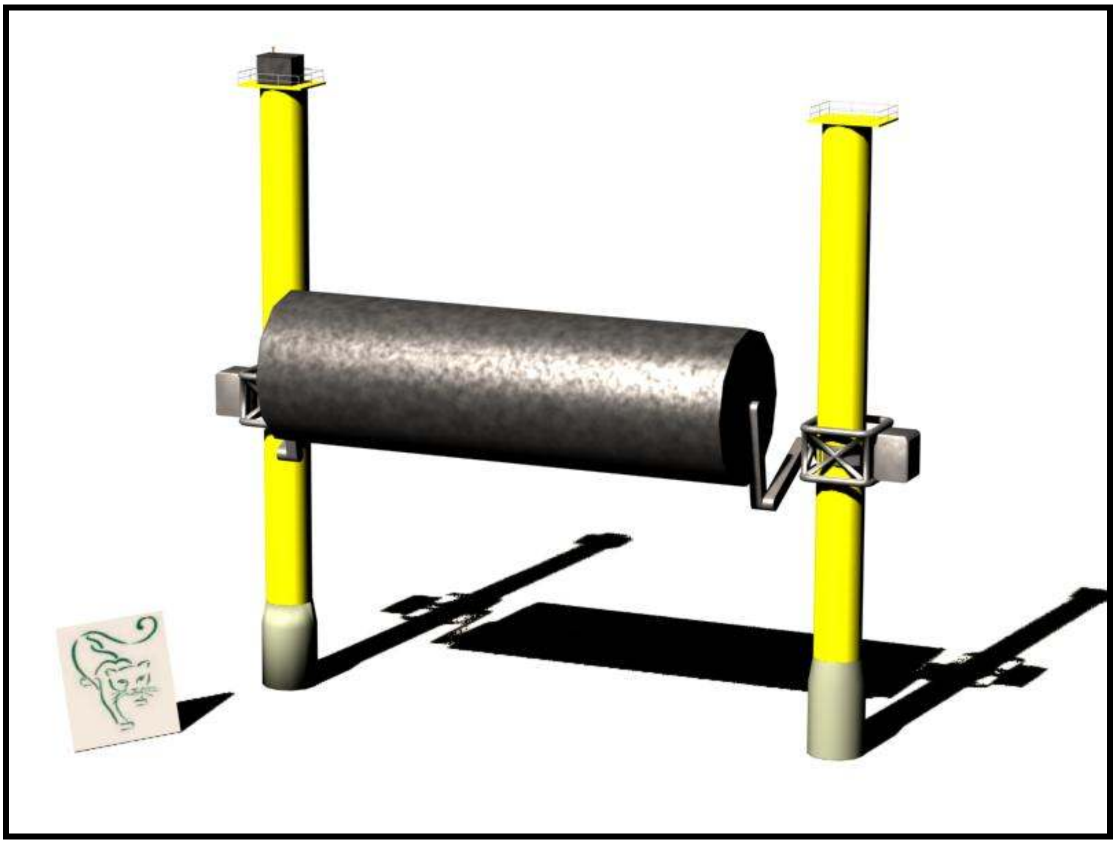
The Green Cat Wave Turbine

Phase 1 Report - SMART: SCOTLAND

July 2005



Introduction

Wave Energy

Renewable Energy is set to play an ever more significant role in the energy balance of the UK and the rest of the world. At the present time hydro electric is the most significant source of electricity generating renewable energy, with wind energy rapidly catching up. However, hydro is limited by the number of suitable sites and wind is likewise likely to be limited by a range of technical and 'political' constraints. As time moves on, other sources of renewable energy will need to be exploited. Biomass may be the next to be exploited for large scale electricity generation, but ocean technologies are widely expected to follow.

The potential wave resource in UK waters is impressive. Opinions vary as to the realistic potential, however, the wave programme review R26 placed the technically achievable resource at around 50TWh or approximately 15% of the total UK electricity generation. As with wind energy the UK has one of the most plentiful resources of wave energy in Europe.

The Forum for Renewable Energy Development Marine Energy group have stated in their document 'Harnessing Scotland's Marine Energy Potential' (2004) that by 2020 10% of Scotland energy can come from marine resources. Further, they state that 7,000 direct jobs could be created as a result.

To aid the development of the commercially viable wave energy 'turbines' that will be required to harness this resource, the UK government has put up significant funding to aid the development of this area. The 'Wave and Marine Current Energy – Status and Research and Development Priorities' report produced by Future Energy Solutions for the IEA summarised the need as follows.

"*It is important to enable concept developers to prove their devices. They must be allowed to work through the complex design and economic assessment and tackle the many technical challenges they face. They also need to be afforded sufficient freedom and support to be able to develop technologies that make optimum use of materials, technology, resource and financing to enable the development of economic technologies. It is therefore recommended that emphasis be placed on supporting the development of individual device concepts rather than only on generic studies.*"

This project aims to start working through this complex design and economic assessment for the Green Cat Wave Turbine concept. The final output of this will be a sufficiently credible assessment of the device's feasibility to allow it to be properly assessed and, assuming this assessment is positive, plan out the steps in development to commercialisation.

The Green Cat Wave Turbine

The Green Cat Wave Turbine is what is sometimes referred to as a 'terminator'. The device is aligned parallel to the wave fronts, at right angles to the principal wave direction, thus 'terminating' the waves. At the present time, we are working on a standard unit of 50m length which would capture an average power of ~1.3MW from a sea with average power of 40kW/m crest length (65% capture efficiency). The peak power rating of the device would be a matter for optimisation but at the present time we are working on a figure of 3.8MW. It is not accidental that these figures are broadly in line with current developments in offshore wind farms. Much of what is currently being learned about installation, power take off and maintenance of offshore wind farms will be directly applicable to this type of wave energy converter.

The closest 'relative' of this device we have been able to identify from our literature review to date is the Bristol Cylinder. The Bristol Cylinder was researched in some detail under the original Department of Energy/ETSU wave energy programme and is reported on in summary form in both the 1985 wave review R26 and the 1992 review R72. However, whilst the conversion from wave to mechanical power is similar the conversion from mechanical rotation to electrical power, which was one of the main problems with the Bristol Cylinder, is completely different. The Bristol Cylinder used a complex hydraulic arrangement to convert the rotational mechanical energy into electrical energy. We propose to convert directly from mechanical energy to electrical with the use of a Direct Drive generator. To our knowledge, the application of a direct drive generator to capture wave energy in this way has never been proposed previously.

