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Practical tidal turbine design considerations: a review of technical alternatives and key design decisions leading to the development of the SeaGen 1.2MW tidal turbine

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Synopsis

This paper starts with a brief account of the pioneering SeaGen tidal turbine and the R&D programme that was necessary to develop it. The main thrust of the paper is to review the technical choices that needed to be taken and to indicate reasons for developing the technology in its chosen form. In order to present the logic behind the SeaGen design the author discusses some of the fundamentals of water kinetic energy conversion and the consequent choice of rotor types. The paper also reviews key structural, operational and economic issues and finally presents some key conclusions, notably that many of the lessons learnt earlier in wind turbine development also apply to tidal turbine development.

1. Introduction: SeaGen and MCT's R&D programme

The SeaGen tidal turbine as developed by our company has a lengthy provenance dating back to the end of the 1970s when the author and his colleagues at that time developed a catamaran-mounted river current turbine designed to pump irrigation water (Figure 1)[1] [2] .

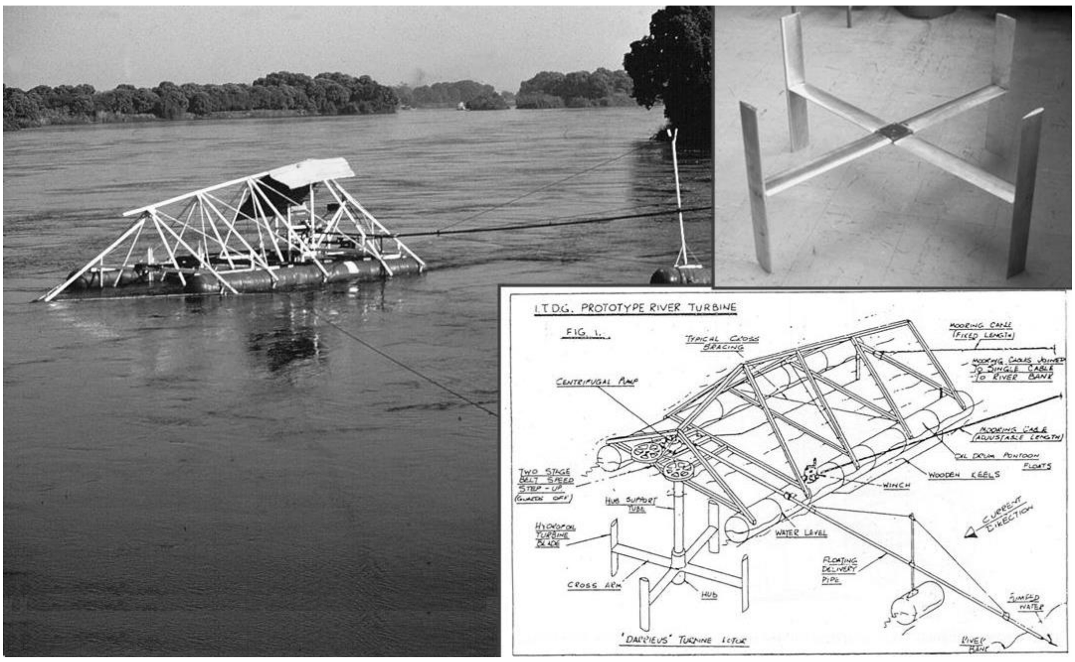

Figure 1: river current turbine on the Nile near Juba, Sudan, 1981 with experimental Darrieus rotor shown top right and schematic arrangement lower right.

This work was carried out by what was then called the Intermediate Technology Development Group (now known as Practical Action) as an overseas aid project. This system was designed following tests of Darrieus vertical axis rotors mounted on the front of a small motor boat on the Thames in the late 1970s . The irrigation system worked reliably for about two years on the river Nile from 1981 at Juba in Southern Sudan and proved capable of lifting approximately 50,000 litres per day through a head of about 5m in currents of 1 to 1.5m/s [3].

By the 1990s as the world began to wake up to climate change issues and of the impending energy crisis caused by peak oil and gas, it became apparent that there may be merit in scaling up the technology for use as a tidal turbine, so a project was initiated to design, build and demonstrate a proof-of-concept system. This work, also managed by the author of this paper, was primarily financed by Scottish Nuclear Ltd. It used a fixed pitch axial flow rotor made from a pair of aluminium castings driving a submerged generator through a small epicyclic gearbox and was mounted on a strut below a raft and tested successfully in the Corran Narrows, Loch Linnhe, Scotland in 1994-5 (Figure 2). This system used twin catenary moorings of heavy chain link deployed up and down stream with heavy anchors. Even so mooring it reliably proved problematic with frequent anchor dragging. The system proved capable of 15kW in about 2m/s from a 3.5m diameter (9.6m^2) rotor. The Proof of Concept system was small but important in being effectively the world's first tidal turbine[4]. As such it has recently been donated to the Museum of Scotland by our company which owned it.

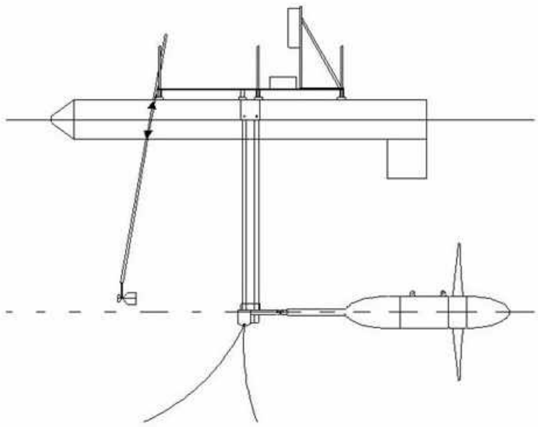

Figure 2: The world's first tidal turbine tested as a "Proof of Concept" project at Corran Narrows in Scotland in 1995 – turbine on left schematic on right

The successful proof-of-concept demonstration confirmed that it is feasible to envisage the use of subsea turbines for power generation, but economic analysis indicated that a certain scale of power production is necessary for cost competitive generation into the grid, in much the same way as has been found for wind projects. In fact water current kinetic energy conversion has much in common with wind energy conversion. Moreover scale is necessary to produce systems robust enough to survive offshore conditions. Therefore our company was set up with the goal of developing commercial scale tidal turbine technology[5], starting with the 300kW Seaflow system that was eventually installed off Lynmouth in Devon in May 2003 (Figure 3). Seaflow's 11m diameter (95m^2) rotor was an order of magnitude larger than the earlier proof of concept system and could generate 300kW in a current velocity of 2.5m/s. This was judged to be about the minimum size for realistic large scale power generation, and was intended to be used to investigate the practicalities of full scale tidal turbines.

Figure 3: the 300kW Seaflow system installed off Lynmouth in May 2003. It had an 11m pitch- controlled axial flow rotor. The power train could be raised above sealevel for maintenance (right).

Issues such as how do you install and maintain them, what are the key structural issues and design criteria to match these, what kind of performance can be achieved in practice, were to be investigated so that the know-how could be used to design and build a larger commercial system that is now known as SeaGen. Seaflow used a pitch controlled axial flow rotor and was mounted on a mono-pile in such a way that the rotor and power-train could readily be raised above water level for maintenance, which is a patented feature. It introduced the concept of pitching the rotor blades through 180 degrees to operate efficiently in a bi-directional flow, which is another feature patented by our company (Fig 4).

