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Tidal Current Energy Technologies

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This paper sets the context for the development of tidal current technology in the face of impending climate change and so called 'peak oil'. Siting requirements are specified for tidal turbines and a general overview of the different technologies under development is given. Specific and detailed descriptions of leading Marine Current Turbine's technology are also highlighted. The paper considers the likely environmental impact of the technology, considering in particular possible (perceived and real) risks to marine wildlife, including birds. It concludes by indicating the planned future developments, and the scale and speed of implementation that might be achieved.

INTRODUCTION

Developments associated with unsustainable use of fossil fuels are rapidly reaching the stage at which changes will be forced on us, by factors beyond our control. Carbon dioxide concentrations in the atmosphere are today higher than at any time in the last 500 000 years and have clearly departed from the natural cycle. In the 150 years since the industrial revolution, atmospheric CO_2 concentrations have risen as much as in the previous 20 000 years (NOAA 2004). Moreover, atmospheric methane (a much worse 'greenhouse gas' in that its global warming potential is over 20 times greater than that of CO_2 [IPCC 2001]), concentrations have more than doubled since 1850; almost certainly due to human activity. These recent increases are most likely a direct result of burning fossil fuel (US Environmental Protection Agency 2002), although this is contested by some scientists representing the oil and gas industry.

However, even if we set aside worries about atmospheric pollution, the other set of buffers we are racing towards are those of 'peak oil'. Very soon, possibly even by next winter, we will for the first time reach a situation where world oil production is no longer capable of keeping up with growing world oil demand; depletion of resources will simply force this to happen. Market forces cannot solve a problem where we have hit the limits of what is physically feasible.

This is the context in which the probably minor and localized environmental impacts and possible inconveniences of applying renewable energy on a large scale need to be seen. Carrying on producing and using fossil-fuelled energy on a continuously increasing scale is plainly no longer an option.

Tidal stream technology is one of the most recent forms of renewable energy to be developed. Since 2001, the UK government has started to take a serious interest in this sector and it is now part of the Department of Trade & Industry's (DTI) R & D programme, having real potential to make a significant contribution to the UK's Kyoto targets. Moreover, it is an area of technology in which the UK has a world lead and which could form the basis of a major 'green' industry with considerable export potential.

Perhaps the reason why this technology has only recently begun to take off and attract serious financial support is that, not only is there growing recognition that we urgently need large scale sources of clean energy to substitute for fossil fuels, but also engineering challenges which were almost insuperable even 25 years ago are becoming solvable today. In short, marine renewables are needed and they are becoming technically possible; they should represent a major industrial growth area in the years to come, although there will be room to succeed for only a few of the numerous solutions currently being promoted and most will fall by the wayside.

A key reason why marine renewables are needed is because land-based renewables such as solar energy, wind energy, or biomass need space to deliver energy which often results in controversy and conflicts over land use. The widely reported difficulties experienced by developers in gaining planning consents for both wind and hydro projects in the UK in recent

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years, illustrate this point. Therefore a key reason to go offshore with renewables is that there is a lot of generally under-utilized space available (still limited by the suitability for a given energy source and other constraints) and offshore technologies can generally be more out of sight and out of mind than land-based ones. There is, however, a significant premium to pay as a result of the extra overheads and costs of working offshore, which may at least partially decrease as the scale of offshore technology usage increases.

TIDAL STREAM TECHNOLOGY

Strengths and weaknesses

The physical principles of tidal stream turbines have much in common with those of wind turbines, since the technology consists of devices that use water in much the same way that wind turbines use air to produce electricity. An advantage of tidal stream technology – compared for example with wave energy technology – is that it is relatively straightforward to engineer, being based on well-understood concepts. By comparison, wave energy confers major problems in that under the most extreme conditions, the forces and loads imposed on the technology can be as much as a factor of 1000 or more higher than under normal operating conditions. By comparison, extreme loads on a tidal turbine operating in predictable conditions are usually seen at no more than 100% above the normal operating loads. This means that the degree of over-engineering required is much lower, and longevity is easier to achieve. As a result, the prospects for rapid progress with tidal stream technology development appear positive.

