

UNDERWATER WINDMILLS

– HARNESSING THE WORLD'S MARINE CURRENTS

The company Marine Current Turbines was longlisted for the MacRobert Award in 2010. Their innovation, the SeaGen tidal turbine located in Northern Ireland's Strangford Lough, had become the world's first official tidal stream power station, accredited as such by OFGEM the UK regulator, and has fed power into the UK grid since 2008. The company's co-founder, Peter Fraenkel, talked to *Ingenia* about how tidal stream generators can become a significant source of renewable energy.

Before the 1990s, few had given much attention to the use of the kinetic energy in marine currents to generate electricity. The Watt Committee report, *Renewable Energy Sources*, published in 1991, discussed tidal ranges and the barrages that might make use of them at length, but made only the briefest of mentions of marine currents, observing that in spite of a number of technical papers, the resource had only been investigated at a very small scale, for lighting navigation buoys.

However, soon afterwards, the Department of Energy had

published its first dedicated look at the possibilities in *Tidal Stream Review* (1993). A year later, Peter Fraenkel and colleagues from IT Power, NEL and Scottish Nuclear began testing the world's first tidal turbine on Loch Linnie.

Twenty years on, and marine currents are the focus of intense research and implementation. There are a number of significant tidal stream technologies under development in the UK, Europe, North America and the Far East that could see tidal energy making an important contribution to the

world's renewable energy mix. Other than Marine Current Turbines, which has pioneered this development, technology developers involved include Hammerfest Stroem, Tidal Generation Limited and Voith.

Now, the world's highest tides and strongest currents situated in the Bay of Fundy in Nova Scotia are to be harnessed using the tidal stream technology. Bristol's Marine Current Turbines (MCT) is part of one of the consortia that is working to make this happen. It is also partnering RWE npower renewables to develop

a 10MW tidal farm in waters off Anglesey, north Wales.

MCT's technical director, Peter Fraenkel, has played a key part in this rapid transition, not least because he has been working on the resource and the problems of its development since the 1970s – longer perhaps than anyone else. He received a Lifetime Achievement Award from his peers at the 2010 International Tidal Energy Summit and his company is now looking to deploy its tidal technology in arrays that will generate hundreds of MW worldwide.

Marine Current Turbines' commercial prototype tidal turbine called SeaGen is located in Strangford Narrows, Northern Ireland. This artist's impression of SeaGen shows the similarity of the technology to a pair of underwater windmills. The physical principles between tidal stream turbines and wind turbines are analogous, the main difference being the much higher density of water as a working fluid

