

# Power from marine currents

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**Abstract:** This paper describes the rationale and the engineering approach adopted for the development of technology for converting the kinetic energy in marine currents for large-scale electricity generation. Although the basic principles involved are relatively straightforward and well understood, being similar to those of a wind turbine, a practical and cost-effective large-scale system designed to extract the kinetic energy of flowing water has yet to be developed. This paper describes the research and development being undertaken through an industrial consortium with the aim of achieving this goal for the first time, i.e. to achieve the world's first commercially viable systems for delivering power from marine currents.

**Keywords:** tidal, stream, marine, current, energy, turbine, axial flow, kinetic energy conversion

## NOTATION

$A$	cross-sectional area swept by rotor
$H$	overall depth of water
$K_0$	constant proportional to mean spring peak velocity at site
$K_1$	constant proportional to ratio of mean spring and neap peak currents
$K_n$	'spring neap factor' (e.g. for maximum neap stream of 60 per cent of spring, $K_n = 0.57$ )
$K_s$	velocity shape factor (0.424 for a sinusoidal flow)
$P$	power
$T_0$	diurnal tidal period (usually 12.4 h)
$T_1$	spring neap period (usually 353 h)
$V$	free stream velocity local to hub height of turbine rotor
$V_{(z)}$	velocity at height above seabed $Z$
$V_{(\text{mean})}$	depth-averaged velocity for whole water column
$V_{(\text{peak})}$	maximum spring tide velocity
$Z$	height above seabed in the water column
$\rho$	density (of sea water)

## 1 RATIONALE FOR USING THIS RESOURCE

There is an emerging market for 'green' electricity derived from renewable resources which in the UK and many other countries includes government-sponsored fiscal incentives for utilities to acquire an increasing proportion of renewable energy-based generating plant. In the UK, the Renewable Energy Obligation will oblige utilities to source at least 10 per cent of their electricity from renewable resources by

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2010. However, land-based renewable energy technologies are already facing constraints owing to conflicts over land use, so an important factor is that the seas offer large open spaces where future new energy technologies could be deployed on a grand scale, perhaps with considerably less impact on either the environment or other human activities.

In fact the oceans represent an energy resource which is theoretically far larger than the entire human race could possibly use, although in practice most of this huge resource is inaccessible. The main potential sources of marine energy are waves, currents and ocean thermal energy; offshore wind is of course also a marine resource, although the energy is not derived from the sea itself. Arguably, unless marine renewable energy resources are developed and used, it will not be possible to meet future energy needs without risking serious damage to the environment either through continuing to burn increasing quantities of fossil fuels or through placing increasing reliance on nuclear power. This is the main justification for investing in these new and so far little-developed energy solutions. However, marine renewable energy resources are generally more costly and difficult to exploit reliably than the land-based options (which is why no great effort to develop them has been made until recently).

It has been obvious to seafarers for centuries that powerful sea currents exist in certain locations where the flows tend to be concentrated. Such locations tend to be where currents, which in the open sea move at low speeds of just a few cm/s, are channelled through constraining topography, such as straits between islands, shallows between open seas and around the ends of headlands. These relatively rapid tidal currents typically have peak velocities at spring tide in the region of 2–3 m/s (4–6 knots) or more. The gross kinetic energy in such flows is extremely large and it appears regularly and predictably in perfect tune with the relative

motion of the Earth, Moon and Sun. Therefore this is a renewable resource that is relatively potent, yet it is one of the few renewable energy resources that can deliver power predictably to a time table, a factor which adds to the value of the output, since from the planning point of view a utility needs to be able to deliver power rather than energy, even if it is energy which generates the revenue. Since the tides are out of phase at different points around the coast, power can often be available at one installation at times when there is slack tide and no power at another. However, at neap tide the energy availability is significantly reduced compared with the springs, and this will be true everywhere. Advanced knowledge of the availability of tidal power will permit a utility to seek to capitalize on occasions when good tidal flows coincide with expected periods of high electricity demand.

Recent studies [1–3] indicate that marine currents have the potential to supply a significant fraction of future electricity needs and, if successfully developed, the technology required could form the basis of a major new industry to produce clean power for the 21st century. The most detailed study so far, ‘Marine Currents Energy Extraction: Resource Assessment’ [2], analysed 106 locations in European territorial waters with certain predefined characteristics to make them suitable for energy exploitation, and the aggregate capacity of this selection of sites amounted to an installed rated capacity of marine current turbines of over 12 000 MW, capable of yielding some 48 TWh of electrical energy per annum. Because of the lack of public domain data on tidal flows, the total exploitable resource remains uncertain, but it is likely to be significantly larger than this.

In fact, some locations, such as the Pentland Firth (between Scotland and Orkney) and the Alderney Race (between the Channel Islands and France), or the so-called Big Russell (off Guernsey), have especially intense currents over a sufficiently large sea area to offer potential for exploitation on a multigigawatt scale. Examples of other intense locations include the Severn Estuary (UK’s north Devon coast), the straits between Rathlin Island and Northern Ireland, the Straits of Messina between Italy and Sicily and various channels between the Greek islands in the Aegean. Other large marine current resources can be found in regions such as South East Asia (e.g. the Philippines, Indonesia, Japan), Australia and New Zealand, Canada and the south east coast of South Africa.

Therefore, in short, there will be a greatly increasing demand for clean electricity and the marine current resource could make a major contribution to this need with the added value of being able to deliver power predictably.

## 2 THE TIDAL/MARINE CURRENT RESOURCE

Marine currents are primarily driven by the tides (i.e. tidal currents or tidal streams) which occur because of the variation in level of the surface of the sea caused by interaction of the gravitational fields of the Moon and to a

lesser extent the Sun with the Earth. There are also geotrophic (or oceanic) currents caused primarily by Coriolis forces acting on the water in the major oceans as a result of the rotation of the Earth. Currents are also generated by density differences in the seas resulting from salinity and temperature variations in different sea areas. However, in European waters the main marine current resource is tidally driven.

### 2.1 The energy in flowing water

The power available from a stream of water is

$$P = \frac{1}{2} \rho A V^3$$

where  $\rho$  is the density of water,  $A$  is the cross-sectional area of the rotor used to intercept the flow and  $V$  is the free stream velocity of the current. The consequence of this cube law relationship is that power and hence energy capture are highly sensitive to velocity. This is clearly indicated in Table 1 showing power densities for various water velocities (in sea water), compared with the wind and solar resources.

It can be seen that the marine current resource at locations with currents exceeding 2 m/s is a relatively intense renewable energy source compared with the better-known alternatives such as solar and wind. It should be noted that 13 m/s is the typical rated velocity, i.e. velocity at which rated (or maximum) power is achieved for a wind turbine.

### 2.2 The tidal cycle

The tidal cycle can be approximated by a double sinusoid; one with a period of 12.4 h representing the diurnal tidal ebb and flow cycle, and the other with a period of 353 h representing the fortnightly spring neap period. The following equation provides a reasonable model for predicting the velocity  $V$  of a tidal current:

$$V = \left[ K_0 + K_1 \cos\left(\frac{2\pi t}{T_1}\right) \right] \cos\left(\frac{2\pi t}{T_0}\right)$$

where  $K_0$  and  $K_1$  are constants determined from the mean spring peak and the ratio between the mean spring peak and the mean neap peak currents,  $T_1$  is the spring neap period

**Table 1** Relative power density of marine currents compared with wind and solar resources

	Energy resource						
	Marine currents					Wind	Solar
Velocity (m/s)	1	1.5	2	2.5	3	13	Peak at noon
Velocity (knots)	1.9	2.9	3.9	4.9	5.8	25.3	
Power density (kW/m <sup>2</sup> )	0.52	1.74	4.12	8.05	13.91	1.37	~1.0

(353 h) and  $T_0$  is the diurnal tidal period (12.4 h). Generally, in UK waters, the maximum mean spring current velocity will be approximately twice the maximum mean neap tide velocity.

