ECONOMIC VIABILITY OF A SIMPLE TIDAL STREAM ENERGY CAPTURE DEVICE

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Participants:
LOG+1 Limited
ALSTOM Power Limited
WUMTIA

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1. ABSTRACT

This tidal stream energy project has compared the overall economics of two horizontal axis tidal turbine devices: a fixed pitch, bi-directional, variable speed turbine generator device with a variable pitch, variable speed turbine generator device that rotates to face into the tidal flow.

The project has established, theoretically, the extent to which the loss in energy conversion efficiency of the simpler to construct fixed pitch device is counterbalanced by a reduction in capital and O&M costs and whether the system is technically feasible and sufficiently economic to warrant further development.

The conclusion is that the simple fixed pitch, bi-directional device is competitive on a life cycle cost basis and worthy of further consideration.

2. EXECUTIVE SUMMARY

2.1 Objectives

The project compares a generic axial, fixed pitch, bi-directional, variable speed turbine generator device with a generic axial, variable pitch turbine generator device that rotates to face into the tidal flow. The principal objective is to identify the circumstances and extent to which the simple bi-directional device may be competitive with the variable pitch device on a lifetime cost basis.

2.2 Introduction

This collaborative project involves the Wolfson Unit for Marine Technology and Industrial Aerodynamics (WUMTIA) of the University of Southampton, ALSTOM Power Ltd - Technology Centre and LOG+1. While not party to the grant arrangements with the DTI, E.ON UK Power Technology Ltd. on behalf of E.ON UK Renewables Developments Ltd., has provided a utility perspective and Converteam Ltd has provided information on generators and power conversion aspects.

The agreed project scope was limited to horizontal axis tidal turbines (HATT), and did not include consideration of alternative approaches such as vertical axis turbines or oscillating hydrofoil systems.

In order to control the performance of a turbine in variable flow conditions such as are typical of a tidal stream, it is necessary to alter the angle of attack of the blades relative to the flow. This can be achieved using a variable-pitch system, with attendant problems of sealing, mechanical complexity, increased cost and reduced reliability, or by using a simple rotor with fixed pitch blades, the rotational speed of which is altered to achieve a specific relationship between current speed and rotor rotational speed.

The hydrodynamic performance of a sub-sea device will only be one parameter in the lifetime cost of each system. The marine environment is particularly aggressive towards equipment operating within it for extended periods with limited access or opportunity for routine inspection and maintenance.

The Operation and Maintenance (O&M) element of the lifetime cost of a tidal stream concept may well be greater than the significant contribution of O&M costs to the cost per kWh anticipated for offshore wind energy, and be a major determinant in the commercial viability of tidal stream energy. A commercially successful HATT system will need a very high level of reliability and accessibility, with the longest periods between routine maintenance inspections consistent with optimum whole-life economics. The premise is that the lowest capital and operating costs are more likely to be achieved if the marine components are kept simple.

The project has attempted to identify and quantify the trade-offs between reliability, efficiency and cost of generic HATTs. The overall economic performance will depend to a varying extent on all aspects of the installation, operation, maintenance and decommissioning approaches adopted.

While revenue assumptions have been made to derive comparative financial returns from the two approaches, the most important output from the project is likely to be the estimated cost of electricity delivered to the grid over each system lifetime, assumed to be 25 years. This will help to establish whether the fixed pitch, bi-directional, variable speed device warrants further development.

2.3 Work Carried Out

The individual contributions to the project are summarised as follows:

- WUMTIA - hydrodynamic design and energy capture of fixed and variable pitch blades for HATT
- ALSTOM Power Ltd - mechanical and electrical concept solutions and lifetime cost estimates
- LOG+1 - lead partner, project management. O&M and electricity market input.

While not party to the grant arrangements with the DTI, E.ON UK Power Technology Ltd. on behalf of E.ON UK Renewables Developments Ltd., has provided a utility, end-user perspective and a peer review capability. ALSTOM has also enlisted Converteam Ltd in considering the generator and power conversion options appropriate to the two devices.
Converteam Ltd. was formerly ALSTOM Power Conversion Ltd., part of the ALSTOM group, but has been sold and is now a completely separate and independent commercial entity.

The project was divided into three work packages, which are closely linked to the partner's responsibilities. While the work packages were reported to AEA Technology chronologically there was a significant amount of iteration between the partners as the project advanced; this applied particularly to the performance of the optimised blades and the development of the cost model and financial analysis of the fixed pitch and variable pitch devices.

WUMTIA's theoretical comparison of the performance of the fixed pitch and variable pitch devices required an understanding of the hydrodynamic behaviour of horizontal axis tidal turbines through use of basic theory, blade element momentum (BEM) analysis and finally a lifting surface panel (LSP) code.

ALSTOM's cost analysis involved estimates of the following for the two devices: capital cost, energy yield (dependent on device performance and availability), operating cost (dependent on device reliability, preventive maintenance activity etc.), other farm costs (permits, leases, general overhead etc.). From this, ALSTOM derived the financial reports for farms of each device (profit, cash flow etc.), compared the financial performance of farms operating the two devices and assessed the sensitivity of the results to changes in the variables/assumptions.

Results from Monte Carlo simulations of device availability, together with cost estimates for capital and maintenance costs, were fed into the cost comparison spreadsheet to provide a comparative cost and revenue performance for each machine in the context of a farm of 30 devices, each rated at 1MW, having a 20m diameter rotor, and operating in a tidal stream with a maximum flow speed of 2.5 m/s. Costs common to the two device types were included at this stage. For cost modelling purposes two turbines were assumed to be attached to a common mounting. This arrangement was chosen to reflect the fact that many proposed devices feature one or more pairs of contra rotating turbines to minimise the net torque transmitted to the mounting structure.

Fault Tree Analysis (FTA) was chosen in preference to Failure Mode and Effect Analysis (FMEA) for the reliability elements of this study because it was considered easier to construct a generic analysis. Use of the FTA technique allows a generic failure to be described without detailed consideration of the precise nature of the failure.

FTA is a ‘top-down’ technique in which a specific top-level fault is identified (in this case, lack of electrical output to the grid when such output would be expected), and all combinations of lower-level fault causing the top-level fault are identified. In contrast, FMEA is a ‘bottom-up’ approach in which all possible faults of all components are identified, and the implications of each fault are assessed, for example providing the answer to the question “What is the effect of a mechanical failure of a main gearbox third-stage planet gear axle?”, FMEA and FTA may in most cases be regarded as providing equivalent information, but meaningful FMEA requires the existence of a fairly detailed design definition of the system; implying loss of generality for the study.

In order to assess overall failure probabilities for the study devices a generic fault tree was created, and the individual fault conditions featured in the tree were ascribed probabilities of occurrence, derived from published data for comparable equipment in a North Sea Oil production context. The generic fault tree could be reconfigured to represent fixed pitch or variable pitch devices and the overall failure probability was then recalculated automatically.

2.4 Main Results

The principal objective of this study has been to identify any circumstances under which “simple but less efficient” devices offer competitive life cycle performance to “complex but more efficient” ones.

Comparison of the variable and fixed pitch design indicates that the energy yield from the fixed pitch design is likely to be up to 10% less than that for the variable pitch design. With a generator of a given capacity, this difference could be accommodated by an increase of about 1.0 m in rotor diameter over the 20m-baseline diameter.

The comparative system cost analysis has demonstrated that the relative merit of the two approaches depends upon the assessment criteria adopted and may be summarised as follows:

- The variable pitch, variable rotational speed machine (with an energy capture performance notionally 10% better than that of the fixed pitch machine) produces more energy in a given period than the fixed pitch, variable rotational speed machine, unless the absolute reliability of both machines is very low,
- The fixed pitch machine always offers lower initial capital cost and unplanned maintenance cost than the variable pitch machine,
- The fixed pitch machine offers lower cost per unit of electricity generated unless the absolute reliability of both machines is very high,
- The percentage increase in energy capture using the variable pitch machine is generally much less than the notional 10% difference given perfectly reliable machines; relative performances encountered during the study implied that the variable pitch machine would generally produce 4 – 7% more energy than the fixed pitch machine, although its worst performance produced 1% less energy.

The discrepancy between the notional and calculated performances arises because the availability of the variable-pitch machine is lower than the availability of the fixed-pitch machine, so some or all of the variable-pitch machine's theoretical energy capture advantage is lost. The availability depends upon reliability and accessibility, but the relative importance of accessibility itself depends on overall reliability. In general the higher the overall reliability of both devices the greater the relative energy capture of the variable pitch machine. The 7% improvement quoted was associated with the highest reliability assumed in the study, and the 1% worse performance reflected the lowest reliability used. For reliability modelling purposes the variable pitch machine is treated as a variant of the fixed pitch machine. Although uncertainties exist in the absolute reliability values, it is considered that the relative reliabilities of fixed pitch and variable pitch machines have been well represented for study.

The baseline case consisted of a farm of 30 off 1 MW turbine units configured with an active DC link and two network bridges, each serving 15 of the turbines. The variable pitch option also allowed turbine axis rotation in yaw, so as to always face into the tidal stream. The baseline case, using the calculated hydrodynamic capacity factor of 22.8% for the fixed and 24.5% for the variable concept and mean failure rates, shows an overall energy production of 53 and 55 GWh per year respectively. Using these energy production figures the cost of electricity is £119 /MWh for the fixed pitch concept, compared to £129 /MWh for the variable pitch concept over a 10 year operating period, and £94 /MWh and £104 /MWh respectively for a 15 year period.

The results shown in the study are based on 110% of rated power being achieved at peak spring current velocity. This is based on the assumption that (consistent with diesel generator set practice) the generator may be operated at such a power output without damage, providing the operation at over 100% rating is of limited duration, and at sufficiently infrequent intervals that the design winding temperatures are not exceeded. The economically optimum design of tidal stream turbine system will probably not require peak spring tide current speeds to generate its rated power, but the definition of the true ‘economic optimum’ device may well depend upon the precise stream parameters at its intended operational location. Therefore the rated speed has been taken to be the peak spring current speed for the purposes of this study.

It is recognised that the hydrodynamic capacity factors could be increased by using a generator rated at below the maximum power available in the stream, and this could lead to a lower cost of electricity. This aspect has not been considered in this study.

2.5 Conclusions

This tidal stream energy project has compared an axial, fixed pitch, bi-directional, variable speed turbine generator device with an axial, variable pitch, turbine generator device that rotates to face into the tidal flow. The project has established, theoretically, the extent to which the loss in energy conversion efficiency of the simpler to construct fixed pitch device is counterbalanced by a reduction in capital and O&M costs and whether the system is technically feasible and sufficiently economic to warrant further development.

The project compared the best theoretical hydrodynamic solution to the capture of energy from a tidal stream with a simple alternative solution that would cost less to manufacture and should be expected to be more reliable during its operational life. The conclusion was that the simple fixed pitch device was competitive on a life cycle cost basis and worthy of further consideration.

A number of tidal stream concepts under development address the problem of reverse tidal flow by including a mechanism to change the blade pitch by 180 deg or more. While this will do away with the cost and reliability implications of a rotator mechanism, it requires a compromise on the blade section that will result in a reduction in the energy yield compared with the best hydrodynamic solution. This would seem to reinforce the case for further consideration of the fixed pitch, bi-directional, variable speed turbine generator device.

Tidal stream devices are likely to be located well away from centres of population and the established transmission and distribution network. The availability of grid connections at a date and cost that does not prevent commercial deployment of tidal stream and other renewable energy devices has to be urgently addressed by the DTI and Ofgem.

Tidal power is arguably one of the more expensive in capacity terms of the available technologies, certainly at this stage of its development. While commercial deployment of devices will help to drive down the capital and operating costs, tidal power will need additional support while the successful concepts become competitive renewable energy options. The Government is proposing differentiated support levels to different renewable technologies; such support will be necessary to enable marine renewable technologies achieve their potential.

2.6 Recommendations

The following activities offer logical steps to the implementation of a commercially successful tidal turbine device:

- Further refinement of the economic analysis methods used to determine parameters for an optimised device,
- Develop design specifications for a tidal stream turbine system and apply suitable processes to optimise the design point for a given set of tidal conditions,
- Undertake further reliability modelling to determine plant redundancy requirements,
- Undertake model testing of two dimensional bi-directional sections and then three dimensional rotors, both for cavitation performance and overall performance to confirm that predicted in the study,
- Install a reduced scale version of the device (around 20 – 30% full scale) in a marine environment, probably with a dump load rather than a grid connection. Test results will be used to finalise the design of the prototype unit,
- Install a full-scale prototype at a suitable location with grid connection. This would not be commercially optimised, but would demonstrate all the major systems,
- Install a multi-unit tidal stream turbine farm using the commercial design incorporating developments from the testing of the prototype unit.

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4. GLOSSARY

Abbreviation	Term	Description
BEM	Blade Element Momentum	Hydrodynamic analysis code which matches knowledge of the change in a fluid's axial and swirl momentum with the lift and drag performance of a blade section.
DNV	Det Norske Veritas	A Norwegian based Classification Society.
DSV	Dive Support Vessel	Class of ship associated with offshore operations typically featuring a Dynamic Positioning system, diver support facilities and 150 tonne crane.
FTA	Fault Tree Analysis	A "top-down" technique in which specific top-level faults are specified and all lower level faults causing it are identified.
FMEA	Failure Mode & Effects Analysis	A " bottom-up" technique in which all component faults are identified and the implications of each fault is assessed.
HATT	Horizontal Axial Tidal Turbine	A tidal stream turbine with a horizontal rotor shaft.
LRU	Line Replaceable Unit	An individual tidal stream turbine that can be replaced in the event of failure or at the end of its design life.
LSP	Lifting Surface Panel	Hydrodynamic analysis code based on quadrilateral boundary elements that solves Laplace's equation for potential flow.
OHL	Overhead Line	As opposed to buried or submerged cable.
O&M	Operation and Maintenance	Control of the day to day operation of the tidal stream farm and the maintenance/replacement of all equipment during the life of the project.
OEM	Original Equipment Manufacturer	Manufacturers of the equipment used in a tidal stream farm.
OREDA	Offshore Reliability Database	A database developed by a number of leading oil companies.
RIB	Rigid Inflatable Boat	Boat with rigid hull and large inflatable tubes down each side.
SCADA	Supervisory Control and Data Acquisition	Controls and monitors all the equipment in the tidal stream farm.
TSR	Tip Speed Ratio	Ratio of the rotational speed at the blade tip to the onset (undisturbed) speed of the tidal current.

Term	Description
Azimuthing	The ability of a HATT to turn so that its axis is aligned with the flow of the tidal stream.
Cavitation	The formation of vapour cavities when the local static pressure (due to high local flow speeds) reduces to that of the fluid's vapour pressure.
Hydrodynamic Efficiency	A measure of the efficiency of the rotor in capturing energy from the tidal stream. It is calculated as the (total energy produced by the rotor over a full tidal cycle) divided by (energy produced by the rotor operating at its rated power over the same time). It therefore does not take account of mechanical or electrical losses in the system, or reliability and availability factors.
Monte Carlo	A system used to predict reliability and availability levels based on the laws of probability.
Tidal Ellipse	Refers to a polar plot of the variation in tidal stream strength and direction over a tidal cycle.

5. PROJECT BACKGROUND

5.1 Introduction

A variety of approaches is being taken to the harnessing of tidal stream energy to produce electrical energy for supply to the grid. The hydrodynamic performance of the sub-sea device will only be one parameter in the lifetime cost of each system. The marine environment is particularly aggressive towards equipment operating within it for extended periods, with limited access or opportunity for routine inspection and maintenance. The O&M element of the lifetime cost of a tidal stream concept may well be greater than the already significant contribution of O&M costs to the cost per MWh anticipated for offshore wind energy and be a major determinant in the longer term whole life commercial viability of tidal stream energy. To develop a commercially successful system it will be essential for the marine components to have the highest possible reliability and accessibility, commensurate with the trade off in reduced efficiency due to longer periods between routine maintenance inspections.

The agreed project scope was limited to horizontal axis tidal turbines (HATT), and did not include consideration of alternative approaches such as vertical axis turbines or oscillating hydrofoil systems. The project compares a generic axial, fixed pitch, bi-directional, variable speed turbine generator system with a generic axial, variable pitch turbine generator system that rotates to face into the tidal flow. The comparison establishes the theoretical extent to which the loss in energy conversion efficiency of the fixed pitch device is counterbalanced by the estimated reduction in capital, operational and maintenance costs.

This is a collaborative project involving the Wolfson Unit for Marine Technology and Industrial Aerodynamics (WUMTIA) of the University of Southampton, ALSTOM Power Ltd - Technology Centre and LOG+1, whose individual contributions to the project are summarised as follows:

- WUMTIA - hydrodynamic design and energy capture of fixed and variable pitch blades for HATT
- ALSTOM Power Ltd - mechanical and electrical concept solutions and lifetime cost estimates
- LOG+1 - lead partner, project management. O&M and electricity market input.

While not party to the grant arrangements with the DTI, E.ON UK Power Technology Ltd. on behalf of E.ON UK Renewables Developments Ltd., has provided a utility perspective and Converteam Ltd has provided information on generators and power conversion aspects.

5.2 Project Objectives

Existing and proposed HATT designs employ either fixed-pitch or variable-pitch blades, with each developer tending to adopt one of these approaches to the exclusion of the other. The principal objective of this study is to identify the circumstances in which one or other of these approaches is superior, on a whole life basis. This will in turn require the project to identify and quantify the trade-offs between reliability, efficiency and cost of generic HATTs through the application of a system approach. The overall economic performance will depend to a varying extent on all aspects of the installation, operation, maintenance and decommissioning approaches adopted.

While revenue assumptions have been made to derive comparative financial returns from the two approaches, the most important output from the project is likely to be the estimated cost of electricity delivered to the grid over each system lifetime, assumed to be 20 years.

5.3 Project Process

The project was divided into three work packages:

- **Work package 1:** The primary objective of this work package was for WUMTIA to conduct a theoretical comparison of the performance of the fixed pitch and variable pitch devices to establish whether they were sufficiently close to warrant the continuation of the project. Other objectives for this work package included the development by ALSTOM of the initial specification and generator power conversion concept and data gathering by LOG+1 on other tidal stream turbine concepts.
- **Work package 2:** The main focus of this work package was on the production by ALSTOM of the concept design for the generator and power conversion system, together with the development of the overall cost model, for which LOG+1 would work up the O&M component. In parallel with this, WUMTIA would finalise the design of the turbine blades for the fixed pitch and variable pitch devices.
- **Work package 3:** The final work package included finalising the hydrodynamic analysis, system validation and sensitivity analysis and completion of the life cycle cost analysis and the final report.

5.4 Wind Turbine Analogy

When considering the Initial Project Specification, and the general concept of a tidal current turbine, it is tempting to use modern wind turbines as models for assumptions; some modern medium-sized wind turbines are operating routinely at similar power and/or torque levels to the generic tidal device, so it might be expected that certain major components or subsystems (e.g. gearbox) could be translated into tidal current service with little or no modification.