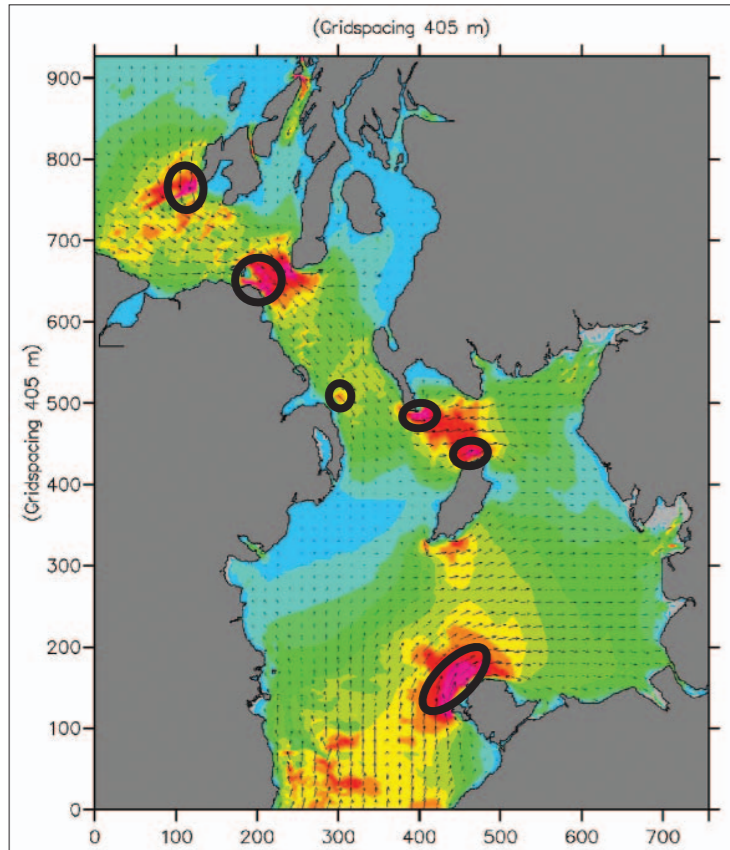


Figure 1. A map showing the pinch points where strong tidal currents are to be found. In this case it is a model of the Irish Sea contoured for velocity at a particular moment in the tidal cycle. The areas marked in magenta are the only ones with strong enough currents for cost-effective energy capture. The magenta colour represents speeds above 1m/s, while the darkest blue represents 0m/s

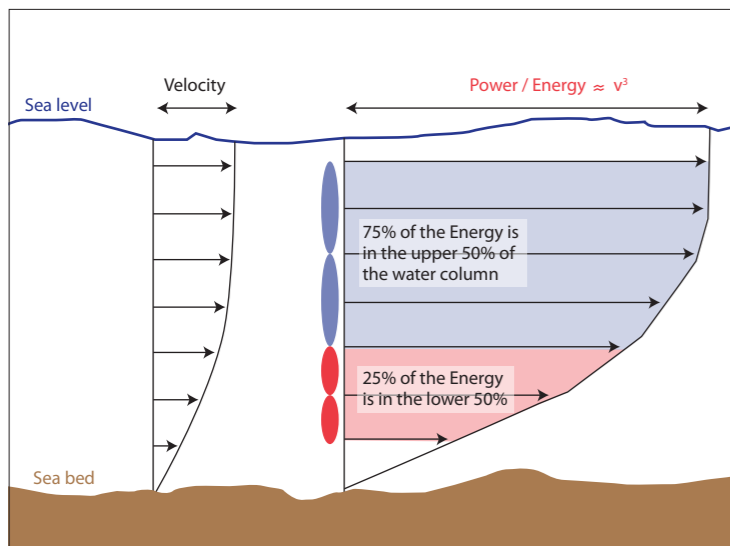


Figure 2. The importance of positioning a rotor high in the water column. The left hand set of vectors show how the velocity typically reduces with depth. Because energy is proportional to velocity cubed, the energy curve is much more skewed with depth such that about 75% of the energy is in the top 50% of the water column

TIDAL STREAMS

Tidal stream turbines are often described as underwater windmills. They are driven by the kinetic energy of moving water in a similar way that wind turbines use moving air. The generator is placed into a marine current that typically results when water being moved by tidal forces comes up against, or moves around, an obstacle or through a constriction such as a passage between two masses of land.

There are sufficient numbers of such fast-flowing underwater currents around the world to make this form of marine renewable energy worth pursuing. In figure 1, the areas between the coasts of Ireland and Scotland that are coloured magenta would merit the application of tidal current capturing systems.

Harnessing the marine currents could also help fulfil the Climate Change Committee's recent request in 2010 that calls for an almost complete decarbonisation of the UK's electricity supply by 2030.

In their report, *Future Marine Energy*, published in 2006, the Carbon Trust estimated that tidal stream energy could meet 5% of the UK's electrical energy needs, reducing the country's dependence upon carbon intensive imported fossil fuels. Other studies have predicted that tidal generators could produce up to 10% of the UK's electrical energy needs. A point not lost on the UK government and the devolved administrations who see the industrial growth opportunities that tidal and wave energy could offer.

Tidal flows have the advantage of being as predictable as the tides that cause them; both in terms of timing and in judging

their maximum velocity. This long-term predictability helps greatly in electricity generation, enabling more efficient grid management and thus reducing the total amount of power that needs to be generated.