Principals of Operation of the Green Cat Wave Turbine

Key Features of the Green Cat Wave Turbine

This device has a number of novel aspects that set it apart from any other wave energy device currently being developed, notably;

- ☐ The use of a 'direct drive generator' to convert the rotational kinetic energy of waves into electrical energy,
- ☐ A very simple robust turbine design,
- ☐ A simple robust structure for fixing the machine to the seabed,
- ☐ The ability to 'dive' under extreme sea conditions,
- ☐ An extremely novel control system that will use measured incoming wave characteristics to 'tune' the turbine to individual waves, thereby increasing energy capture.

In order to understand the operation of this device it is necessary to have a basic understanding of the nature of sea waves. Whilst sea waves appear to 'roll' in towards the shore with water height initially rising then falling, in reality (in the absence of tidal streams) individual water particles do not move very far and in fact (for 'ideal' waves) they move irrotationally around elliptical paths completing a revolution every time a wave passes through. In deep water (>30m for a typical sea state) this elliptical path approximates to a circular path.[1]

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[1] To help visualise this, imagine that you are on a boat in deep water watching a buoy moving around on the waves. At a wave crest the buoy is at its highest point quarter of a wavelength. Later it has fallen to its

This particular device will operate a little under the surface of the waves, where the waves tend to be closer to the ideal circular motion, as this reduces problems with breaking waves. Note that the optimum diameter of this device is determined by the wavelength of the sea waves and not the wave height, so the rotor may be rotating in a circular orbit which is significantly less than its own diameter.

The turbine/reactor

As noted above, wave motion in deep water is basically circular. Under the surface this circular motion is also present however the radius scribed (and hence energy available) reduces exponentially with depth and as an approximate rule of thumb, 95% of the energy is contained in the top ¼ wavelength of sea depth. The Green Cat Wave Turbine is effectively a reaction turbine being forced around by the motion of the water particles around it.

The turbine/reactor is a massive cylinder of the order of 16m in diameter and 50m long. The cylinder will be neutrally buoyant so that it can 'hang' at a short distance under the sea surface. The cylinder is likely to have the ability to increase or decrease its buoyancy to rise to the surface for maintenance or sink to avoid the severest storms, respectively.

Interaction with Waves

Ideal sea waves in deep seas cause water particles to move in an approximately circular orbit as the wave passes over the particle (see figure 1).

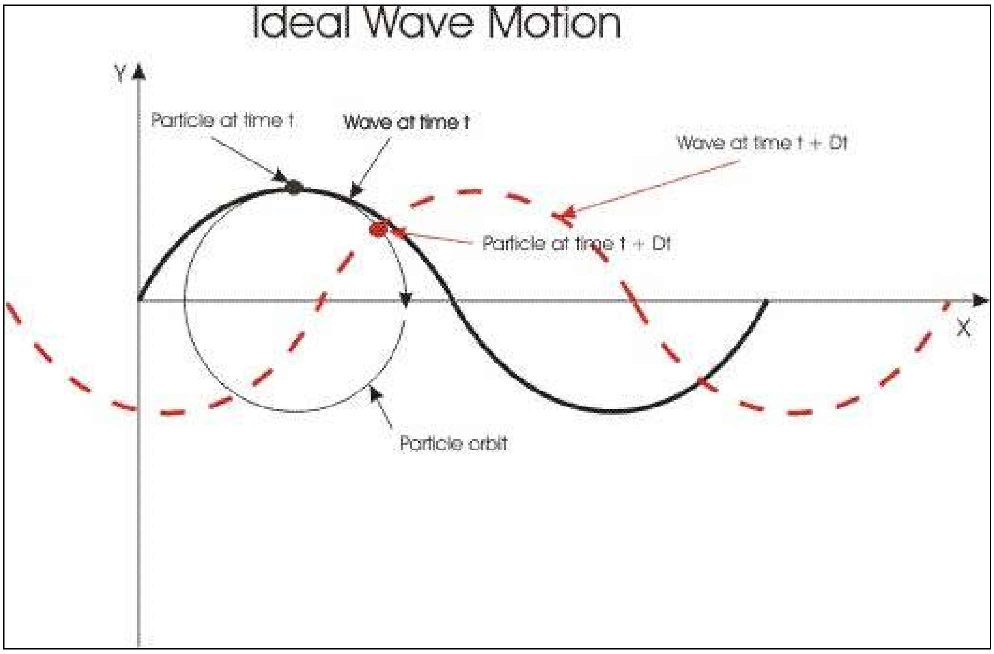

Figure 1 – Wave Particle Motion

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mid point but it will also have moved horizontally by a distance approximately equal to the wave amplitude. When the wave has moved on another quarter wavelength the buoy will be at its lowest point but will have returned to the horizontal centre point, and so on.

The turbine, being a submerged cylinder aligned with the wave crest, will follow a similar orbit to the particle at the surface, but at a small depth beneath the surface (see Figure 2).

The reason for the cylinder being submerged is to minimise problems associated with waves breaking on the device, as would be the case for a turbine on the surface.

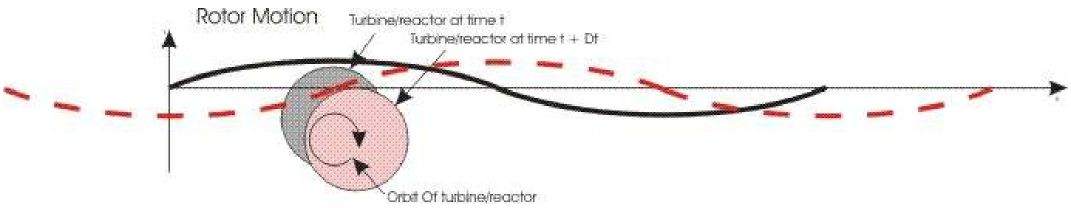


Figure 2 – Turbine/Reactor Motion

Note;

1. The cylinder orbits an eccentric axis parallel to its own, the offset from its own axis being related to the wave height (and not its own diameter).
2. The cylinder's motion is irrotational like that of the particle motions it mimics ie the top of the cylinder will always be at the top regardless of where it is in its eccentric orbit.

Power Take Off

The direct drive generators will be contained within the turbine situated around the central axis of the cylinder. The centre of each generator will be connected to the support structure via an extendable armature whose extension will be set by vector control of the generator.