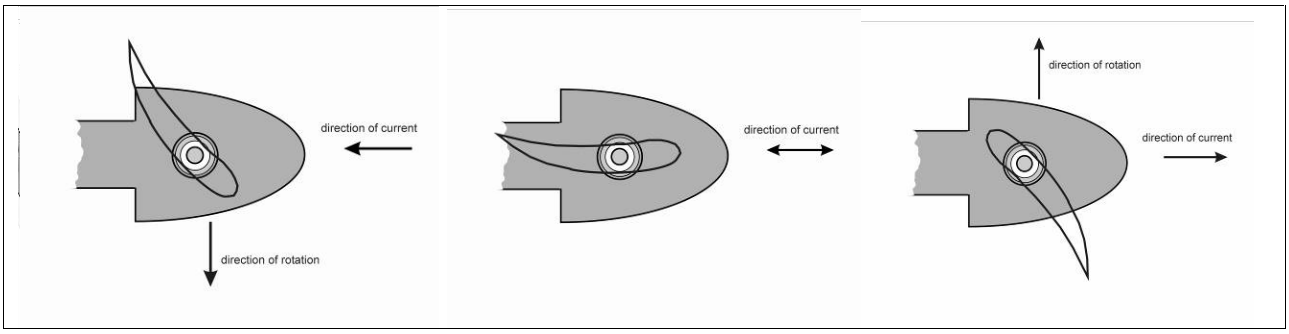

Figure 4: better rotor performance can be obtained by using efficient cambered foils and pitching the rotor blades 180^{o} (left and right). This also offers a passive means for stopping the rotor (centre)

The Seaflow test programme from 2003 to 2006 [6] [7] was crucial to informing the design process which led to the development of the SeaGen commercial system. In fact a key reason for giving the history of this R&D programme in this paper is to stress the fact that crucial lessons were learnt at every stage, which proved essential to the success of later developments.

2. Fundamentals of water kinetic energy conversion

Extracting energy from flowing water involves much the same physical principles as have been well established for extracting the energy from wind by using wind turbines. The water current kinetic energy resource is determined by the speed and cross-section of flow that can be intercepted. The basic equation for instantaneous power availability is...

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

where P=Power, ρ=density of water, A equals cross-sectional area and V is the free-stream velocity at hub height at the location of interest. Therefore A and V are the only two variables that determine power and hence energy availability (energy being the integral value of power with respect to time) where A is technology specific and V is site specific..

The main point to note is that, all other things being equal, the swept area of flow intercepted dictates how much energy can be captured; just as oil comes in barrels, coal can be measured by the truck load, tidal or other water kinetic energy comes in square meters, much like other renewable energy including wind and solar energy. So the area of current cross-section intercepted is critical. The more swept area the more energy can be captured.

The further key factor that also influences energy capture is the efficiency of energy conversion; different devices and power transmission systems can have significantly different levels of efficiency. Rotor efficiency is conventionally defined as the percentage of shaft power produced by a kinetic energy converter of the power in the undisturbed upstream flow passing through an area equal to the cross section of flow intercepted.

The maximum theoretical efficiency of an ideal kinetic energy converter in a free stream (i.e. where the flow is uniform and the flow boundaries are far from the rotor) is 59.3%, a realisation generally attributed to a German aerodynamicist named Albert Betz [8](although it was also published by Lanchester and by Zoukowski)[9]. This is because if the device took out 100% of the energy, the flow would obviously stop, so sufficient residual kinetic energy is required to carry away the flow after it passes through the device. This so-called Betz limit defines the optimum arrangement where the flow downstream of the rotor is reduced to 1/3 of the original flow velocity at which point energy conversion is maximised.

In practice imperfections in the conversion mechanism result in a lower efficiency than the Betz Limit. The best modern wind turbines typically can touch about 50% peak efficiency and generally achieve efficiencies in the upper 40s (i.e. 75 to 80% of what is theoretically possible). The losses are largely due to a combination of friction and form drag (i.e. losses inherent in moving something fast through a fluid caused by stirring the fluid and resulting friction losses)[10] . Further losses, mechanical and electrical, occur between the rotor and the grid connection. Figure 5 shows how typical wind turbine rotors compare in terms of Cp or efficiency; clearly the high speed axial flow rotor has a significant advantage[11].

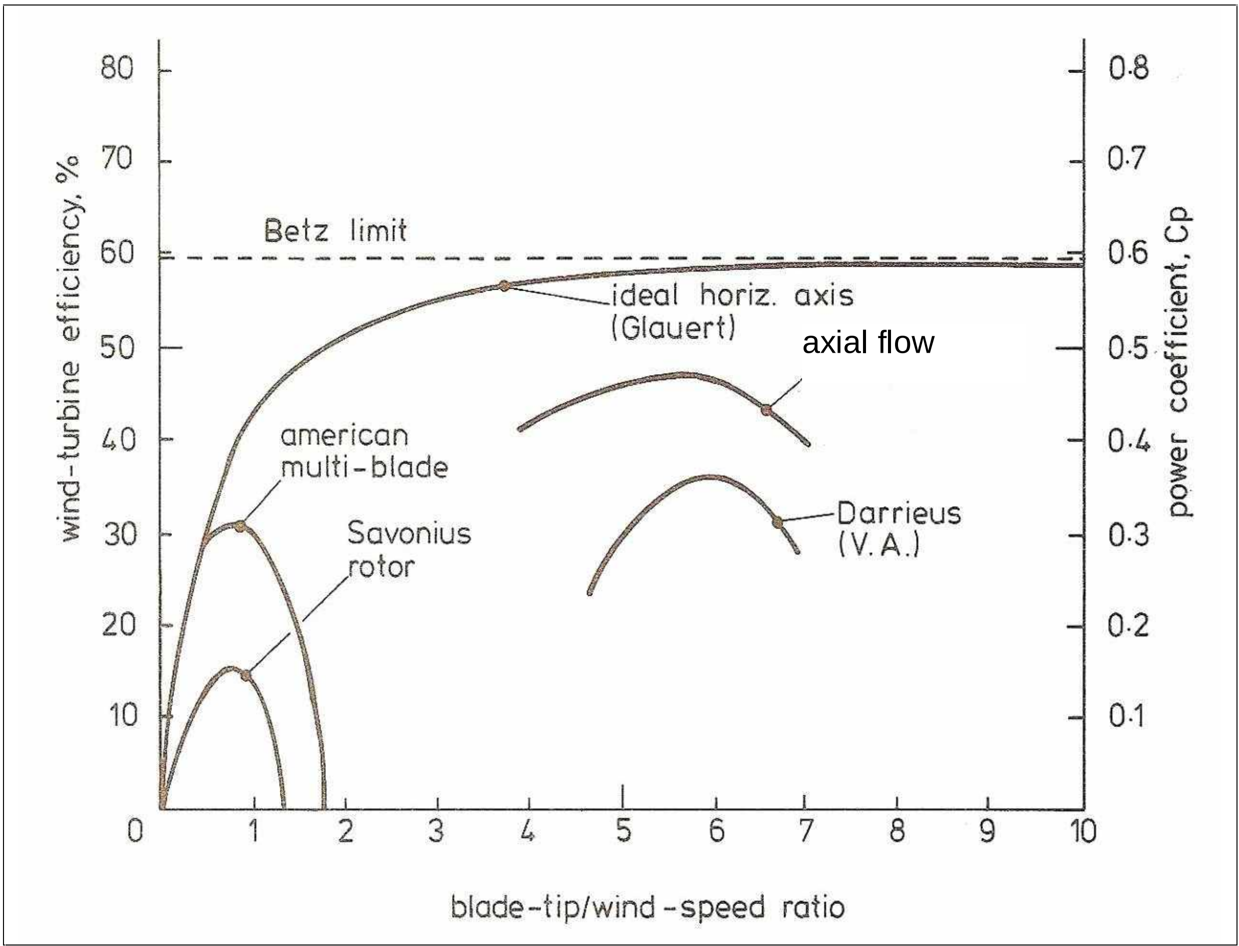

Figure 5: Rotor efficiencies for wind-turbines; similar results can be expected for water kinetic energy turbines. Note the typical modern high tip-speed ratio axial flow wind turbine rotor achieves 48% efficiency while low tip-speed devices are inherently inefficient.