DESIGN CHALLENGES

There are three factors that govern the energy capture by any water current kinetic energy converter: the swept area of the rotor(s); the speed of the flow (kinetic energy is proportional to the velocity cubed) and the overall efficiency of the system. There have been many challenges to make tidal turbines commercially viable, among these has been the need to place the systems in the right locations where the water depth, current flow patterns and distance to the grid make a project economically viable, and to make units efficient and easy to maintain.

Perhaps the greatest challenge relates to creating an underwater structure with foundations capable of withstanding extremely hostile conditions. The drag from a 4.5m/s current such as MCT's SeaGen experiences at the peak of a spring tide at Strangford is equivalent to designing a wind turbine to survive wind speeds of 400 km/h (250 mph).

MCT's most recent turbine installation is located in Strangford Narrows, Northern Ireland. Known as 'SeaGen', it became operational in 2008 using twin 16m diameter rotors each sweeping over 200m² of flow that develop a rated power of 1.2MW at a current velocity of 2.4m/s. It is accredited by Ofgem as a UK power station and is the largest and most powerful water current turbine in the world, by

a significant margin, with the capacity to deliver about 10MWh per tide, adding up to 6,000MWh a year. Its distinctive shape and functions have been developed by years of trials of locating and operating underwater systems.

SEAGEN

SeaGen has its rotors mounted on a wing-like cross-arm carried on a liftable sleeve that can be raised above the water for maintenance. This also enables the device to

locate the rotor relatively high in the water column, where the majority of the energy is to be found. Surface water moves much faster than water deeper down near the seabed and, because energy is proportional

to the cube of the velocity, the vertical energy distribution is heavily skewed towards the surface – to the extent that about 75% of the available energy is in the upper 50% of the water column. So devices with rotors near the seabed would lose a large proportion of the available energy.

The current at Strangford moves at 10kts, 4m/s, and is 25m in depth. Defending the structure against such forces and doing so at reasonable cost has been a significant challenge. One of the main challenges caused by the high energy of the site is during installation, so MCT's engineers decided to adapt a method tried for large offshore windturbines. The structure was ballasted to weigh 1,000 tonnes so as to be safe to stand temporarily on its quadrapod base relying on friction with the seabed. Then pin piles, each 1m diameter by 18m long were drilled into place through the footings from a temporary work platform on top of the structure so that the turbine structure acted as its own installation system.

This was a pioneering process, and MCT's engineers are now working with what they have learned from this experience to reduce the costs and improve the efficiency of the process. MCT is not only developing knowledge of its own tidal current turbines, but building up a whole field of knowledge about construction and installation methods that will be of use to other engineers working in similar conditions.

ROTOR PREFERENCES

SeaGen uses two-bladed rotors, partly because this makes maintenance easier when raised from the operating position

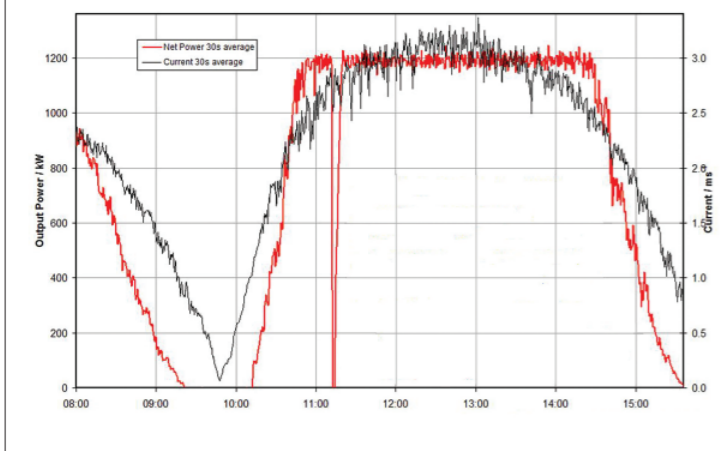


The Rambiz heavy lift crane-barge (lifting capacity over 3,000 tonnes) which delivered the 1,000 tonne SeaGen prototype to its site in Strangford Narrows in April 2008. SeaGen, fitted with its temporary drilling platform at the top of its structure, can be seen suspended below the crane jibs. The four-legged jacket which stands on the seabed is also visible