As noted above the nearest relative to this device is the Bristol Cylinder, the early work on which (led by Dr Evans a mathematician at Bristol University) concluded that the optimum turbine for this purpose was a cylinder. Further points of note were that the optimum cylinder radius was related to wavelength with ~8m radius being optimum for ~150m wavelength waves, the cylindrical shape apparently being preferred due to problems with reflected waves from other geometries. In practice, the cylindrical shape suffered from some problems due to second order effects ignored by the original analysis. In theory, other geometries can give a similar effect and may offer a more efficient overall solution. It is intended to explore this later in the project using Computational Fluid Dynamic (CFD) simulation techniques developed since the time of the original work on the Bristol Cylinder.

The Cylinder is an extremely efficient way of mechanically capturing the energy of ideal waves that the device has been tuned to and even in real sea conditions the energy capture efficiency is predicted to be reasonable. The ETSU review of wave energy R72 published in 1992 predicted a capture efficiency of 64%. Hence, a device located in seas with an average energy of 40kW/m with a 50m active length could be expected to capture, at least, an average power of 1,280kW. To achieve this, the device would need a maximum output of at least 3.8MW and would need to keep generating in all but the most treacherous seas when it would be submerged well out of the way of the most energetic part of the waves. Note that a neutrally buoyant cylinder of 16m diameter and 50m length would weigh ~10,000 tonnes.

The Cylinder

The cylinder needs to be a neutrally buoyant cylindrical body 50m in length by approximately 16 m in diameter. Further it needs to be capable of sinking to avoid major storms and float to the surface for maintenance and to enable the device to be towed into shore for major repairs. Structurally it will need to withstand substantial forces due to; different wave conditions along its length, braking waves and out of phase reaction with waves. It will also need to be able to transfer the force captured along its length to the two direct drive generators at either end.

The basic design concept is based on an elementary submarine, the structural strength and the main source of buoyancy is provided by the pressure hull whilst the element in contact with the sea waves is a secondary hull attached to the pressure hull by a series of radial discs. The space between the two hulls would be used as ballast tanks normally being filled with sea water but which could be filled with air to float the device so that it could be ‘towed in’ for maintenance.

The pressure hull would be a 50m long 12m diameter steel cylinder with hemi-ellipsoidal ends. The cylinder would be reinforced with internal radial rings. An internal chassis would transfer the forces from the cylinder to the stub axles. A detailed structural analysis of the pressure hull is beyond the scope of this study but in order to estimate the mass and to aid the cost estimates that will be done later, some order of magnitude calculations were performed on the design. The shell is likely to require ~20mm rolled steel plate, the reinforcing rings are assumed to be T sections of ~150mm * 150mm and 15mm thickness at 600mm centres. Four equally spaced axial ‘purlins’ would carry the loads from the cylinder to the ends where the loads would be transferred to the stub-axles via reinforced webs constructed from 40mm steel plate. The outer hull of the device would be attached to the inner hull by a series of steel disks at 10m centres effectively providing 5 separate ballast tanks. Additional support would be provided by a lattice of support struts. As with the pressure hull, the outer hull would be rolled steel with internal ring reinforcement, but this would not need to be nearly as strong. 4mm steel with 150mm * 150mm T section rings of 10mm thickness and 1200mm centres has been assumed.

The pressure hull would require ~2,000m^2 of 20mm rolled steel or approximately 40m^3 which, depending on the grade of steel (likely to be Structural Steel S355J2G3 or similar), will weigh 312 tonnes. Each of the reinforcing rings would weigh approximately 1.32 tonnes and at 600mm centres there would be approximately 75 rings (depending on hemisphere cross section), hence total weight of rings ~100 tonnes. If the purlins are assumed to be 200 * 300mm I beams of 20mm thickness then they would weigh 15.6 tonnes (for 4 units). The stub-axles, if they are assumed to be 500mm diameter and 2m in length would weigh ~6 tonnes (for 2 units). The internal webbing to transfer the forces from the cylinder to the axles would weigh approximately 23 tonnes. Hence total pressure hull structural steel weight would be ~470 tonnes.

The secondary hull would require ~2,700 m^2 of 4mm rolled steel or approximately 11m^3 which would weigh approximately 84 tonnes. The reinforcing rings would weigh ~1.2 tonnes and there would be 42 rings hence total weight 50.4 tonnes. The radial disks would weigh ~8.4 tonnes for all five disks. Assuming a spoked arrangement with 24 spokes per ring and 3m spoke length of 50 * 50mm and 10mm thickness angle iron then there would be a further ~25 tonnes of steel for this structure. Giving a total weight for the secondary hull of 168 tonnes and total mass for the entire rotor (excluding ballast and control equipment) of ~640 tonnes.

When the ballast tanks are flooded the displacement of this device is approximately the volume of the pressure hull. Therefore, for the device to be neutrally buoyant it would need to weigh 5,652 tonnes. Assuming the ballast is provided by concrete then (at 2,400kg/m^3) 2,355m^3 of concrete will be required.

The Armatures

Armatures would connect to either end of the cylinder and would be able to vary in length and hence ‘tune’ the device to different wave amplitudes. An articulated arm arrangement will control the effective length of the arm by controlling the degree to which the device tends to ‘lag’ the wave motion, however, the implications on capture efficiency of this operation would need to be considered. Even if this mode of control can be utilised at an acceptable cost there is still likely to be a need for another, possibly hydraulic, control mechanism to ‘fine tune’ the device and for storm avoidance and maintenance routines.

At the present time it is anticipated that the armature and the rest of the dynamic part of the structure will be a steel fabrication. However, we note that due to constant variations in load that fatigue will be an issue that will require careful consideration. The hydraulic or otherwise driven actuators that are used to vary the length of the armatures is an area of particular concern. The forces required will be massive and the environment extremely hostile.

The Direct Drive Generator

Background

The generator is one of the most technically challenging elements of this project. The turbine will capture energy at a frequency of between 0.06-0.3Hz (3.6-18 rpm). The first difficulty this presents is the enormous torque associated with a given power. 3.8MW of mechanical power at 3.6rpm (0.06Hz) equates to a torque of >10MNm.

Beyond the physical difficulties of transferring this power to an electrical generator there is the question of what form a generator driven by such an extreme mechanical input should take. In a machine design such as this there are a number of conflicting objectives. The key ones with respect to this machine are;

1. To get the airgap energy density up as high as possible in order to reduce machine physical size. This requires a small airgap between the generator stator and rotor,

2. To use a reasonably large airgap between the stator and the rotor to allow achievable manufacturing tolerances,
3. To get the number of magnetic pole pairs up to achieve as high as practical electrical generation frequency. This requires a large diameter machine,
4. To keep the pole pitch and slot pitch at a reasonable level so that the airgap flux densities of ~1Tesla can be achieved, and a sensible stator winding is possible,
5. To get the number of stator slots up to achieve reasonable voltage waveform and acceptable space harmonics,
6. Keep reasonable slot pitch so that sufficient copper can be inserted to keep copper losses low,
7. To restrict the rotor diameter to a sensible value that can be manufactured to acceptable tolerances.