There are a number of key issues facing the designer of a water current kinetic energy turbine and unlike with wind turbines where the technology has largely converged on what might be called the "technology of choice" (axial flow, yawed, pitch-controlled rotor mounted upstream of a tubular tower) water turbines are at an earlier stage of development and many more variations of rotor and structure are being promoted. However, since it can be expected that what works well in wind will in most cases also work well in water (the energy conversion principles are completely analogous) so the lack of convergence of tidal turbine concepts may seem surprising and possibly reflects a lack of appreciation by some designers of what has been learnt from the development of wind turbines over the last few decades.

The next paragraphs will review some of the options and seek to suggest their respective merits and disadvantages.

2.1 Kinetic energy conversion principles: lift versus drag

All methods of extracting energy from (or imparting energy to) a fluid require relative motion between the fluid and a suitable moving mechanism. Generally the most efficient interaction of this kind results from generating lift forces with as little drag as possible. Lift is defined as a force on a device in a fluid normal to the relative direction of flow while drag is the force in the direction of flow. Paddle wheels and other such mechanisms rely on being pushed by the flow generally at a speed slower than the free stream velocity whereas turbines (and for that matter screws or propellers as well as Bermuda rigged yachts when tacking) rely on presenting a suitably shaped streamlined body to the flow in such a way that the flow is deflected by a small angle and thereby generates a strong reactive force at right angles to the general direction of flow. Drag dependent devices are so inefficient that it is proposed to dismiss them as being a realistic way to generate power from marine currents without wasting space on any further discussion. Numerous books on wind turbine developments deal with such issues – see for example [10 & 11].

2.2 Methods for driving a generator; rotor types

The key requirement from a water current kinetic energy turbine rotor is the need for as high efficiency as possible over as broad a spectrum of velocities as possible. There is also generally a need to be able to stop or regulate the rotor speed even in strong flows, and lastly a design which can control or limit extreme thrusts and forces by sometimes deliberately reducing efficiency would obviously be beneficial.

The following rotor options are generally under consideration by developers:

2.2.1 Axial flow rotors

Sometimes known as a "horizontal axis" rotor, this involves having hydrofoils arranged around a hub radially. They ideally should have rounded leading edges, sharp trailing edges and the most efficient profiles tend to be cambered, where the suction or downstream surface is more convex than the pressure or upstream surface. The most efficient foils can achieve lift/drag ratios of over 50 (i.e. the lift force over 50x greater than the drag force). The lift tends to increase linearly with angle of attack or angle of incidence to the flow until at a certain angle boundary layer separation takes place and the foil stalls. Stalling leads to a sharp increase in drag and consequent loss of efficiency so the aim is to operate as near to the stall as possible but without stalling. A well shaped cambered foil with a round leading edge will operate at higher angles of attack and hence higher efficiencies than a less favourably shaped foil.

The rotor blades need to be twisted to allow for the different angle of attack at different radii. Also the faster the rotor turns relative to the flow velocity, the finer the pitch of the "screw" effect. Slower rotating rotors need a coarser pitch and fast ones a fine pitch. There is also a relationship between the so-called "solidity" of the rotor and its speed relative to the flow. High tip-speed-ratio fine-pitch rotors need a low solidity – i.e. relatively slim rotor blades with large gaps between them, to avoid the wake from the preceding foil. The optimum geometry is generally determined by some form of blade element model where flow vectors are considered in relation to slices of foil at different radii; however modern rotor design models many of which were developed by wind turbine manufacturers and researchers, are complex and take full account of radial and tangential as well as axial flow effects[12].

The number of rotor blades has little effect on the performance – it is the swept area which matters most – and also the solidity needs to be optimised to suit the pitch of the rotor. The rotor solidity is defined as the chord length of a foil multiplied by the number of foils – so for example for a given pitch of rotor there can be 4 blades of chord "x" at a given radius or 2 blades of chord "2x". Since the bending forces on foils operating in water tend to be very large compared with an equivalent wind turbine there is an advantage in going for fewer thicker blades for strength reasons rather than a greater number of slimmer blades. The downside is that thicker blades have a lower aspect ratio which leads to a small loss of efficiency compared with slimmer blades.

Axial flow rotors can also either have fixed pitch rotor blades where the angle of attack and the twist are chosen as a compromise to suit the most common operating conditions or a pitch mechanism can be fitted in the hub to permit the angle of attack of a blade to be adjusted. Pitch control is almost universally used on larger wind turbines for very good reasons and it seems that similar factors apply with water current turbines. The main advantages of pitch control are as follows:-

- Greater efficiency at low water speeds as the angle of attack can be continuously optimised to obtain as much power as possible
- Deliberate power shedding at velocities above a certain level, usually defined as the rated velocity; this considerably reduces the thrust and hence the forces on the rotor and the structure in high velocities – typically reducing forces to a fraction of what would be felt under extreme conditions by a fixed pitch rotor(see Figure 6). The structural savings more than compensate for the cost and complication of pitch control
- Complete operational control since even when the flow is strong the blades can be pitched into a neutral or "feathered" position to stop the turbine – this is generally a requirement for power plants – unstoppable generators tend to be unpopular with operators!
- The possibility to operate efficiently in bi-directional tidal flows by pitching the foils through 180 degrees, a patented feature on our company's systems. This avoids the need to yaw a rotor to face the flow.