However, compared with wave or wind technologies, the siting requirements for tidal turbines are far more site-specific. There are only a few sea areas with high enough average tidal current velocities needed for cost-effective energy recovery. In practice, locations are needed with mean spring peak tidal currents faster than 4–5 knots (2–2.5 m/s), or the energy density will be inadequate to allow an economically viable project. Such locations are found at 'pinch points' where the underwater topography causes currents to accelerate, such as straits between islands and the mainland and shallows around headlands.

In the UK, various studies (ETSU 1993, ICIT 1995, Tecnomare *et al*. 1995, Black & Veatch 2004) have been carried out to determine locations suitable for tidal stream energy generation. Although the UK tidal stream data base is fairly limited at this stage, to the authors knowledge, there is no other country with more detailed information available. Resource data world-wide is sparse but work is in hand to try and remedy this.

The study sponsored by the DTI (ETSU 1993) assessed UK sites of which the eight largest may have an aggregate energy capacity in the order of 62 TWh of electricity per annum (about 20% of the UK's electricity needs) from 18 000 MW of installed capacity if fully developed.

An EC sponsored study (Tecnomare *et al*. 1995), analysed 106 locations in European waters with certain predefined characteristics making them suitable for tidal stream energy exploitation. The aggregate capacity of this selection of sites amounted to an installed capacity of marine current turbines of over 12 000 MW; capable of yielding some 48 TWh of electrical energy per annum. A much more recent study by Black & Veatch (2004) gives an estimated UK extractable resource of 22 TWh for tidal stream, using a modified and probably more accurate methodology. In short, estimates so far completed suggest that something in the order of 5–10% of the UK's present demand for electricity supply could ultimately be met from tidal stream projects.

If we go ahead and develop this resource, it offers a number of benefits compared with alternatives that might otherwise compete for the necessary investment:

(1) The tidal stream resource represents scheduled energy delivery as tides are driven by gravitational interaction of the sun, moon and earth, and therefore predictable far into the future. Although tidal energy is intermittent, there is no energy at slack tide and much less energy around the period of neap tides, but from the generator's perspective, knowing when energy is available is a major advantage. It allows dispatchable (i.e. contractable) energy supply;

(2) relatively straightforward physical requirements for tidal stream and reduced extreme conditions make it possible to develop technology with reasonable certainty of success, which so far has allowed rapid progress. The modular nature of the technology permits small early stage projects, keeping the 'entry price' for investors and hence the financial risks relatively low too;

(3) The environmental impact of tidal stream technology is thought to be low. Some key issues:

(i) Effect on flow and sediment transfer. As the technology is modular, it can be limited to a scale at which its effect on natural processes is minor. It would be counter-productive for the user to over-develop exploitation of a particular resource: taking out too much energy by adding too many turbines would reduce the overall energy capture and deliver diminishing returns. The tidal stream resource is unusual in being self-regulating as an energy supply; any significant reduction in water transfer will reduce the energy capture and will therefore be commercially undesirable;

(ii) threat of impact on marine wild-life from turbine rotors: as will be explained in more detail later, the speed of underwater turbine rotors is very low compared with wind turbines or with a ship or a boat propeller, and therefore they are unlikely to be a serious threat to marine wild-life. Underwater noise is also likely to be low due to the low speed of operation;

(iii) conflicts with other users of the sea: the technology needs to be applied in locations with unusually high velocities which tend to be dangerous for navigation and hence are generally avoided for commercial ship traffic and fishing; arguably tidal turbines fitted with navigation aids will provide a fixed reference which may be an aid rather than a hindrance to navigation; and

(iv) pollution: this technology substitutes for fossil fuels and thereby diminishes atmospheric pollution. Any lubricating oil or other potential pollutants are present in very small quantities and are so well contained they are most unlikely to escape. Only relatively small amounts of antifouling paints (compared with ships) of the most environmentally acceptable kind (copper or glass based) need to be used, and it is possible that such paints may be unnecessary in practice. Decommissioning is relatively rapid and straightforward and ought to leave conditions above the seabed exactly as they were before the project, although the base of the pile is likely to be left in place cut-off at or just below seabed level. There is no other potential pollutant; and