The topology selected for this device was the ‘brushless dc machine’, using rare-earth permanent magnets with a modular stator.

Electrical Design

The key characteristics of the mechanical input to the generator are related to the wave characteristics as follows;

Characteristic	Symbol	Units
Wave Height	H	m
Wave Period	T	s
Wave Length	λ	m
Wave Phase Velocity (Celerity)	c	m/s
Gravitational Constant	g	9.81 m/s^2
Density of Water	ρ	1053 kg/m^3
Mechanical frequency	f	Hz

$$E = \frac{\rho g \lambda H^2}{8}$$

$$P = \frac{E}{2T}$$

By placing typical ranges of values for the wave conditions likely to be encountered in the above equations and setting suitable practical limits, we can define the operating range of the generator. The frequency of the mechanical input ranges from 0.06 Hz – 0.3 Hz. The power ranges from 0 to 80kW/m crest length, hence for a 50m device with two generators, each would need to be rated at 2MVA.

As this device will be operated in a ‘Brushless DC’ configuration there is no theoretical limit on the output frequency of the generator, however, in practice the efficiency of the machine is significantly compromised if the electrical output is less than 20 Hz. As a starting point we have set the limit as 18 Hz electrical for an input of 0.06 Hz mechanical which requires a machine with 300 pole pairs. Assuming the use of Neodymium-Iron-Boron (Nd-Fe-B), also known as rare-earth magnets, then a pole pitch of 40mm is possible. This gives an airgap diameter of 7.6m and hence a total machine diameter of ~8m.

In classic machine design the stator winding would typically employ a 2 layer winding having 6 or more slots-per-pole-per-phase (q). For a machine with a pole pitch of 40mm this would lead to an excessive number of extremely narrow slots, which would be difficult and expensive to wind and would have a poor fill factor reducing efficiency. Therefore in this application we are driven to use a fractional slot arrangement to achieve reasonable slot dimensions. The key drawback with fractional slot windings are the space harmonics (or more strictly sub-harmonics) and associated leakage reactance and iron losses that they can create. The number of slots must be carefully selected to keep space harmonics to a manageable level. As a starting point a stator design with 624 slots has been selected giving a slot pitch of approximately 38 mm.

The induced emf of the machine is determined by the number of turns making up a winding and the magnetic flux linking with it from each pole. For the initial design it was decided to keep the winding voltage under 1,000 volts as electrical machinery operating at over 1,000 volts is classed as HV and comes under more demanding regulations.

In practice the airgap flux density (B) that can be achieved in this type of machine is limited to approximately 0.9 Tesla and the electric loading (A) is limited to approximately 40,000A/m hence required ‘active’ length of the machine can be calculated from the following equation;

$$P = kBAD^2 Ln \cos\theta$$

Where;

P	Machine output	W
k	constant	2.83
B	Flux Density	Tesla
A	Electric loading	A/m
D	Airgap diameter	m
L	Active length	m
n	Rotational speed	Hz
cosθ	Power factor	

Hence the machine will require an active length of approximately 2.3m.

Thermal Design

Having completed an electrical design, it is necessary to assess the generator cooling requirements and estimate the maximum temperature of the stator winding and the rotor magnets. The winding temperature is limited primarily by the capability of the selected electrical insulation material. The magnet temperature is limited by the demagnetization temperature of the material and the properties of the epoxy resin or other fixing medium used to hold them in place. However it is also important to consider the temperature differentials occurring in the rotor and stator structural elements and the associated thermal stresses in the mechanical structure.

Past experience with this type of machine has shown that it is difficult to get efficiency up much above 90-92%. This relatively large level of losses is primarily due to iron losses in the stator and to a lesser extent in the rotor plus some copper losses in the stator winding and a small amount of friction and windage losses. Assuming a 70:30 split between the stator and rotor and a full load efficiency of 90% then 60kW of heat has to be removed from the rotor with a further 140kW from the stator.

The problem of high losses is compounded by the low rotational speed which limits the possibility of natural cooling by transferring heat to the air in the airgap. Typically machines of this scale would employ some form of forced cooling usually with air being blown through radial or axial ducts in the lamination stack.

Mechanical Design

The torque generated by this machine could be in excess of 5MNm at each generator, if the shear stress on the main shaft is to be limited to ~50N/mm^2 then a shaft of approximately 800mm diameter will be required. A substantial rotor hub, which will be keyed to the rotor shaft, then links the shaft to the 5 rotor discs and reinforcing webs. The rotor discs would support a cylindrical yoke, this would be the final structural (non-active) element of the rotor.

The active structure would consist of a laminated ‘back-iron’ cylinder, keyed to the yoke, these laminations would have slots cut in them which would locate the permanent magnets. The permanent magnets would be bonded in place with epoxy resin and the complete structure would be bound with glass fibre tape (or similar) which would be resin impregnated to provide both structural strength and environmental protection.

The stator would be based on a modular design. The stator winding electrical design detailed above is easily achieved with a single layer design with current go and return paths in adjacent slots thus allowing fully wound stator modules of two slots or multiples of two slots to be produced. The windings would be built up of insulated conductor bundles secured into parallel sided slots in the stator stack with edge strips. The end windings would be strapped to a rigid insulating structure (typically an epoxy glass laminated material) to provide a firm support against vibration.

The stator modules would be contained within a fabricated outer casing probably of carbon steel plate, strengthened by flanges and annular stiffening rings welded to the outside of the casing. The stator modules would be attached to the casing using key bars fitted into dovetail slots cut in the lamination pack

Environmental Protection

This type of wave energy application will be extremely challenging for any Generator the environmental protection will need to be to a very high standard as this machine will be submerged most the time and will need to be submerged to 30m depth on occasion. The enclosure will need to be to IP68 at a minimum. In addition to the particulate and moisture ingress protection it will require considerable corrosion protection. The bearings will be low maintenance units with double seals. Note at this stage it is not clear whether the machines would be located within the pressure hull or appended to the ends of the pressure hull.

Power Take-off

The generator output will vary from 200 volts to 1kV with maximum power regularly coming from the lower voltage end of the range. This will be converted to a regular 690 volt, 50 Hz ac output of varying power by an IGBT converter. The output from the converter would be filtered and then fed into a unit transformer via an isolator. The unit transformer would be a standard oil insulated unit with integral LV fuses. The 33kV output from the transformer would be transferred to the collection 'string' via a standard RMU circuit breaker.