TIDAL POWER GENERATION

As can be seen from the chart showing performance through half a typical tidal cycle SeaGen generates according to its design specification, namely 1.2MW at 2.4m/s. The red line signifying the power output dips sharply at 11.15 am during a demonstration of the potential for rapid power shut down on command. The ramp up back to full power is slightly slower, due to a grid constraint, but can be rapid, and the high degree of controllability when under power is shown on the graph. SeaGen produces fully grid-compliant electricity and the two turbine rotors may even be operated independently with one shut down; the system is in fact an 'array' of two independent turbines on a single structure.

The area under the red line represents the 5.2MWhs of energy delivered on that tide, which was an average tide between neaps and springs, so it exemplifies average power capability. MCT estimates that Seagen's annual output from its 1.2MW of capacity will amount to 6,000MWh per year, allowing for 5% routine downtime. This implies a load factor of 66%, very high for a renewable generator reliant on a naturally variable resource. However this partly reflects the unusually energetic resource at Strangford and MCT expects more generally to achieve load factors in the 40 - 50% band. By uprating the system to 2MW at 2.4m/s (which the company's engineering team are currently working on) and by increasing the rotor size from 16 to 20m diameter, it is expected to continue to be able to capture as much energy even at less energy intensive locations in future.



SeaGen with its cross-arm and twin rotors raised out of the water to allow access for maintenance from a small boat. In this instance, the engineers are replacing a rotor blade: a relatively straightforward operation using the boat's onboard finger crane and a small service vessel to deliver the 1.5 tonne blade

(a two-bladed rotor parked horizontally need not be raised as high as a three-bladed one to clear the surface) and partly because a two-bladed rotor is more cost effective than a three-bladed one. Above ground, the world is so used to seeing three-bladed wind turbine rotors that it is hard to believe that there is any other way of designing such structures, but, even in the wind industry, there are signs that the virtues of the two-bladed rotor are being re-examined, and in environments where noise and visual disturbance are not a concern, such as offshore sites, they may enjoy a renaissance. For marine current devices their strengths are evident, but experimentation with other designs continues.

The two rotors not only deliver twice the energy for less than twice the cost, but enable the rotors to be mounted on balanced arms well out from the disturbed wake of the support structure and tower. The cross arm is raised above the sea for maintenance, an essential measure since tidal streams are dangerous places in which to work. There is a significant advantage in being able to elevate the equipment above the tide race quickly and at low cost. The alternative of organising a salvage operation with a crane barge every time maintenance is needed (as they are with submerged sealed units) would be prohibitively expensive.

SeaGen's rotor blades can be adjusted automatically in pitch

thereby reducing peak loads and enabling the system to generate on the ebb and flood tides without having to turn the rotor around (yawing) to face the flow. The reversal of blade pitch is one of many patented features of SeaGen, and an example of one of the principal aims of the company to generate valuable intellectual property.

Perhaps even more importantly, pitch control allows SeaGen to stop and park its rotors even during full current flow in less than five seconds. Pitching the rotor blades into a neutral position to stop the turbine gently is an essential requirement for any power generation system. By comparison, fixed pitch turbines require a strong brake to stop them and, if the brake fails and they lose their grid connection they cannot be stopped and are in danger of overspeeding and self-destruction. In this respect SeaGen follows the trend for virtually all modern wind turbines which also use pitch-controlled axial-flow rotors in much the same way for most of the same reasons.