An alternative idealization of this is to assume a mean power level in a cross-section of flow as follows [4]:

$$P_{(\text{mean})} = \frac{1}{2} \rho A K_s K_n V_{(\text{peak})}^3$$

where  $\rho$  is the density,  $A$  the cross-sectional area of flow,  $K_s$  a velocity shape factor (0.424 for a sinusoidal flow),  $K_n$  a spring neap factor (e.g. for maximum neap stream of 60 per cent of spring,  $K_n = 0.57$ ) and  $V_{(\text{peak})}$  is the maximum spring tide velocity.

The velocity of a tidal current is also generally modified to some extent by a combination of other factors such as residual momentum, global oceanic marine circulation, wind fetch and density variations and superimposed on all this, at least near the surface, are the rotating velocity vectors caused by passing waves. However, at high-velocity sites of the kind suitable for power generation, when a strong tide is flowing, the tidal current vector generally exceeds all these other effects by a significant margin.

The current will also vary in velocity as a function of the depth of flow. The velocity at a height above the seabed  $Z$  approximately follows a seventh power law as a function of depth in the lower half of the flow [5]

$$V_{(Z)} = \left( \frac{Z}{0.32h} \right)^{1/7} V_{(\text{mean})}, \quad \text{for } 0 < Z < 0.5H$$

and in the upper half

$$V_{(Z)} = 1.07V_{(\text{mean})}, \quad \text{for } 0.5H < Z < H$$

It can be shown from this that approximately 75 per cent of the energy is to be found in the upper 50 per cent of the flow.

In practice, areas with high flow velocities will generally be relatively turbulent and flow modelling is not as simple as this and many variations can occur depending both on location (and hence seabed bathymetry) as well as on the state of the tide (flow patterns and velocity shear changes through the tidal cycle).

### 2.3 Siting requirements for energy exploitation

The main aim is to find locations with fast flowing water, a relatively uniform seabed (to minimize both turbulence and the loss of velocity near the seabed), sufficient depth of water to allow a large enough turbine to be installed and preferably such conditions extending over a wide enough area to permit the installation of a large enough array (or 'farm') of turbines to make the overall project cost effective. In addition the location needs to be sufficiently near to a shore-based grid connection to allow the energy produced to be delivered at reasonably low cost. Finally, it also has to be

where it will not cause serious obstruction to other users of the sea.

The depth of water ideally needs to be in excess of about 15 m at low tide and probably no more than 40 or 50 m at high tide. The minimum level will accommodate a rotor of about 10 m diameter, probably about the smallest that might be considered robust and powerful enough to be cost-effectively deployed in this way at sea, while the upper limit depends on the type of technology and installation method to be used. In practice most fast flowing locations in UK waters are in any case less than 50 m deep since it is often a reduction in depth that causes the flow to accelerate.

The velocity characteristic of a tidal stream can best be defined by the mean spring peak. Economic analysis of the technical concepts being developed by Marine Current Turbines Limited suggests that a minimum of approximately 2 m/s mean spring peak is needed and ideally 2.5 m/s or more (i.e. 4–5 knots) in locations with typical bidirectional sinusoidal tidal flows. However, a lower peak velocity in the order of 1.2–1.5 m/s becomes economically viable in locations with continuous or quasi-continuous flow (e.g. rivers, oceanic or geotrophic currents). This is important since the main justification for applying this technology relates to the cost effectiveness with which it can deliver useful energy and one of the most sensitive parameters in the economic analysis is the flow velocity (since, as indicated earlier, energy is related to velocity cubed).

## 3 CONCEPTS FOR THE EXPLOITATION OF MARINE CURRENTS

### 3.1 Basic requirements

The end product is delivered energy, which clearly needs to be obtained at the least possible cost. The energy captured will be a function of the swept area of the turbine rotors in a field, their average efficiency at converting kinetic energy and the load factor (or capacity factor) for the site. Load factor may be defined as the ratio of the average power of the system to the rated power.

It follows from this that the rotor area needs to be as large as possible to fill the space, although there are constraints which limit this since if the rotor blades pass too close to the flow boundaries the effects on performance are likely to be counterproductive. Efficiency also needs to be as high as possible with costs as low as possible, two requirements that are sometimes not easily reconciled and therefore need good engineering compromises. In the last resort it is cost effectiveness that matters, but good cost effectiveness generally requires good efficiency.

The load factor also needs to be as high as possible; the lower the rated velocity (which is the velocity at which rated power is developed) relative to the site mean peak velocity, the higher the resulting load factor. Therefore there is a trade-off between rated velocity (hence rated power) and load factor in order to maximize energy capture. Exactly as

with wind turbines, there is always an optimum rated velocity for a given site which will maximize the resulting energy capture (and hence the return from the investment).

Clearly any outages for technical reasons will severely reduce the practical load factor, so reliability will be a key requirement for any successful offshore renewable energy technologies, especially bearing in mind that adverse weather may delay remedial measures much longer than would apply for an onshore technology. Therefore, apart from considerations of energy capture and general cost-effectiveness, any power system operating in the sea needs to be sufficiently robust and reliable to function for lengthy periods without human intervention. It is believed that the maintenance interval for marine renewable energy systems of any kind needs to be five years or more, because the cost of offshore operations needed to undertake maintenance or replacement of components is much higher than for an equivalent land-based technology and is of course subject to suitable 'weather windows'. Therefore it is worth investing money to achieve long operational lives for components.

A further factor relating to underwater technologies is that there is likely to be a build-up of marine growth and corrosion also raises a range of technical problems. Modern techniques such as cathodic protection may give some protection but the design needs to be tolerant of these effects.

### 3.2 Types of rotor

The physical principles for exchanging kinetic energy between flowing water and a rotor are similar to those for

wind. Although there are a large number of devices that have been promoted for extracting energy from fluid flows, in practice, if reasonable efficiency is to be achieved, it is necessary to use a mechanism which relies primarily on generating torque and hence power from lift forces rather than drag. There are only two generic types of kinetic energy conversion rotor that are driven primarily by lift forces and those are the conventional axial flow or 'propeller' type of rotor and the cross-flow or 'Darrieus' rotor (see Fig. 1).

The main advantage of the Darrieus rotor is that the shaft power is taken out perpendicularly to the flow, which lends itself to having a drive train either on the seabed or in a surface vessel, while an axial flow rotor either has to have the drive train entirely at rotor hub level (i.e. in the centre of the flow) or needs some form of right-angled energy transmission mechanism. However, the Darrieus has several disadvantages:

1. It involves considerably more rotor structure per unit of swept area (which increases costs).
2. It generally does not self-start but needs to be driven up to a speed at which the rotor blades unstall when crossing the flow.
3. It could be difficult to stop in an emergency situation, because it cannot readily be turned out of the flow (either an axial flow rotor can be yawed 'edge on' to the flow or the individual rotor blades can be pitched into a feathered position).
4. It depends much more than an axial flow rotor on having a good surface finish in order to maintain a high lift:drag ratio which is needed to achieve reasonable efficiency—this may be difficult to maintain under the sea [6].

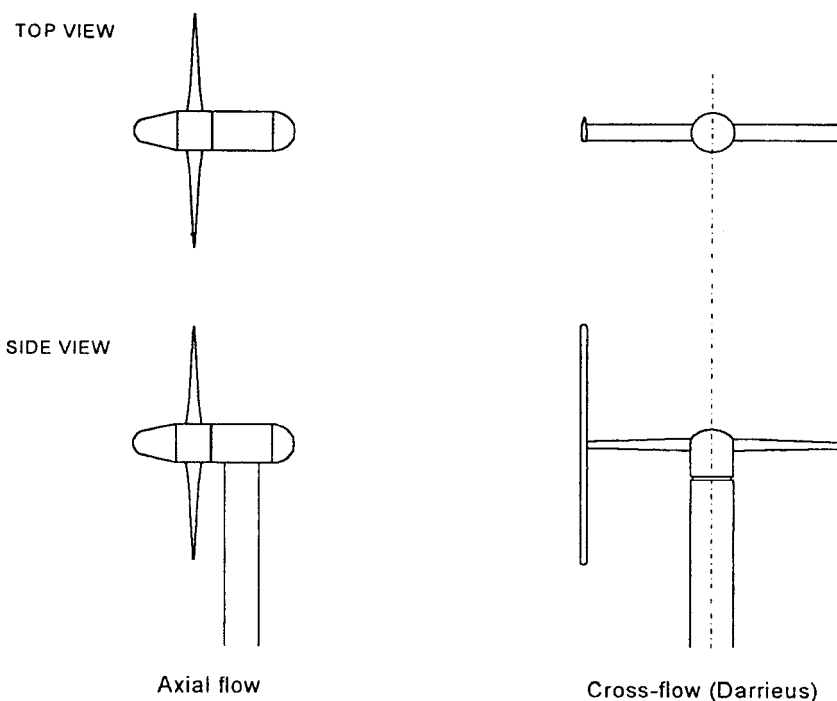


Fig. 1 Basic rotor concepts

There are other disadvantages of the Darrieus, such as greater sensitivity to cavitation, plus, in the case where there are four or fewer rotor blades, the development of major cyclic lateral forces. These problems individually might be considered solvable, but when considered in combination they tend to make the Darrieus considerably less attractive than it might appear on first consideration. However, this has not stopped a number of people from proposing their use on the grand scale as tidal current turbines.