The collection 'string' cables (XLPE) would pass out of the structure to the sea bed through a J-tube hang-off. The cables would then be buried in the sea bed either by being 'ploughed in or buried in a 'jet-cut' trench between units and the offshore substation. We have assumed that the offshore substation would be located in the centre of a long array of these machines with a collection 'string' going off in each direction.

The offshore substation would be a containerised unit consisting of two incoming 33kV switchboards feeding a 33kV busbar which then feeds on to a 33kV to 132kV transformer. The 132kV transformer then connects to the transmission cable via a 132kV switchboard.

The 132kV cable would then be buried in the sea bed again ploughed or jet-cut depending on seabed conditions. The cable would ideally be landed on a sandy beach, if this is not possible the directional drilling would need to be employed to get the cables safely out past the effects of breaking waves. Once onshore a transition chamber would be required to convert from marine cables to onshore cables which would then be buried to the onshore substation building.

The onshore building would be a single story structure consisting of four internal rooms finished in the local building style. This building would house a switchboard, metering facilities and the local control room/SCADA. The grid connection to the onshore substation is assumed to be a woodpole 'trident' style single circuit overhead line.

Structural Form (Towers and Foundations)

It is worth noting in this respect that whilst the device is currently being designed for a sea with an average energy of 40kW/m instantaneous energies can easily exceed 1000kW/m. The device will be sunk under the most extreme seas however it is anticipated that under normal operating conditions there will regularly be individual waves that exceed the devices power capture capabilities ‘detuning’ the device so that these waves pass over the device safely will be key to limiting the forces on the structure.

The device would be securely attached to the seabed by a pair of towers one for each end of the cylinder. In theory it would be possible to mount the device on a pair of monopiles, however, there are very few vessels that can deploy monopiles in water depths in excess of 25m. Also there are concerns that the oscillating nature of forces may give rise to problems with monopiles in certain ground conditions. In practice a Concrete Caisson or steel Tripod type of structure may be necessary.

As the device is intended to be neutrally buoyant the forces on the foundation during normal operation are likely to be modest being primarily due to reacting against the torque generated by the Direct Drive generator. The greatest forces likely to occur either when the device is being sunk for storm conditions or when it is being raised out of the sea for maintenance.

During storm conditions the device would be sunk down to near the seabed well away from the most energetic part of the sea, see Figure 3. There may even be an opportunity to have the device continue to operate at moderate depth taking advantage of the fact that the rotation characteristic of sea waves are present, with reduce amplitude, at depths of several meters.

It was originally planned that the structure would be able to ‘yaw’ the device into the prevailing path of the most energetic waves. However, it is now felt that the additional cost of building a structure capable of transferring the loads through a yaw rind would outweigh the value of additional generation. This assumption will be checked in a wave tank and through extensive simulation in CFX.

Another area that will need to be considered in the foundation design is the electrical interconnection. As noted above the cables will be buried in the seabed they will need to enter the structure or at least enter protective ducting (J tubes) at the device foundation. There will be a requirement for a unit transformer and a variety of electrical isolators and circuit breakers which should ideally be contained in environmentally protected cabin which is easily accessible for maintenance and for component replacement. This will be achieved by extending the foundation above sea level. This would have the added value of giving a visual marker of where the device is for shipping.

Control System

The key processing that the control system needs to manage is that of taking information about the real sea-state at a given point in time and use it to allow the amplitude and frequency of cylinder orbit to be ‘tuned’ for maximum energy capture.

In normal operation of the device, this can be broken down into a few key steps: receive an electrical input signal from a wave buoy, or other wave detector, with information about wave frequency, direction, and amplitude; use these inputs to feed into an electrical ‘black box’ control system in real time; one signal will be sent to the generator via a power electronic converter, to vary the frequency of orbit of the cylinder and one output will control the phase, and hence the torque, of the electrical generator, again via the power electronic converter - this control of the generator phase will give rise to a change of angle of the hinged armature linking the cylinder and generator to the support structure, which will vary the amplitude of the cylinder's orbit. A feedback loop will allow the device to be self-monitoring.

In addition, the control system will send a signal to lower the device when severe storm force waves are detected by the wave monitoring equipment, and to raise it again when the storm has subsided. The control system will use self learning algorithms to 'learn' about the wave climate in which it is situated (by use of, for example, neural networks) so that the feedback loop can incorporate a prediction of the next wave state.

Detailed design of the control system has yet to be carried out. However, the process to be adopted is to produce a working computer model of the control system with the simplest input conditions - a perfectly sinusoidal input sea wave with the turbine un-yawed with respect to the wave crests – and then gradually increase the complexity of the model to incorporate the statistical nature of real sea states, with wave direction taken into account.

Once a working model of the control system is produced, the outputs from the 'black box' section will be used as control inputs to the CFD model of the wave device, so that the hydrodynamic performance of the device can be estimated. Adjustments to the control system could then be made if, for example, modelling suggests that the control system will create intolerable stresses on the device.

General Assembly for Manufacturing, Deployment, Maintenance and Retrieval

At such an early stage of development relatively little thought has been given to manufacturing, deployment, maintenance and retrieval. However the notes below list some of the key considerations. These will be reviewed in Phase 2 of the project as we develop the feasibility designs and start to talk to manufacturers about 'real' costs for the device.

Cylinder and Associated Tanks Seals etc

If polymer and/or steel structure is favoured then there should be a number of companies who could manufacture these components under contract, at least for the first few machines. If concrete is favoured then the shear mass of these will require them to be manufactured in a dock-yard so that they can be launched and floated out to the site.

Armatures

As the armatures and the rest of the dynamic structure is likely to be fabricated from steel (or iron), the manufacture will need to occur in a fabrication yard, possibly in several pieces for assembly on site.

Direct Drive Generator

The generator will need to be manufactured by a rotating machine manufacturer. The scale should not pose an insurmountable problem being similar in scale to a large hydro generator. Sourcing the rare earth magnet material may prove a greater challenge. Historically the main source of affordable rare-earth magnets has been China, however, there have also been quality control problems with these materials. This will be a key area in the quality control process. The machine must also survive in hostile conditions so environmental protection is going to be vital to reliability.

Foundation and Towers

It is envisaged that the foundation will be based on designs used for offshore platforms or possibly designs being developed for offshore wind turbines in deep water. The optimum foundation will depend very much on seabed conditions at the preferred site. The manufacture would be carried out by a marine fabrication yard.