(4) the ERoEI (Energy Return on Energy Invested) for a tidal turbine is predicted to be higher than for most energy technologies. Although not fully investigated, the ERoEI for wind turbines has been found to be between 4 and 6 months (depending on the wind regime and the technology) (Danish Windpower 1997). Since the weight of material and the level of energy capture of tidal turbines currently under development are similar to those parameters for wind turbines, the ERoEI seems likely to be of the same order. Any energy technology with an operational life of ≥20 and an energy payback of around 6 months (which is to be expected in this case) represents an excellent investment in terms of energy payback likely delivering 40× the energy needed to build, install and operate it. Clearly it makes sense to prioritize investment in renewable energy technologies and in energy conservation in terms of achieving the best possible EroEI.

COMPANY BACKGROUND AND DEVELOPMENT HISTORY

In 1976, the Intermediate Technology Development Group, were looking for ways of using renewable energy to help people in remote areas of the world improve their self-sufficiency. The company realized then that there might be some virtue in looking at the use of an 'underwater windmill', driven by current, for pumping irrigation water out of many fast flowing rivers. The preferred design was based on tests of Darrieus (vertical axis) rotors mounted on the front of a motor boat and tested on the River Thames, UK. As a result the company developed a larger river current turbine for pumping irrigation water out of the River Nile, Sudan. This was a 3 m diameter Darrieus type turbine driving a pump and mounted under a pontoon. It successfully pumped 50 cubic metres per day through a head of 7 m and ran for nearly 2 years until the civil war in Sudan and lack of suitable local business interest caused the programme to be terminated.

Interest in applying renewable energy declined during the 1980s, which was a time of falling oil prices, but by the mid 1990s interest revived in the large scale use of renewables largely as a response to the perceived threat of global warming, highlighted as the Kyoto process got under way. The company revisited the 'underwater windmill' concept and started to think about scaling up tests previously carried out on the Thames and the Nile. To this end, in 1994, IT Power designed and demonstrated an axial flow tidal turbine system, at the Corran Narrows on Loch Linnhe, Scotland, in partnership with Scottish Nuclear (as was) and the National Engineering Laboratory (NEL). This was intended as a proof of concept project, to lead to larger scale developments. The project was effectively the starting point for present activity; it proved the concept viable, but it also highlighted numerous technical challenges including the difficulty of reliably mooring floating tidal turbines. The demise of Scottish Nuclear as an independent company brought that initial work to an end.

By the end of the 1990s, the company had gained the support of the European Commission's

Joule Programme for the 'Seaflow Project', to develop the world's first full-scale (300 kW) offshore tidal turbine. Earlier work indicated that the main difficulties of designing and developing a viable water current turbine for use at sea related to the practical details of building, installing and operating something large enough to survive offshore conditions. It was therefore decided that testing models or undertaking land-based studies would not solve the most challenging problems. 'Seaflow Project', Marine Current Turbines (MCT) Ltd's 300 kW system, is thought to be the world's first significant size offshore tidal turbine, and was installed at the end of May 2003 off Lynmouth, Devon. It was intended to produce the first 'full-size' tidal turbine, a system to test all the real problems of developing viable offshore technology. Key issues such as survivability, techniques for installation and access, control, impact on the local environment, etc., were to be addressed. Seaflow will be discussed further in the context of MCT Ltd's R & D programme later.

From 2001, the DTI officially included 'Tidal Stream' as eligible for financial support from the government's Renewable Energy R & D programme following completion of a study on the potential commercial viability of the technology (Black & Veatch 2004). This gave a positive evaluation to MCT Ltd's techno-economic model. Following this, the DTI also agreed to co-finance the Seaflow Project.

