonstration tidal power plant in the Philippines, possibly to be followed by a 1000 MW plant, with arrays of vertical-axis turbines mounted in a permeable causeway, or tidal fence, between two islands, extracting power from tidal current flows.

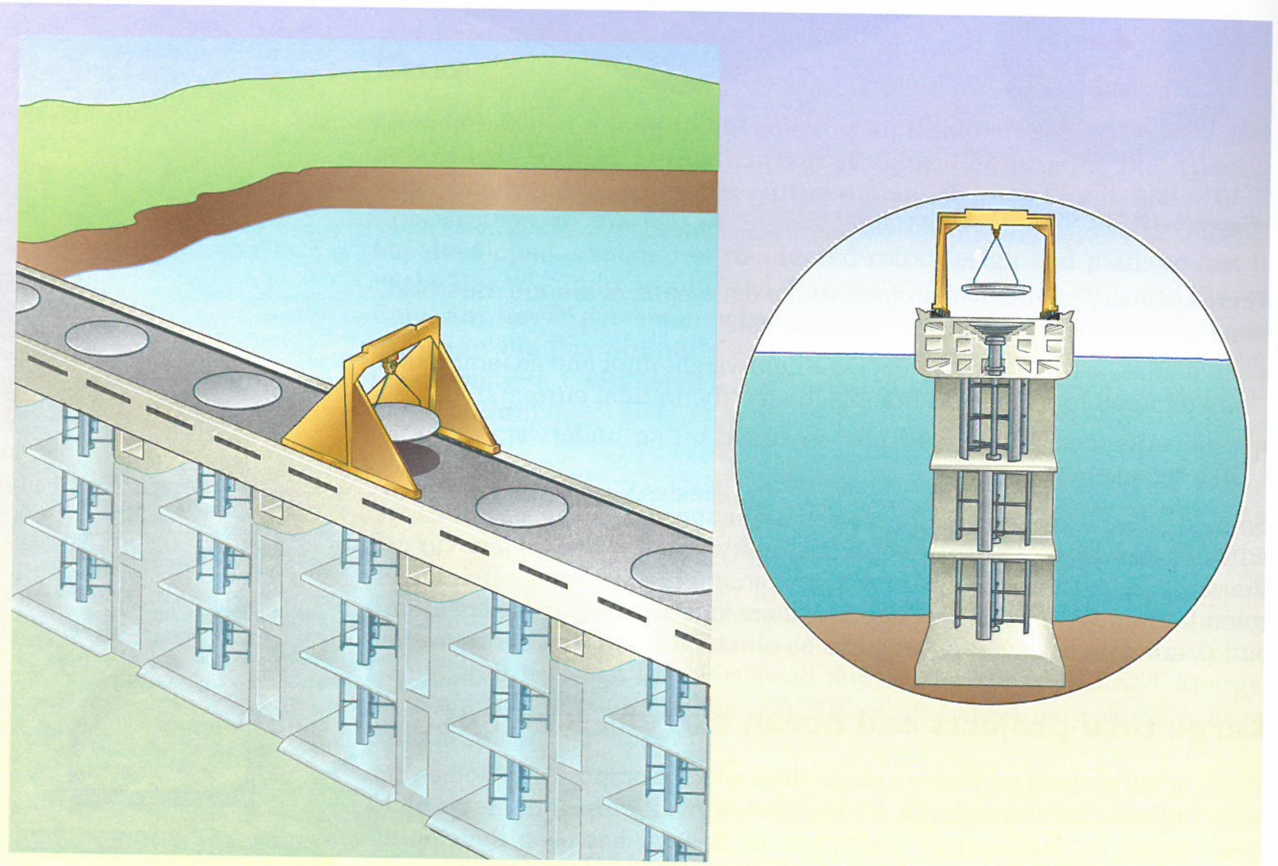


Figure 6.51 Blue Energy's tidal fence concept (source: adapted from Blue Energy, 2011)

Even though projects on that scale may be very speculative, they do indicate the potential for large-scale tidal current systems.

6.11 Tidal current assessment

Although tidal barrages offer larger amounts of energy per project, and tidal current technology is in its infancy, at the time of writing, the prospects for the latter look more promising.

Tidal current systems may also be easier to develop than the wave energy systems described in Chapter 8. Whereas wave energy systems have to operate in a chaotic interface between air and water and have to try to capture energy from multiply-vectored wave motions using complex technology, tidal currents are smoother, laminar flows, in a much more stable, although still turbulent, undersea environment, and the energy can be captured using relatively simple turbines.

Not surprisingly then, given the relatively easier technological challenge, tidal current projects have proliferated – in 2011 there were perhaps 100 different devices under development around the world at various scales. Few are likely to be commercially successful, but those that are may reap large rewards. One study suggested that the annual world market for tidal technology might be £155–444 billion (Westwood, 2005).

The UK is well placed to exploit tidal flows in geographical terms (Atlas of UK Marine Renewable Energy Resources, 2011). A study by ABPmer has suggested that ultimately about 36 GW of tidal current device capacity might in theory be installed in the UK. It estimated that devices in under 40 m depth might generate around a total of up to 94 TWh per year – about a quarter of the 2010 UK electricity requirement (ABPmer, 2007).

However, it is unlikely to be possible to harness all of that resource, and certainly it could take time to do so. The DTI/Carbon Trust Renewables Innovation Review in 2004 put the UK's total practical tidal current resource at around 31 TWh per year, about 10% of UK electricity demand at the time, while a subsequent study by the Carbon Trust, taking economic and other constraints into account, put the tidal figure at only 18 TWh per year (Carbon Trust, 2006).