Installation

As the design progresses we will always keep an eye on the practicalities of how the device will be installed and more importantly maintained and repaired.

As far as possible all moving parts will be designed such that they can be raised well out of the sea for maintenance, by filling the void (ballast tanks) between the two hulls with air and using the resultant buoyancy of the cylinder to lift the generator and bearings clear of the sea. The components most likely to fail are the generator, bearings, armatures, transformers and cylinder, all of these will be designed so that they can easily be replaced and the faulty component taken back to land for repair or scraping.

It is currently envisaged that the foundation would extend up out of the sea and would have a small enclosure to protect the transformer and switchgear and which would also provide protection for any maintenance teams working on the device.

Maintenance

The methods of arranging maintenance and inspection of the wave devices will have a critical impact on the availability and hence performance of the project. As a starting point we are proposing that regular inspections should be performed at 3 monthly intervals. There would be more detailed examinations annually where routine maintenance such as hydraulic oil changes would be performed. At longer time scales, perhaps 5 years, the device rotors would be taken in to a dry dock to facilitate a detailed inspection, corrosion protection and overhaul of the generator and power converter. There are a number of methods for transporting personnel and equipment out to the units; helicopters might be appropriate for personnel and light loads, small support vessels would give greater flexibility but have more travelling time and are more constrained by weather conditions.

It is envisaged that each device would have a mini-substation mounted in the ‘tower’, there would be a small control room. Any maintenance related to the mini-substation, grid connection or many nuisance trips could be fixed from the control room. The generator and power converter, however, will be located in the pressure hull of the cylinder. Access to the pressure hull will require the device to be ‘floated’ and accessed either by some form of flexible ramp from the control cabin.

The periodic ‘towing-in’, inspection and overhaul of the cylinder would be performed by a substantial support vessel/tug and probably a secondary small support vessel. The rotor would first be ‘decouple’ and allowed to rotate freely in light sea condition. Then the two main pins connecting the rotor armatures to the support structure would be removed and the rotor would be towed away. Replacing the rotor would follow the reverse procedure, the rotor would be towed out to a point adjacent to the support structure, the armatures would then be guided in to place by some form of temporary 'jig', before replacing the pins, removing the jig, removing the tow-lines and re-coupling the rotor.

All of the critical components would be constantly monitored by multi-layer online condition monitoring, which would aim to identify maintenance issues before they become 'catastrophic' failures.

Even with regular maintenance and the foresight of on-line condition monitoring there will still be break downs. This device has been designed so that relatively large modules can be replaced quickly. For example at least one complete rotor with generator and power converter will be kept on standby to replace a broken down unit. Likewise at least 1 containerised substation and control room will be kept in standby should they need to be replaced.

Maintenance Effort Required

- 3 month inspection - As a starting point it is assumed that maintenance teams will be made up of 3 persons at least one of whom should be a qualified engineer to act as 'Senior Authorised Person'. It has been assumed that one team would be able to inspect 2 machines per day. These inspections will check on the general behaviour and condition of the machines, in particular looking for signs of moisture ingress, oil leaks, vibrations etc. These inspections will not normally involve any dismantling or running tests on any emergency procedures. Should any problems requiring immediate remedial action these will be scheduled as soon as possible. For the purpose of building up a first order estimate of maintenance costs it has been assumed that 10% of 3 month inspections will identify problems and that the average effort required of a maintenance visit will be 4 men for 2 days including one senior authorised person.
- Annual Inspections – these will be more thorough than the 3 monthly inspections and will involve the removal of covers to do thorough visual inspections. Hydraulic oils will be changed as will all air breathers and filters. The condition of the transformer, switchgear and umbilical will be examined and the switchgear tested. The rotor will be run through a storm avoidance 'sinking' procedure. The ballast tanks will then be pumped out and the device decoupled to allow access to the rotor. Thorough visual inspections will be made of the generator and power converter and any limited lifetime components, such as electrolytic capacitor banks will be changed out. It has been estimated that these inspections will take a team of 4 persons 3 days per machine.
- 5 year dry dock inspections – The rotor being inspected would be collected and towed-in, it is assumed that the following day a replacement rotor would be towed out and installed. It is assumed that the dry dock works would include inspection replacement of corrosion protection, removal of bio-fowling, overhaul and if appropriate replacement of generator and converter, NDT testing and if appropriate replacement of armature, testing and if appropriate replacement of bearings, overhaul of trimming tanks and pumps, overhaul of ancillary services.

Breakdown Maintenance

There are two major classes of breakdown, those where only personnel and light tools are required and those that require substantial support vessels. The first class would be for nuisance trips and C&I failures and could easily be serviced by flying men out or shipping them out in a small versatile vessel such as a Wheel Housed RIB (used to access some oil and gas fields) or a more specialist craft such the support catamarans being used for some offshore wind farms. The second class would be for a major component failure or a structural failure.

Typical access costs

- Helicopter costs £1,000/hour (assume 4 flying hours per trips)
- Small support vessel (these would probably be owned by the maintenance company and will cost anything from £50,000 for a RIB to £250,000 for more specialist vessel. In addition to the boat we have assumed a crew of 2 and further operating costs of approximately £30,000 per annum. As a starting point we have assumed £3,000/day.
- Large support vessel costs depend to a large extent on market conditions, particularly in the oil industry. It is understood that prices for a substantial support vessel can vary from £10,000/day to £30,000/day and there may be availability issues and costs associated with moving vessels to the area. As a starting point we have assumed £20,000/day including crew.

Performance

Energy Capture

A key attraction of the Green Cat Wave Turbine is that, in the presence of a small amplitude monochromatic wave with a wavelength to which the device is 'tuned' (i.e., its diameter corresponds with the wavelength, and its amplitude and frequency of rotation correspond to those of the wave, respectively), the energy capture from hydrodynamic theory is 100%. Assuming the device to be sized appropriately to the average wave climate of the North Atlantic and rotated at appropriate frequencies, its capture efficiency bandwidth can be expected to be high.

With 'tuning' being paramount, it is expected that an array of buoys will be situated around the device (or farm of devices). Each will sense the wave climate (wave amplitude, frequency and direction at the single point measured) and it is expected that a signal processing technique using a self learning algorithm will be used to combine all inputs, giving a picture of the wave climate upstream of the device(s).

With the wave climate estimated, active control of the generator torque will be used to change the angle of a hinged arm joining the device axis to its axis of rotation. This will result in control of the device's orbital radius, 'tuning' it to the incident wave height.

It is expected that when heavy seas are sensed, vector control will initially limit energy capture by ‘de-tuning’ the device. This is analogous to active pitch control of a wind turbine. When seas reach storm levels, the device will be lowered towards the sea bed.