Both types of rotor can have fixed blades or variable pitch blades. A complication with variable pitch cross-flow or Darrieus-type rotors is that the blades need to be cyclically pitched, i.e. they need to go through a complete pitch range cycle once per rotor revolution, while variable pitch axial flow rotors only need adjustment on a time scale related to the variation in flow (i.e. normally coinciding with the diurnal tidal cycle).

A further option often suggested is to enclose the rotor in a Venturi-like shroud in order to accelerate the flow and thereby to gain a higher rotational speed (which reduces torque and hence might simplify the mechanical drive train). This has been tried on a number of occasions with wind turbines where generally the structural complexity and cost of such a large passive component as a diffuser surrounding the rotor has made the savings from a smaller and faster rotor generally seem insufficient to compensate for the added cost of the shroud. In water a further problem is that (as will be explained in more detail later) the rotor blade tip velocity needs to be limited to around 10–15 m/s to avoid the development of cavitation. Increasing the flow velocity tends to need the entire rotor to be speeded up in proportion, so a marine current turbine in a Venturi will tend to be more difficult to design to avoid serious loss of performance due to rotor blade tip cavitation.

### 3.3 Extractable energy and loads on the rotor

Whatever type of rotor is used, the theoretical upper limit of efficiency for extracting energy from a free stream (at least

where the flow boundaries are relatively far from the rotor periphery) is 59.3 per cent, which can be derived from actuator disk theory [7]—a conclusion commonly attributed to Betz.

In practice, a tidal turbine rotor, which generally will be large in relation to the flow cross-section (i.e. with its upper and lower edges close to the surface and the seabed) may benefit from an effect called ‘blockage’. This is where the flow is constrained by the boundaries so that it cannot diverge to the extent that it would when decelerated through a rotor in free space, and as a result a greater mass flow of fluid passes through the rotor and this manifests itself as a higher efficiency than might be expected had the boundaries been further away. With wind tunnel tests of wind turbine rotors the effect of flow boundaries preventing the development of the same flow divergence as in free space needs to be corrected for, or an exaggerated idea of the rotor efficiency would be gained, but in the submarine turbine case this may be an exploitable benefit in which the flow boundaries effectively act as an efficiency augmentor by increasing the mass flow through the rotor compared with what would happen if flow boundaries were far from the rotor. As mentioned before, excessive use of blockage will, however, prove counterproductive.

Although the much greater density of water compared with air (by a factor of around 800) yields high energy densities at low velocities, it also yields correspondingly large forces on the rotor structure compared with a wind turbine. Hence, a submarine current energy converter has loadings that are quite different from those of an equivalent wind turbine. Figure 2 indicates the salient characteristics of speed, power, thrust, load and torque that could apply to an axial flow submarine turbine with rotors in the diameter range 10–24 m.

The dominant steady state loads are bending forces on the rotor blades caused by the high lift forces that can be generated in such a dense medium as water; however, unlike a wind turbine, weight is of secondary importance and centrifugal loads, which partially balance bending loads

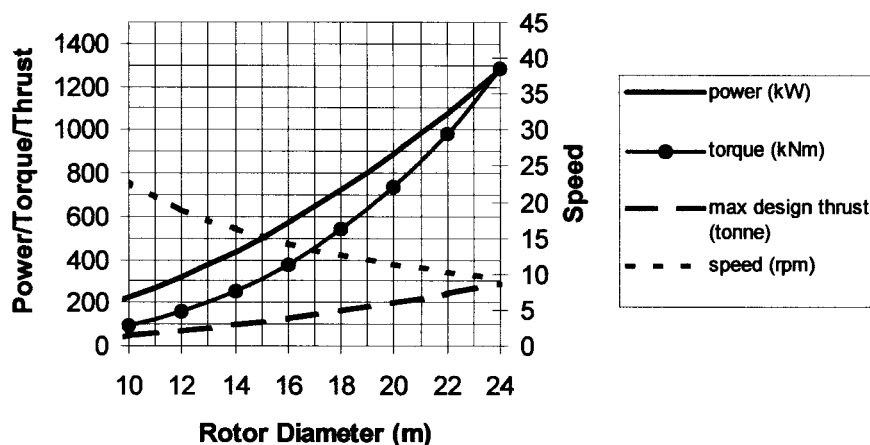


Fig. 2 ‘Typical’ operating conditions for a tidal turbine rotor (rated velocity 2 m/s, average efficiency 30 per cent)

on a wind turbine, are of course negligible at such low rotational speeds. Note that the torque and thrust figures relate not to normal 'rated' operating conditions but to occasional overload conditions corresponding to 4 m/s velocity which could conceivably occur if extreme wind fetch flow coincided in both timing and direction with an extreme spring peak flow.

Rotor speed has to be limited by the need to avoid significant cavitation; this is not so much to limit potential surface degradation (another worry with cavitation) but to prevent boundary layer separation which has the same effect as stalling, i.e. of dramatically reducing the lift-drag ratio and hence the efficiency of the rotor. With an axial flow rotor, cavitation develops at the rotor blade tips in particular at the upper part of the swept path where static pressure is least; in practice blade tip velocity needs to be limited to around 12–15 m/s. Figure 3 indicates how cavitation varies with depth; clearly the greater the static pressure the higher the velocity that is possible before the overall pressure falls to the vapour pressure of water at which cavitation can be initiated. This situation is more critical with a Darrieus type of rotor where the whole blade rather than just the tips moves at much the same relative velocity to the water.

It should be added that the pressure distribution around a lifting surface such as the blades of a tidal turbine varies significantly with the profile; e.g. a sharp-nosed profile will have a much more 'peaky' pressure distribution (a parameter called the suction coefficient can be used to describe the 'peakyness' of the suction pressure distribution; this is the ratio of the least pressure—usually occurring at around 0.25

chord—to the average suction pressure). Conversely, a blunt and relatively thick section will have a lower suction coefficient, implying a more uniform negative pressure distribution across the chord length on the suction side. It follows from this that the tidal turbine rotor designer needs to employ a hydrofoil section having as low a suction coefficient as is compatible with maintaining reasonable hydrodynamic efficiency, in order to delay the onset of cavitation. Fortunately, this also results in a thicker and therefore a stronger rotor blade, which is an important additional benefit in terms of resisting the high flapwise rotor blade bending forces that are generated.