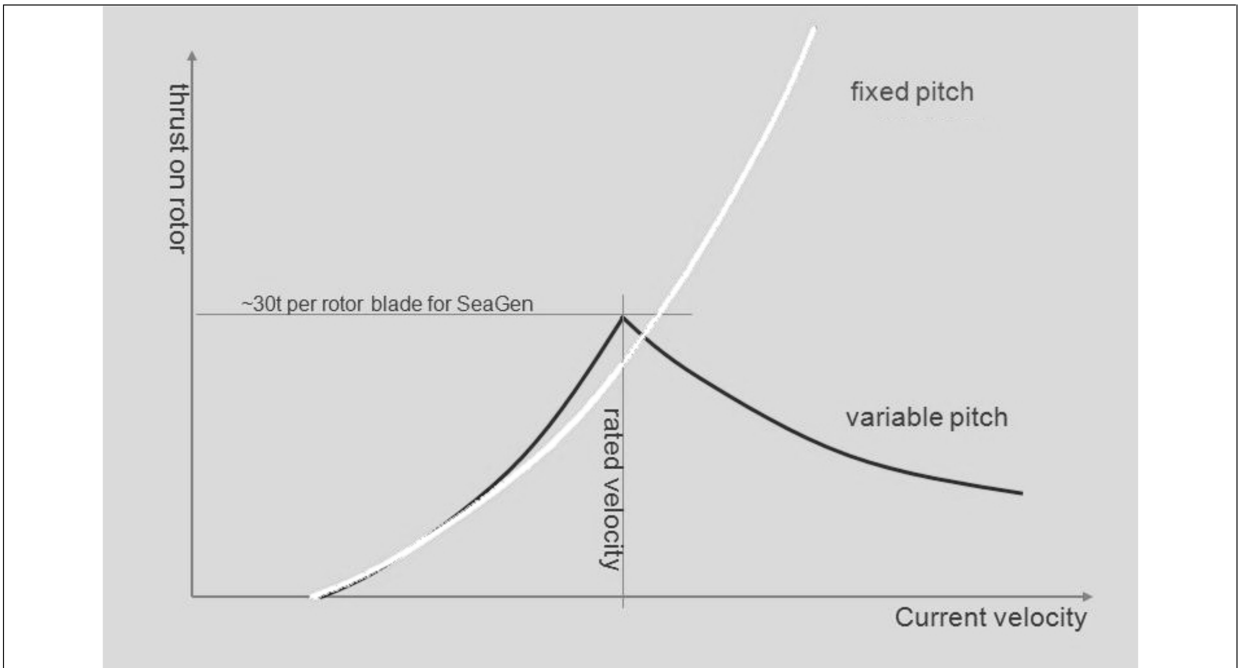

Figure 6: how a variable pitch rotor can limit the thrust such that it actually decreases for velocities higher than rated; conversely a fixed pitch rotor sees much greater thrust levels

Some developers propose using fixed pitch axial flow rotor blades with no method for facing the rotor towards the flow, so that the leading edge of the blades on one tide becomes the trailing edge on the reverse tide. This demands a symmetrical profile (no camber) where the leading and trailing edges are relatively sharp to minimise drag; hence the maximum angle of attack without stalling is inevitably much smaller than with a high-lift foil section and the lift/drag ratio will be compromised. As a result rotors of this kind are likely to be little more than half as efficient as a well optimised pitch controlled axial flow rotor, the implication being that about twice the rotor swept area will be needed to achieve the same level of energy capture.

In summary, pitch controlled axial flow rotors have proved to be the "technology of choice" for large wind turbines primarily because they are the most efficient form of kinetic energy converter and they are fully controllable to an extent not possible with other types of rotor. This is the reason why our company has focussed on developing water current turbines with pitch-controlled axial flow rotors.

2.2.2 Cross-flow turbines

With cross-flow turbines the axis of rotation is at right angles to the flow instead of being aligned with it. Such devices are sometimes called "vertical axis" rotors even though it is possible to have the axis of a cross-flow rotor aligned horizontally across the flow. The only reasonably efficient version which utilises lift as its primary mode of propulsion is the so-called "Darrieus Rotor" invented in 1926 by the man who gave it this name (ref). This type of rotor has a number of symmetrical foils arranged to sweep a cylindrical path cutting across the flow twice per revolution. It works because when the foils travel at more than about 3x the speed of the current the angle of attack becomes about correct for maximum lift and minimum drag and in that situation the tangential component of the lift vector exceeds that of the drag vector and hence results in a nett torque to propel the rotor. Much higher radial force vectors are generated and these need to be carried by the internal strength of the foils and their support structure.

Because the angle of attack of the blades changes constantly as the rotor turns, the driving force is cyclic and sinusoidal, but by having several rotor blades, or in some cases by arranging the rotor blades in a helix, this cyclic variability can be smoothed out.

Well optimised Darrieus rotors have been reported to achieve 30 to 35% efficiency which is similar to, or perhaps slightly less than a fixed pitch axial flow rotor (Figure 5).

The advantage most generally claimed for the Darrieus is that it can be convenient to have the driven shaft perpendicular to the flow rather than in the middle of the water column, so the generator can either be above water level or on the seabed. The disadvantages are relatively poor efficiency (compared with axial flow) so it needs to be larger to collect the same amount of energy. It is also structurally more complicated in that the rotor blades need to be held away from the axis by streamlined struts. This structural disadvantage is aggravated by the large cyclic radial forces generated by the vertical foils as they cut across the current which inevitably introduces major fatigue issues and also the added cost and parasitic drag of the struts.

Lastly Darrieus rotors do not self-start – they need to be driven to about 2x the speed of the current before they produce net torque. They also are not controllable to stop them in a strong flow other than through using a brake or spoilers, neither of which is necessarily fail-safe. Pitched Darrieus devices have been experimented with, (and the Voith Schneider ship propeller is of that kind), but pitching is complicated mechanically with many underwater bearings as it needs to be cyclic to match the speed of rotation (i.e. one cycle per revolution). The fatigue implications are formidable.

2.2.3 Reciprocating foils

In recent years there have been proposals and even developments of unconventional devices where hydrofoils are arranged to reciprocate backwards and forwards across the current instead of rotating. In such cases they drive a lever which in turn will power a reciprocating power train usually involving hydraulic rams pumping high pressure hydraulic fluid to a rotary hydraulic motor as a means to produce an output suitable for coupling to an electrical generator.

Such devices can have the angle of attack of the foils optimised through the use of hydraulic actuators, but because the foils need to be reversed in their direction of travel at the end of each stroke, there is an inevitable period when they have to be slowed down, stopped and then reversed and accelerated back to speed when they will not be generating much or any energy. Also not only has the mass of the structure and the foil got to be decelerated, stopped and re-accelerated but a significant “bound mass” of water represented by the circulation inherent in generating lift has similarly to be stopped and restarted in the opposite direction when the lift vector direction is reversed. Force, as Newton first pointed out, is proportional to the rate of acceleration, so rapid reversals to minimise the dwell time cause very large forces (which in turn needs strong and costly structure to handle them) while slow and gentle reversals lead to long dwell times when no energy can be collected.

This “dwell” time represents a loss of energy as the flow continues past without being used effectively. A solution is to use two foils out of synch with each other so one is always generating. But even so, this involves provision of a less well utilised moving structure than is the case for example with an axial flow rotor where the foils continuously interact efficiently with the flow. It is the equivalent of having a pitch controlled axial flow rotor and making it rotate first one way and then the other by reversing the blades after say 180 degrees of rotor movement; clearly this will work, but much less efficiently than if steady state conditions are established with continuous rotation.

It has been claimed by one developer that the justification for a reciprocating foil device is that by sweeping a shallow and wide (rectangular) tranche of flow such a device is more suitable for use in shallow water. However a row of axial flow rotors of small diameter (each of a diameter equal to the vertical sweep of the reciprocating foil) can achieve the same result more efficiently and it may be expected more reliably due to involving smaller and steadier forces.

2.2.4 The use of ducts and augmentors

A venturi or a duct with a narrowing cross-section can be used to accelerate the flow (because $Q = VA$ where Q is the flow rate, V the velocity and A the cross-sectional area of the flow). It has often been proposed that by placing a turbine, generally axial flow, in a duct of this kind, the performance can be radically enhanced bearing in mind the cube relationship between kinetic power and velocity.

However as might be expected there is a fallacy in these assumptions because speeding up the flow through a venturi has no effect on the energy content; energy is neither added nor removed, so the power flow through any cross-section remains nominally constant (other than friction losses in the duct may cause a small loss of power as the flow moves along the duct). This can be explained readily because there is a pressure drop at the throat of the venture (Bernoulli's well known equation clarifies this) which exactly cancels out the supposed benefit from accelerating the flow.