The tidal current 'band-wagon' really started rolling following the DTI's declaration of interest, and a number of new players came on the scene. At the present time the key companies in order of their present stages of development are:

(1) Marine Current Turbines Ltd, Bristol UK: Seaflow Project. As discussed above. It is still under test (http://www.marineturbines.com);

(2) Hammerfest Strøm: a Norwegian consortium led by an electricity utility and supported by the Norwegian government have developed a 300 kW axial flow experimental prototype which was installed in a fjord in northern Norway in December 2003. In some respects it is similar to the Seaflow project, except this system uses a gravity foundation and is grid-connected (http://www.e-tidevannsenergi.com/index.htm);

(3) Engineering Business 'Stingray'; this device, rated at 150 kW is unusual in having a hydroplane driven up and down in a vertical reciprocating or see-saw motion by the current so that it can drive hydraulic rams which in turn power a hydraulic motor to drive a generator. This project was supported by the DTI and operated briefly and temporarily in the Shetland Islands, UK in 2002–3, but the developer has since removed the system from the water and put the project 'on hold' (http://www.engb.com/services.html);

(4) Lunar Energy/ Rotech RTT1500: this device has an axial flow rotor which is installed within a large tunnel-like duct some 21 m in diameter and 27 m long which sits on the sea-floor. The rotor drives a generator through a hydraulic power transmission system. Lunar Energy have so far tested models in a laboratory (http://www.lunarenergy.co.uk/);

(5) SMD TiDel: this has a pair of axial flow rotors attached at either end of a horizontal streamlined wing-like structure which is tethered to float like a tension buoy in the water column. This is moored through a trapeze like mooring system attached to two anchor points on the seabed. Being buoyant, the uplift from the wing and turbines keeps the moorings tensioned and they can be released to float to the surface. This concept involves the pair of turbines floating vertically at slack tide and being trailed in the downstream direction by the drag of the current when the tide is flowing. So far, a 'one tenth' scale model has been experimented on in a test flume (http://www.smdhydrovision.com); and

(6) North American developments: a number of small prototype systems have been tested in the US and Canada in the last 2 or 3 years. Companies with actual systems under test include Verdant Power (http://www.verdantpower.com) and Underwater Electric Kite (UEK) Corporation (http://uekus.com/); these systems are moored floating devices and none is much larger than 30 kW. The Americans are generally considered to be some distance behind Europe but they are making progress.

Apart from the companies and their projects listed above, there are numerous other organizations who claim to have a tidal powered system under development, but none of these are believed to have anything significant under test in authentic offshore conditions as yet.

In conclusion, it can be seen that most tidal stream technology projects are very recent, mostly post 2000, compared with R & D on wave and wind which goes back to the 1970s.

Marine Current Turbines Limited's Seaflow and Seagen Projects

'Seaflow' is a landmark project – the world's first sizeable tidal current powered system to function under true exposed offshore conditions. The Seaflow turbine has a single 11 m diameter rotor, with full span pitch control, and is installed in a mean depth of seawater of 25 m approximately 1.1 km off the nearest landfall at the Foreland Point lighthouse below Exmoor in North Devon, UK. It has exceeded its 300 kW rated power under favourable flow conditions. It is not grid-connected but as an experimental test-rig dumps its power into resistance heaters capable of absorbing the maximum power.

A key patented feature is that it is mounted on a steel tubular pile, 2.1 m in diameter, set in a hole drilled in the seabed and tall enough to always project above the surface of the sea. The entire rotor and power system can be physically raised up the pile above the surface to facilitate maintenance or repairs from a boat, a vital requirement as the use of divers or any other form of underwater intervention is virtually impossible in locations with such strong currents.

At the time of writing Seaflow is virtually unique as a sea powered renewable energy project in having successfully weathered two winters in exposed sea conditions, and has demonstrated that it is feasible to produce sufficiently robust technology to survive in unforgiving conditions exposed to the incoming Atlantic storms. In this respect, tidal stream is ahead of wave energy.

Although MCT Ltd is responsible for the design and owns the project, various other participants included Seacore Ltd (a leading offshore engineering company based near Falmouth, UK), IT Power (a renewable energy consultancy), Bendalls Engineering (a steel fabricator from Carlisle, UK), Corus UK (part of the Anglo-Dutch steel company – formerly British Steel) and also German partners in the form of ISET (a renewable energy R & D company attached to Kassel University) and Jahnell-Kestermann (a major manufacturer of gearboxes). The total project cost is approximately £3.5 million of which 60% was subsidized by the UK government, the EC and the German government and 40% came from MCT Ltd and the partners.