SeaGen's rotor design methodology is similar to wind turbines but since the forces in the sea are much greater the blades need to be correspondingly much stronger. The specialist structural design using carbon fibre lay up for key structural components was carried out by Aviation Enterprises Ltd, and involved

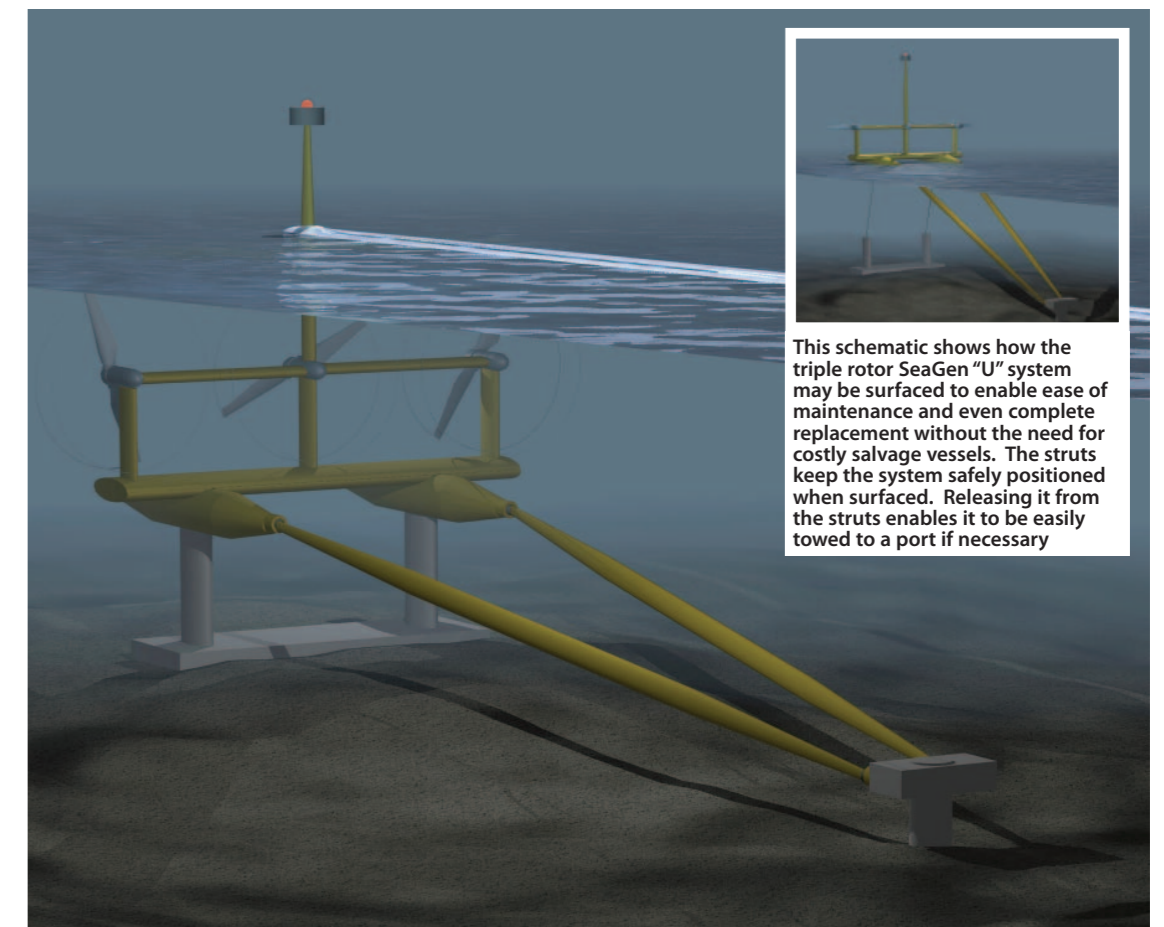
engineering for high stress flow from a carbon fibre mainspar into steel root castings designed to interface with the rotor hub. Each rotor blade on the 1.2MW SeaGen routinely carries a distributed load of over 30 tonnes at an effective radius of about six or seven metres from the hub centre-line, so the bending moments

on these cantilevers are formidable, especially when dynamic loads resulting from turbulence and other stresses, are also taken into account.

OPERATING SEAGEN

SeaGen has generally operated reliably with mostly minor glitches of the kind to be

expected with any new technology of this complexity. Most down time has been as a result of either minor component failures of the kind familiar to the offshore wind industry or to special tests being carried out to determine the systems performance, both in terms of productivity and in terms of structural integrity.