The device will be positioned a little below the sea’s free surface for two reasons. It needs to be near the surface to capture the most energy, as wave particle orbits are greatest there, decreasing exponentially with depth. However, it is expected that a fully submerged device will experience fewer fatigue problems or efficiency losses due to waves breaking on it, and corrosion due to air and salt water will be reduced. Thus, for a small overall decrease in energy capture, the device’s longevity will be much increased.

Energy Capture Losses

As the device uses the minimum number of steps to convert sea wave motions into electricity, a high level of overall energy capture can be expected. However, there are a number of energy loss mechanisms which will affect the hydraulic performance of the device:

- Uncertainties in wave measurements – The wave buoys used to monitor the sea state surrounding the device (or farm of devices) will measure the properties of each wave at one instant in time and at one geographical position. In real seas, waves do not progress uniformly in one direction or maintain their height and frequency uniformly. Thus, there will always be a level of uncertainty in the sea climate interacting with the device, which will prevent it being perfectly tuned to each wave state it encounters.
- Real sea states – Even if the wave climate is perfectly known, it typically consists of multiple wave frequencies and amplitudes, with some waves travelling in slightly different directions. The device will be tuned to the underlying wave frequency for a particular wave state and will loose energy in the other components comprising the wave front – this is an unavoidable energy loss mechanism. The key to minimising this is to size the rotor correctly for the local wave climate.
- Cylinder size – The cylinder size has to be optimised for the wave climate. Previous work has suggested that a 16m diameter cylinder would be the best for a North West Atlantic climate. This will be tested by CFD modelling, as well as looking at other rotor shapes, such as cylindrical ovals.
- Directional losses – these result from reduced energy capture efficiencies when waves arrive at an angle to the device.

In addition, the energy delivered to shore by the device is limited by losses comprising:

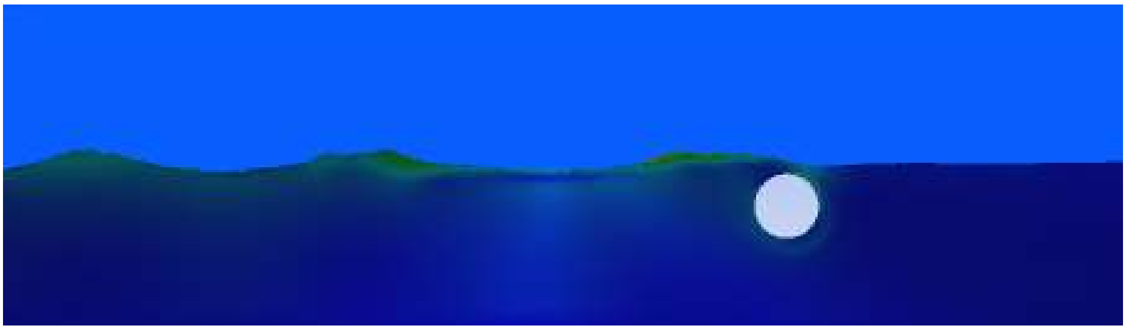
- Generator and transmission losses and lack of availability – all of which are dealt with elsewhere in this report.

CFX Modelling

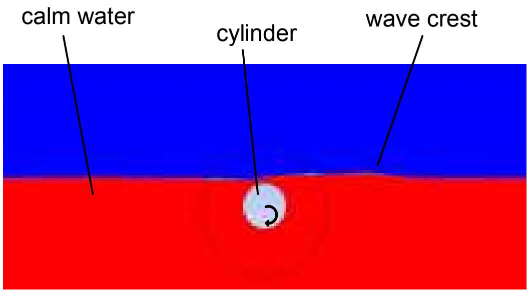
The CFX modeling has a number of objectives, all of which are geared towards establishing an estimate of the energy yield of the device, static and dynamic forces acting on it, and the effect of the device on the sea around it. These goals are to be achieved for both idealized and ‘realistic’ conditions, stationary and dynamic situations, and for real control system inputs.

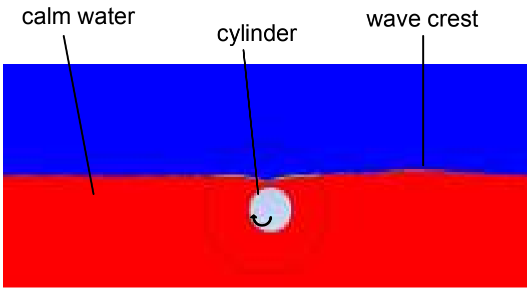
Producing a 2-D model of a sinusoidal wave interacting with the cylindrical rotor of the Green Cat Wave Turbine requires several complex elements of the software’s capability to be utilised. Firstly, the mesh of points at which the computations take place has to incorporate a stationary and a rotating part. Secondly, it must be able to cope with regions of water and air in both these parts. And thirdly, it must be able to cope with rotational motion in an irrotational fluid in which there is no net ‘flow’ in any direction. As a result, developing a model of even the most straightforward cases is challenging.

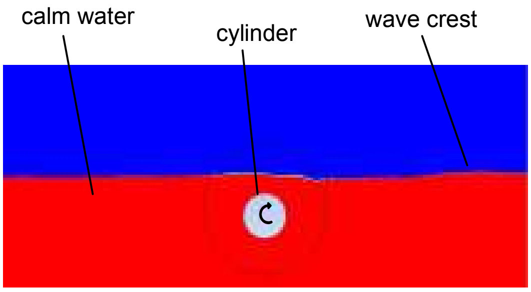
CFD modeling of the device can be used to verify the predictions of academic studies which suggest that the cylinder of the Green Cat Wave Turbine should be a perfect wave absorber. Of course, this is true to the first order, but CFX also reveals higher order interactions between the cylinder and the incoming waves which have been suggested by more recent researchers:

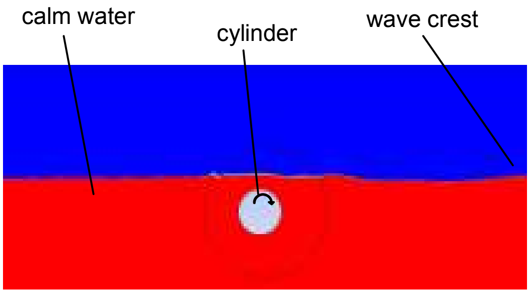


As can be seen from the sequence of results presented in the figures below, our model can simulate a rotor ‘absorbing’ an incoming wave thereby capturing the energy in the wave.