### 3.4 Dynamic effects

The dynamic and transient loadings on the system are complex and a major part of the planned research and development programme is to address the need to get a better understanding of dynamic effects. The design approach for the first systems is to try to use a rigid (i.e. non-compliant) structure wherever possible so that any resonant frequencies generated are lower than the natural frequency of key structural members. The main drivers in terms of excitation are the passing frequency of rotor blades to the pile, vortex shedding from the pile and effects from passing waves. Passing waves also have implications for causing transient cavitation at moments when the wave vector reinforces the current vector. Structural problems caused by waves (e.g. slam on the structure above the

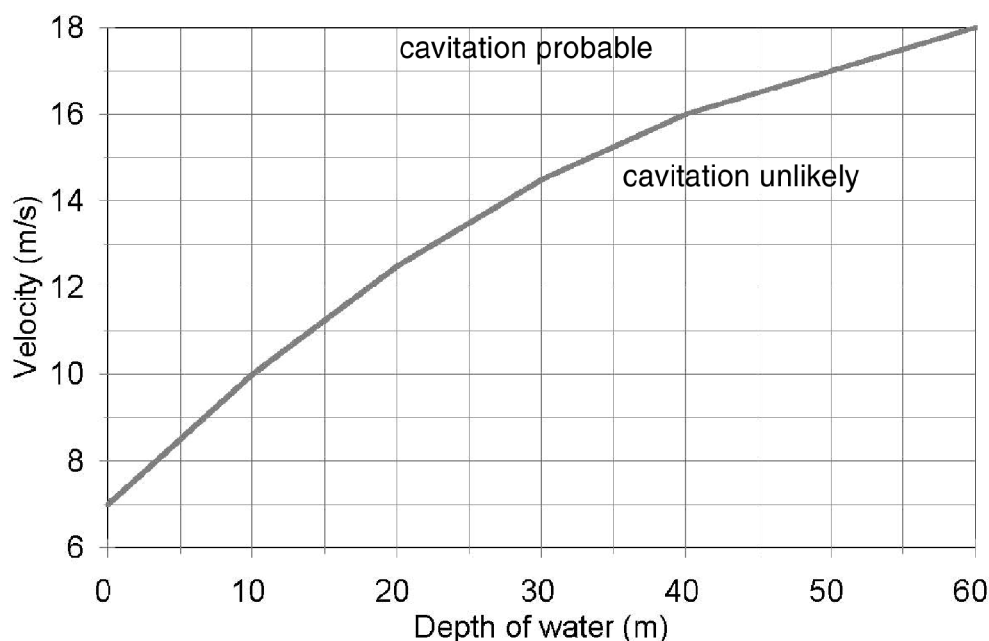


Fig. 3 Velocity needed for cavitation to be initiated as a function of water depth

surface) have been calculated to be relatively small compared with the loadings caused by rotor thrust. Hence reserves of strength to cater for worst wave conditions (say 50 year return) are relatively small. Interactions between waves and strong currents have been reported to be severe in certain locations and therefore preferred locations will be chosen, at least for early projects, that are not too exposed to oceanic waves. The site for the planned experimental prototype off north Devon is relatively sheltered in that respect.

The variations in static pressure and velocity across the vertical water column also impose interesting dynamic effects on the rotor blades to an extent that is not paralleled either by wind turbines or by conventional low head hydro turbines; the tip of the blade of a typical 15 m diameter rotor will experience a 1.5 bar cyclic pressure variation as it moves from the top to the bottom of its circular path, in addition to potentially large velocity fluctuations.

### 3.5 Methods for installation

Installing any kind of system in the sea is at best difficult (it has to withstand storms, corrosion and a host of other hazards for a long time). Economic analysis suggests that systems of this kind need an overall design life averaging 20–30 years to achieve a good return. The overriding technical problem with tidal current turbines is the high axial thrust that needs to be reacted against, which can demand designing for an extreme horizontal force on the rotor of megawatt sized systems in the order of 1000–3000 kN depending on the local maximum stream velocity and rotor size.

As shown in Fig. 4, there is a choice of mounting a rotor underneath a floating vessel which is then moored or of installing it on a structure attached to the seabed. The

floating vessel could either be on the surface or be held by tension moorings below the surface. An installation could be piled into the seabed or be held in place as a gravity structure (no doubt with something more positive than simple friction to prevent movement).

Figure 4 illustrates how a gravity base is only feasible in shallow water while a floating device is essential in deep water. The use of a monopile (or a jacketed multiple piled support in deeper water) offers an intermediate solution with cost advantages over the other options.

In practice it is almost impossible to carry out extensive underwater operations using either divers or remotely operated vehicles (ROVs) in the kinds of locations of interest, owing to the high flow velocities and limited periods of slack tide. Therefore Marine Current Turbines Limited has developed a turbine concept based on using a monopile (similar to the second from left in Fig. 4) installed from a jack-up barge. A monopile is a tubular steel tower inserted into a hole drilled in the seabed. A jack-up barge can drill the necessary hole, usually in hard seabed surfaces, by using a rotary rock drill and install the pile using its on-board crane. Marine Current Turbines' commercial partners, Seacore Limited, are specialists in placing monopiles (having installed a number of wind turbines on monopiles at sea) and they have the capability to drill holes and to place piles up to 4 m in diameter even in hard rock. Most locations with high velocity currents tend to have hard or rocky seabeds because scour from the currents tends to remove any soft or loose material.

Although a floating system appears to be more versatile, since installation or removal of a floating moored system should be relatively quick and hence inexpensive, mooring and anchoring such a turbine reliably in the open sea is technically difficult. There is a large upward force component on any anchorage in addition to the large horizontal component, unless a catenary mooring with clump weights

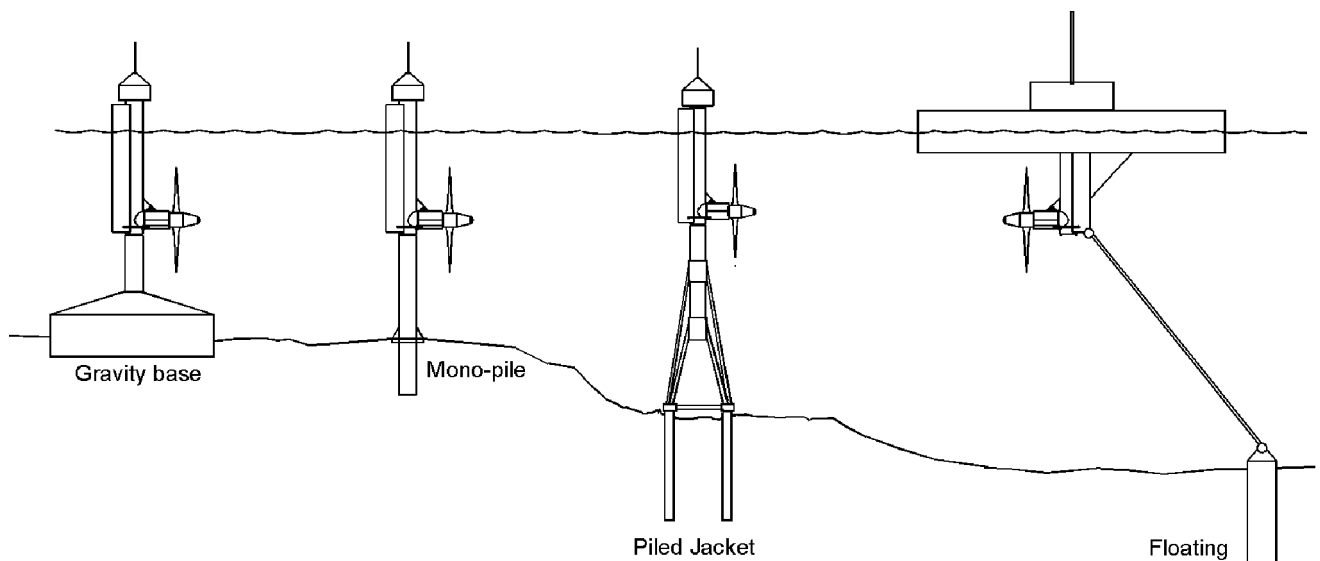


Fig. 4 Examples of possible system configurations

is used, which demands a lot of horizontal space. Moreover, the thrust force reverses direction with each tide and this needs to be accommodated by the mooring system. The technology used by the offshore oil and gas industry for mooring semi-submersibles may offer one possible solution.

However, so far as first generation systems are concerned, Marine Current Turbines Limited plans to install rows of turbines mounted on individual monopiles much like the arrays of wind turbines that make up a wind farm. However, because tidal streams are generally bi-directional, the turbines can be installed close together transversely across the stream; wind turbines (which can receive flow from virtually any direction) need to be sufficiently spaced out to prevent the wake of any turbine seriously interfering with the flow through a downstream unit. Therefore it is possible to group marine turbines much more closely together than wind turbines, with advantages in terms of installation costs and cable costs. A packing density for tidal stream turbines of from 50 to 100 MW/km<sup>2</sup> seems feasible, which is up to 10 times the array density of typical wind farms.