This approach is of limited use; the conditions experienced by a tidal turbine are not simply direct analogues of those experienced by a wind turbine, scaled by some function of relative density and current speed. For example, tidal current velocities are predictable over very long timescales and are not subject to random excursions over these values, whereas wind velocity is an expression of a series of stochastic processes, including random gusts. The tidal turbine arguably therefore needs lower structural margins on rotor blades. Conversely, the tidal-turbine working environment is corrosive, with suspended solids leading to at least the possibility of erosive damage over the lifetime of the device. Another important consideration for tidal turbines is the presence of marine life.

A comparison of some of the factors affecting wind and tidal stream turbines is given in Table 5.1 below:

Feature	**Effect / Implications of Feature on**	
	Offshore Wind Turbine	**Tidal Current Turbine**
Fluid density	~1.25 kg/m^3	~1025 kg/m^3
Max velocity during normal operation	~25m/s	2-5m/s
Velocity for rated output	~12m/s	2-5m/s
Max velocity during life	50m/s +	As for normal operation
Variation of velocity with time	Stochastic, variable in magnitude and direction over timescales of the order of seconds to years.	Variation in magnitude & direction predictable for given location over periods of years.
Rotor diameter (typical)	90-120m	15-30m based on current designs
Limitations on rotor diameter	Mechanical integrity, primarily fatigue life due to self weight stresses	Mechanical integrity, cavitation at tip, water depth. Speed reduced as diameter increased. Limitation is on blade stress, primarily due to thrust forces being much greater resulting from higher density of fluid
Variation of flow pattern	Complex (turbulence)	Complex (turbulence + waves if top of rotor near surface)
Corrosion	Salt spray conditions	Immersion in salt water will require careful consideration of material combinations
Erosion	Unlikely to be a serious problem	Potential for serious problem; may exacerbate corrosion
Maintenance access	Weather dependent	Depends on deployment method but probably more difficult than offshore wind
Marine growth	Not an issue	Could be important for performance and maintenance
Rotor rotational speed	<15 rpm for large machines	7-20 rpm based on current designs

Table 5.1 Comparison of some of the factors affecting wind and tidal stream turbines

5.5 Environmental and Other Impacts

Unlike a wind turbine, the tidal stream turbine, being submerged, will have neither a direct visual effect nor a noise effect on human beings in normal conditions. There are, however, a number of areas in which submerged devices could have potentially significant environmental impacts or raise safety considerations for other maritime users and activities. Such areas include: ecology, pollution, coastal processes and interference with the tidal flow, noise and navigation safety considerations. Such issues will need to be taken into account in selecting a location for an individual tidal stream turbine or an array of turbines, and are likely to have cost and time implications. There is not likely however, to be a significant difference between the environmental impacts of the two devices compared in this study; environmental impacts are not considered further in this report.

5.6 UK tidal energy resources

As stated in Path to Power, the June 2006 BWEA report on wave and tidal power, "The UK possesses some 35% of Europe's wave resource and 50% of its tidal resource. BWEA, using data from the Carbon Trust's Marine Energy Challenge (MEC), estimates that 3GW of wave and tidal capacity could be installed in the UK by 2020. .... In the long term, 3% to 5% of current UK electricity demand could be met by tidal stream energy."

While there is clearly a substantial UK resource of tidal stream energy, by its nature it tends to be located close to headlands in the west and north of the UK, which in turn are less accessible from the existing grid infrastructure. Each location clearly also has its own characteristics, with some such as Portland Bill being very asymmetric in current speed and direction. The tidal ellipse for a specific location is likely to be a major determinant of the technology to be applied, with the facility for the devices to be rotated to meet the flow direction being much more important in some locations than others.

5.7 Assumed tidal stream conditions

A tidal stream features a continuously changing current velocity, with a pattern of change being in principle different for every location, but predictable for a given location with reasonable accuracy over periods of the order of years. For the purpose of this project, we have assumed a symmetric tidal ellipse with the tidal stream varying in magnitude over the semi diurnal ebb and flow cycle and a fortnightly spring/neap period, but have considered the sensitivity of the fixed pitch devices to a limited range of off axis tidal flows.

It should be remembered that the variable pitch azimuthing machine features a rotor which operates at low efficiency in a 'reverse' flow; the azimuthing feature allows optimum presentation of the rotor either to rectilinear flows or to flows in which the 'reverse' tidal current is off-axis with respect to the 'forward' current.

5.8 Existing HATT tidal stream devices

Information was gathered on existing tidal stream energy capture devices and the following were selected as offering the most direct comparison with the two HATT devices being considered in the study.

Tidal Stream Turbines promotes a horizontal shaft two bladed turbine of 1 to 2 MW for current design of 20m diameter rotors. The concept has undergone initial river tests and water tank testing of a scale device is planned for 2006. Each turbine unit is mounted on a horizontal structure attached to the main upright, the whole unit being semi-submersible and attached to a gravity foundation on the seabed, which will allow the turbine to turn to follow the tidal flow. The turbine generator unit is raised to the surface for maintenance purposes using the buoyancy of the nacelle.

Marine Current Turbines (MCT), probably the most advanced of the current developers, offer 1MW horizontal shaft axial flow turbine units under the names Seagen and Sea Array. Two full-size commercial units are due to be installed in Strangford Narrows in Northern Ireland shortly. The turbine units, mounted in pairs on a monopile, use variable pitch blades with a sufficient range of pitch change to operate in both tidal flow directions. The structure includes a mechanism to raise the turbines to the surface for maintenance purposes.

SMD Hydrovision has a horizontal shaft 2 bladed fixed pitch turbine with 18 m diameter rotors device called TidEL, which comprises two 500 kW turbines mounted on a frame designed to float clear of the seabed and to move in such a way as to follow the tidal flow.

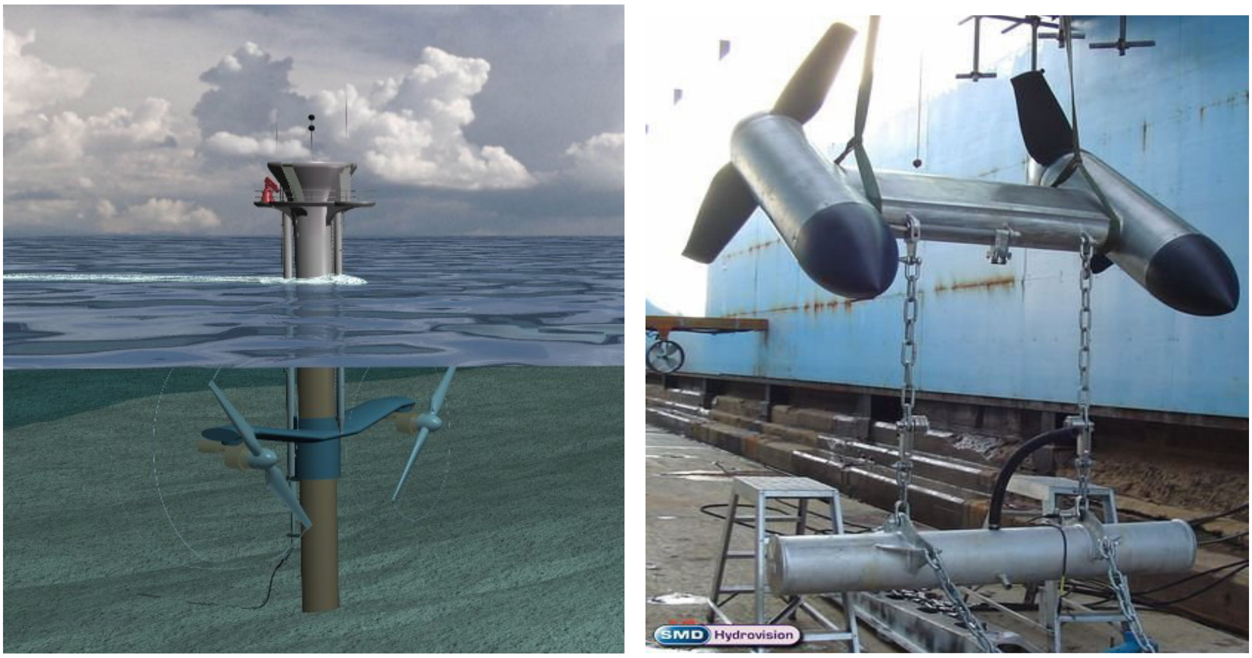


Figure 5.1 Marine Current Turbines (above left) and 1/10 scale model TidEL (above right)

Swan Turbines Ltd are developing a horizontal shaft three bladed turbine. The current programme is to develop a 350kW medium scale demonstrator unit, together with modelling and cost optimisation by summer 2006. The plan is then to install a pre-commercial system of 1 MW capacity between 2008 and 2010. Each turbine unit is mounted on a frame attached to the seabed. The emphasis is on simplicity and a gearless low speed generator, offering high efficiency over a range of speeds, has been developed. The unit will be raised the surface for maintenance purposes. It is not known whether the unit can rotate to follow the tidal flow or the nature of its blade design, with fixed or variable pitch blades.

Hammerfest Strom AS is a joint venture between ABB, Rolls Royce, Statoil and Sintcef. A 300 kW horizontal shaft axial flow turbine was installed off the coast of Norway in 2003. The submerged structure weighs 120 tonnes and has gravity footings of 200 tonnes. The three-bladed rotor is 20 m in diameter with a variable pitch range that allows it to operate in both tidal flow directions. We do not have any information on the performance of this prototype device.

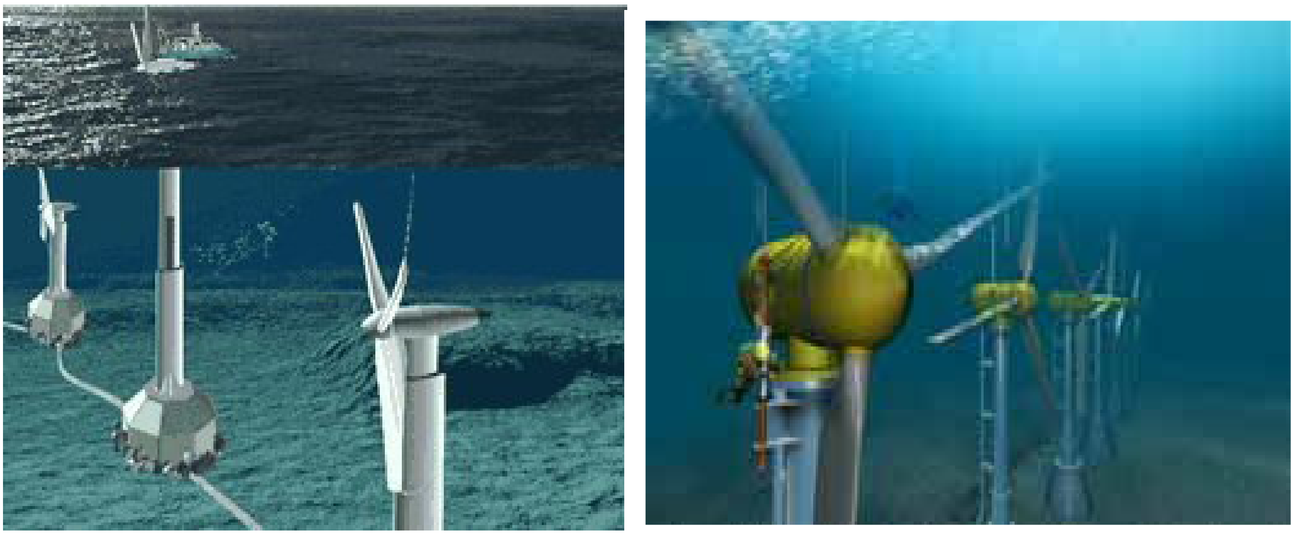


Figure 5.2 Swan Turbines (above left) and Hammerfest Strom devices (above right)

Tidal Generation Ltd is developing a 1 MW horizontal shaft three blade fixed pitch turbine. A 1MW prototype unit is due to be installed at the European Marine Energy Centre in Orkney in 2006. Commercial units are planned by 2010. Each turbine unit is mounted on the frame attached to the seabed. The frame is a lightweight structural design for easy installation and removal and is designed to follow the tidal flow.

Tidal Hydraulic Generators Ltd are developing a horizontal shaft axial flow turbine of between 250 kW and 1 MW depending on stream velocity for an array of five 6m-diameter rotors. A prototype unit is planned for 2007 to be followed by a 10 MW farm by 2009. The turbine units are mounted on a frame attached the seabed that can be installed or lifted within a day. No information is available on whether the blades are fixed or variable pitch to facilitate bi-directional flow.

5.9 Generic device for study purposes

This project is quite deliberately not specific to any existing or proposed device, although it requires certain assumptions to be made. A conceptual generic tidal turbine was defined, to the level of block diagrams, sketch layouts and some basic performance and structural calculations, to provide a basis for cost and reliability estimates, and to ensure that assumptions made in order to perform the study were realistic. Some of the assumptions are also the subject of sensitivity studies.

The generic devices take the form of horizontal axis turbine assemblies each having a single, un-shrouded rotor driving an electrical generator via an appropriate mechanical transmission system. For the fixed-pitch machine, the rotor blades are set at a fixed pitch, whilst for the variable-pitch machine, a mechanism and control equipment is provided to allow the blade pitch to be continuously adjusted in order to maximise energy extraction from the tidal stream and the nacelle is able to rotate about the vertical axis so that the rotor axis is always in line with the current flow. The designs for both the fixed pitch and variable pitch options use cage type induction generators connected to power conversion electronics systems to provide a 50Hz supply to the grid from the variable-frequency generator output, over a fairly wide range of input rotational speeds. For the variable pitch option it would be possible to operate the turbine at fixed speed and use a simple cage induction generator connected directly to the grid. However, the directly-connected asynchronous (cage) induction generator could only operate to generate power over a narrow range of rotational speeds close to the synchronous speed, with little opportunity to maintain optimum tip speed ratio over the range of tidal conditions encountered. The hydrodynamic capacity factor for this type of installation would be much lower than for the option including power electronics, and the directly connected option was therefore not considered further for this study.

5.10 Initial Project Specification

The initial outline for the project proposed two variants; Option 1 being a fixed-pitch device and Option 2 being a variable-pitch device with the following idealised parameters:

	OPTION 1	OPTION 2
Blade Pitch	Fixed	Variable
Flow Direction	0 and 180 degrees	0 degrees
Rotor Axis	Horizontal	
Rotor Axis Depth	20m	
Maximum Rotor Diameter	20m	
Nacelle Body	2.5m diameter by 6m long	
Current Speed	0 to 5 m/s	
Starting	Self-start at current speeds > 1m/s	

Table 5.2 Initial project specification

In order to frame the project, a specification was created for a generic device. The values quoted below are considered reasonable initial assumptions for a device to operate in some of the more attractive UK sites, but should not be interpreted as representing the economically optimum device. The values quoted in Table 5.3 below should be considered to be generic and are not necessarily completely consistent with each other.

The choice of 2.5m/s rated velocity was determined by study of Reference 1, with the intention of making the study applicability as wide as possible; in terms of peak spring tidal velocity V_{sp}, 2.5 m/s is exceeded by 41 of the 57 sites listed, together accounting for more than 95% of UK tidal stream resource.

The partners identified the 20m rotor diameter and 1MW unit rated power per device early in the project and, for the purposes of whole life cost analysis, deployment of 30 such devices to make a 30MW wind farm. These assumptions are consistent with the prototype device and large array definitions in the 2006 BWEA report "The Path to Power". The Path to Power identifies four stages of marine renewable deployment in the UK. The capacity definitions for these stages of deployment are:

- Prototype device—single pre-commercial device up to 1MW in size
- Small array—small arrays up to 5MW in total export capacity
- Large array—large arrays up to 30MW in total export capacity
- Significant project—commercial projects in excess of 30MW

Parameter	Value	Unit
Generator rated power	1	MW
Maximum tidal current – spring tide	2.5	m/s
Ratio of peak spring tidal current speed : peak neap tidal current speed	2.0	-
Rotor diameter	20	m
Maximum nacelle diameter	4	m
Maximum nacelle length	10	m
Water depth	40	m
Number of blades	3	
Transmission voltage	33	kV
Cable distance from device to shore	5	km
Number of devices per farm	30	

Table 5.3 Device assumptions

The power conversion solution selected will comprise rectifier equipment located in each turbine nacelle, which will convert the variable frequency AC output from each induction generator to DC at about 3.3kV. The DC output from each unit is connected via a common link to a single network bridge that converts the output from the tidal stream farm to 50Hz AC. This network bridge may be located either on a dedicated platform located centrally in the tidal stream farm, or onshore if the farm is close to land. The output from this bridge is connected to the grid via a step-up transformer to raise the output voltage to 33kV or 132kV.

6. BLADE DESIGN FOR FIXED AND VARIABLE PITCH TURBINES

6.1 Hydrodynamic Performance of HATT - Predictions

6.1.1 Summary

This WUMTIA study was the key element of Work Package 1, with the objective of providing:

- An understanding of the hydrodynamic behaviour of horizontal axis tidal turbines through use of basic theory, Blade Element Momentum (BEM) analysis and finally a Lifting Surface Panel (LSP) code, and
- An answer to the relevant question of by how much a mechanically complex controllable pitch turbine outperforms a simple fixed pitch, bi-directional system.

WUMTIA initially confirmed the basic theory, identified relevant computational tools and developed a methodology to define the turbine blades and analyse tidal behaviour. Validation studies were carried out using BEM and LSP code. The developed tool for investigating tidal behaviour was used to investigate a number of different concept HATTs. A study of comparative performance has shown that the use of a variable pitch system has only a limited influence on the delivered energy. However, the ability to vary the pitch allows machine power to be limited to its rated value for higher current speeds.

6.1.2 Background

The performance of devices that use the kinetic energy associated with a current or wind the performance is that of a low-head (wind or tidal) turbine. In this case the available power P for a given device capture area A and associated wind/current velocity V is

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

where the power coefficient Cp is a measure of the overall hydrodynamic efficiency of the device. This will depend on the tip speed ratio (blade tip speed to current velocity), Mueller, (2005). The theoretical (Betz) maximum efficiency is 0.59 with practical values lower than this. The much greater density of water results in a tidal turbine being able to generate comparable amounts of power to a wind turbine with, for example, 20% of the diameter of a wind turbine and in a current of 30% of the wind speed.

The gravitational attractions of the moon and sun, as the earth rotates, generate local tidal currents converting potential into kinetic energy. The magnitude of the local tidal range is influenced strongly by the local seabed bathymetry and shoreline orientation. The local behaviour of tides is controlled by dominant semi–diurnal (period 12hrs and 25 mins) and diurnal periods and with monthly variations in maximum and minimum range (spring and neap tides). Predicting the time of local high and low tides and to a lesser extent their magnitude has occurred for many centuries. It is this predictability that makes the use of tidal energy attractive. The key is the behaviour of the local tidal range, back flow and secondary induced flows. It is usual that tidal currents will be most strongly associated with close-to-shore locations that ease the problem of connecting the generating system to the local electricity network. Although tidal energy is the main source of marine currents, additional oceanic (geostrophic) currents such as the Gulf Stream could also offer possible locations although these will more usually be associated with deep water.