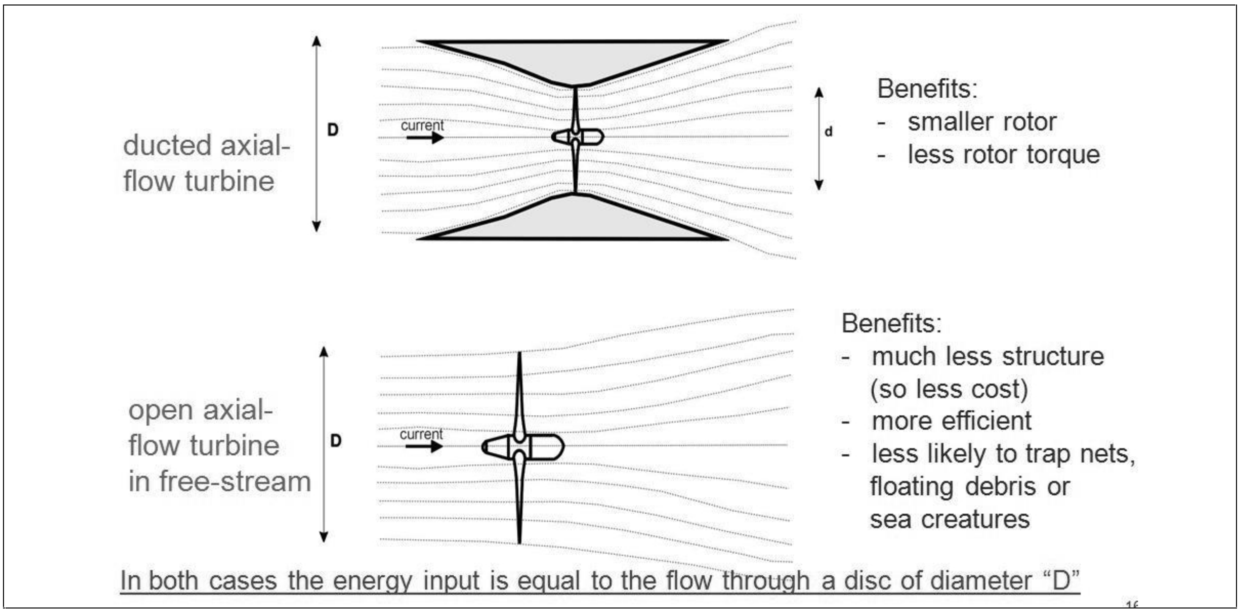

Figure 7: ducted and open axial flow rotors

Certain technology developers claim this can be used to overcome the Betz limit, however this is impossible since the limit applies to any device regardless of how it works; it is based purely on considerations of taking momentum out of a flowing fluid. If the efficiency of a ducted turbine is calculated on the basis of the cross-section of flow entering the duct (i.e. the cross section before it is accelerated by the duct) then Betz applies and it can be seen that the efficiency of such a device when referenced to the entry cross-section is no better than for a turbine of a similar swept-area to the cross-section of the entry flow to the duct; see Figure 7. Sometimes when huge efficiency gains are claimed, this is based on referencing the efficiency to the cross-section of the throat of the duct where through dividing by a smaller number it exaggerates the efficiency. However in reality both Betz and any logical definition of efficiency needs to be referenced to a cross section of the fluid in the free-stream, as it was undisturbed before reaching the device, since that is the "raw material" from which energy is to be extracted.

Ducted rotors have been tried and tested in the wind industry on a number of occasions usually with claims that the efficiency would be hugely enhanced, but in practice this has never been achieved and therefore ducted windturbines are no longer considered as being a good idea (other than for small scale ones where a duct can offering physical protection to a fast spinning small rotor). The marginal cost of a large duct structure tends to be disproportionate to any possible benefits, since a ducted turbine can never outperform an open rotor turbine sweeping the same cross-section of fluid that enters the duct. Nevertheless a number of tidal turbine developers argue that the use of a duct, despite the huge extra cost for the materials required, is beneficial.

An important further issue with ducts that is not generally discussed by their advocates is the risk to marine mammals should they be drawn into a duct by an accelerating flow which would effectively funnel them into the faster moving rotor with no easy escape path. This could of course also be a serious hazard for any divers working on such a project even when the freestream is slow moving near slack tide, the flow through the duct could be too fast for a diver to cope with if he were to get entrained in the flow.

2.3 Converting rotor shaft power to electricity

A rotor large enough to generate sufficient power for a cost-effective grid connected system will turn quite slowly. To avoid cavitation rotor tip velocities generally will need to be less than about 15m/s near the sea surface. This constraint limits the rotational speed; for example SeaGen with 16m diameter rotors has a design speed of 14rev/min. Although low speed generators exist it is technically difficult, but probably not impossible, to produce one that is compact and efficient at such low speeds. Hence SeaGen follows the common solution used for windturbines of using a gearbox. Our company's design team has explored many alternatives including the use of a hydraulic pump to drive a much faster running hydraulic motor (rejected as riskier, significantly less efficient, and expensive to develop) and the possibility of a directly driven permanent magnet alternator (an attractive option as it is efficient but no suitable technology was available at the time required).

The power train used for SeaGen therefore consists of a gearbox with a capacity of 460kNm torque at 14 rev/min and an output of 1000 rev/min to the generator developed by Orbital 2 and made in the Czech Republic by Wikov (see Figure 8). This demanded a three stage speed increaser and the selected design has an epicyclic 8 planet wheel first stage, followed by a 5 planet second stage and then a final spur gear stage. Traditional planetary gearboxes use three planets per stage but the use of larger numbers of planet wheels greatly reduces overall size and weight.

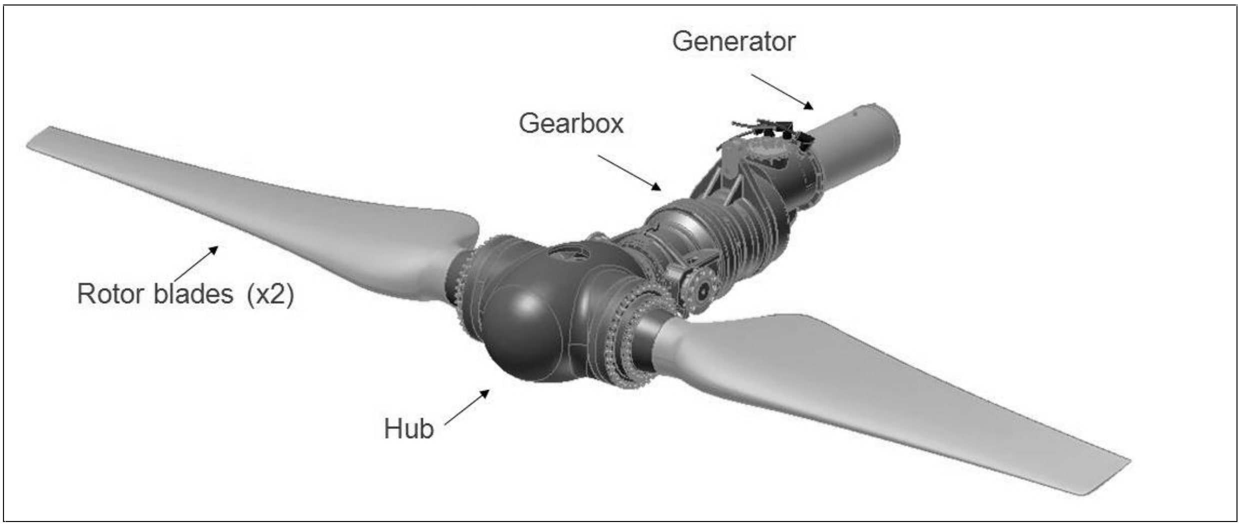

Figure 8: the SeaGen power train showing the rotor, gearbox and generator assembly

The gearbox option, although mechanically complex and although it also introduces significant numbers of wearing components, is well tried and efficient and relatively low risk, which is why it was chosen. On SeaGen the gearbox efficiency is over 95% and the overall optimum efficiency from water to wire is about 44% (rotor 48%, gearbox 97% and generator and power conditioning 95%).