### 3.6 The drive train and extracting the power

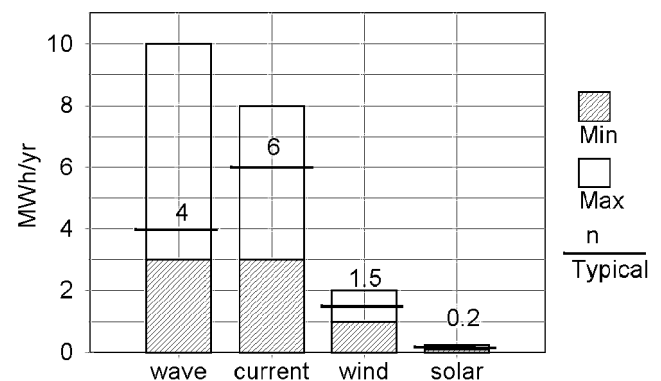
The rotor of a tidal turbine runs at low rotational speeds (10–20 r/min) and generates correspondingly high levels of torque (200–1000 kNm). Therefore the drive train poses some interesting technical challenges. The most likely solution in the short term will be to use a similar system to a wind turbine, namely a gearbox driving a generator. For most machines this will need at least a two-stage speed increaser, requiring an epicyclic gearbox to keep the size and weight within reasonable limits. There are also possibilities for using hydraulic transmission or for developing special low speed directly driven alternators (a seemingly promising trend at present with wind turbines). The power train may be encased in an air-filled nacelle using sealing arrangements for the drive shaft much like those used for ship (or submarine) propeller shafts, or alternatively it is possible to use dedicated sealed gearbox/generator units that can run immersed in water and therefore need no external casing. Submersible mechanical and electrical machinery is becoming relatively commonplace and large submersible pumps of similar power levels to the generators needed for a tidal turbine are standard commercial products. The output is delivered via a marine cable laid across the seabed to the shore, probably at a voltage of 11 or 33 kV.

### 3.7 The technology and its competitive advantages

There are undoubted difficulties in developing technology to operate reliably for long periods under the sea, but this has been successfully achieved in other contexts and there are good reasons to expect the rewards from developing this technology to be more than sufficient to justify the neces-

sary investment in research and development. This is because marine current turbines have a number of advantages that should ensure that this technology finds a major role in delivering clean energy in the future. The main reasons that marine current turbines can be expected to be cost competitive are the following:

1. A suitably energetic marine current location can offer four times the energy intensity of a good wind site and some 30 times the energy intensity of sunshine in the Sahara (see Fig. 5) in terms of energy captured per unit area of interface; hence marine current turbines need only be a quarter the swept area of a wind turbine of the same power (or 1/30 the size of an equivalent solar photovoltaic array) and smaller size generally produces lower costs.
2. A marine current turbine can deliver energy to a timetable since the tides are accurately predictable: therefore the end product of predictable power is inherently more valuable to a utility than randomly generated electrical energy; wave and to some extent wind energy is predictable over short time horizons, but tidal currents are predictable years in advance.
3. Not only are the turbines relatively small (compared with other renewable energy devices) but because of the bidirectional flow they can be packed much more closely together, aligned across the current at less than 50 m intervals; this leads to a compact installation which in turn yields further savings in cabling and installation costs.
4. Since weight is not a critical factor for a submerged turbine, the construction can be a steel fabrication so the manufacturing costs per tonne promise to be relatively low.
5. Physical conditions under water tend to be relatively predictable and calm, so extreme conditions require much less 'over-engineering' than would apply for wind- or wave-powered technologies. This also helps to keep costs down; there is no underwater analogy to an atmospheric hurricane.



**Fig. 5** Relative energy capture per unit size from four types of renewable resource (per m for waves and per m<sup>2</sup> for the rest) taking account of typical load factors and likely technical efficiency of the systems

Apart from these potential economic advantages, an environmental impact study [3] indicated that the technology should pose no serious threat to marine life or to the local environment. The low tip velocity of tidal turbine rotors makes them significantly less of a threat. Also, the low visual profile (in some cases zero visual profile) should make it acceptable to planners to grant permission for large installations relatively close onshore.

#### 4 REVIEW OF RECENT DEVELOPMENT WORK SO FAR COMPLETED

The first attempt to evaluate a national tidal current resource, in 1992–3, was the ‘UK tidal stream energy review’ [1]. This desk study confirmed that there is a large tidal current energy resource, capable theoretically of meeting some 19 per cent of total UK electricity demand at that time, of which 20 TWh could be delivered at around 10 p/kWh, i.e. not economically under the cautious and (with the benefit of hindsight) incorrect costing assumptions applied.

In 1993–4, a consortium consisting of IT Power, Scottish Nuclear and NEL developed a ‘proof of concept’ experimental tidal current system. This involved an axial flow 3.5 m diameter rotor suspended below a floating catamaran pontoon. It successfully developed some 15 kW in 2.25 m/s current velocity at Loch Linnhe, Scotland, in 1994 and, although quite small, it remains the largest marine current turbine so far demonstrated [8].

Under the JOULE 2 energy research programme, DGXII of the EU supported a technical and resource assessment of marine current energy in Europe [2]. The technical study (completed in 1996) examined relevant technology from related areas (wind, hydropower, ships and the offshore oil and gas industry) and found that electricity cost is specially sensitive to the size of machine, economic parameters (lifetime, discount rate), O & M (Operation and Maintenance) costs and the load factor obtainable at a particular site. It estimated electricity unit costs for ‘first-generation systems’ deployed on a small scale at around 0.05 ECU/kWh (3.5 p/kWh) for a 3 m/s rated current under favourable circumstances (i.e. with high load factors). This is encouragingly close to what is needed for commercial viability.

The Regional and Urban Energy Programme, DGXVII of the EU, financed a feasibility study on supplying Orkney and Shetland with electricity from tidal stream turbines [3]. Island communities, which frequently have higher than normal conventional energy costs, are likely to be the most attractive initial market for electricity from tidal streams. Actual on-site current measurements were used in conjunction with a three-dimensional computer model to produce the tidal stream characteristics for two sites. Consideration of a cluster of eight turbines of

20 m diameter showed a predicted electricity cost of approximately 6 p/kWh. Larger clusters would reduce costs further.

Commercial marine current turbine technology already exists, albeit on a very small scale. At least two products are made in the UK, both consisting of a small propeller-like rotor, about 50 cm in diameter, that can be hung over the side of a yacht or leisure boat so that the passing flow can be harnessed to keep its batteries charged either when moored in a tidal flow or when under sail without the benefit of an engine.

Therefore the basic concept of utilizing marine current energy has been convincingly demonstrated and is well understood. What remains to be proven is that it can be applied on a large scale at a cost and with a level of reliability that can allow it to compete successfully with conventional methods of energy generation.

A project was launched in September 1998 with the financial support of the JOULE 3 programme of DGXII of the European Commission [9]. It involves the development of what is expected to be the world’s first ‘commercial scale’ marine current turbine, a system rated at 300 kW to be installed on a monopile, socketed into the seabed in south-western UK coastal waters. The target date for commissioning the system is summer of 2002. Marine Current Turbines Limited was formed to take responsibility for the commercial development of the technology [10].

It is expected that this project will lead directly to a second phase involving the development of a full-scale demonstration of a cluster of perhaps four or five larger turbines each of about 1 MW. This in turn will lead to commercial exploitation of the technology within a lead time of 5–10 years.

A recent development is that the DTI, through ETSU, commissioned and published a study by consultants in April 2001, which among other things revisited the results of the 1993 tidal stream review, but which primarily aimed to provide an independent evaluation of the cost and performance being claimed by advocates of marine current energy such as Marine Current Turbines Limited; this study [11] broadly endorsed the results of earlier studies such as those of references [2] and [3] and estimated that electricity costs from sites with mean spring peak velocities of more than 2 m/s will be in the range 4–6 p/kWh and that there is a reasonable chance for costs to fall a further 30 per cent with economies of scale from larger schemes. It concluded that ‘these figures are of the right order of magnitude to encourage commercial interest in the technology’.