The amount of energy that can be extracted from a given location will be associated with the appropriate selection of possible type/capacity of the extraction device. For example, estuarine barrage schemes are able to extract significant amounts of power; the La Rance scheme in France has a generation capacity of 240MW based on a basin area of 22km^2 and a tidal range of 8.55m. However, other types of device, principally variations on vertical or horizontal axis rotating systems, will only be able to extract energy associated with that of the mean current within their capture area. For horizontal axis machines, this will be controlled by their blade diameter and for vertical axis machines by their height and diameter. The complete reversal of flow will result in times when the local current is below a critical value for viable operation of the device. In addition the tidal range will possibly constrain a minimum water depth in which the device can operate and likewise the magnitude of the current will drop in rough proportion to the increase in local water depth.

6.1.3 HATT Concepts

There are four main strategies for operating HATT:

(1) Fixed rpm, fixed pitch:

(2) Fixed rpm, variable pitch: as tidal current increases, control pitch to maximise energy capture within the rated power of the generator.

(3) Variable rpm, fixed pitch: as tidal current increases, control rpm to maximise energy capture within the rated power of the generator.

(4) Variable rpm, variable pitch: as tidal current varies control both rpm and pitch to:
   a. Maximise energy capture within the rated power of the generator.
   b. Maximise power within generator set limit.

The variable direction of the tidal current; primarily reversing by 180 degrees through the tidal period gives the following design options:

- Ideally to maximise power capture, variable pitch devices should be able to azimuth the complete nacelle about the vertical axis to face the tidal flow. Other options are to weathervane whole turbine system or have fixed orientation at a given site, chosen to minimise yaw influence throughout tidal cycle, and be able to change the pitch of the blade by 180 degrees or more to maintain a single direction of rotation. The latter option will however require a symmetrical blade section.

- Fixed pitch devices can also either azimuth the complete nacelle about the vertical axis to face the tidal flow or weathervane the whole turbine system. Alternatively the nacelle could have a fixed orientation at a given site, to minimise yaw effects over the tidal cycle, with the blade section shape designed to work as a bi-directional device.

An interesting design choice for bi-directional devices is whether to use a high performance asymmetric section with much poorer performance when working in opposite direction flow or use a symmetrical section that performs the same in both directions.

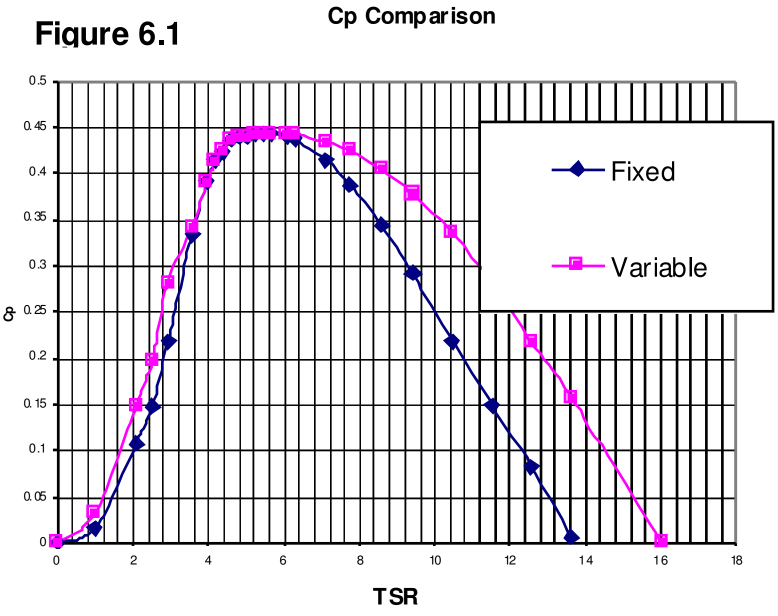
6.1.4 Available computational tools and analysis

The following computational tools were used by WUMTIA during the analysis:

- Blade Element Momentum Code (BEM) - existing Fortran code developed and validated for predicting performance of stall regulated wind turbine blades as a series of DTI/EU contracts up to the mid-90s.
- PropGen - an in-house code to automate the process of defining a rotational propeller or turbine blade originally developed to produce marine propeller geometry suitable for use with Palisupan and other codes, and modified to generate a horizontal axis wind turbine/tidal turbine with a final prescribed wake pitch specified by the user.
- Palisupan - a surface panel code developed by Turnock initially to investigate ship rudder/ propeller interaction which provides a reasonable compromise between computational effort and physical accuracy in modelling the flow interaction achieved by the use of a lifting surface panel method.
- Adaptflexi - a powerful geometry manipulation system that its purpose designed to generate high-quality surface panels and RANS (Reynolds Averaged Navier Stokes) meshes. Palisupan is integrated within its environment to automate a geometry definition and post-processing analysis.
- Panvise - a visualisation tool matched with Adaptflexi and Palisupan.

The study then analysed a generic tidal cycle, derived a simple turbine blade geometry sufficient for this stage of the analysis (blade optimisation was addressed in Work Package 2), identified the relevance of cavitation to the performance of the selected blades and carried out a high level performance comparison between the fixed and variable pitch devices. The results of this comparison are shown in the adjacent Figure 6.1.

Figure 6.1



6.1.5 Output of Study 1

The work demonstrated the ability to predict accurately the performance of a HATT using a lifting surface panel method (LSP). This study included: an investigation of the influence of the sensitivity to the numbers of panels used, developed methodology for a fixed wake using BEM analysis and investigated sensitivity of results and validated predictions against experimental (full and model) scale data for comparable wind turbine tested in early 1990's.

The influence of blade number and pitch was analysed using an existing BEM code originally developed for use with horizontal axis wind turbines and compared with results of LSP. Good agreement was obtained when compared with published theoretical and experimental results. A parametric approach was developed for generating a computational model of a HATT suitable for use with LSP or with BEM.

A performance analysis tool was produced which is capable of using the non-dimensional power performance curve of a HATT and calculating total power delivered for particular tidal conditions eg spring maximum and ratio of spring/neap tides. This has included evaluation of the performance of the following devices:

- Unidirectional fixed pitch device;
- A typical fixed pitch design or equivalent variable pitch device;
- A theoretical device which can maintain constant Cp;
- A theoretical device that reduces rpm to limit maximum power.

The interim conclusion was that the concept of using a fixed pitch bi-directional device, when combined with generator system that can use a variable range of rpm, offers comparable performance to that of a more sophisticated and inherently more mechanically complex system that uses a controllable blade pitch and azimuths to face the tidal flow.

6.2 Design of three bladed tidal turbine blades for bi-directional fixed pitch or azimuthing variable pitch operation

6.2.1 Optimisation Study

The second stage of analysis by WUMTIA was in essence an optimisation study for the blade design of a 20 m diameter three bladed HATT, making further use of the tools developed and validated in the first stage. The design goal was to maximise power output over a complete tidal cycle for an assumed location with a maximum spring mean current of 2.5 m per second. The turbine was to be sited in water of 40 m depth with an axis of rotation at 20 m depth. The analysis included blade selection and development of the design strategy, taking account of the explicit constraints imposed as a result of other structural and environmental considerations, in addition to assumptions introduced by other partners. The results consisted of two blade designs in terms of section shape and variations in blade twist, thickness and chord with the radius from root to tip.

There are limitations imposed by the scale of the study and for the devices in question there is only limited operational experience available so the design constraints associated with, for example, marine growth had to be estimated. The objective of the optimisation study is to maximise power output through a complete tidal cycle. As shown in the previous study, power is proportional to the cube of tidal current speed and so the highest possible power is only generated for a limited amount of time.

One of the constraints of HATT arises from the relatively low stream kinetic energy extraction efficiency. The most advanced devices operating today are targeting an efficiency of around 40-45%; however the Betz theorem limits efficiency to 59.6%. The following strategy was adopted for selecting viable blade designs: design and select section, optimise planform/pitch/blade setting, evaluate selected blade performance, evaluate the blade loading, modify section thickness, modify blade root and, finally, check performance.

The main constraint on selected blade shape is the ability to withstand the applied design load, the control of which is through selection of a suitable thickness/chord ratio. Altering the blade taper can control the root bending moment. A further constraint for the variable pitch device is the method by which the hydrodynamic shape is merged into the necessary circular cross-section at the blade root to allow for blade pitch change. It was only possible to make a rough assessment of the likely performance degradation of the proposed new bi-directional sections with cavitation number.

Experimental evidence suggests that tidal turbines may experience strong and unstable sheet and cloud cavitation, and tip vortices at a shallow depth of shaft submergence. Acceptable levels of cavitation on marine current turbines are not yet clear. Another factor to be considered is how different blade materials will respond to possible cavitation erosion.

The tidal cycle performance analysis program, developed as part of Work Package 1, was further modified to include a final control strategy. This strategy assumes that the rate of revolution of the blade can be modified within prescribed rpm limits, typically plus or minus 50%, to find the tip speed ratio that gives maximum delivered power. A further refinement is that this can be modified to limit power output at a rated power, typically chosen to be 10% above rated value.

6.2.2 Blade Parameters and Optimisation Tools

The optimisation study required a series of suitable shape definition parameters. A reasonable blade shape for a tidal turbine, based on a wind turbine, had been found in the first series of investigations. The method of parametrically adjusting this shape provided a reasonable approach for determining which blade shape parameters should be chosen.

The basic BEM code, cwind, used in the first phase, was extensively reworked and a series of 9 variants (*tidal_bemv1:9*) were developed to facilitate an automatic optimisation approach.

A spreadsheet was developed to allow the full geometric shape definition required for the surface panel code to be developed from the same parameters found in the optimisation study. The shape was specified at 10 spanwise stations starting at an initial hub/blade diameter ratio of 0.2. A later study confirmed that only small gains in performance are obtained if smaller values are used (2%). In a real design this region is primarily structural and contributes a limited amount to performance.

The overall pitch setting of the blade, along with the blade tip speed ratio (TSR), determines the thrust and power developed. These were dimensionalised in terms of, for this study, three blades with a maximum diameter of 20m. Blade chord, pitch and thickness were required for the blade at each spanwise station. Together with a specified section shape, known for the variable pitch blade and derived for the bi-directional blade, this allowed a ruled shape to be constructed. Variations in shape were controlled by modifying the blade taper, area, pitch and thickness.

The optimisation process explored the geometric design space as well as the range of TSR and blade pitch settings. The execution of the analysis required an iterative solution to capture the necessary operating angle of attack for each section. This was accomplished, resulting in a simple strategy of exploring each variable at equal separation between a minimum and maximum constraint. Typically, such a global search created of the order of 33,000 evaluations. Once an optimum had been found, 2 or 3 additional cycles of user specified progressive refinement was usually sufficient to finalise the design. The large number of evaluations gives a clear indication of the sensitivity of the design space to the various choices of design/flow variables.

6.2.3 Bi-directional fixed pitch tidal turbine blade

The most important component of the bi-directional concept is the identification of a section shape that works equally well in both forward and reverse tidal directions. Such a shape requires 180deg rotational symmetry about its mid-chord. Previous work at the University of Southampton has developed a similar concept for use with rim driven marine thrusters.

In this work, the 2D section analysis code, Xfoil, was used to analyse the performance of a range of angles of attack up to the initial onset of stall (separated flow). This section lift and drag performance is required by the BEM code. A sensitivity study was carried out for the effect of thickness/chord ratio (t/c) on lift and drag. It was found that the section shape performed best at its design t/c. In principle, a section shape could be optimised for each of the required spanwise t/c. This was beyond the resources of this study but would be required for a final design.

The analysis carried out of this numerically developed bi-directional section does not allow prediction of performance beyond stall. This information is important in being able to predict such performance parameters as turbine starting torque and runaway speed. However, section performance beyond stall can be extrapolated based on knowledge of measured section performance. It is well documented for wind turbines that experimentally measured 2D stall parameters under-predict the section lift beyond stall on a real blade. This is because the rotating blade causes spanwise flow within the stalled region on the downstream face of the blade. This effect was measured in the early 1990's at the University of Southampton and was used to make an estimate of the likely behaviour beyond stall. For a limited number of cases, the sensitivity of this assumption was assessed by varying the values used in the section performance curve.

Figures 6.2 and 6.3 show the performance (Cp vs. TSR and Ct vs. TSR) for the final blade shape. The shape of the curve reflects the performance of the section with a more limited range of operation without stalled flow. However, at the maximum power condition (N=17rpm, U=2.5m/s) all of the sections are operating on or close to their optimum angle of attack (eg max lift/drag ratio). Figure 6.4 shows the torque generated with a 2.5 m/sec current.

Structural analysis was assessed using the surface panel code. Figure 6.5 shows a typical output indicating local surface pressure variation. This can be imported directly as a load map for use with a commercial finite element analysis code.

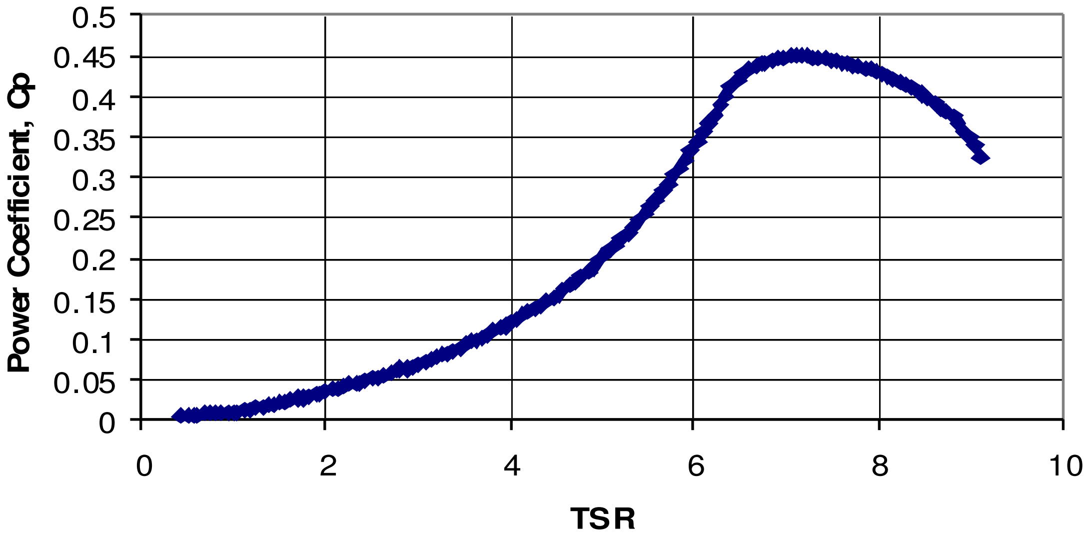


Figure 6.2 Cp performance of Optimum Bi-directional blade

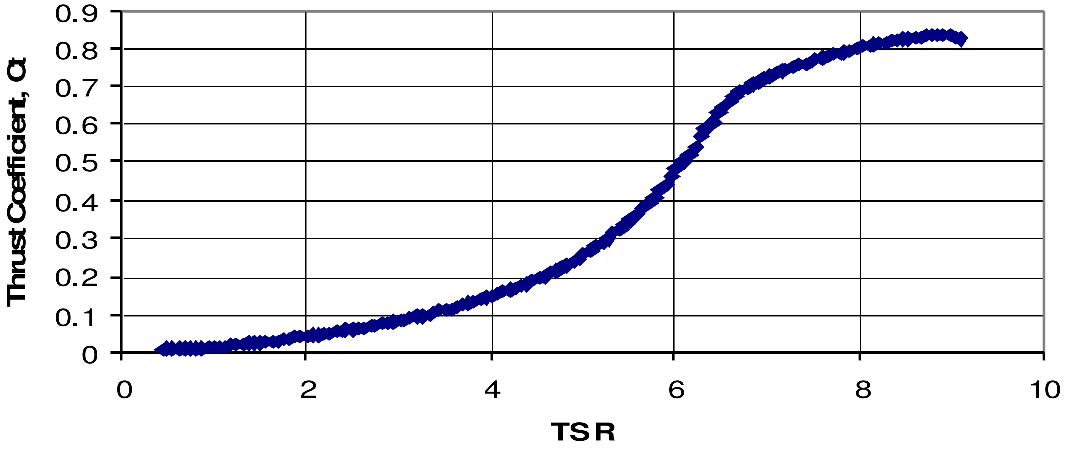


Figure 6.3 Ct Performance of optimum blade

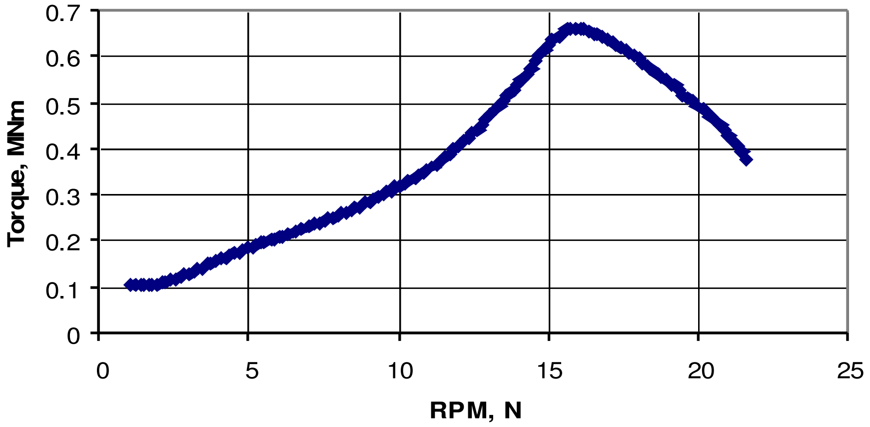


Figure 6.4 Torque generated with 2.5 m/s current

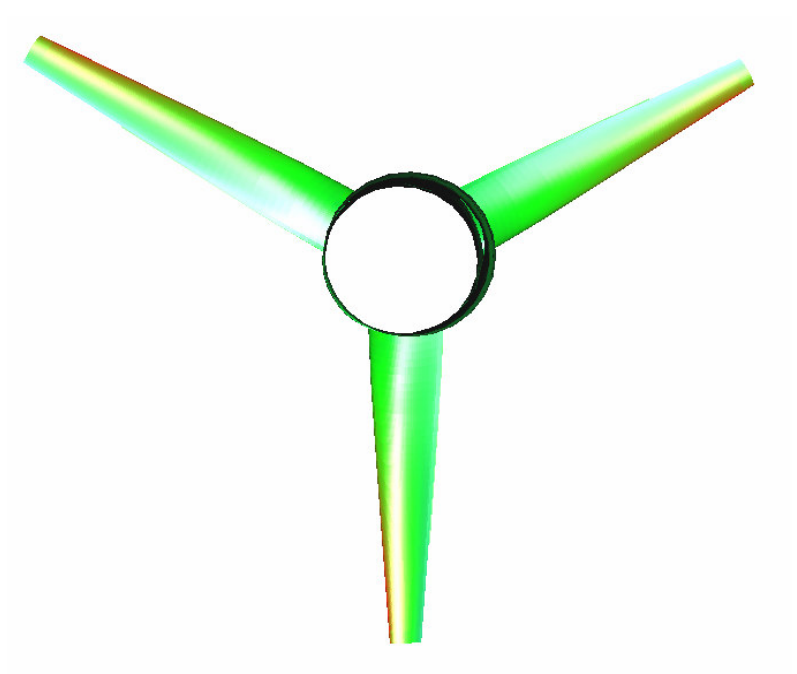


Figure 6.5 Pressure map

A simpler beam theory approach was used to find the appropriate spanwise t/c variation. It is worth noting that the design loading case is driven by the maximum spring tide (rather than extreme events as required for wind turbines). Hydrodynamic loads (primarily in the flow direction) rather than centripetal loads dominate in the radial direction. This allows greater mass to be placed at higher radii and reduces the need for small t/c towards tip. As a result the t/c distribution for the bi-directional blade can have a much smaller variation and the section will be operating in its known range.