3. Structural issues

A tide race is an extremely aggressive environment and until now it was almost unheard of to seek to moor a vessel let alone install a structure in such a location. To illustrate the extreme conditions, the SeaGen tidal turbine at Strangford Narrows in a 4m/s spring tide current experiences the same drag that a land-based structure would feel in a wind speed of about 400km/h; there are no examples known to the author of land-based structures designed to withstand such extreme atmospheric environmental loads. The thrust routinely experienced by SeaGen with its twin 16m diameter rotors even at rated power and rated velocity of 2.4m/s is approximately 600kN per rotor, with over 1500kN or 150 tonne on the structure as a whole. Safety factors require strength capable of carrying much higher loads than this. Each rotor blade with a 600mm root diameter needs to carry a load of 30 tonne routinely and approaching double that level transiently. Without the extensive use of carbon fibre it would have been difficult to accommodate such high loads.

Despite the extreme loads to be handled it may seem surprising that the key design drivers are not so much the peak loads but the need to avoid resonance (i.e. the frequency of the key load case drivers matters as much as their magnitudes) and the other key design issue is fatigue which is similarly dictated by load driver cyclic frequencies. So far as the structure is concerned welds were critical as potentially the weakest and most critical points and a lot of effort was needed on the weld details so as to avoid stressing welds too severely. A design life in excess of 20 years (25 years for SeaGen) seems vital for any grid connected power plant of this kind.

A key element of any tidal turbine, regardless of its form, is anchoring it to the seabed. Whether it uses a rigid structure piled into the seabed, a gravity foundation or whether it floats and is moored to anchors, a given level of rotor power will generate a given reactive force that needs to be engaged with the seabed. In virtually all locations with tide races the seabed is rocky, since any soft material would not stay in place but would have been eroded away. However even hard rocks have very limited load-bearing capability compared for example with steel or other structural materials, so a large area of engagement is necessary between any foundation or anchor structure and the rock to avoid it crumbling and fragmenting under load. For example, SeaGen at Strangford needs four steel tubular piles of 1m diameter each penetrating over 9m into bedrock to avoid overloading the ground.

Alternative foundations that have been considered (and which are favoured by some other developers) are gravity foundations, monopile foundations and floating devices with anchors. In all cases the reaction to the drag or thrust on the structure needs to be transferred into the seabed. Problems with gravity foundations, apart from the enormous weight needed with coefficients of friction which may in some cases be as low as 10%, are scour, where erosion can undermine the structure, while anchors suffer similar problems as well as the difficulty of making them engage reliably to resist thrusts in opposite directions. Because of uncertainties over coefficients of friction, the reduced weight of solids when submerged in water, and the extra drag caused by the profile of a gravity foundation, our own estimates suggest over 1500 tonnes are needed per MW of installed capacity. This makes gravity foundations rather unattractive for tidal turbines that are large enough to be commercially competitive, but possibly more suitable for small machines of no more than 200-300kW maximum capability.

4. Operational issues

4.1 The need for accessing the system for maintenance

The perfect maintenance-free electricity generator has yet to be perfected, meanwhile any such plant will from time to time need at least an inspection and possibly occasional repairs. There are in reality two options; you either have a system that projects above the surface at least when maintenance is needed so that it can be boarded safely; ideally from a small boat or there will be a need to recover the entire system, probably to a port. The latter option is extremely costly especially to cope with minor faults. Also if the system cannot be boarded while it is operational it can be difficult to trace faults as the conditions when they occurred cannot be replicated and witnessed by human operators.

For this reason the SeaGen system is surface breaking and essentially can be boarded at almost any time, even when it is running at full power. Future submerged versions are planned but these too will be surfaceable for maintenance by a small crew delivered by small boat such as a Zodiac or a RIB.

In all cases it pays to have an extensive monitoring or SCADA system such that not only can the control system respond effectively to any faults that may develop but also any human intervention can be planned with advance knowledge from diagnostic sensors.

Another key issue relates to velocity shear effect – see Figure 9.

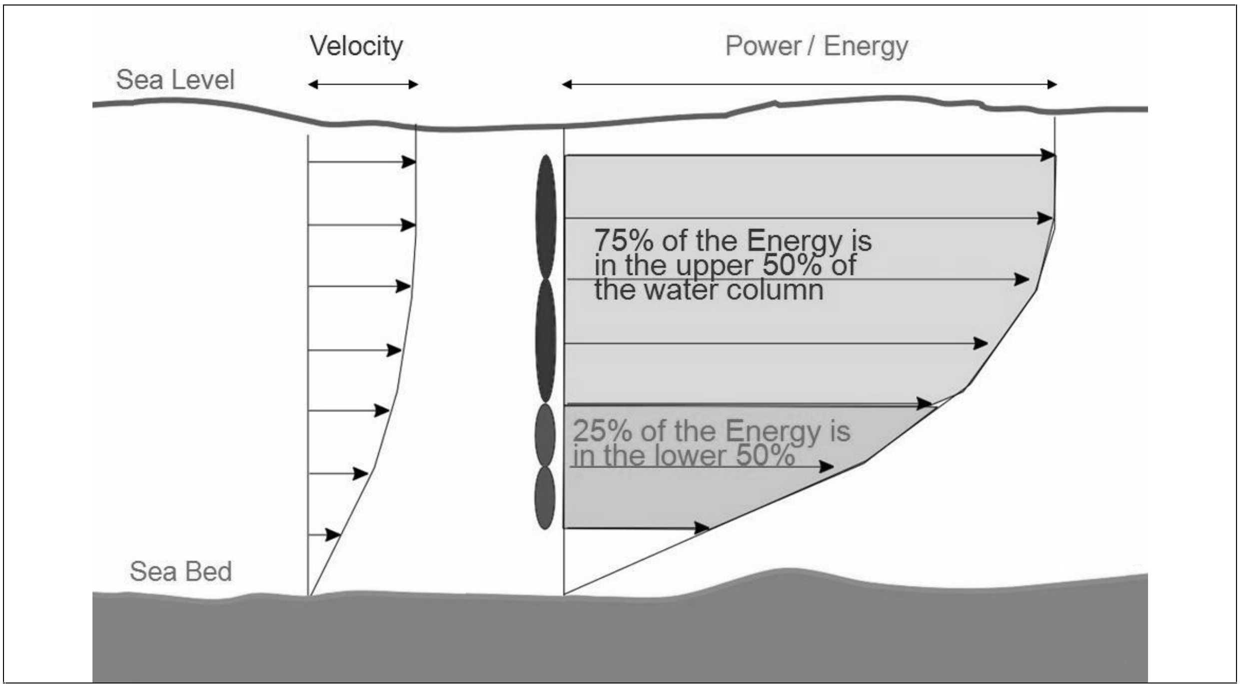

Figure 9: an illustration of how the effect of velocity shear is magnified in terms of energy availability as a function of depth due to the cubic relationship between velocity and energy.