Following the conclusions of this report, the DTI undertook to include tidal stream technology within the scope of its support for renewable energy research and development and it has also provided some important and substantial financial assistance for the initial part of the research and development programme that Marine Current Turbines Limited is undertaking with its industrial partners.

## 5 MARINE CURRENT TURBINES' PLANNED DEVELOPMENT PROGRAMME

### 5.1 The Marine Current Turbines axial flow turbine on a monopile concept

#### 5.1.1 Phase 1 of research and development programme: single-rotor 300 kW experimental test rig

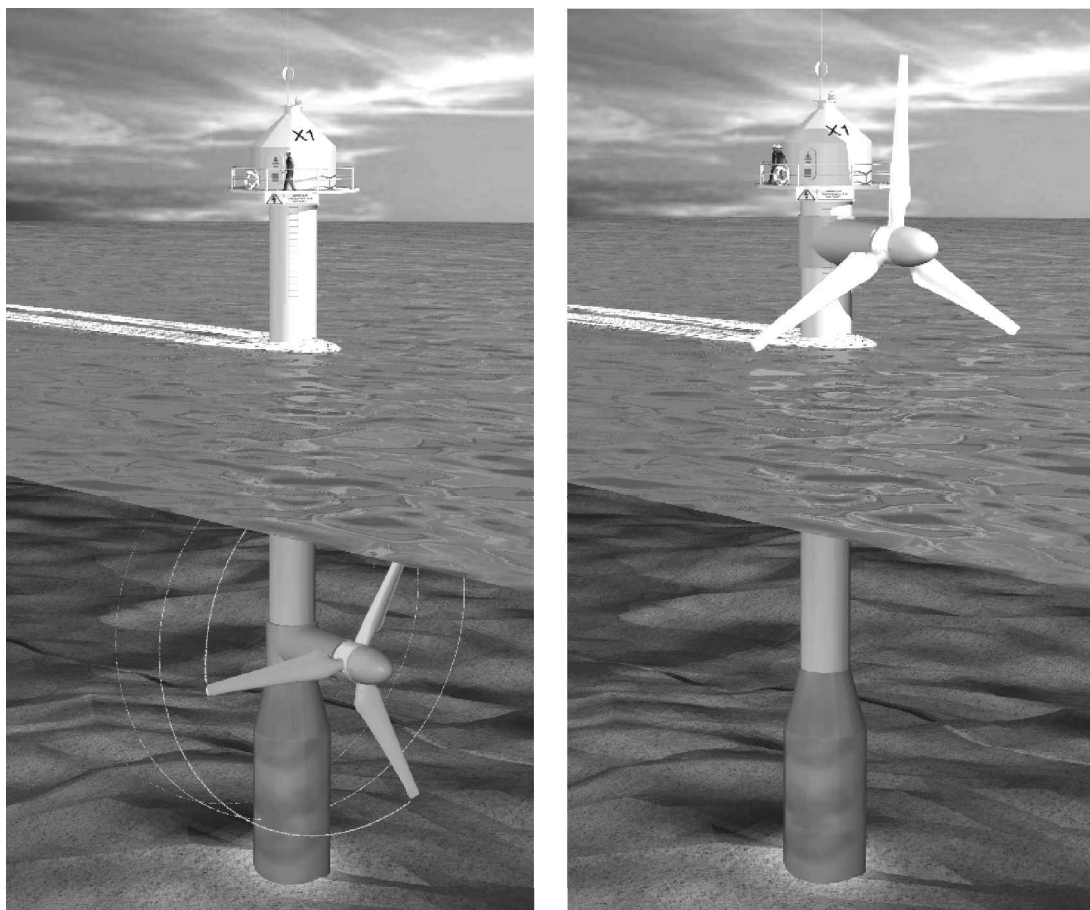
Marine Current Turbines Limited in partnership with a consortium of other companies is developing initially a form of turbine similar to that illustrated in Fig. 6. It consists of a rotor mounted on a monopile in such a way that the turbine drive train and rotor can be raised above the surface for maintenance. The first prototype will be similar to the artist's impressions of Fig. 6 and will be installed, subject to gaining the necessary permissions, off Foreland Point, north Devon, during 2002. It will be rated at 300 kW (e) and have a single 12 m diameter rotor.

The project involves Marine Current Turbines Limited as the coordinator and developer, working with Seacore Limited (which specializes in the installation of piles at sea—having carried out this function for two offshore wind farms already—who will do the installation using one of

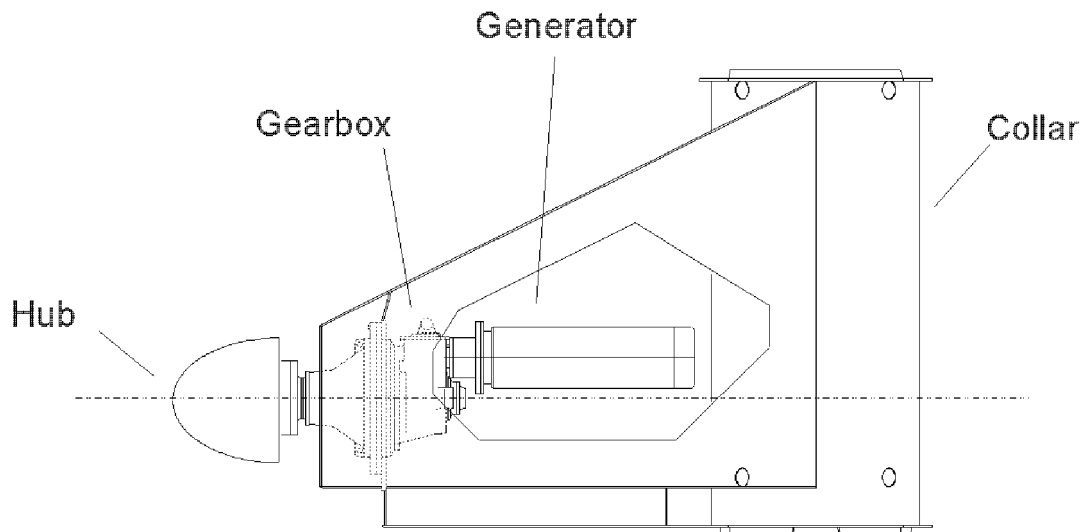
their jack-up barges), IT Power Limited (the original developers of the technology carrying out some of the design work), Bendalls Engineering (precision steel fabricator, who will be mainly responsible for the steelwork), Corus UK Limited (formerly British Steel—until merged recently with Hoogovens of the Netherlands—who are supplying specialized expertise and materials), ISET (which is a design and research department of the University of Kassel in Germany—doing much of the electrical design as well as work on rotor design in partnership with MCT and IT Power) and Jahnle-Kestermann (a German gearbox manufacturer specialising in wind turbine and marine gearboxes). Also W. S. Atkins has a key role with technical inputs relating to the rotor and structural design.

Jahnle-Kestermann are designing a two-stage epicyclic gearbox unit specifically for the system which contains the main bearings with an overhung shaft to carry the rotor. The casing is a structural component and is also watertight, making it effectively a submersible gearbox which is seawater compatible (Fig. 7).

The generator is in a watertight casing bolted to the back of the gearbox with a disk brake and coupling internally mounted between the gearbox and generator. Cooling is



**Fig. 6** How a turbine system may be installed on a monopile so that it can be raised above the surface for servicing and replacement



**Fig. 7** Prototype 300 kW tidal turbine drive train shown installed in the chassis which is in turn attached to a collar concentric with the pile, which can be raised above the surface of the sea

effectively provided through the submerged and wetted casings of the drive train components. The system is designed to run at variable speed using electronic power conditioning to produce a mains quality 50 Hz output.

The original concept envisaged a fixed pitch constant speed system as is commonly used for wind turbines, but it was felt to be too risky to rely on stall regulation of such a novel system since failure to stall would potentially cause unacceptably high loads on the drive train and the only methods for control would be either to trip the electrical system and let the rotor run away or to rely on the mechanical brake. Since it is believed for reasons to be elaborated below that rotor pitch control is a necessary requirement for the commercial technology, it was decided to introduce this on the prototype too. The facility for varying the rotor blade pitch not only permits accurate speed control but also is expected to significantly improve the efficiency, especially at part load.