These estimates may be pessimistic and depend on the assumptions used. For example, Professor Stephen Salter has argued that existing estimates of the tidal stream resource ignore changes in the resource that might be caused by the physical installation of turbines lowering the current velocity (and thus lowering the energy 'lost' to seabed friction). Looking at the Pentland Firth, he claimed that 'Any small reduction in velocity caused by turbine installations will release large amounts of energy. About one third of the present total friction loss could be extracted, giving a possible resource of 10–20 GW, much higher than previous estimates' (Salter, 2008).

On a similar basis, Prof. David Mackay at Cambridge University has claimed that the UK tidal current resource has been seriously underestimated, by perhaps a factor of 10 or more (MacKay, 2007). Similarly, DECC's 2050 Pathways report noted the following.

> It has been widely quoted that the total UK tidal stream potential is of the order of 17 TWh/year. This is derived from a method that provides the most conservative estimate. ... However, academic research has highlighted uncertainties surrounding the calculation of practical resource and other methods of estimating the tidal stream resource have resulted in higher technical potentials of up to 197 TWh/year. ...
>
> Industry and academics across a range of disciplines, including oceanography, turbulence, marine energy and physics, need to collaborate to come to a consensus on the appropriate methods for estimating resource and the subsequent predictions that result.
>
> (DECC, 2010b)

Whether or not these views are confirmed, the resource is far from small and significant resources have also been identified elsewhere in the world. (Hardisty 2007, 2009).

Perhaps inevitably, estimates of what might actually be obtained in practice are fluid when a technology is at a relatively early stage of development. It is not clear which systems will be successful in the long run, much less where they can best be sited, how much of the resource they can harvest, and at what cost.

It is reasonable to draw parallels with wind power (see Chapter 7): significant cost-reducing improvements can be expected when and if capacity is established and as economies of volume production are achieved. A 2011 Carbon Trust report claimed that, given targeted and accelerated development, by 2025 electricity costs could be comparable to those from offshore wind projects, and, for the best sites, possibly even to those from land-based wind projects and nuclear plants (Carbon Trust, 2011).

Environmental Impact

In addition to operational and economic issues, if tidal current devices are to be used on a wide scale then a key issue will be their environmental impact. As indicated earlier, this is a major concern for tidal barrages and may also prove to be of some significance for tidal lagoons. In contrast, most studies of tidal current turbines so far have suggested that impacts will be low. Even large arrays will not impede flows significantly and as the rotor blades will turn slowly (slower than wind turbines, and much slower than the turbines in barrages and lagoons) they should not present a hazard to marine life – fish will be unaffected. Certainly experience with MCT's SeaGen has not indicated any problems. At the time of writing, no seal deaths have been attributed to the turbines since their installation in 2008. A sonar system has been used to detect the approach of any marine mammals and shut the turbines down.

All structures put in the sea will have some impact, and this needs to be, and already is, carefully assessed when considering possible locations. Comparing various tidal schemes is difficult – although tidal current turbines may have less impact than barrages or lagoons, many 2 MW tidal turbines are required to equal the output of, say, an 8 GW barrage, but then again a lower-rated network of turbine farms and arrays around the UK coast may be able to give as much *useful* output – the power available when needed – as a single large barrage.

6.12 Summary

In terms of actual developments, while there is continuing interest in tidal barrages and lagoons around the world, and there are some significant barrage projects in Korea, at the time of writing it is tidal current turbines that have caught the imagination of many engineers, and some large developments seem likely to go ahead.

As this chapter has shown, the energy potential is significant, especially in the UK: an expansion programme (DECC, 2010b) could theoretically deliver by 2050:

- up to 21.3 GW of tidal current generation capacity delivering 69 TWh per year
- 20 GW of tidal range capacity (barrages and lagoons) delivering 40 TWh per year.

The key issues facing this technology area are cost and environmental impact.

Barrages have some similarity to low-head hydro, and thus their economics are likely to be relatively challenging. Once built, tidal barrages may be able to generate at reasonably competitive electricity costs for long periods, but capital costs remain stubbornly high. Thus it is hard to see large-scale barrages as viable except as public-sector led projects. By contrast, smaller, easier and quicker to install, tidal lagoons might conceivably be more viable as private investments.

However, at the time of writing, overall it seems that tidal range projects are not economically attractive in a UK context, given the financial climate.

As regards the environment, some of the impacts will be positive and of global significance. For example, the carbon dioxide emissions resulting from power generated via fossil fuel plants could be avoided if this power could be provided through tidal barrages instead. The negative impacts are more localized and further research might show how these can be reduced. One of the key factors will probably be how people perceive barrages, Given that so far most large tidal barrage projects have been opposed by environmental groups in the UK, it may be hard to win approval, and, at the very least, design compromises might be needed in response to public concerns. Overall, although there are disagreements, it seems likely that schemes that block entire estuaries are generally likely to have the largest impact per MW installed and per useful MWh delivered.

The outlook for tidal current devices is more encouraging, since they are modular with relatively short installation lead times and lower environmental impact. At present, generation costs for tidal current turbines are relatively high, but this is for prototype devices. Some manufacturers have claimed prices may fall relatively quickly, given the right support, and, with an expanding commercial market, 'mass' production of turbines.

The large potential of tidal energy has been talked about for many years, but the economics have often been seen as challenging. Now, with increasing concerns about climate change and energy security, it seems that priorities may be changing and more effort is being put into developing new technologies. While interest in barrages and lagoons remains, the rapid development of tidal current technology could well mean that it will become the leading approach in this field.