Because the surface water moves fastest and the water in contact with the seabed (in the boundary layer) is much slower moving, there is much more energy near the surface than near the seabed. This effect is exaggerated by the cubic relationship between velocity and power or energy; a 10% variation in velocity, which seems minor, yields a 33% variation in power/energy. Hence with a typical velocity shear profile, about 75% of the energy is in the top half of the water column. A completely submerged device is invisible, therefore it either needs to have an exclusion zone for marine traffic (marked appropriately with buoys or markers, which is difficult in a tide race) or it will need enough clearance above its rotors to allow the largest likely vessels to pass over it safely. In contrast a surface piercing system like SeaGen (Figure 10) has been permitted by the Maritime and Coastguard Agency to operate with a 3m clearance above its rotors as operators of deeper draft vessels can see it and will keep sufficiently clear while the majority of leisure vessels do not have enough draft to be at any risk. It therefore seems likely that completely submerged tidal turbines will either need complex permitting arrangements or they will need to be so low in the water column that most of the energy will pass over the top of them and be lost.

Figure 10: SeaGen installed: operational in a strong current (left) and raised to enable inspection and maintenance (right) – note the person above the starboard power train for scale

4.2 Installation problems

At present installation can generally cost more than the system being installed; the offshore wind industry suffers from the same problem. The difficulty is that tidal turbines are installed in hostile locations where construction operations are handicapped by both the movements of the very tides that are to be utilised as well as by adverse weather. Underwater human intervention is at best difficult due to the very short time windows around slack tide – commonly 15 to 30 minutes. The deeper the water the more difficult; in fact depths of over 40m in tide races are probably completely inaccessible to divers because at such depth mixture gases are needed and constraints in the speed with which a diver can descend and surface are such that the slack tide periods are too short.

As a result it is generally necessary to develop a technique for installation relying entirely on surface vessels. However maintaining station in a tide race is at best challenging. This is why the jack-up barge appears to be an interesting installation vessel as it can stand on relatively low drag legs (with its hull clear of the water) in a tide race without need for moorings. Floating installation vessels such as crane barges need secure moorings with typically four or more anchor points, unless very powerful and expensive DP (Dynamically Positioned) vessels are used.

Although a gravity foundation appears to be a good solution as in theory at least it can be quickly dropped to the seabed. Grid connecting it is difficult and as mentioned, any system sufficiently powerful to be cost-competitive is likely to need such a heavy gravity foundation that only the world's largest, comparatively rare and most expensive crane barges could handle them. All other solutions involve engaging foundations with the seabed, which in the rocky locations common to virtually all tide races, demands rotary drilling of sockets followed by insertion and grouting of piles or of a monopile structure.

In many respects the monopile, as used for our company's Seaflow system, seems the most straightforward solution but it generally needs a large jackup barge with pile gates to install it. Suitable jackups for use in tide races are not common; they need rapid leg jacking capability and ideally need to stand safely in a tide race of up to 40m depth. This can be achieved but such vessels are rare and tend to have high daily charge rates, so they are expensive to use and often not available due to their scarcity.

MCT and others are working on less costly installation procedures and a number of patent applications are being filed in this area. With SeaGen at Strangford a temporary work platform was bolted to the top of the turbine structure above water level. The entire assembly was placed in situ by a large crane barge. It was ballasted to stand safely in the flow (albeit with the rotors furled to minimise drag) and then levelled using sacrificial hydraulic jacks. Pin piles were then drilled, from the corners of the temporary work platform, into the seabed through conductor tubes to stop the current disrupting the drill string (see Figure 11)

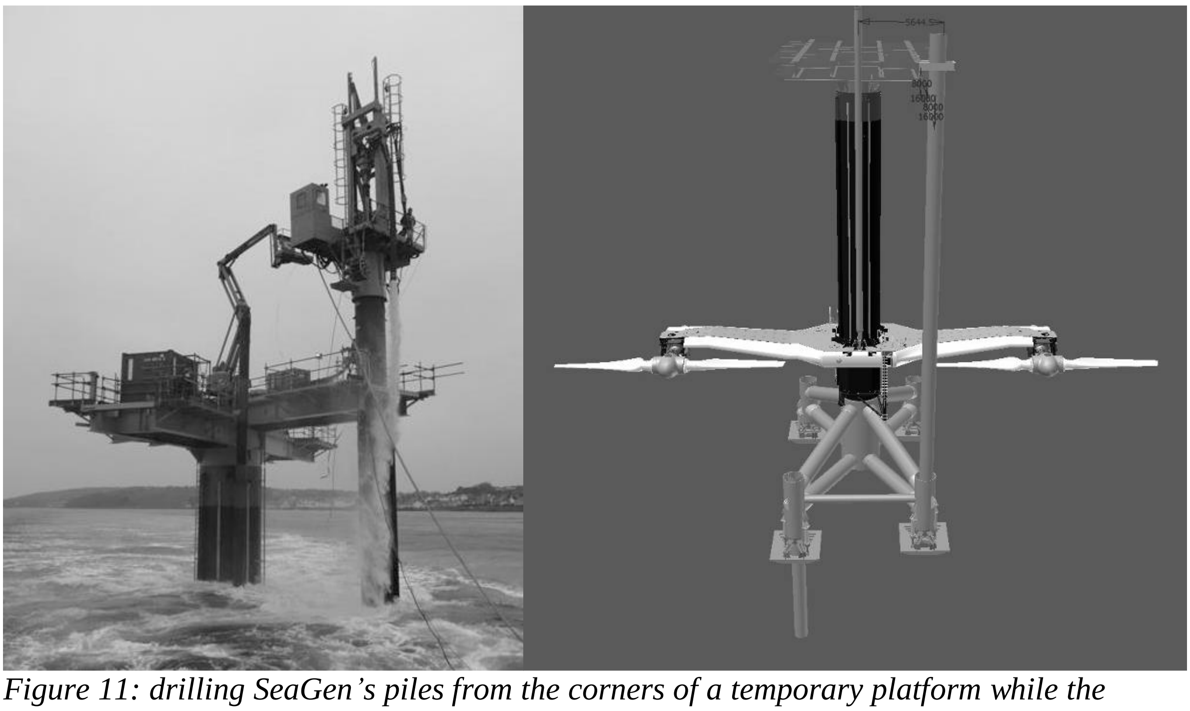

Figure 11: drilling SeaGen's piles from the corners of a temporary platform while the structure stood ballasted sufficiently for stability in the tide race; the complete arrangement is shown on the right

After the piles had been inserted and grouted into place, the platform was removed and the normal superstructure replaced it. This procedure obviously worked but was slow and hence costly. Improvements to speed the process and to use less costly vessels are therefore under development.

4.3 Connecting to the grid (grid compliance)

Any modular power system needs to be interfaced with others, windturbines in wind farms being a good example. To do this requires the production and export of grid compliant electricity. Most tidal turbines, SeaGen included, run at variable speed so it is necessary to provide frequency converters and transformers combined with electronic power conditioning between the generators and the grid. This issue often seems to be neglected by tidal turbine developers as the equipment necessary to produce the grid compliant output is costly and takes significant space. In the case of the 1.2MW SeaGen system it occupies no less than 3 floors inside the structure, extending below water level (see Figure 10) a volume of approximately 50 cubic meters; most of the smaller tidal turbines currently under development and often designed to operate submerged do not appear to have space for provision of equipment to do this, so they will presumably have to export "raw" electricity to be converted on shore. In such cases each turbine will need its own umbilical and will be unable to be interfaced directly with other units in an array, which will impose a significant cost and loss of efficiency penalty.