The rotor blades are of fabricated steel construction, consisting of a tapered main spar at approximately one-third chord, with ribs skinned with steel plate, much the same as most ship's rudders or ship stabilizer hydrofoils. The profile for the prototype is a modified NACA 634xx, xx being 35 (or 35 per cent thickness:chord ratio) near the root and tapering to 15 per cent near the tip.

The drive train and rotor are mounted in a chassis attached to a liftable collar that is a loose concentric fit to the pile. The lifting mechanism for the prototype is a reduced-scale version of the hydraulic system commonly used to lift jack-up barge legs.

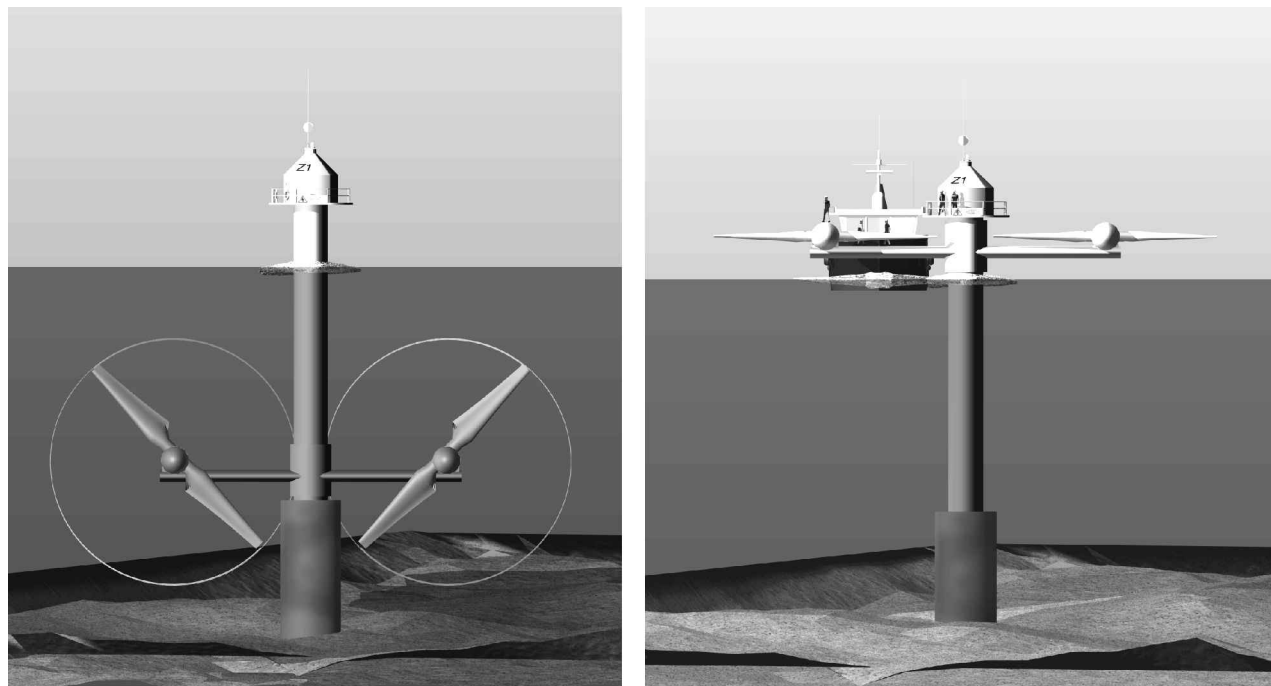
It is planned to run the single-rotor experimental prototype for only about one year before replacing it with a system that will be intended to be the precursor for the commercial systems to follow later.

### 5.1.2 Phase 2 of research and development programme: twin-rotor 600 kW pre-commercial prototype

The primary goal of the technical development programme is to improve the cost effectiveness of the technology in order to bring down the cost of the electricity that can be produced so as to make the technology commercially competitive with other methods of generation as soon as possible. A major part of the cost consists of the overheads involved in installing a pile at sea and providing a cable connection to the shore. Therefore by installing twin rotors on a pile as shown in Fig. 8, it is possible to double the energy produced compared with a single rotor of the same size (the diameter is generally limited by the depth of water) yet this can be done for significantly less than twice the cost. Depending on various factors, a twin-rotor system will typically be 30 per cent more cost effective (installed cost) than a single-rotor system of the same rated power, and moreover it can operate in shallower water owing to the smaller vertical height of the rotors.

There are several other advantages of a twin-rotor system of the kind shown in Fig. 8 compared with a single-rotor one:

1. The torque reaction of the two rotors and the swirl component in their wakes will tend to cancel each other out.
2. The wake from a streamlined horizontal wing used to support each power train and rotor has less disrupting effect on the flow through the rotor than the wake from the much larger thickness of pile does for a single rotor.
3. When raised, the 'wings' form a working platform for maintenance purposes, making access to the power trains and rotors much easier, as shown on the right-hand picture of Fig. 8.



**Fig. 8** Artist's impressions of how a twin-rotor turbine system may be installed on a monopile so that it can be raised above the surface of servicing and replacement. Note that a small work boat or tug is adequate for gaining access, 'wings' act as a working platform and rotor blades are set horizontally and to neutral pitch when raised

However, despite its undoubted advantages, the twin-rotor system introduces a number of potential structural and dynamic problems which are being studied, but it is believed these can all be solved. One of the main areas for concern is the excitation modes that the structure might experience from various excitation drivers such as the rotor blade passing frequency and also from vortex shedding by the pile.

### 5.1.3 Phase 3 of research and development programme: array of twin-rotor 1 MW pre-commercial prototypes

The twin-rotor 'phase 2 prototype' will form the basis for commercial technology to follow. This will be tested and refined further in phase 3 as a small cluster or 'farm' of four or five twin-rotor turbines (see Fig. 9), primarily to gain operational experience of a working array of turbines as well as to check on interactions and control problems that can be expected when running multiple units in parallel with each other.

The phase 3 systems will be uprated to from 0.75 to 1 MW ( $2 \times 375$  to  $2 \times 500$  kW rotors and drive trains) depending on the local current rated velocity, by a combination of improvements in efficiency and slight increase in rotor diameter. Phase 3 will also be partially self-financing from revenue resulting from sale of electricity.

### 5.1.4 Commercial projects

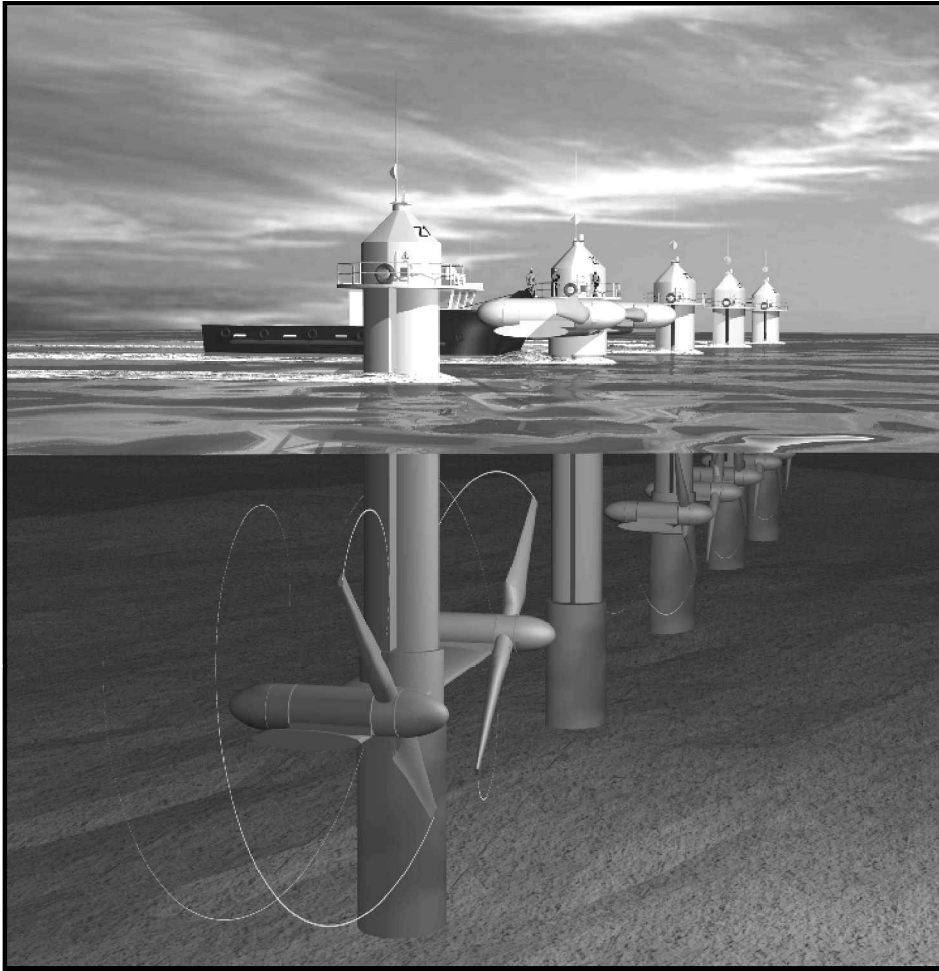
After approximately 12 months of satisfactory operation of the phase 3 system, it is planned that work will start to