The Seaflow test programme has yielded a wealth of vital data to help the development of commercial technology to follow. It has also been successful in confirming that various key conceptual ideas actually work effectively in practice, including the fundamental concept, the axial flow rotor, the marinized power train, the use of a surface breaking monopile and structure, together with low cost intervention for maintenance from small boats.

MCT Ltd started work on the successor to Seaflow, a twin rotor system with rotors mounted either side of a tubular pile, which is called Seagen. This new £8 million project involves many of the same partners as Seaflow and it is also supported by EDF Energy (formerly London Electricity), by Guernsey Electricity (the Channel Island utility) and by Bank Invest (a Danish specialist investment bank focusing on innovative and clean energy technologies). The project is also supported by the DTI.

While Seaflow, the first phase of the R & D programme, was intended to be no more than an experimental test bed, Seagen is probably the most important development as it will be the prototype to prove the commercial technology to follow. While Seaflow proved technical feasibility, Seagen is needed to prove the economic and commercial feasibility.

The Seagen system has its rotors mounted at the outer ends of a pair of streamlined wing-like arms projecting either side of the supporting pile. Each rotor drives a power-train consisting of a gearbox and generator each rated at around 500 kW. The total rated power is approximately 1000 kW.

Essentially Seagen produces three times the power of Seaflow at around twice the cost, giving a significant improvement in cost-effectiveness. Seagen is due to be installed at some point this year (2006) and will be followed by an array of similar systems to be installed in an open sea location, where economies of scale will yield a further improvement in cost-effectiveness. The aim is to have a technology that can be deployed in commercial projects by 2007–8 and which will rapidly become cost-competitive with offshore wind projects which are already judged to be viable. It is also planned to initiate demonstration projects in other geographical regions at that time.

Environmental Impact of Marine Current Turbines Ltd's technology

The Seaflow project was subject to a detailed and independently completed environmental impact study, carried out by Casella Stanger (2001), prior to gaining the necessary consents. The study predicted that the project was unlikely to cause any significant adverse environmental impact. No harmful effects have been detected so far, in that underwater acoustic measurements indicate that noise levels and frequencies are unlikely to be disturbing for the marine fauna in the area (Stephen Parvin *pers. comm.*, Subacoustech Ltd, Bishops Waltham, UK), there have been no known leaks of pollutants, the seabed appears unaffected and wake measurements confirmed that the turbine becomes undetectable at a distance of 200 m downstream of the rotor.

The primary concern expressed in the original Seaflow EIS was visual impact of a device sited in a tourist centre and close to a National Park (Exmoor, UK). It is not aesthetically pleasing, however it is far enough offshore not to be highly visible. In the event, the people and towns' council of Lynmouth, and Lynton, Devon, UK, been most hospitable towards the project: Lynmouth hosted one of the first hydro projects in the world in the late 19th century from where it obtained all its electricity until the terrible flood disaster of 1953 destroyed the hydroplant.

So far there has been only one complaint regarding perceived light pollution from the mandatory flashing beacon on the top of the turbine structure provided for marine safety reasons. Being only 25 watts it is not especially visible, particularly when compared with the lighthouse nearby at Foreland Point, Devon, UK or the lights of Swansea, and Port Talbot, Wales usually visible across the estuary. So we believe the technology has been generally well received so far.

The Seagen project is presently subject to a new environmental impact study in the hands of Haskoning UK Ltd. The proposed location is environmentally highly sensitive as it is within a Marine Nature Reserve and comes under the European Habitats Directive; seals and other marine mammals are present, as are occasional basking sharks and a variety of seabirds.

According to the present environmental studies, there is not considered to be any risk to birds above water, but the remote possibility that diving birds could collide with turbine blades needs consideration and if necessary, mitigating measures. The types of birds likely to be affected include diving ducks as well as cormorants. Seabirds could be at risk, including terns, gannets and auk species. The risk of collision arises from a combination of factors, but most notably the presence of these birds within the working area of the turbine itself, along with bird behaviour and hunting characteristics, current speed and depth of turbine blades below the water surface. Taking account of these factors, it was considered that the overall risk of collision is extremely low or potentially non-existent under the large majority of situations, but nevertheless, the company intends to check that these assumptions are correct when the system is operational. A greater concern is the possibility of impacts with rotor blades from common (or harbour) seals which are protected and a lot less common than their informally used name suggests. However, we believe much of the concern is perceived rather than real. It needs to be understood that the flow conditions through a tidal turbine are relatively gentle. The rotor turns under the influence of the moving water and the maximum rotational speed with Seagen is 15 r.p.m. (i.e. one revolution in 4 seconds); the maximum rotor blade tip velocity is 10–12 m/s.