The surface panel analysis also provides a check of performance against that predicted by the BEM code. Definition of the correct downstream turbine wake is important for obtaining satisfactory performance. Fortunately, BEM analysis can supply most of the necessary information to construct such a wake. The construction of a suitable LSP mesh requires considerable care to achieve a high quality mesh with regular quadrilaterals that control panel size, aspect ratio, low skew, lack of planarity and proximity. The low pitch of the blade and its intersection with the assumed hub provided a considerable challenge.

6.2.4 Variable pitch turbine blade

A similar approach was followed for the variable pitch blade with the planform\optimisation resulting in a significant improvement in performance giving a maximum Cp of 0.49, Figures 6.6, 6.7 & 6.8. Figure 6.9 shows the optimum pitch angle setting as the tip speed ratio varies.

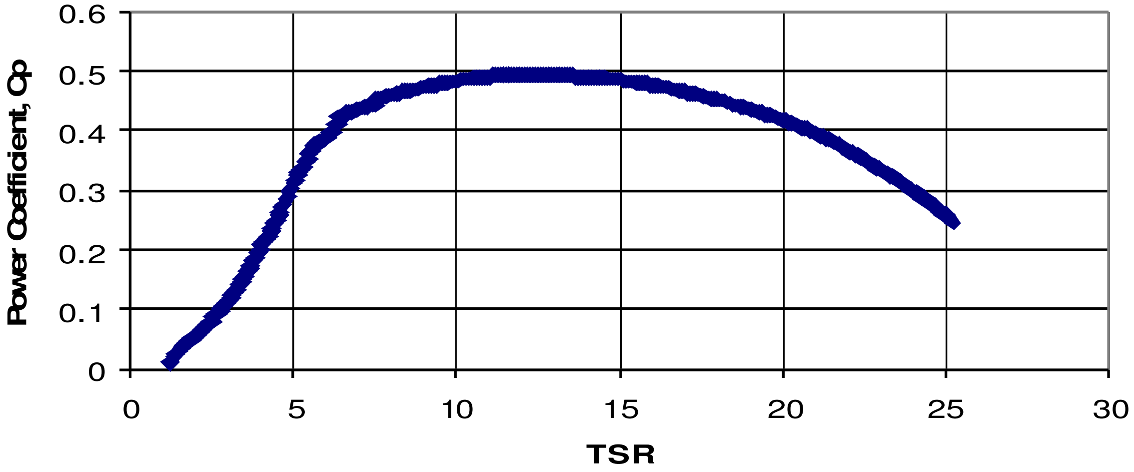


Figure 6.6 Cp performance of Optimum Bi-directional blade

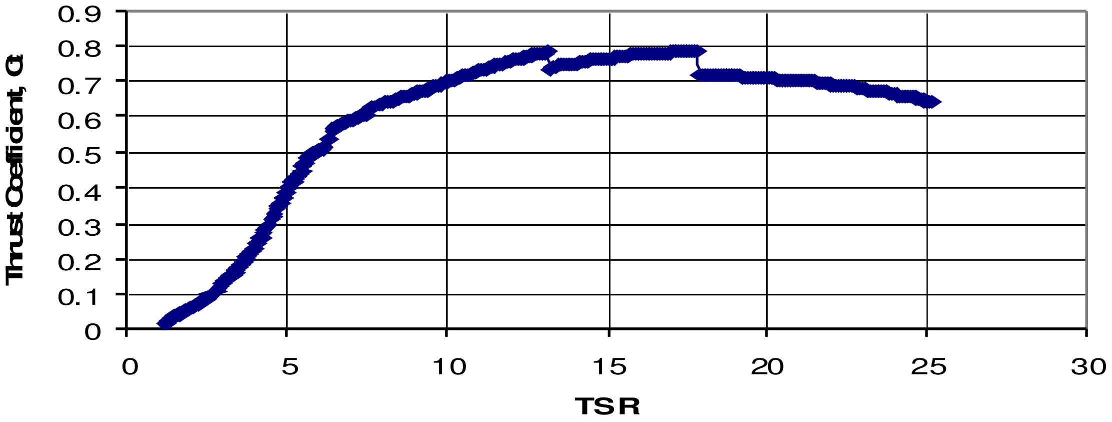


Figure 6.7 Ct Performance of optimum blade

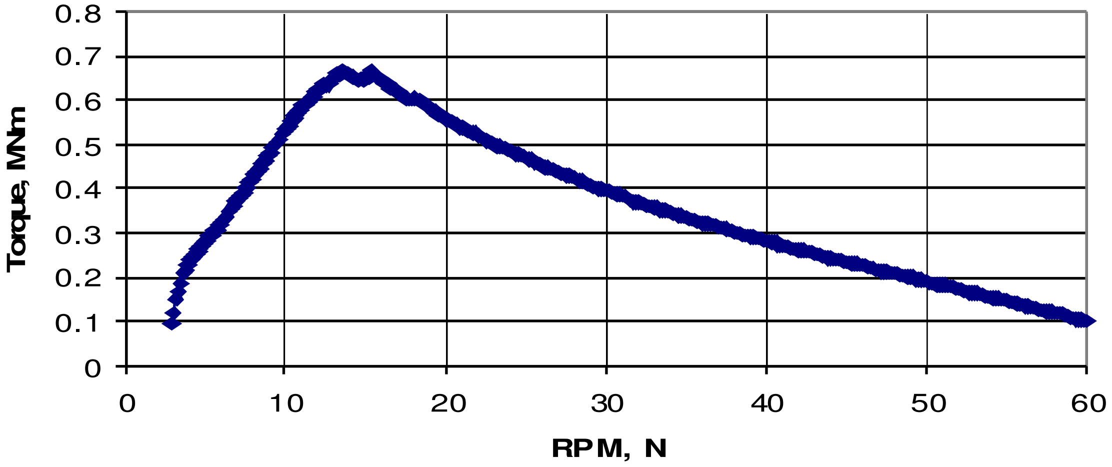


Figure 6.8 Torque generated with 2.5 m/s current

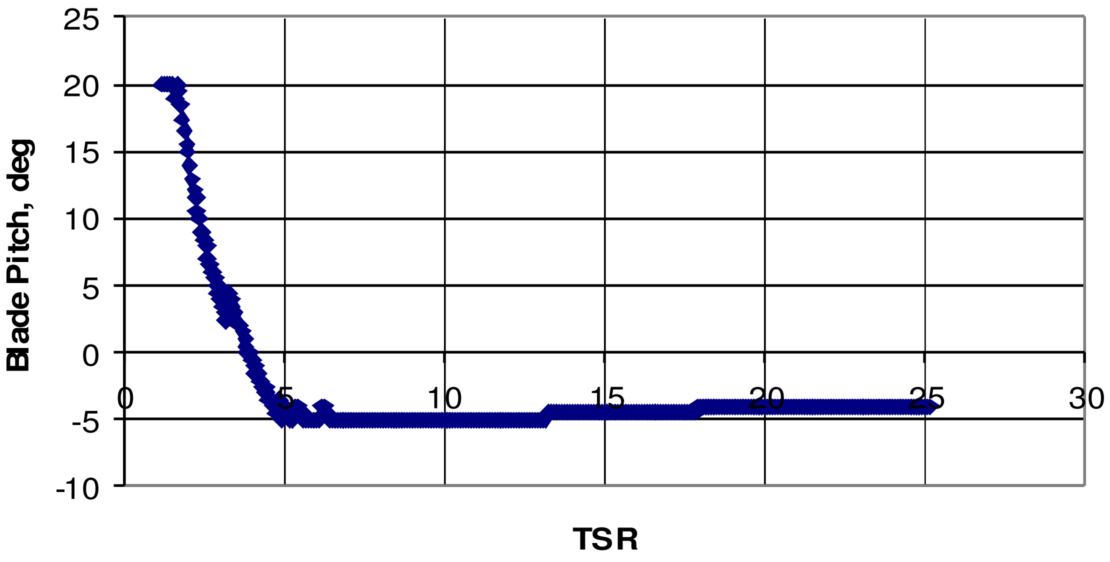


Figure 6.9 Optimum Blade Pitch Setting

Note: Discontinuities in the performance curves are associated with the discrete jumps of 0.5 degrees in the pitch setting used.

6.2.5 Yaw Characteristics

Many tidal sites are relatively bi-directional, however, some sites can have flow reversal of 20° or more away from 180° such as the flow around islands and headlands, for example Portland Bill where a swing upon flow reversal of around 35° from rectilinearity is present. It is thought that if a yawing turbine, rather than a fixed turbine, was to be used at unusual sites such as Portland Bill an extra 10% of energy may be harnessed.

Experiments have been carried out to measure power and thrust on a model marine current turbine under yawed flow conditions. Such experiments show that there is a consistent decrease in power and thrust with an increase in yaw angle. Optimal orientation for any turbine is based on the design flow speed.

Momentum theory suggests that the power is proportional to the square of the cosine of yaw angle (γ) and the thrust as a cosine of the yaw angle:

$$C_{Pow} = 4a(\cos\gamma - a)^2$$
$$C_T = 4a(\cos\gamma - a)$$

Where: C_{Pow} is the Power coefficient, $C_{Pow} = \dfrac{Q\Omega R}{0.5\rho\pi R^2 U_0^3}$

C_T is the thrust coefficient, $C_T = \dfrac{T}{0.5\rho\pi R^2 U_0^2}$

a is an axial flow factor
U_o is the tidal speed (m/s)

Ω is the rotation speed (rad/s)
ρ is the density of water (kg/m^3)
Q is the rotor torque (Nm)
T is the rotor thrust (N)

Batten et al demonstrated that the data attained from experiments fits to the momentum equations and the cosine square rule. Thus the curve fits obtained may be confidently used to compare the effect of fixed and yawing turbines at different locations.

In this study the power comparisons have made an implicit assumption that no such variation exists and that the two principal tidal directions are 180 degrees apart. However, as over 60% of the power is developed when the tidal current is between 2.0 and 2.5m/s and is likely to be closely aligned with the axis of the tidal turbine (γ small), this is deemed reasonable.

6.3 Comparison of variable and fixed pitch design

6.3.1 Blade power curves

Figure 6.10 plots the power curves of both optimised blades as well as the variable pitch blade working at a constant pitch of -5°. It is worth noting that the bi-directional blade has an 8 % increase of blade surface area. This reflects the poorer section performance and is then seen as a drop in power capture over a lunar cycle. However, this drop in performance is nowhere near as bad as would be first seen from the large decrease in area beneath the curve of the bi-directional device. This is associated with how much of the tidal cycle a device can operate at a particular TSR. If a suitable generator control can be implemented the fixed-pitch bi-directional device can be made to operate at or near its optimum TSR. The range of effective TSR operation is significantly lower than for the more robust aerodynamics of the conventional variable pitch device but the power captured will not be. As an example of this, for the variable pitch blade operating at a constant design rpm it is:

i) TSR ≥30.0 (slow current, <0.55m/s) it is stationary for 21.4% of lunar tidal cycle and generates no power
ii) TSR ≥20.0 (modest current, <0.9m/s) it operates for 13.5% of time but generates 1.2% of power
iii) TSR ≥10.0 (reasonable current, <1.78m/s) it operates for 44.2% of time and generates 36% of power
iv) TSR<10.0 (high current, <2.5m/s) it operates for only 20.9% of time but generates 62.8% of total power.

The control ability to move the operating rpm to give at or near optimum TSR will allow more power to be generated in current regimes ii) and iii).

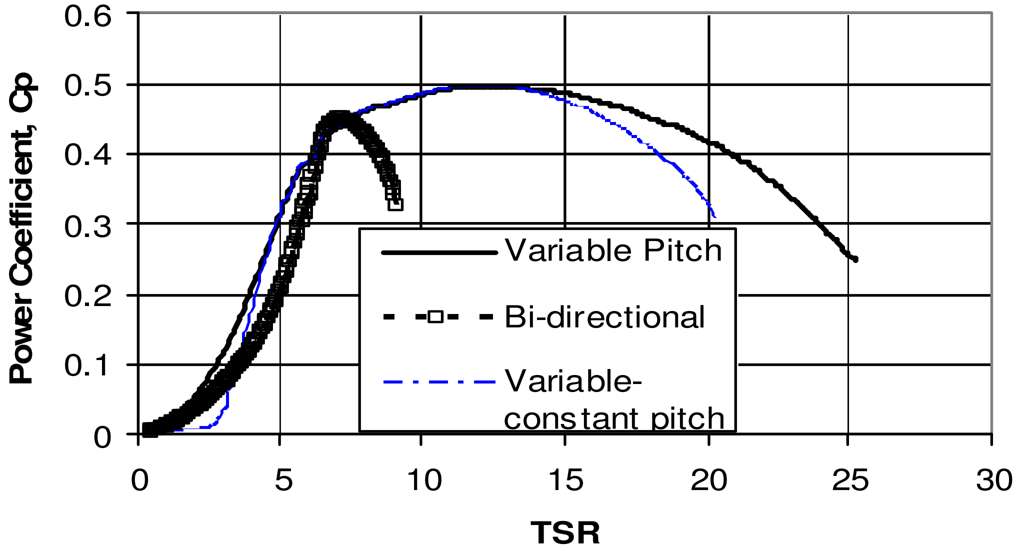


Figure 6.10 Comparison of blade power capture

Table 6.1 below summarises the energy capture based on these performance curves for a series of control strategies. It is assumed that a 10% exceedance of the rated generator capacity is acceptable.

Diameter	Rated Power +10%	BI-DIRECTIONAL DESIGN		VARIABLE PITCH DESIGN			
m, [hub/D =0.2]	MW	Fixed RPM (14.0)	Variable RPM	Fixed RPM (17.0) Variable Pitch	Variable RPM, Variable Pitch	Fixed RPM (17.0) Constant Pitch	Variable RPM Constant Pitch
20	1.1	114	160	169	177	166	177
20	0.75	90	151	158	163	156	163
20	1.25	114	161	169	178	167	177

Table 6.1 Comparison of various control strategies (energy in MWh over 29.4 days)

The total capacity is taken to be the rated power over 29.4 x 24 hours. For the three rated generators of 1.14, 1.0 and 0.68 MW the energy they could have absorbed would be 802, 704, 481 MWh respectively. For the purposes of the economic assessment hydrodynamic capacity factors of 23% and 25% were used for the bi-directional and variable pitch devices; based on a rated 1MW generator capacity (802 MWh) and 20m blades. Hydrodynamic capacity factors assume 100% reliability and 100% availability. It is worth noting that a 1m increase in blade diameter will allow the bi-directional device to capture the same amount of energy as the best performing 20m variable pitch devices.

6.3.2 Axial Load

One of the effects of a less efficient blade is an increase in axial load (more energy is transferred into axial load rather than into rotating the blade). The maximum axial load coefficient (Ct) is 0.83 for the bi-directional blade (and constant pitch setting of variable pitch blade) but the ability to pitch the blade allows a value of less than 0.8 to be achieved at optimum TSR for the variable pitch device.

If both blades are assumed to operate at maximum Cp for a maximum current of 2.5m/s the increase in axial load will be 3.75% for the bi-directional device. For the proposed 1m increase in diameter this would give an increase in axial load of 14.4% overall. This would need to be reflected in greater strength of the support structure and seabed foundations.

6.3.3 Summary

A number of areas of uncertainty arise from the exclusive use of numerical analysis tools, which in general relate to the actual section performance when either stall or cavitation occurs. Use of suitable model scale experiments will reduce this uncertainty. The recommended strategy would be 2D section performance tests in a cavitation tunnel to evaluate the drop-off in section performance with varying degrees of cavitation. This would then need to be compared with results of three dimensional blade tests in a circulating water channel or towing tank. Although these would be at model scale they would allow the necessary modifications to the 2D performance curves to be made to give a calibrated 3D performance. Scale effects can then be accounted for in the usual way.

A final area of uncertainty is associated with the blockage effects associated with the turbine operating in a finite depth channel with a free surface. The interaction of free surface waves (onset and radiated/diffracted) as well as the change in free surface controlled by the turbine's extraction of energy can again be approached based on experiments. It is likely that blockage for the proposed design will have a limited effect although this will depend on the tidal range at a given site as well as the local site bathymetry. This is an area of considerable research interest.

7. MECHANICAL AND ELECTRICAL SYSTEM DESIGN OPTIONS

7.1 Device Block Diagrams

Generic block diagrams have been developed to illustrate the main relationships between the various elements of the fixed-pitch and variable-pitch approaches. These relationships have been quantified to allow important design considerations to be identified, e.g. cooling requirements and size of components. The purpose of the block diagrams is to indicate the main generic influences exerted by each element on the others, without causing the diagrams to be specific to a particular solution. For example, the heat flow from the generator to the nacelle volume may in practice take place as a fluid flow of air circulated by the generator cooling-fan, if the machine is so equipped.

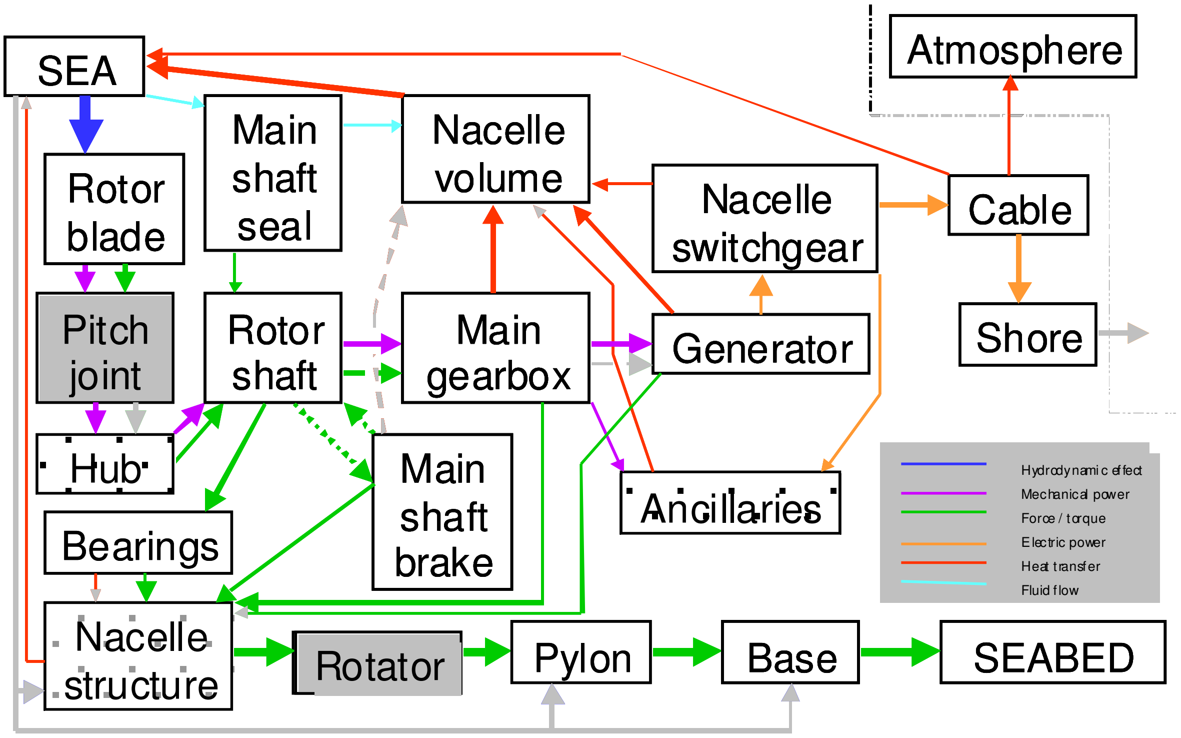


Figure 7.1 Initial Conceptual Block Diagram for Fixed and Variable-Pitch Machines

Components specific to variable pitch device

Components differing between fixed- and variable –pitch devices

The block diagrams do not represent all possible solutions, e.g. where a generator is designed for direct drive. Each device includes components and systems not directly part of the main power flow path, but important for practical operation. Some of these features are listed below. The list is not exhaustive; some of the items are optional, some complementary, or alternative means to achieve the same end. In some cases the details of the equipment described by a particular heading will differ between the fixed pitch and variable pitch systems. This study assumes common components between fixed pitch and variable pitch designs unless commonality is impractical or implicitly precluded.