install commercial projects. These will generally involve batches of systems with an aggregate installed capacity in the range 20–30 MW, as this scale of installation is needed to obtain favourable economics. It also so happens that about 30 systems can generally be installed during the weather window from around March to the end of September and that 30 MW is a practical power level for a cluster of systems having a common electrical ring main and transformer. Hence it is expected that large projects will be built up from 20–30 MW groups, each taking a jack-up barge a summer season to install. Each such group will have an independent ring main, probably of 11 kV, and probably a transformer to feed into the 33 kV 'umbilical' taking the power ashore.

It is also possible that a high-voltage d.c. system will be used for interconnection of the variable frequency a.c. generators and to link to a power conditioning system ashore, although such developments will be more likely later on with larger projects.

## 5.2 Economics—driving down costs

The development of a commercially successful technology which can make a useful contribution to future world energy needs is dependent on getting the system costs down to the level where the cost of generation can compete favourably, first with other renewables and ultimately with any other form of power generation. On the basis of existing



**Fig. 9** Phase 3 of the research and development programme envisages the installation of a small array of five units, each of from  $2 \times 375$  to  $2 \times 500$  kW. Note that the second system in the array is shown here raised for maintenance, with the nearest rotor blade pitched and the far rotor blade furlled (neutral pitch)

technical design options, the plan is to seek to drive down costs through the development programme as indicated in Fig. 10.

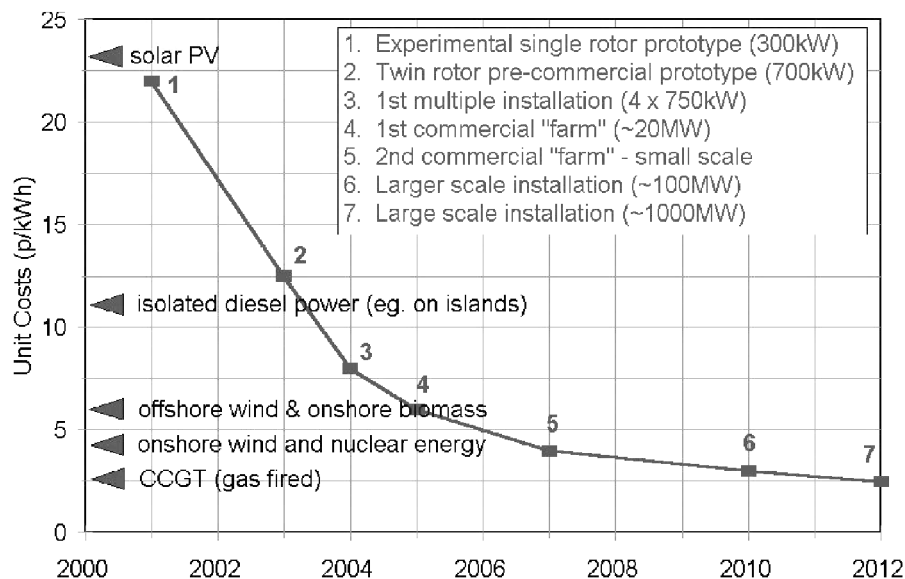
Points 1 to 3 on the cost-reduction curve are the systems to be developed under the previously described phased research and development programme, point 4 is the first commercial project and the improvements thereafter can be gained from a combination of improving the technology generally, economies of scale and reductions in the marginal cost of projects generated by expanding existing projects (so as to avoid duplicating a large part of the grid connection costs).

Although this may seem ambitious, similar cost reductions have been achieved for other technologies such as wind turbines. Installed costs for on-shore wind turbines have come down in real terms from over £2000/kW in the early 1980s to around £700/kW today, while offshore wind turbines are expected to cost around £1000/kW today. Offshore wind turbines are in some ways the main competitor with tidal current turbines as a large-scale

source of clean electricity, but there are many synergies between these technologies, not least being that they both lend themselves to installation on monopiles and both demand significant quantities of submarine cable for interconnections. Therefore marine current turbines are not in reality an alternative to offshore wind, but rather it can be expected that success for offshore wind will be helpful for tidal current developments too, since both require similar investment in infrastructure and installation plant such as jack-up barges.

## 6 CONCLUSION

There is no doubt that it is technically feasible to extract energy from marine currents and that the tidal current resource is large enough to have the potential to make a major contribution towards meeting future energy needs. However, the main area of uncertainty relates to the



**Fig. 10** How Marine Current Turbines Limited intends to develop its technology; what will be needed to make tidal current turbines commercially competitive

economics; there is no guarantee that cost effective systems can be developed although there are good indications that the potential to achieve this goal exists, given suitable research and development. More to the point is to predict how long it might take to drive the costs of this method of power generation down to the level where a thriving new industry can develop in order to take it forward on a self-sustaining commercial basis. The analysis suggests that this should be possible within 5–10 years, a goal which Marine Current Turbines Limited and its partner companies are committed to.

## REFERENCES

- 1 Tidal stream energy review, UK DTI. Report ETSU T/05/00155/REP, prepared by Engineering and Power Development Consultants Limited, Binnie and Partners, Sir Robt. McAlpine and Sons Limited and IT Power Limited for the ETSU, UK Department of Energy. Crown Copyright 1993.
- 2 The exploitation of tidal marine currents (non-nuclear energy JOULE II project results). Report EUR 16683EN, DG Science, Research and Development, The European Commission Office for Official Publications, Luxembourg, 1996.
- 3 Feasibility study of tidal current power generation for coastal waters: Orkney and Shetland. Final Report, EU contract XVII/4 1040/92-41, ICIT, March 1995.
- 4 Cave, P. R. and Evans, E. M. Tidal stream energy systems: economics, technology and costs. In Third International Symposium on Wave, Tidal, OTEC and Small Scale Hydro Energy, Brighton, 1986.
- 5 *Offshore Installations: Guidance on Design, Construction and Certification*, 1990 (UK Department of Energy, HMSO, London).
- 6 Kihoh, S. and Shiono, M. Power generation by tide and tidal current. In Proceedings of *Advanced Materials '93*, Vol. V/A, *Eco-materials*, 1994, pp. 41–44.
- 7 Duncan, W. J., Thom, A. S. and Young, A. D. *The Mechanics of Fluids*, 1960 (Edward Arnold, London).
- 8 Paish, O. and Fraenkel, P. Tidal stream energy: zero-head hydropower. In International Conference on *Hydropower into the Next Century*, Barcelona, 5–8 June 1995.
- 9 Fraenkel, P. L., Clutterbuck, P., Stjernstrom, B. and Bard, J. 'Seaflow': preparing for the world's first pilot project for the exploitation of marine currents at a commercial scale. In Proceedings of Third European Wave Energy Conference, Patras, September–October 1998.
- 10 <http://www.marineturbines.com>.
- 11 Commercial prospects for tidal stream power. Binnie, Black and Veatch, Redhill, DTI/ETSU, Harwell, April 2001.