As it passes through the rotor, the water follows a helical path (like a screw thread) and the rotor blades behave a bit like being threaded onto the flow path – the water passes not at right angles to the blades as might be expected, but at a very shallow angle to the rotor blades (< 10°). So, the blades do not cut across the flow path. As a result any marine animal entrained in the flow would tend to be swept between the rotor blades rather than into them. In reality it seems likely that marine animals inhabiting areas with such strong currents, have the agility and sensory awareness to avoid collisions. This of course also applies to diving birds.

The word 'blade' is unfortunate in this context, implying something sharp and potentially lethal; in fact the rotor blades of Seagen will be large, smooth, made from composite plastic with blunt rounded leading edges having a radius of about 100–150 mm like the leading edge of an old fashioned (i.e. slow flying) aircraft wing. So, in summary, we believe that:

(1) marine mammals, diving birds or fish will generally avoid passing through the turbine rotors or they will at least manage to dodge the rotor blades if they pass through a rotor;

(2) in the improbable event that some fail to take avoiding action, the chance of actually hitting a moving rotor blade when passing through its swept area is still quite small since statistically 17 out of 18 passages through the rotor by randomly drifting objects of (for example) 20 cm cross-section would pass straight through without making contact with the rotor (smaller objects than this would even less frequently make contact and vice-versa); and

(3) if physical contact occurred, it would in most cases be glancing (i.e. at a slight angle) off a smooth and not very fast moving surface, so the likelihood of injury or mortality would be small.

It is worth putting the hazard from our turbine rotors in perspective by comparing the threat from boat and ship propellers. Ship propellers interact relatively violently with the water as far greater power densities are involved with energy being applied to the water column rather than absorbed from it. More importantly, ships and boats obviously do not stay in one place like a tidal turbine but can appear suddenly and unexpectedly in what was previously calm water. A ship or boat propeller when it puts energy into the water generates considerable suction that can pull anything swimming nearby towards it, the hull also generates suction, so the area of influence of a ship propeller can be much larger than might be expected. A tidal turbine rotor, which is driven by the water, does not suck or draw anything towards itself.

Although for the reasons outlined, the risks of turbines harming wild-life seem small, Marine Current Technology Ltd. are proposing to sponsor an extensive and detailed independent monitoring programme to check whether, when the tidal turbine system is functioning, there are any significant environmental issues relating to marine creatures. One concern is that the rotor might in some way unexpectedly attract some species, perhaps by seeming to be prey. If this were to occur, the company believe mitigating measures could readily be taken to provide greater warning (e.g. changing or increasing the underwater noise, using light or bright colouring of rotor blades, even through provision of artificial lighting, etc.).

The Seagen project will not only allow development of the technology to the stage where it can be successfully deployed in the open sea for commercial electricity generation but it is also intended to ensure we gain a thorough awareness and understanding of how the system interacts with its surroundings, including with mammals, birds and fish, and that if necessary we can then take effective measures to solve or mitigate any such problems that might be discovered.

In conclusion, although MCT do not expect their 'Seagen' technology to cause significant environmental impact, it is most important to confirm that this is indeed the case. A key objective is to develop a truly benign energy generation technology, not just because it feels nice to achieve this, but because it is also commercially beneficial.

COMMERCIAL TIDAL STREAM TECHNOLOGY: THE FUTURE

In the face of Global Warming and Peak Oil, there is an urgent need to prove and bring on stream new clean energy technologies such as tidal turbines. The technology under development by Marine Current Turbines Ltd has the potential to be commercially viable well within the next 5 years and it is hoped that it will be effectively demonstrated through the Seagen project in less than a year from now. The key to arriving at this result is to gain the operational experience to develop the reliability of the systems, to value-engineer them in order to get costs down and to ensure they can reliably deliver electricity from the seas with minimal environmental impact.

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