Examples of ancillary components and systems that might feature in a tidal current turbine include: rotor brake (capable of stopping rotor), rotor lock (prevents rotation of already stationary rotor), bilge pump, nacelle pressurisation system, rotor shaft seal, inflatable rotor shaft seal, cathodic protection system, anti-condensation heater, navigation/anti-collision lights, control system, deployment/retrieval related systems (e.g. winch, ballast pump), condition monitoring system, nacelle rotator system and brake. Some of these components are indicated explicitly on the initial system block diagram above, whilst others could be considered to be included in the 'Ancillaries' block.

An un-shrouded tidal turbine for 1MW power output is unlikely to turn faster than 20 rpm, and may well turn more slowly. Most conventional electric generators require an input shaft speed two orders of magnitude higher. Appropriate arrangements must therefore be provided to generate electrical power in a suitable form for onward transmission. There are several ways in which this problem may be addressed.

For both fixed and variable pitch devices, the main power flow is from the tidal stream to the grid, via a rotor, transmission, generator and electrical interface (generator and some form of power conditioning). These items are analogous with early wind turbine experience and there are several approaches for these components, provided the concepts for 'transmission', 'power conditioning' and 'generator' are technically consistent. The concepts for a practical fixed pitch and a practical variable pitch device considered in this report may not be strictly optimal for a practical machine, but will be reasonable initial assumptions. The main options for the transmission and generator type are listed below.

Possible Gearbox / Generator Combinations	Two-stage gearbox (ratio 1:64 max)	Three-stage gearbox (ratio 1:512 max)
Induction (asynchronous)	Unlikely	Feasible option
Doubly-fed induction	Possible	Feasible option
Synchronous	Unlikely	Feasible option

Table 7.1 Possible Gearbox / Generator Combinations

Permanent magnet generators with direct drive or single stage gearbox options were considered but discarded for the purposes of this project, but they may well reappear as permanent-magnet generators become better developed. The main issue related to the control of the permanent magnet generators under fault conditions; necessary increases in rating for the power electronics to cope with the higher voltages generated during overspeed could undo the economic premise of the fixed pitch device.

The induction generator was chosen to avoid the need for regular brush replacement, which would be an intrinsic feature of either a suitable synchronous generator or the doubly-fed induction generator options.

The use of fixed speed, directly connected, induction generators for the variable-pitch option was considered. However, the reduction in revenue (due to the lower capacity factor) together with the need to purchase reactive power from the grid made this option less attractive than using a variable pitch, variable speed generation system with power conversion equipment. Hence for the variable pitch turbine, the studies were conducted using variable speed turbines with induction generators connected to the grid via power conversion equipment.

7.2 Generator/power conversion concepts

At the very outset of this project, it was thought that there would be a significant difference between the generator and power conversion systems required for the fixed pitch and variable pitch devices, with the system for the variable pitch device likely to be analogous to the doubly fed induction generator systems used for modern wind turbines. The system for the fixed pitch, bi-directional, variable speed device was expected to require more complex, and expensive, power conversion electronics.

In discussion with Converteam, however, it became clear that the same generator and power conversion system approach could be applied to either the fixed pitch or the variable pitch device. A number of different systems were considered in conjunction with Converteam, including the following:

- **Option 1** The first option was a simple system consisting of a single turbine, AC generator and power converter with a step up transformer. This arrangement is usually used in near to shore, low-power projects, and would be suitable for a pilot project or technology demonstrator. It would be a poor choice for a farm as there is no opportunity to take benefit from the common costs of a farm installation.

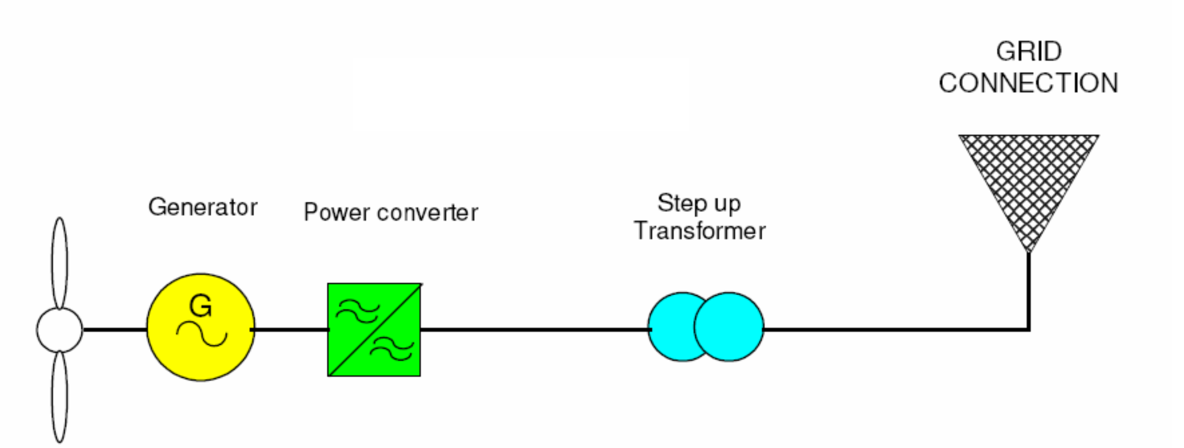


Figure 7.2 Option 1 – Single System

- **Option 2** The second option, involving multiple generators each with a dedicated power converter, would provide a high level of system flexibility, allowing generators to rotate at different speeds as well as individual generators to be shut down. However the system is complex and it would be a high-cost solution with no cable or transformer redundancy.

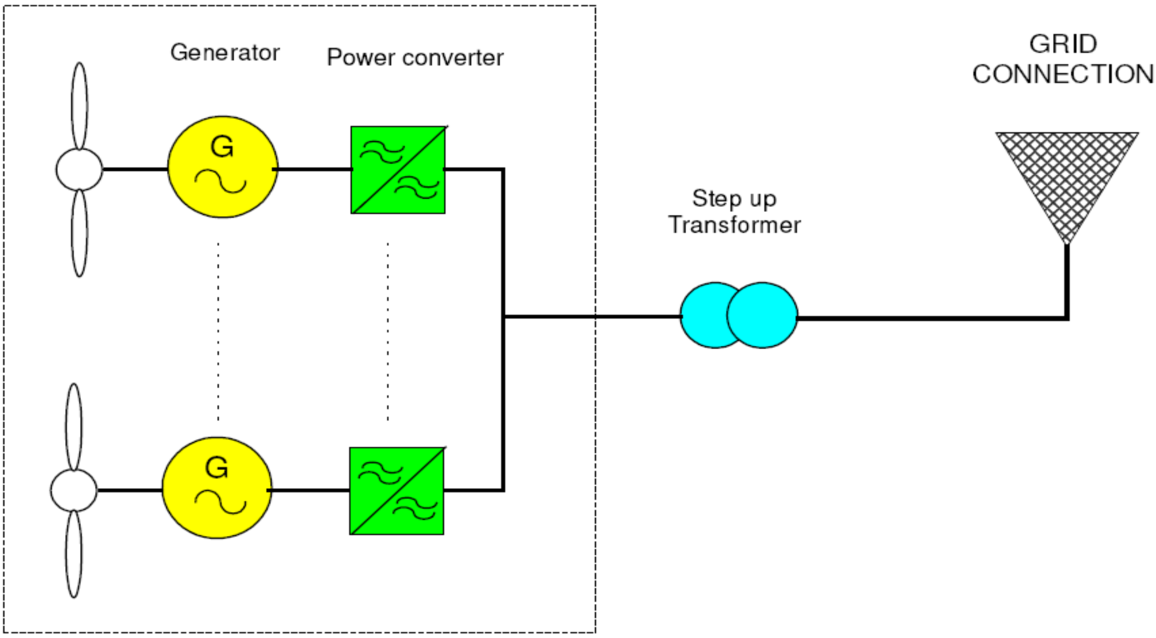


Figure 7.3 Option 2 - Multiple turbines, single system

- **Option 3** The use of multiple induction generators connected to a single power converter is appropriate where there is little variation in turbine speed across the farm. This is important; high circulating currents between the generators would occur if the differences in speed were significant. In the absence of such large circulating currents, this option offers a lower cost in comparison with the other system configurations for a high-power farm. Again there is no cable or transformer redundancy and in this case no inherent converter redundancy is possible without a reserve converter.

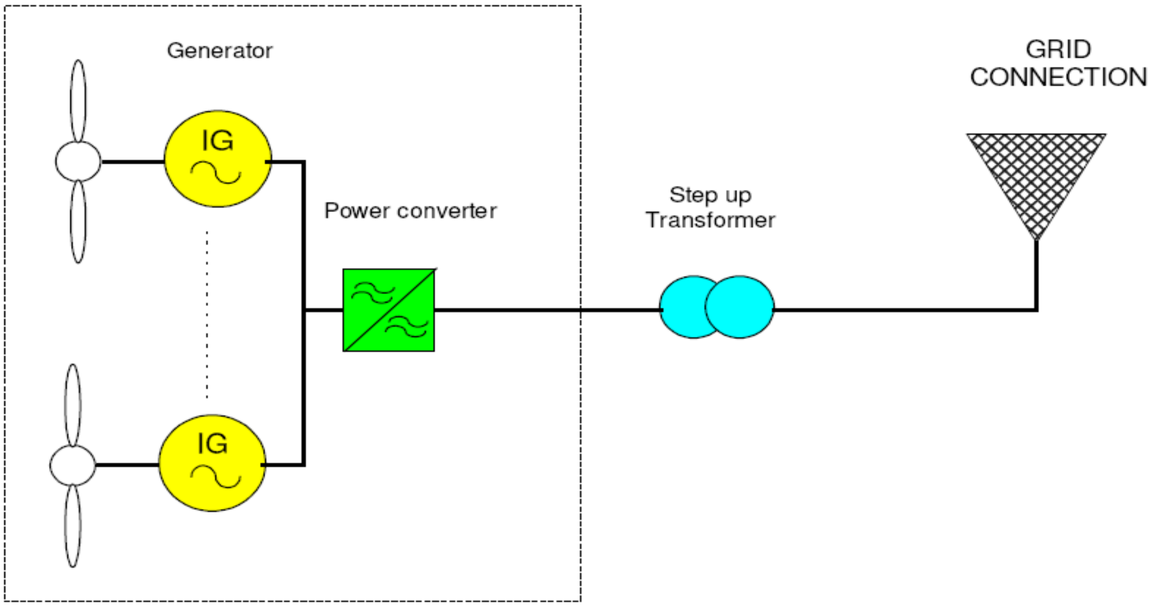


Figure 7.4 Option 3 – Multiple induction generators

Option 4 Under the active DC link option, each generator has a dedicated power converter machine bridge that feeds a common DC link; a single network bridge then feeds the transformer. This option is suitable for projects where generators are located closely together but not necessarily rotating at the same speed. Individual generator control is possible but if the converter network bridge needs to be shut down, power generation ceases. The assumed farm capacity of 30MW would in practice imply the use of two network bridges, each serving half the farm.

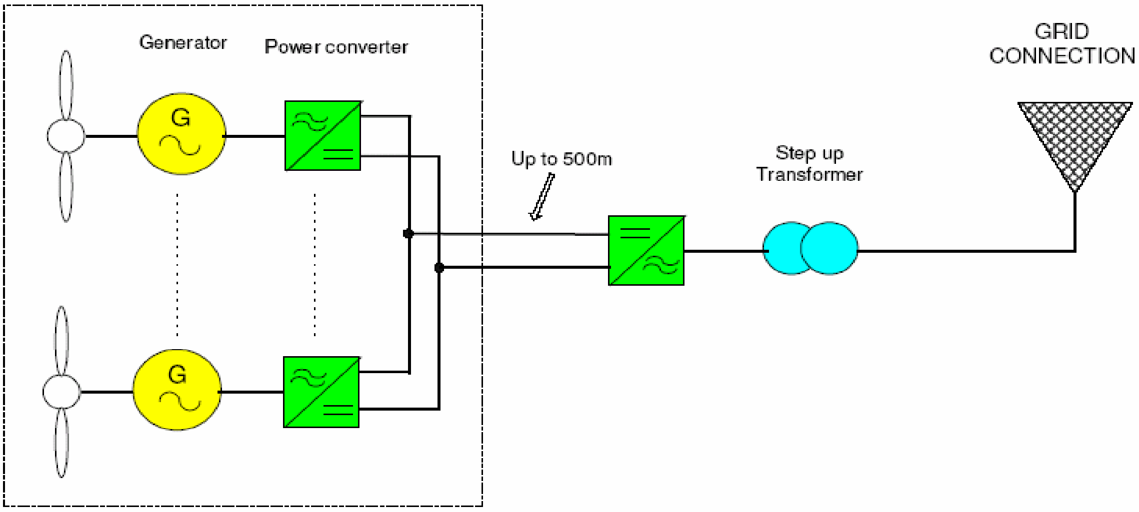


Figure 7.5 Option 4 - Active DC Link

Option 4 was selected as the basis of the study as representing the most economic overall solution consistent with a practical layout of turbines on the seabed. In summary, this will comprise rectifier equipment located in each turbine nacelle, which will convert the variable frequency AC output from each induction generator to DC at about 3.3kV. The DC output from each unit is connected via a common link to a single network bridge that converts the output from the tidal stream farm to 50Hz AC. This network bridge may be located either on a dedicated platform located centrally in the tidal stream farm, or onshore if the farm is close to land. The output from this bridge is connected to the Distribution Network.

7.3 Farm scale architecture

A fundamental assumption is that tidal turbine devices will be deployed in 'farms' comprising a number of individual turbines sharing certain common facilities and a common grid connection point. Whilst for the purposes of this study the assumption is that a farm will include 30 turbines, it should be noted that no effort has been devoted to determining an optimum farm size. The optimum farm size will be very dependent on specific site conditions. It is, however, necessary to consider the subject of farm scale operations briefly in order to establish the relative importance of the differences between fixed-pitch and variable-pitch turbines.

7.4 Connection to Distribution System

Initial deployments of marine turbine devices are likely to entail up to 30 devices with the nominal rating of devices constrained to about 1 MW per device by the available water depth, although some developers are now considering 2MW devices. The resulting farm capacity of some 30MW will be connected for export to the local network either at 33kV (distribution) or 132kV (distribution in England and Wales and transmission in Scotland). It has been assumed here that 33kV and 132kV are part of the Distribution Network.

Normally up to 20 MW can be readily connected at 33kV, with up to 30MW possible if the connection is to a particularly strong 33kV network. Due to the rural locations likely to be chosen for marine turbine devices, it may be more appropriate to connect the majority of farms over 20MW to the 132kV network. Connection at 132kV will be more expensive than at 33kV and, as with all connections, the actual cost will be location specific. As has been found with wind clusters and small wind farms, the connection cost could become a critical item in the financial viability of a marine turbine project.

As typically described above, each marine turbine device will generate 1MW of alternating current (AC) electricity and this will then be converted to direct current (DC) as the AC will not be at fixed frequency. Cables operating at DC will then take the output to a central, offshore hub where there will be an inverter to AC at a frequency of 50 Hz. Also positioned at this point will be a transformer and associated switchgear to raise the voltage to 33 kV or 132kV.

A 33 kV or 132 kV submarine cable will be installed to dry land where there will be an export meter and synchronising switch allowing connection to the local Distribution Network. At this point filters will be required to ensure voltage fluctuation/unbalance and harmonics do not exceed levels laid down in National Engineering Recommendations P28, P29 and G5/4. The operation of the generators will also need to conform to G75 and G59/1. Each installation will need to be studied by the relevant Distribution Operator for connection and the levels referred to in the documents listed discussed and adhered to.

G75:	Recommendations for the Connection of Embedded Generating Plant to Public Electricity Suppliers' Distribution Systems Above 20 kV or with Outputs over 5 MW
G59/1:	Recommendations for the Connection of Embedded Generating Plant to Public Electricity Suppliers' Distribution Systems
G5/4:	Limits for harmonics in the United Kingdom supply system
P28:	Planning limits for voltage fluctuations caused by industrial and domestic equipment in the United kingdom
P29:	Planning limits for voltage unbalance in the United Kingdom

7.5 Deployment and installation considerations

The device mounting structures have been assumed to be either a monopile with one or more devices per pile (sketches a & b below), or mounted on cross-arms or a semi-submersible structure anchored to the seabed and allowed to swing with the current direction (sketches c & d below) . The variable pitch devices mounted on a monopile will have rotating mechanisms to turn the devices during slack water to face the next tide tidal flow. The cost of the two installation methods has been assumed to be similar, within the scope of this project.

There are numerous proprietary approaches to the provision of maintenance access to tidal turbines, some the subject of patent applications or grants. Nothing in this report should be regarded as a comment on any specific system. However, the maintenance access systems may be divided into three broad categories, which will have different_costs relating to the type and size of boat/ship/crane and time taken to carry out the operations:

- **Changing the device geometry** (a&b). The device may be mounted on a tower fixed to the seabed, with the tower extending above the water level. The device is raised up the tower and clear of the water (eg by means of a jacking device) and may then be accessed from a boat or lowered onto a barge for transport onshore. MCT is an example of this approach.
- **Changing buoyancy** (c&d). The device is mounted onto a semi-submersible structure that can be manoeuvred to the surface by changing the buoyancy, where it may be accessed from a boat or lowered onto a barge for transport to shore. The TidalStream device is an example of this approach.
- **Detaching important elements from the seabed-mounted part of the device** (e&f). The device is mounted on a pylon fixed to the seabed, which does not extend above the surface. The device is detached from the pylon by divers or an ROV, lifted clear of the water by a heavy lift crane, and lowered onto a barge for maintenance there or onshore. An example is the Hammerfest Strom device.