This schematic shows how the triple rotor SeaGen "U" system may be surfaced to enable ease of maintenance and even complete replacement without the need for costly salvage vessels. The struts keep the system safely positioned when surfaced. Releasing it from the struts enables it to be easily towed to a port if necessary

Triple rotor SeaGen "U" system shown in its operational position secured to the seabed by a pair of struts. A 2 MW at 2.4 m/s version of this is due to be installed by MCT in the Bay of Fundy in 2012. An optional streamlined mast is provided to give visibility like a submarine periscope and hence ensure the likelihood of consent to operate the rotors near the surface where most of the energy is to be found

ENVIRONMENTAL CONCERNS

Because it is the first of a kind SeaGen serves as a testbed for tidal power generation. To date, it has not yet had a full year of operation unconstrained by other research considerations. From installation until November 2009 the system could only be operated when two marine mammal observers were on board, and able to look out for seals that might be in danger from the rotors (which rotate at about 14 rpm). Further seal monitoring restraints continued to reduce operation to daylight hours until March 2010, so energy yield was significantly reduced.

There is great concern to avoid sanctioning anything that could cause negative environmental impact at the Strangford site. After two years of independent environmental monitoring no sign of a detrimental effect has so far been detected. At the time of writing, seal movements near the turbine still have to be monitored in real time using sonar by an operator onshore who can shut the turbines down within five seconds if they feel a seal might be in danger. It is expected that this requirement may soon also be relaxed as there are no signs yet of seals having so far been harmed.

The environmental monitoring programme which will run for five years in total will cost some £2 million by the time it concludes. It has been very useful in terms of environmental data acquisition and giving new insights on the behaviour of seals and other marine wild-life endemic to this environmentally significant location.



The common seal, which despite the name suggests, are in decline and need to be protected from harm. This one at Strangford has a cell-phone frequency transponder attached to the back of its head to allow it to be tracked. Its movements can be plotted by a computer as part of the major environmental monitoring programme being conducted primarily by Queen's University Belfast and the Sea Mammal Research Unit of the University of St Andrews to ensure that SeaGen is not causing any environmental harm

FUTURE DEVELOPMENT

MCT is now concerned not only with ensuring that its SeaGen type device is installed in other locations, but also with the conception of new forms of this technology that are both more powerful (to gain further economies of scale) and viable in shallower and in deeper water than the 20 m to 40 m range that suits the current design. In shallower water the existing twin rotor system would provide too small a swept rotor area to be cost-effective, while deeper water brings concerns about taller tower structure cost and strength.

A potential solution under consideration and already patented is a buoyant support tethered to the seabed by rigid but hinged struts. This system, which is based on the same rotors, control systems and power-trains as the existing SeaGen, has been labelled SeaGen "U" and is already under development. A 2 MW at 2.4 m/s version with three rotors is planned for installation in the Minas Straits of the Bay of Fundy in Nova Scotia, Canada by 2012-3. Systems rated at over 5 MW with up to six rotors are expected to follow. The wind industry has improved the cost-effectiveness and efficiency of wind turbines by gradually enlarging them – a few years ago 1 MW was the norm but today up to 5 MW systems are preferred. There is a similar pressure to develop larger in order to improve their cost-effectiveness and generate electricity more cheaply.

Peter Fraenkel thinks that as with all new technologies,

tidal turbines will be initially too expensive to be immediately competitive. They will need to benefit from economies of scale and learning curve effects to get their costs down. As a result he believes this new renewable energy technology market needs government subsidies such as ROCs (Renewable Obligation Certificates) to help finance early stage small projects, and to see the technology through the stage between R&D and full commercial competitiveness. Fraenkel is confident that tidal turbine technology will become competitive reasonably quickly but the first projects will need support to leverage the necessary investment.

The potential market for green power generation is significant. A Carbon Trust survey, published in January 2011, noted that the environmental and low carbon market is worth over £112 bn a year in the UK and employs over 900,000 people. It is forecast to grow by 25% over the next four years. Marine current technology now has a clutch of companies that are set to make a substantial impact on renewable power generation and add to these figures.