More refinement of this model will be required before more complex scenarios are attempted.

The next challenge is to develop our understanding of the interaction between sea waves and the device and produce a range of power performance curves.

Generator and Power Converter

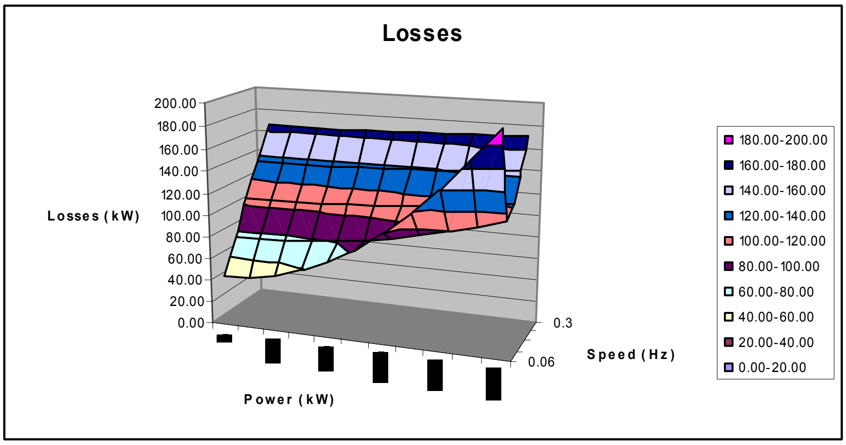
There are three main categories of losses in the generator namely those associated with the friction and windage, those associated with field flux and those associated with the stator currents or load.

Friction and Windage - The friction losses in a machine like this are expected to be pretty modest (<1%) and windage is expected to be negligible.

Field Losses - The losses due to the field flux will be present regardless of what power is being generated, they are however approximately linearly related to the speed of rotation. Based on the performance of similar designs of machine developed for wind turbine applications it can be assumed that the Open Circuit Iron Losses could be as high as 5% of rated power at maximum speed falling linearly with speed.

Load Losses – The current losses are primarily due to ohmic losses in the stator windings. These are related to the square of current but are also non-linearly related to speed. Furthermore, current is linearly related to power and power has a tendency to be greatest at lowest speed, which is almost the inverse situation to the Field losses. In this particular type of machine load currents have relatively little impact on losses due to the field currents.

The total simulated loss plotted against power and speed is shown in the graph below.



Predicted Losses for 2MW direct Drive Generator

These are the losses from the generator alone. When the power converter is attached to the generator it will be controlled to try and boost voltage at low speed (by injecting reactive power) and hence reduce current. This will tend to reduce the low speed high power peak. The inverter will however add a switching loss to the overall power loss of approximately 2.5% of total power.

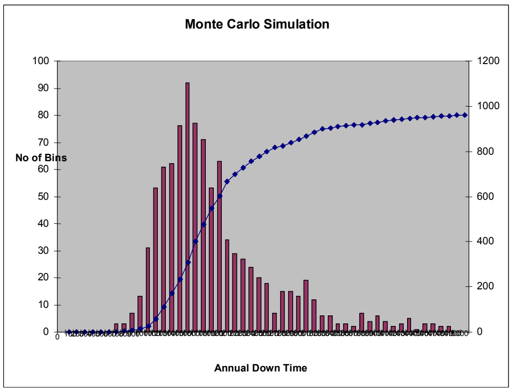
Electrical System

In theory the power system has two main components of loss, the first relates to the energy required to keep the cables energized, the second relates to the copper losses. In practice the losses are dominated by the copper losses and the system is usually designed to ensure that these do not exceed 5% of total power at full load and depending on the lifetime value of electricity lost compared to increased capital cost, this can be tightened to as low as 3%.

Availability

In any power generation plant, a failure or malfunction of any component part leads to a cost penalty due to the cost of the repair and the loss of revenue resulting from the lost generation. This second aspect is particularly important for wave generators as access can be limited due to the remote location and weather limitations coupled to potentially extended repair times due to the extreme conditions.

As a starting point, to estimate the device's availability we have broken the device into its major sub-systems, 18 in total, and further classified these in terms of the class of failure/likely nature of repair. These 18 sub-systems have then been assigned normalised estimates of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR). These individual profiles were then combined using a Monte Carlo simulation to give an overall estimate of availability. Clearly at this early stage of the development there is uncertainty surrounding the MTBF and MTTR profiles and this model will continually be updated as our understanding of the device improves. As a starting point where data has been available from similar systems, such as offshore wind farms, this has been used in preference to data taken from previous 'theoretical' studies and finally where no previous data exists engineering judgement has been used to produce first order estimates.



The figure to the left shows a typical output from the model indicating the average down time to be ~1,700 hours or ~81% availability. The 90% confidence levels suggest that the annual availability could be as high as 90% or as low as 62%. This is clearly too low for a commercial machine but probably not unrealistic for an early device.

Further the analysis has identified the rotor structure, the coupling structure, the main bearing, the condition monitoring system and the power conversion units as the areas of initial concern.

Forward Work Priorities

This document captures the main concepts behind the Green Cat Wave Turbine. However, this device is still at an early stage of development and there will inevitably by significant changes as our understanding of the issues develops and the device is optimised. The conceptual designs for the main elements will need to be developed to a stage where they can be costed and the overall device economics assessed. The key priority areas for consideration are as follows;

1. Performance modeling – we now have operating CFD models of this device which we will use to check the hydro-dynamic design assumptions and optimize the device. We will validate these computer models against miniature models in the Glasgow University wave tank. Once we have validated the model we will produce a series of performance curves that can be used to estimate generation from any site.
2. Develop control system – we will develop our control system model to an extent where we can define what input data we require and optimise the level of tuning that the system applies so that we can estimate control losses as well as feed into the fatigue/reliability analysis.

3. Structural design – at this stage the structural design has been based on an elementary assessment using ‘extreme’ static loads, no attempt has been made to assess dynamic loads or fatigue.
4. Cost estimates – the device will be broken down into components at the level that they would be procured and prices sought from potential suppliers. However, we may seek prices for some selected sub-components as a cross check on priced quoted by potential suppliers.
5. Supply chain development – in parallel with seeking quotes we would build up a picture of how the elements of this device are to be procured and what the key drivers are for those suppliers. We will also consider manufacturing/assembly options and locations.
6. Identify potential project sites – whilst this device has been developed with a view to being deployed in the most energetic seas to the north west of Scotland, the prototype machines and first generation may actually be better to be deployed in a more accessible location.
7. Forward programme of work – we will continue to review and update our route map to market.