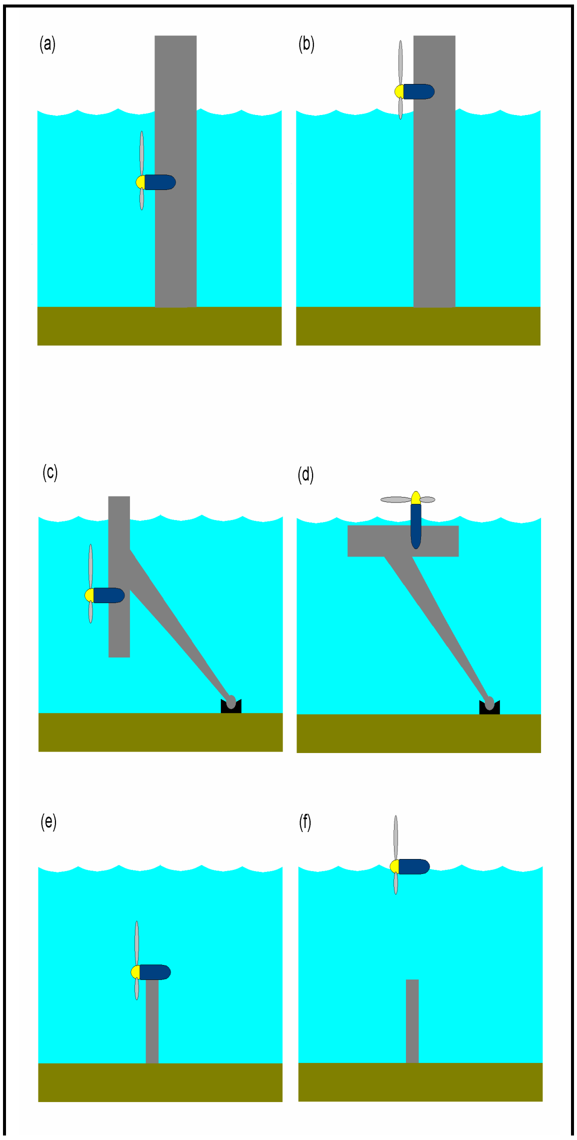


Figure 7.6 Maintenance access options

Maintenance of the tidal turbine with the device mounted in the operational position will be affected by weather conditions, the mounting concept and resulting accessibility. For the purposes of this project, we have assumed that it will be necessary to remove the device from the mounting structure and either carry out repairs to the device on a surface vessel, or return it to shore. In the latter case a replacement device could be installed in the same operation.

A related issue is the provision of appropriate facilities to allow safe human access to the interior of the installation. The project has recognised the importance from both a cost and safety perspective of minimising the use of divers in the construction and maintenance process but detailed consideration is outside the scope of this project.

7.6 Operation and maintenance

In deriving a cost for the operation and maintenance (O&M) for a tidal stream turbine device it has been necessary to make a number of assumptions since no units have yet been installed anywhere on a commercial basis, and hence there are no data bases or track records that can used. The scheduled O&M cost has been calculated on the assumption that a tidal stream farm comprising 30 off 1MW individual units is installed at a location 5km off the UK coast line, and that a suitable overhead line connection is available close to the shore. Scheduled maintenance has been based on an annual service visit to each turbine module with a major overhaul every five years when the complete turbine nacelle would be removed from its mounting and taken to a shore facility. Note, however, that costs of such operations are modelled as constant annual fees that are applied as average per-period cash flows.

The design of the turbine nacelle mounting system has not been defined as part of this study, but the same support system is assumed for both fixed pitch and variable pitch turbines, enabling a valid comparison between the maintenance costs of both types of turbine to be made. To keep maintenance costs to an economic level, and to minimise delays due to adverse weather, the turbine mounting support system would be designed so that turbine nacelles can be brought to the surface and be de-coupled from their mountings without the use of divers or a floating crane. However, it is assumed that divers would carry out an inspection of each turbine support structure every 5 years. This maintenance regime is seen as a conservative cost basis. The intention would be to include sufficient monitoring equipment to enable the annual maintenance visit and 5 year overhaul periods to be extended so that scheduled visits to each turbine could be extended to once every 5 years and the major overhaul period extended to 10 -15 years.

Control, monitoring and operation of the tidal stream farm is assumed to be from a remote facility that is an existing generating plant and that the operators of that plant could monitor/control the tidal stream farm without additional manpower resources. A high level of SCADA equipment would be included in each tidal stream turbine to ensure that all the important parameters were available both to operators in the control centre and to maintenance staff.

For the purposes of this study the major mechanical and electrical components housed in the nacelle, along with the rotor blades, were considered as a single replaceable unit for the purposes of maintenance, and have been termed a Line Replaceable Unit (LRU). In the event of a failure of a component in the LRU, or for some aspects of scheduled maintenance, the LRU would be removed as a complete unit by a support vessel and either repaired or returned to shore for more major servicing. To maximise the availability of the complete system, the support vessel could install a serviceable LRU to replace that removed for maintenance/repair.

The scheduled maintenance requirements for each turbine are based on typical scheduled maintenance requirements for offshore wind turbine units with appropriate modifications for tidal stream turbines. Estimates of the frequency and costs of unscheduled outages have been calculated using the Monte Carlo simulation method. This estimates the probability of failure for each type of turbine and the time taken before the unit is returned to service (failures solely causing degradation of output are not modelled). Using this system, and allocating an average cost for_each intervention to repair a failed component, the unscheduled maintenance costs for fixed and variable pitch turbines can be calculated.

The total scheduled O&M cost for a tidal stream farm of 30 units is estimated at £1.125m p.a. for a fixed-pitch installation, and £1.209m p.a. for a variable-pitch installation. The costs have been derived from maintenance cost data for offshore wind farms, which operate in a similar environment. This equates to an annual cost per LRU of 5% of initial capital cost. The unscheduled outage costs for a tidal stream farm have been estimated using North Sea Oil installation reliability data. The data were used to provide an estimate of the number of failures, and thus number of interventions, per period.

Unscheduled maintenance costs are modelled as a percentage of LRU cost (to reflect an average cost of repair) plus a fixed fee per intervention (to reflect any special charter/hire provisions or specialised crew fees which may be applicable). These figures include the cost of intervention for unscheduled outages and the loss of electricity production for the unit downtime. Overall availability is modelled as scheduled availability (95% used for all cases) multiplied by unscheduled availability, which is derived from the Monte Carlo simulation. This depends on device reliability and repair probability, which in turn was based on the probability of suitable sea conditions (when the significant wave height was less than 1m).

7.7 Decommissioning considerations

It is almost inevitable that the landlord for any of these devices around the UK will be the Crown Estate, who will include as a requirement of the lease or licence an obligation to decommission the offshore installation, but not necessarily the cables, on completion of its useful life. This requirement is in the process of being reinforced through a DTI consultation. On the assumption that the mounting structure will consist of a monopile, the requirement is likely to be to remove the structure to a level some distance below that of the surrounding seabed. This requirement will of course be common to both the fixed pitch and variable pitch devices. A notional sum has been included in the cost model.

7.8 System design assumptions

The list below details the main assumptions used in the performance of this project, in addition to those in the Background above.

Assumption	**Remarks**
Fundamentals	
Output takes the form of electricity.	Exclude outputs in the form of mechanical power, compressed gas, hydraulic power, heat, electrolysed hydrogen, desalinated water, chemical reaction product or other energy vector or commercially valuable commodity
Output is compatible with the UK grid system	50Hz, appropriate voltage & frequency limits etc. for compliance with Grid and Distribution Code.
Devices are located in identical conditions in Crown Estate waters.	Neglects variation that may occur between individual sites in a farm. Implies that applicable data for UK conditions are readily for the study.

Tidal Stream Conditions	
The tidal stream will vary over the semi-diurnal ebb and flow cycle with a period of 12.4 hours and a fortnightly spring /neap period of 353 hours	Simplifying assumption intended to make the study conclusions useful for a wide range of potential UK sites. Ignores effect of solar precession cycle.
Device in tidal stream with uniform velocity over the area swept by the blades.	Simplifying assumption that will generally not be true in practice owing to vertical velocity gradient and wave circulation effects.
The maximum tidal stream velocity at the site is 2.5 m/s	Assumption intended to make study conclusions useful for a wide range of potential UK sites.
Turbine axis is aligned in both directions with the tidal direction	Simplifying assumption that will generally not be true in practice but will provide a reasonable first approximation for many potential UK sites.
System Design	
Shore equipment 100m from the shore high water mark	To isolate report conclusions from effects of unusual site-specific features such as high cliffs, extensive areas of marshland, etc.
Electrical connection to 33kV 200m from shore equipment	Relates to strong 33kV connection for assumed farm size of 30 devices of 1MW each
Array configuration does not affect device performance	Simplifying assumption, meaningful analysis of actual array effect requires site-specific information.
No location constraints	Simplifying assumption, constraints site-specific.
Device performance identical for 'forward' and 'reverse' flow	Simplifying assumption.
Identical accessibility	Maintenance access issues are identical for fixed and variable pitch devices.
Corrosion protection free	No separate allowance for cost of replacement

	of sacrificial anodes or impressed-current protection.
Business & Commercial	
Cost elements are identical for fixed and variable pitch systems except where explicitly defined otherwise.	Overall system economics will have sensitivities to maintenance method, scale of farm etc., but fixed and variable pitch systems will use same values for each variable unless an intrinsic feature of the fixed or variable design precludes this.
Cost estimates for 'series production' rather than 'development'	Development costs several times higher; likely to preclude viable business case.
No special offset	Business model does not include special sources of finance e.g. DTI 'Wave and Tidal Stream Energy Demonstration Scheme'.
Analysis & Mathematical Modelling	
Cavitation effects negligible	Detailed analysis of these effects is beyond the scope of the study.
Reliability data applicable	Assumed that any reliability data used are representative of performance of component or system in tidal turbine context

8. COMPARATIVE SYSTEM COST ANALYSIS

8.1 Cost Analysis Model Methodology

The development and use of tidal turbines will require economic justification at a variety of levels. The development of the tidal turbines and their installation methods will require Original Equipment Manufacturers (OEM) to be satisfied that a viable market exists for their products. At the other extreme the electrical utilities that will buy the output and potentially develop, own and operate the tidal farms will need to be satisfied that the electricity produced by the tidal turbines can be utilised for an economic return in an auditable manner. If this utility business rationale is not satisfied then the market will not develop and the OEMs will not be attracted. For the purposes of this study the business model has been created from the electrical utility viewpoint, with the sole revenue source for the business deriving from the sale of electrical energy into a grid system and the relevant renewable financial support/incentive mechanism.

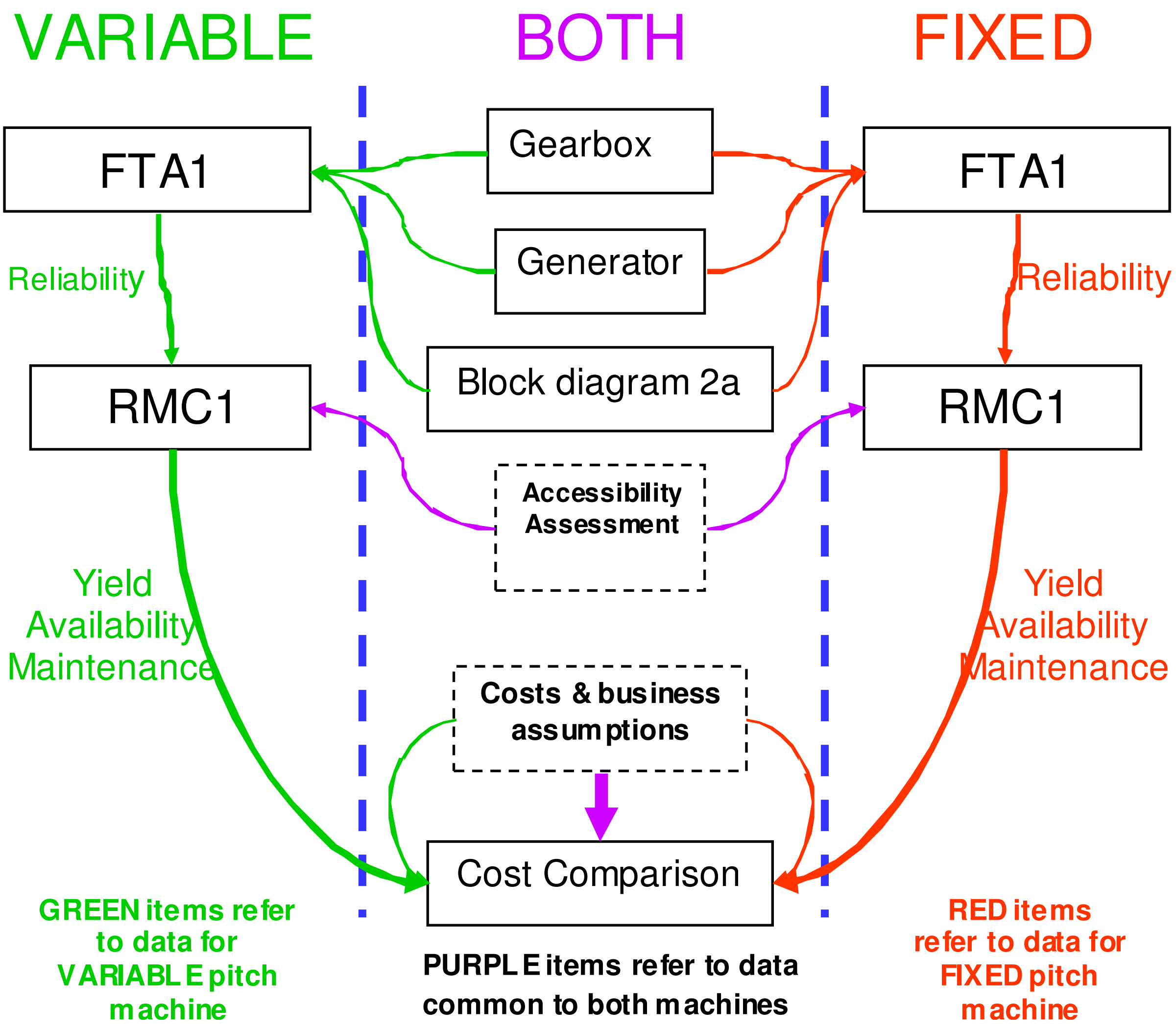
The purpose of this study is to assess the relative economic performance of two broadly similar devices that are physically different in detail. It is thus clearly necessary to consider all factors having a significant impact on the cost of the devices and on the revenue earned by the devices. Since the devices only generate revenue in the context of a working 'farm', it is also important to appreciate costs and benefits that are common, or broadly similar between the two devices. These additional costs and benefits affect the sensitivity of the study result to the differences between the machines.

Reliability and availability simulations, together with cost estimates for capital and maintenance costs, are fed into a spreadsheet, which provides a comparison of cost and revenue performance for each machine in the context of a 'farm' of a specified number of machines installed according to a user-defined schedule and (if so desired) automatically replaced at the end of their useful life (which may differ between the fixed- and variable-pitch machines). Costs common to both machine types are included at this stage. The spreadsheet model run duration was chosen to be 30 years to encompass the assumed 25-year mounting life and so to allow costs for decommissioning to be included.

Fault Tree Analysis (FTA) was chosen in preference to Failure Modes and Effect Analysis (FMEA) for the reliability elements of this study because it was considered easier to construct a generic analysis. To use FMEA, it is necessary to consider in detail each failure mode of each important component, which implies a level of detail design definition inconsistent with the aims of this study. The FTA technique allows a generic failure to be described without detailed consideration of the precise nature of the failure.

The block diagram at Figure 8.1 below describes the solution process followed.

Figure 8.1 Block Diagram of main information flow during study



KEY:
FTA1 = Fault tree analysis spreadsheet
RMC1 = Monte Carlo analysis spreadsheet
Blockdiagram2a = Generic tidal turbine system initial design tool
Gearbox1 = Epicyclic gearbox initial design tool

Accessibility Assessment
Installed machines will not always be accessible/repairable owing to weather conditions

8.2 Reliability and Availability Simulation Methodology

The simulation model used to predict reliability and availability levels for tidal stream turbine farms is based on the "Monte Carlo" method, described in Appendix A. The result of any Monte Carlo activity is always a simulation of the process, not an analysis of it. In principle, two successive Monte Carlo simulations of the same event with identical initial conditions will produce different answers. These answers will, however, be such as to permit the estimation of a 'true' value within some confidence interval.

Monte Carlo techniques are generally most suitable for situations where the probability equations for the process are intractable or, possibly, not capable of explicit formulation. The complexity of this approach increases geometrically with the probable number of failures during the device lifetime. The explicit calculation method also becomes more complex if the probabilities of each event are themselves functions of some other variable.

A situation that was considered as part of this study was the effect of seasonal weather conditions on the repairability of the device, assessed for the purposes of the study by assuming that repair probability P_{UA} is a function of elapsed time. The underlying assumption is that whilst the possibility of repair depends on the availability of appropriate spare parts and other resources, an overriding consideration is simply whether the device is accessible in order for the repair to be performed. For example, a device which fails at the onset of winter is likely to be out of commission longer than one which fails identically at the height of summer, simply because weather conditions preclude maintenance access to the former device.

For this study, several modelling approaches were considered before construction of the actual models. All the models use the concept of time measured in 'periods', with values chosen to be of significance to the desired outcome. No specific timescale is explicitly defined for a 'period'; it needs to be long enough to allow modelling of a meaningful proportion of the device lifetime, but short enough to capture detail. An instance of unserviceability can never be shorter than a complete period, so use of excessively long periods will lead to unrealistically low estimates of device availability. It is vital that values of transition probabilities used in the simulations are scaled to match the period chosen for the series of experiments. For this reason, use of excessively short periods not only results in extra computer time, but also implies that failure probabilities (as entered) become negligibly small. Typical period and experiment durations used for this study included:

240 periods (20 years with 1 period ≡ 1 month)
312 periods (6 years with 1 period ≡ 1 week)
1560 periods (30 years with 1 period ≡ 1 week)

The reliability of the fixed and variable concepts was assessed using data taken from the OREDA handbook (Ref. 10). This handbook is a DNV publication providing statistical data from Offshore Oil & Gas operations (ENI, BP, Exxon, Norsk Hydro, Phillips, Statoil, Shell, TotalFinaElf). The data are considered to be "High quality reliability data" for both topside and sub sea equipment, giving failure modes, observed number of failures, failure rate, uncertainty limits etc. Data are given as number of failures in 10^6 hours, for mean, upper and lower values (90% confidence).

An example of the OREDA failure rates and the overall calculated failure rates for the concepts is shown in Table 8.1 below.

OREDA Data	No of failures *		Unplanned Availability	
	Fixed	Variable	Fixed	Variable
Mean	52	71	92.6%	90.1%
Max	143	194	81.1%	74.5%
Min	3	5	99.6%	99.4%

*Mean number of failures per device over 30 years, determined from the Monte Carlo simulation. This was converted, assuming a constant failure rate, to a number of failures per turbine per unit time for cost modelling purposes.