The power conditioning used in SeaGen is around 98% efficient but the 2% loss manifests itself as waste heat which at full power is about 24kW. This heat is dissipated through a cooling system which dumps it through a heat exchanger into the sea. Moreover the heat is used to maintain "comfortable" conditions for the electronic systems within the SeaGen structure. A dehumidifier is also provided to avoid condensation problems that could lead to reliability issues for the electronic systems.

4.4 Safety

Since the structure of SeaGen occasionally accommodates human operators, "health and safety" is a crucial issue. Electrical safety is vital and all high voltage areas are appropriately shielded to prevent accidental contact by staff. An automatic fire extinguishing system is also fitted. Emergency equipment is provided to enable rescue of personnel in the event of an accident and drills are carried out by staff sometimes in cooperation with the local Maritime and Coastguard Agency. Staff also generally wear survival suits, life-jackets and safety harnesses when embarking or disembarking the turbine. Extensive operational handbooks have been developed with detailed procedures specified to cope with a variety of potentially dangerous eventualities.

5. Economic issues

5.1 Targets to be met for commercial competitiveness

Electricity, the product from a tidal turbine, can be sourced from numerous alternative methods of generation, most of which are better established and lower in cost. The main virtue therefore of this technology is the capability to produce electricity without atmospheric pollution. Hence commercial competitiveness depends on generating at low enough cost to compete with conventional methods of generation after allowing for the incentives such as

ROCs (tradable Renewable Obligation Certificates) provided to encourage development of clean methods of power generation and to penalise excess dirty power generation..

At the time of writing the UK government had not finalised the level of subsidy for tidal turbines but the Scottish government was offering 3 ROCs per MWh in addition to the base price for electricity, which is worth approximately £200/MWh in total. There has been discussion of higher levels of subsidy up to 5 ROCs (which is what the Scottish government already offers for wave energy electricity).

Tidal turbines therefore need to generate at a cost that gives a reasonable internal rate of return, probably in excess of 15% for early risky projects, with whatever can be earned through the combination of sale of electricity plus the value of ROCs or other revenue support. our company's techno-economic model suggests that this requires systems of at least 1MW rated power and probably nearer 2MW depending on siting conditions. The size requirement is because of the significant fixed overheads which are not proportional to the revenue earning capability inherent in offshore projects. These overheads include connection costs, mobilisation and demobilisation costs for installation and O&M costs. Therefore SeaGen was developed as a "megawatt scale" system – indeed at the time of writing it remains the world's only tidal current turbine with a capability exceeding a megawatt – and it is recognised that there is a need to try and achieve even larger scale levels of power production if the technology is to develop to be commercially competitive with other methods of electricity generation. The wind industry has shown the need for larger individual generators and has steadily improved its cost-effectiveness through moving from wind turbines of a few hundred kW in the mid 1980s, to around 1 or 2MW in the 90s and as much as 5MW per unit today, with even more powerful wind turbines under development. Tidal requires similar development for the same reasons.

The other key issue with any renewable energy technology is whether it can pay back the energy needed to manufacture, install, operate and decommission it reasonably quickly – in other words the ERoEI or Energy Return on Energy Invested. Without achieving an adequate energy return it would be pointless to develop such technology as the pollution from manufacturing it would not be balanced by the savings from using it. In the case of SeaGen analysis suggests that the ERoEI is from 6 to 12 months and the life is in excess of 20 years, so this suggests a pay back of 20 to 40 times the energy invested which is a good return by any standards.

6. Future developments – SeaGen 2

Our company is developing a variation on the SeaGen theme which uses exactly the same rotors, power trains and control systems but deploys them on a different structure. The purpose is to increase the flexibility by which the SeaGen power train technology can be applied.

The existing surface piercing system (as in figure 10) is ideally suited to locations with water depths in the range 20 to 40m – less than 20m requires the rotor size to be too small to be cost-effective with a twin rotor configuration and more than 40m introduces structural problems and access problems due to the height of the support structure needed.

Therefore it is proposed to develop in parallel a system where rotors may be deployed across the direction of the current along a horizontal streamlined structure which when operational is seated on a solid footing that lays on the seabed. However our company has recognised that it is essential to be able to gain access to any such system for maintenance or repairs without requiring specialist vessels with cranes of lifting equipment to fish for the system every time access is needed. So a unique and patented arrangement in which the structure can be floated to the surface without need for external lifting is under development. The structure is kept under control by a pair of struts hinged to a foundation. The struts also serve to carry the power cable and instrumentation cables from the seabed to the device. Figure 12 illustrates how this works.

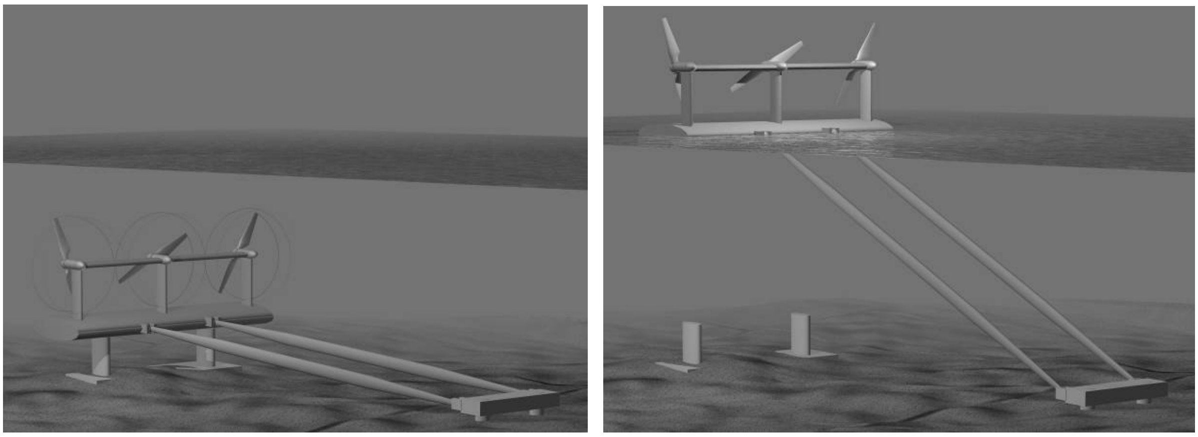

Figure 12: SeaGen 2 system utilising an array of SeaGen power units mounted above a buoyant deck that can be positioned operationally on supports set on the seabed (left); this can be surfaced independently without needing major lifting or salvage vessels (right)

7. Conclusions

Our company has developed the world's first commercial scale tidal turbine a twin 16m rotor 1.2MW system called SeaGen. The design approach has benefitted from many analogous factors that were learnt from the much more mature wind industry to the extent that similar features to wind turbines are used to good effect as follows:

- pitch-controlled axial flow rotors (for controllability and to limit loads)
- control system to limit power and thrust to acceptable levels and to allow safe shut-down even in strong currents
- planetary gearbox driving a conventional induction generator (most efficient option)
- a steel support structure piled into the seabed
- full scale power conditioning to achieve grid compliant output (permits interconnectivity)
- accessibility by maintenance staff even when the system is operational (essential for some kinds of problem solving)

This paper has reviewed alternatives such as different types of rotor, the use of venturis or augmentors, etc, but found that such things that have been tried and abandoned in the wind industry appear to have no significant advantage when operated under water either. Hence the technology approach that has evolved for wind turbines appears broadly to suit water kinetic energy conversion too.

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