Table 8.1 Failure rates and availability

8.3 Life cycle cost comparison of fixed and variable pitch devices

8.3.1 Financial Assumptions

Assumptions	Units	Fixed Pitch Farm	Variable Pitch Farm
Rated Plant capacity	MW	30	30
Capacity factor	%	23	25
Plant life	Years	15*	15*
Year cost base		2006 £	2006 £
NPV discount rate		10%	10%

* 15 years for principal LRU life, other elements have longer assumed lives.

Table 8.2 Financial assumptions

8.3.2 Cost Analysis

The schematic at Figure 8.2 below illustrates the major categories to which costs were allocated for the purposes of the study.

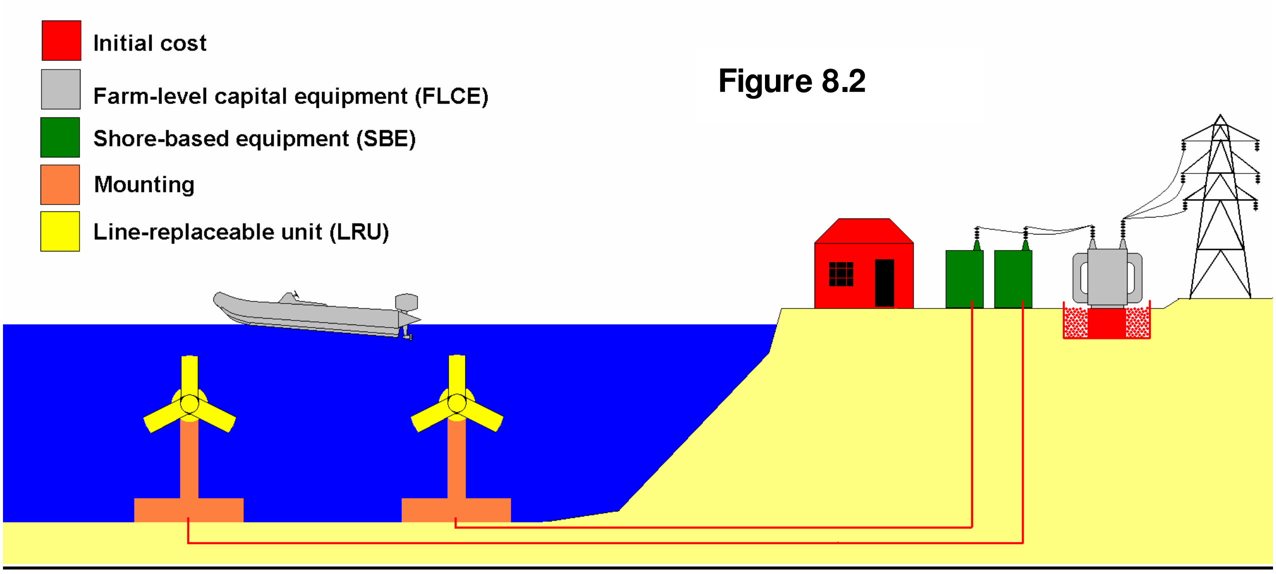


Figure 8.2

- Initial cost: Incurred at the start of the project, and covers elements such as land purchase, construction of roads, buildings, transformer bunds and similar items which could be considered to have 'infinite' life within the context of a tidal turbine farm.
- Farm-level capital equipment (FLCE): Paid once at start of project and upon FLCE life expiry. Includes items associated with farm operation but having finite life, such as grid connection equipment, workboats and so on.
- Shore-based equipment (SBE): Covers purchase and replacement of items associated with individual turbines but located ashore, the prime example being the network bridge equipment.
- Mounting: A device designed to hold one or more turbines, having a finite life but modelled as having zero failure rate. The variable pitch mounting includes provision for rotating the nacelle.
- Line replaceable unit (LRU): Essentially, the turbine plus directly associated power generation and conversion equipment (gearbox, generator, device bridge and ancillaries), all located subsea and having a finite life, finite failure rate and weather-dependent access restrictions.

The costs have been estimated for the fixed and variable concepts. For the purposes of the cost modelling results these costs have been factored to produce an overall cost of £1.250m/MW for the fixed concept, which then produced a cost of £1.318m/MW for the variable concept. This represents a 5.4% increase in cost for the variable pitch concept compared to the fixed pitch concept (consideration of the original cost estimates showed the components added or increased in cost relative to the fixed pitch items to represent a premium over the fixed pitch prices of about 7.5%; the overall effect including the items common to both solutions was then about 5.4%).

Cost of connection to the grid was modelled using the assumption that the connection would cost £120,000 per megawatt capacity, leading to a connection cost for the farm as modelled of £3.6 million. This assumption requires caution in its application because it is only a typically average cost for a 10MW to 20MW installation. For smaller sites the cost of connection could be understated and for larger sites, including the 30MW farm modelled, it could be overstated. It should be recognised that the minimum cost of a connection at the present time (2006) is likely to fall within the range £1 million - £2 million, and may be greater if the particular circumstances dictate the installation of a significant length of overhead line. In some circumstances, the connection cost could preclude the financial viability of an otherwise attractive tidal farm. Annex E of Reference 15 discusses this topic further.

The cost estimates for a farm with 30 off 1MW units, with 2 units per mounting is shown in Table 8.3 below. Operation & maintenance assumptions and estimates are shown in Table 8.4.

Cost Item		**Number per farm**		**Farm cost**	
	Cost	**Fixed**	**Variable**	**Fixed**	**Variable**
Initial set-up cost	£ 3,750,000	1	1	£ 3,750,000	£ 3,750,000
Farm Level Capital Equip,	£ 4,500,000	1	1	£ 4,500,000	£ 4,500,000
Shore Based Equip.	£ 150,000	15	15	£ 2,250,000	£ 2,250,000
Mounting - Fixed	£ 300,000	15		£ 4,500,000	
Mounting - Variable	£ 322,500		15		£ 4,837,500
Line Replacement Unit - Fixed	£ 750,000	30		£ 22,500,000	
Line Replacement Unit - Variable	£ 806,250		30		£ 24,187,500
			Total	£ 37,500,000	£ 39,525,000
			Cost/MW	£ 1,250,000	£ 1,317,500

Table 8.3 Cost estimates

Operation and Maintenance	Intervals	Fixed Pitch Total Cost (2006 £)	Variable Pitch Total Cost (2006 £)
Routine O&M (per MW/year)	p.a.	£37,500	£40,300
Major servicing	5 yrs	included in above	included in above
Unscheduled Interventions (£/intervention)	as required	£24,000	£25,700
Fixed annual farm running cost	p.a.	£320,000	£320,000
Rates	p.a	included in above	included in above
De-commissioning costs, per mounting	At yr 25 after mounting commissioning	£25,000	£25,000

Table 8.4 Operation & maintenance assumptions and estimates

8.3.3 Cost model results and cost of electricity

A number of cases have been analysed using the Cost Model; a list of the cases analysed is included as Appendix B. Using the unscheduled availabilities from the Monte Carlo simulations, the calculated hydrodynamic capacity factors and a fixed scheduled availability of 95%, the Cost Model calculates the annual energy produced, as shown in Table 8.5. For the base case, assuming the mean failure rates predicted using the OREDA data the annual energy production is 53 GWh for the fixed concept and 55 GWh for the variable concept, thus the variable concept produces 4.6% more energy. Note that the actual energy produced by each variable pitch concept is 20% of the total energy potential of a 1 MW generator. For the maximum failure rates predicted by the OREDA data the energy production falls by 12%, whereas for the minimum failure rates it increases by 8%.

The calculated cost of electricity are shown in Table 8.6 for the cases discussed. The Base case has a calculated cost of electricity over a 10 year operating period of £119 /MWh for the fixed pitch concept, compared to £129 /MWh for the variable pitch concept. These reduce to £94 /MWh and £104 /MWh for a 15 year period. Again the increase for the worst and reduction for the best OREDA failure assumptions can be seen. It must be noted that these latter figures assume a “best case” for the rate of failure, and are very sensitive to this assumption.

Case	Description	Reliability	Number of failures per device over farm life		Hydrodynamic Capacity Factor		Availability		Annual Energy Production MWh		Total Energy Production (25 yr) MWh	
		OREDA	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable
1.0	Base case, mean OREDA data	**Mean**	1288	1766	23%	25%	88%	86%	52,641	55,044	1,316,031	1,376,109
1.1	as above, Max OREDA (high Failure rate)	**Max**	3564	4838	23%	25%	77%	71%	46,108	45,557	1,152,692	1,138,916
1.2	as above, Min OREDA (low Failure rate)	**Min**	66	112	23%	25%	95%	94%	56,663	60,721	1,416,579	1,518,019
6.4	as 1.2, modified maintenance schedule	**Min**	66	112	23%	25%	91%	88%	54,340	56,738	1,358,503	1,418,458
9.0	as 1.2, with 50% annual running cost	**Min**	66	112	23%	25%	95%	94%	56,663	60,721	1,416,579	1,518,019
9.1	as 1.2 with 50% initial farm cost	**Min**	66	112	23%	25%	95%	94%	56,663	60,721	1,416,579	1,518,019
9.2	as 1.2 with 50% FLCE cost	**Min**	66	112	23%	25%	95%	94%	56,663	60,721	1,416,579	1,518,019
9.7	as 1.2 with 50% LRU cost	**Min**	66	112	23%	25%	95%	94%	56,663	60,721	1,416,579	1,518,019

Table 8.5 Annual energy production

Case	Description	Reliability	Annual Energy Production MWh		Cost of Electricity £/MWh			
					Fixed		Variable	
	Discount rate + 10%	OREDA	Fixed	Variable	10 years	15 years	10 years	15 years
1.0	Base case, mean OREDA data	**Mean**	52,641	55,044	£ 118.68	£ 94.00	£ 128.95	£ 103.97
1.1	as above, Max OREDA (high Failure rate)	**Max**	46,108	45,557	£ 178.09	£ 150.00	£ 218.89	£ 188.82
1.2	as above, Min OREDA (low Failure rate)	**Min**	56,663	60,721	£ 91.63	£ 68.67	£ 91.44	£ 68.73
6.4	as 1.2, modified maintenance schedule	**Min**	54,340	56,738	£ 94.73	£ 71.09	£ 97.05	£ 73.04
9.0	as 1.2, with 50% annual running cost	**Min**	56,663	60,721	£ 88.35	£ 65.46	£ 88.37	£ 65.74
9.1	as 1.2 with 50% initial farm cost	**Min**	56,663	60,721	£ 88.68	£ 66.72	£ 88.63	£ 66.91
9.2	as 1.2 with 50% FLCE cost	**Min**	56,663	60,721	£ 87.68	£ 66.10	£ 87.74	£ 66.34
9.7	as 1.2 with 50% LRU cost	**Min**	56,663	60,721	£ 70.93	£ 55.23	£ 70.50	£ 55.15

Table 8.6 Cost of electricity

8.4 Conclusions and Recommendations

In some respects the tidal turbine industry of 2006 is comparable to the wind industry of the early 1970s, with a large number of possible permutations of the various design options, a diversity of approach and a shortage of hard evidence as to which approaches are likely to have a commercial future.

The principal objective of this study has been to identify any circumstances under which “simple but less efficient” devices offer competitive life cycle performance to “complex but more efficient” ones. The results demonstrate that the relative merit of the two approaches depends upon the assessment criteria adopted and may be summarised as follows, within the range of performance parameters studied:

- The variable pitch machine (with an energy capture performance shown to be notionally 10% better than that of the fixed pitch machine in the rotor hydrodynamic study) produces more energy in a given period than the fixed pitch machine, unless the absolute reliability of both machines is very low,
- The fixed pitch machine always offers lower initial capital cost and unplanned maintenance cost than the variable pitch machine,
- The fixed pitch machine offers lower cost per unit of electricity generated unless the absolute reliability of both machines is very high,
- The percentage increase in energy capture using the variable pitch machine is generally much less than the notional 10% difference given perfectly reliable fixed and variable pitch machines; relative performances encountered during the study implied that the variable pitch machine would generally produce 4 – 7% more energy than the fixed pitch machine, although its worst performance produced 1% less energy.

The cost analysis shows that to be economically viable the reliability of a real device must equal or better the best reliability assumed for the study. This would seem to be a challenging target, but it should be noted that the study configurations incorporate no redundancy; it is possible that the overall reliability of a real device could be significantly improved given careful detail design and the incorporation of redundant features in specific areas.

It is recognised that the hydrodynamic capacity factors could be increased by limiting the power output from the rotor, and using a generator rated at below the maximum potential power available in the tidal stream. This would require a re-matching of the rotor diameter to the generator, but should have the effect of reducing the cost of electricity. Further consideration would need to be given to the matching of the power conversion equipment, fault cases where the power output exceeded the limit, and the impact on capital cost.

As indicated above, the variable-pitch variable-speed machine is superior in terms of capital cost per MWh to the fixed-pitch variable-speed machine when the reliability of both machines is very high. However, within the study, the maximum improvement calculated for the variable-pitch machine was a cost per MWh less than 4% better than for the fixed-pitch machine. Within the limitations of the study, the fixed-pitch approach offers the more robust design concept, with the theoretically better performance of the variable pitch device only being delivered when high absolute reliability is consistently achieved. This reinforces the view that it may be beneficial for designs to start simple (more robust and reliable) and later on to become more sophisticated. Wind turbine development followed a similar path.

Additional remuneration for 'renewable' generation over the commodity price of electricity generated is currently via an obligation on electricity suppliers to purchase a specified portion of their supplies as 'renewable generation' in the form of Renewable Obligation Certificates (ROCs). At present there is no differentiation between technologies but as electricity suppliers all face the same cost pressures they tend to follow each other's choices. Currently this choice is predominantly wind.

The Government proposes to amend the Renewables Obligation (RO) following the recent Energy Review and has issued a consultation proposing differentiated support levels to different renewable technologies and give additional certainty on long-term ROC prices. These changes to the RO will require new primary legislation and so will not be introduced until towards the end of this decade at the earliest.

Tidal power, whilst having a popular appeal in terms of 'green-ness perception' and environmental impact, is arguably one of the more expensive in capacity terms of the available technologies, certainly at this stage of its development. Its merits as part of a renewable portfolio lie in the predictability of the energy source allied to the perception that it is a development area whose time has come. While commercial deployment of devices will help to drive down the capital and operating costs, tidal power will need additional support while the successful concepts become competitive renewable energy options. Therefore higher value ROCs should be introduced for marine renewable technologies and be sustained while successful concepts achieve their potential.

Although the options analysed produced a variety of outcomes, there is sufficient encouragement to further investigate the fixed pitch device. The following activities offer logical steps to the implementation of a commercially successful tidal turbine device:

- Further refinement of the economic analysis methods used to determine parameters for an optimised device,
- Develop design specifications for a tidal stream turbine system and apply suitable processes to optimise the design point for a given set of tidal conditions,
- Undertake further reliability modelling to determine plant redundancy requirements,
- Undertake model testing of bi-directional sections both for cavitation performance and overall performance to confirm that predicted in the study,
- Install a reduced scale version of the device (around 20 – 30% full scale) in the field, probably with a dump load rather than a grid connection. Test results will be used to finalise the design of the prototype unit,

- Install a full-scale prototype at a suitable location with grid connection. This would not be commercially optimised, but would demonstrate all the major systems,
- Install a multi-unit tidal stream turbine farm using the commercial design incorporating developments from the testing of the prototype unit.

9. BIBLIOGRAPHY

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APPENDIX A: MONTE CARLO SIMULATION TECHNIQUES

A1. Explanation of Monte Carlo simulation methods

The term 'Monte Carlo' is used to describe methods of solution using the laws of probability to reach a statistical estimate of a desired quantity. The basic principle is that a process may be simulated by an average of a series of random events if certain characteristics of the events are appropriate to the process being simulated. The Monte Carlo simulation runs the process a large number of times, assigning random values to the events and taking an average of all the outcomes. The result of any Monte Carlo activity is always a simulation of the process, not an 'analysis' of it. In principle, two successive Monte Carlo process runs of the same event with identical initial conditions will produce different answers. The average result for the large number of processes run converges to a common solution. Monte Carlo techniques are generally most suitable for situations where the probability equations for the process are intractable or, possibly, not capable of explicit formulation.

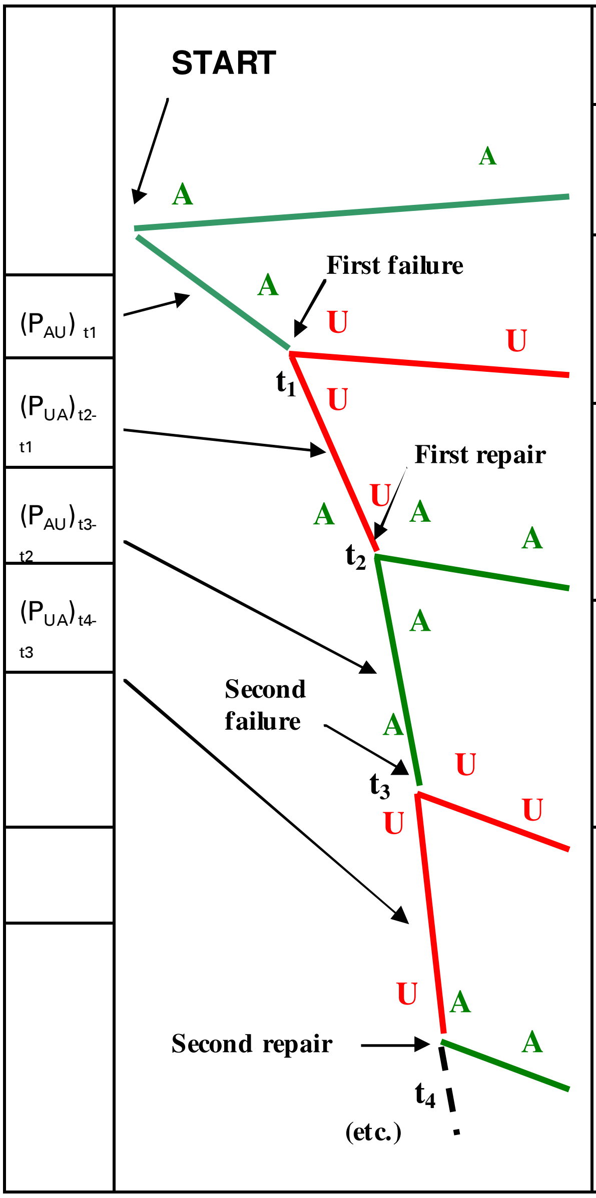
For example, if (as is required for this study), it is desired to estimate the proportion of its lifetime for which a device will be operating correctly, and the number of occasions during that period when it will become necessary to repair the device, it is in principle possible to construct a 'tree' showing the probability of each of the following circumstances:

1. Device operates without failure for whole design lifetime
2. Device operates for most of design lifetime, fails, but cannot be repaired before design lifetime expires
3. Device operates for most of design lifetime, fails, is repaired, and operates for remainder of life
4. Device operates for most of design lifetime, fails, is repaired, fails again and cannot be repaired
5. (and so on...)

Figure A.1 below illustrates the situation for a device, which may be in either of two mutually exclusive states, state 'A' (available) or state 'U' (unserviceable). The transition AU, with probability P_{AU}, represents failure, and the transition UA, with probability P_{UA}, represents repair. The overall lifetime of the device T_T comprises N equal time intervals I. The time during which the device is available is T_A. The availability of the device overall is given by T_A/T_T. The device starts in state 'A', and in any given interval 'I' its probability of failure is constant and is described as $(P_{AU})_I$. The probability of device failure over its complete lifetime T_T is denoted by $(P_{AU})_T$ – note the single subscript.

The diagram gives expressions for the probability of each outcome. By definition, the sum of the probabilities of all possible outcomes (i.e. including those not shown in the diagram) is unity. It is apparent that the complexity of this approach increases geometrically with the probable number of failures during the device lifetime.

Note that the probability expressions given in the diagram cannot in general be evaluated without knowledge of the intermediate times $t_1 \ldots t_n$. By definition, these are unknown, because they represent the times to random failure events, and (potentially random) repair times following each failure event. The explicit calculation method also becomes more complex if the probabilities of each event are themselves functions of some other variable. A situation considered as part of this study is the effect of seasonal weather conditions on the repairability of the device, assessed for the purposes of the study by assuming that P_{UA} is a function of elapsed time. The underlying assumption is that whilst the possibility of repair depends on the availability of appropriate spare parts and other resources, an overriding consideration is simply whether the device is accessible in order for the repair to be performed. For example, a device which fails at the onset of winter is likely to be out of commission longer than one which fails identically at the height of summer, simply because weather conditions preclude maintenance access to the former device.



Final State	Overall probability	Availability
A (no failure)	$(1-P_{AU})_T = (1-P_{AU})_I^N$	T_T/T_T (100%)
U (one unrepaired failure)	$(P_{AU})_{t1}*(1-P_{UA})_{T-t1}$	t_1/T_T
A (one repaired failure)	$(P_{AU})_{t1}*(P_{UA})_{t2-t1} * (1-P_{AU})_{T-t2}$	$[T_T-(t_2-t_1)]/T_T$
U (one repaired failure, one unrepaired failure)	$(P_{AU})_{t1}*(P_{UA})_{t2-t1} * (P_{AU})_{t3-t2}*(1-P_{UA})_{T-t3}$	$[t_1+(t_3-t_2)]/T_T$
A (two repaired failures)	$(P_{AU})_{t1}*(P_{UA})_{t2-t1} * (P_{AU})_{t3-t2}*(P_{UA})_{t4-t3} * (1-P_{AU})_{T-t4}$	$[t_1+(t_3-t_2)+(T_T-t_4)] /T_T$

Figure A.1 illustration of device states

The general approach adopted to modelling these problems is that a computer simulation of the device may exist on one of several mutually exclusive states, with probabilities of each possible transition between each pair of states defined either as a constant or as some arbitrary function, with, in general, the probability of transition from state 'X' to state 'Y' P_{XY} not equal to the reverse transition probability P_{YX}. The model is run for a large number of experiments, with specified values of the various probabilities and/or specified constants for the various probability equations. For each experiment, the model iterates through a predetermined number of time periods by generating a random variable in each simulated time period. By comparing the random variable with the appropriate transition probabilities, the appropriate 'destination' for the transition is chosen (which can include the 'transition' from state 'X' to state 'X', i.e. preservation of status quo). A record is then incremented of number of periods in a given state, number of transitions between particular states, or other interesting information.

The records of each experiment in a series may then be analysed statistically to produce estimates for the model, such as averages and standard deviations for availability, number of repair events required in a given lifetime and so on.

A2. Explanation of Monte Carlo simulation models

For this study, several modelling approaches were considered before construction of the actual models used. Consideration of the various conditions in which a tidal turbine might exist led to the concept of an 'eighteen state' model, representing the machine throughout its life cycle. The 'eighteen state' model was considered to be comprehensive, but as a result included conditions which would probably have little effect on the outcome of the comparative study. The complexity of the model increases rapidly with increasing number of states (in part, because the number of possible transitions increases geometrically with the number of possible states), and it was considered that the additional information provided by this model did not justify the extra complexity relative to a simple system. The 'eighteen state' model encouraged the development of a notation to identify the various states, which was preserved (with one modification) for subsequent work.

Elimination of the (assumed) least frequently encountered states from the 'eighteen state' model led to the development of a 'five state' model. Contemplation of this model led to the conclusion that it still represented excessive detail for the purpose of this study (although either the 'eighteen state' or 'five state' models might be worth further study in the context of an investigation focused on the detailed economics of a particular device).

All the models use the concept of time measured in 'periods', with values chosen to be of significance to the desired outcome. No specific timescale is explicitly defined for a 'period'; it needs to be long enough to allow modelling of a meaningful proportion of the device lifetime, without the creation of excessively large computer files, but short enough to capture detail. An instance of unserviceability can never be shorter than a complete period, so use of excessively long periods will lead to unrealistically low estimates of device availability.

It is vital that values of transition probabilities used in the simulations are scaled to match the period chosen for the series of experiments. For this reason, use of excessively short periods not only results in extra computer time, but also implies that failure probabilities (as entered) become negligible. As an example, a device with a failure probability of 0.0001 per hour has a 50% probability of failure after a period of 6931 hours (0dp), or about 9½ months. To model the same device at periods equivalent to one second, the failure rate per period must be entered as 0.00000003. A failure rate of 0.0001 per hour is possibly too high for economic viability of a tidal turbine. Typical period and experiment durations used for this study included:

240 periods (20 years with 1 period ≡ 1 month)
312 periods (6 years with 1 period ≡ 1 week)
1560 periods (30 years with 1 period ≡ 1 week)

A2.1 ‘Eighteen-state’ model

Figure A.1 below shows the main features of the ‘eighteen state’ model. The various states are identified and described fully in the table below. An important feature of this model was that each state was associated with a three-by-three matrix expressing the output as ‘scaled full’ (i.e. whatever would be expected given the conditions at the time), ‘degraded’ or ‘zero’, and the accessibility of the device as ‘irrelevant’, ‘accessible for repair’ or ‘inaccessible for repair’.

The CD & DC transitions (and corresponding pairs between other states) were to be determined by a random or partially random variable; these transitions representing occasions when the weather and/or sea state became unsuitable or suitable to permit safe access to the device.

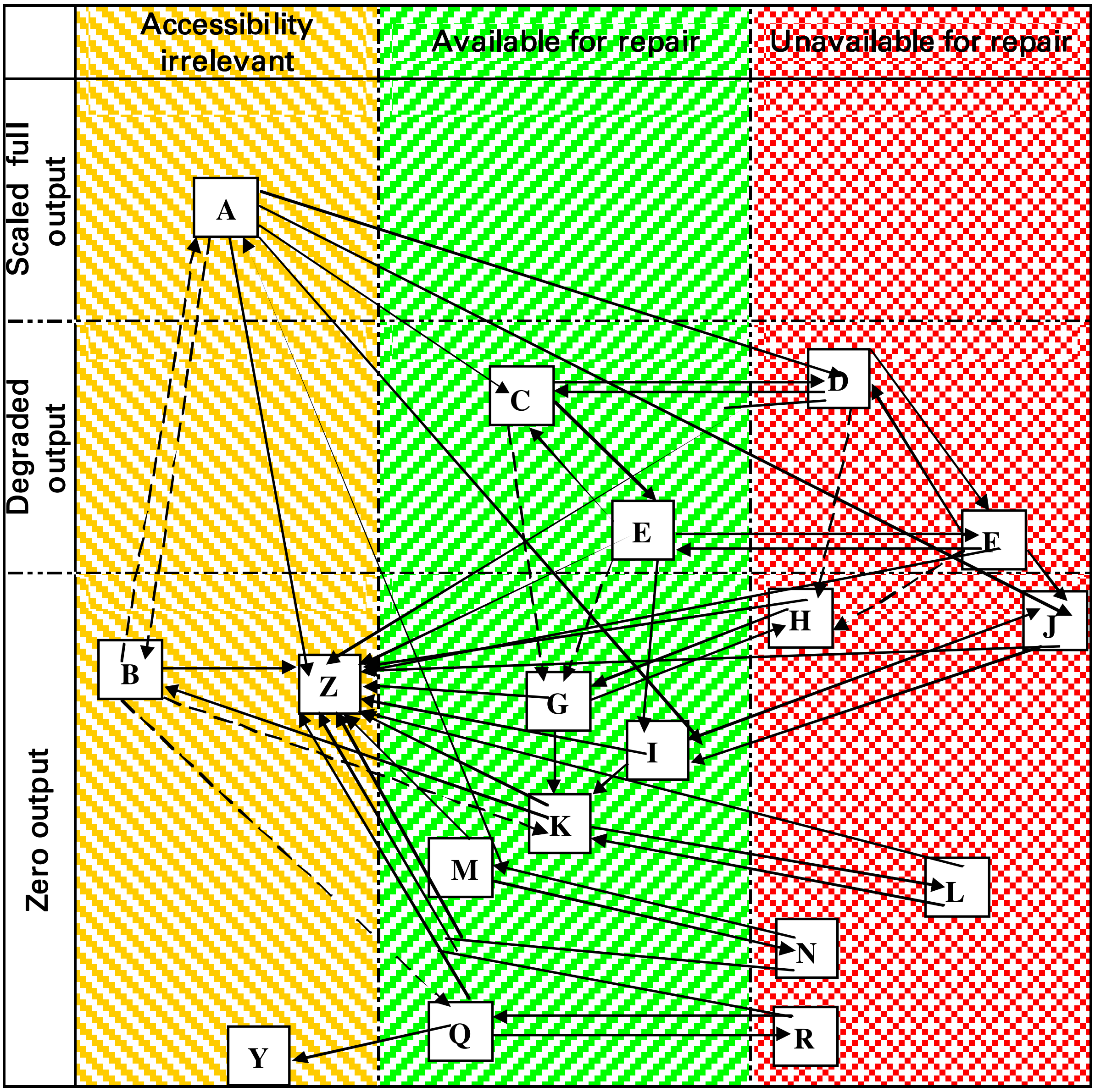


Figure A2 Main features of "Eighteen-state model

Certain transitions (shown with dashed arrows in the diagram) were solely the result of operator action. It was contemplated that operator strategy might affect overall farm economics, by (for example) only permitting limited degradation before shutting the machine down. However, a machine having been repaired or reconditioned was assumed to be returned to service as soon as possible without operator action. It was assumed that the probability of destruction would always be lower from a non-operational than from an operational state.

The effect of 'operator strategy', whilst possibly of importance to the operator of a tidal turbine farm (and an interesting topic for study in its own right), is not directly relevant to the aims of this study, so for this purpose represents an undesirable complication.

It was assumed that each instance of degradation (state 'E' or 'F') would be associated with a reduction in device yield, modelled as a simple percentage of original output, as a percentage of output at the time of degradation or as a random variable such that the effect of each degradation of output would vary from incident to incident.

One reason for moving away from this model was that exploration of the full solution space would require very large amounts of computer time to correctly represent the effects of those transitions having a low overall probability of occurrence.

Notation	Description	Accessible?	Output	Remarks
A	Serviceable & operating	?	100%	Most of elapsed time in this state for economic viability
B	Serviceable but deliberately shut down	?	0%	
C	Faulty but operating	Y	0-100%	Output not explicitly defined
D	Faulty but operating	N	0-100%	Output not explicitly defined
E	Faulty, output (further?) degraded	Y	0-100%	CE transition implies reduced output
F	Faulty, output (further?) degraded	N	0-100%	DF transition implies reduced output
G	Faulty, deliberately shut down	Y	0%	To allow repair during scheduled maintenance period?
H	Faulty, deliberately shut down	N	0%	As an alternative to destruction?
I	Failed completely	Y	0%	
J	Failed completely	N	0%	
K	Undergoing repair / refurbishment	Y	0%	Remove marine growth etc. or repair ?
L	Interrupted repair / refurbishment	N	0%	
M	Commissioning	Y	0%	Once per life cycle
N	Interrupted commissioning	N	0%	
Q	Decommissioning	Y	0%	Once per life cycle (if not destroyed)
R	Interrupted decommissioning	N	0%	

Y	Decommissioned	?	0%	Out of water?
Z	Destroyed	?	0%	Beyond economic repair

Table A1 Monte Carlo notation

Whilst the above forms a comprehensive representation of the life cycle of a device, most of the time must be spent in state 'A' for economic viability. It is questionable what value may be had from the fine detail of the minority of the time spent not operating.

A2.2 'Five-state' model

A significant difference between the 'eighteen state' and the 'five state' models was that for the 'five state' model, accessibility was no longer considered as an explicit feature of the solution. Seven of the eighteen states in the 'eighteen state' model directly corresponded with seven of the other states, the sole distinction being whether repair operations were possible. The model could be simplified by replacing the duplicated states with variable transition probabilities, such that (for example) a low value for repair probability could correspond to winter conditions and an inaccessible device, whilst a higher value might reflect summer conditions.

It was also recognised that some of the states were trivial for the purpose of calculating device availability and maintenance. For example, logically, a device having been repaired would indeed spend a short time in state 'B' (serviceable but shut down) before being returned to full operation, but in practice the amount of time spent in 'B' would be short (of the order of a few hours) compared to a time step of the Monte Carlo simulation (of the order of a week, or perhaps a month).

The result of these considerations was the model shown at Figure A3 below. Operating states are as described for the 'eighteen state' model above, except that the accessibility of the device is not explicitly known from the operating state.
The diagram includes notations for the probabilities of various transitions (omitted from the 'eighteen state' diagram for clarity).

Note that P_{VW} where V=W represents the probability that the machine will remain in its present state. Also, P_{KK} may be related to the mean time to repair the machine. P_{II} and P_{CK} may be related to the accessibility of the machine owing to weather conditions (although these also depend on the availability of parts and labour to conduct a repair).

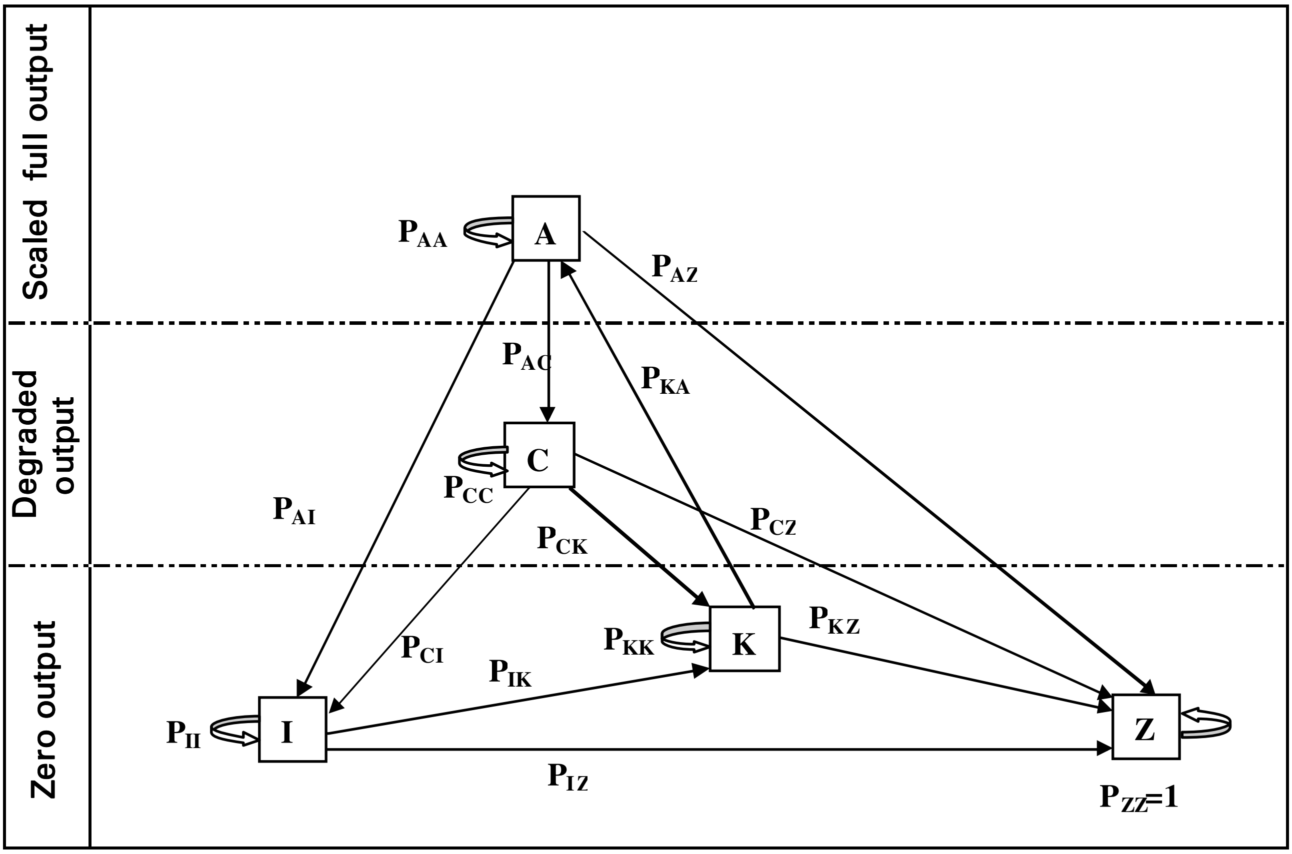


Figure A3 Five-state model

Probabilities of transitions between the various states are also shown in **Table A2** below.

		Final state				
		A	C	I	K	Z
Initial state	A	P_{AA}	P_{AC}	P_{AI}	0	P_{AZ}
	C	0	P_{CC}	P_{CI}	P_{CK}	P_{CZ}
	I	0	0	P_{II}	P_{IK}	P_{IZ}
	K	P_{KA}	0	0	P_{KK}	P_{KZ}
	Z	0	0	0	0	1

Table A2 Probability of transition between states

The total number of possible sequences for a run of N time periods is thus 4^N, although some of these sequences are trivial, and if the objective is to estimate the availability and number of repair events, it is likely that many sequences will be equivalent. However, it should be remembered that the above model, run with time periods representing one week for 52 periods, i.e. representing one full year of operation, could produce in principle any of approximately 2×10^{31} possible outcomes, ignoring the fact that, as implied above, some of the outcomes are 'impossible'.

This example highlights how complex even an apparently simple model such as the above may be in practice. It was considered desirable to simplify the model even further for the purposes of this study.

A2.3 'Two-state' model

The 'five-state' model may be simplified further by assuming that the probability of device destruction is identical for each device, and in any event sufficiently small to have little effect on the overall farm economics. It may be argued that, for the purpose of calculating device availability, it matters little whether a device has 'failed' (state 'I') or is 'under repair' (state 'K'), because in neither case is it generating. The foregoing arguments imply a three-state model, which is working normally, working at reduced output or not working. As a final simplification, ignoring the state of degraded operation results in a 'two-state' model (with a change of notation), which is either in state 'A' (available and operating) or state 'U' (unserviceable). This forms the basis of the model used for most of this study, Figure A4.

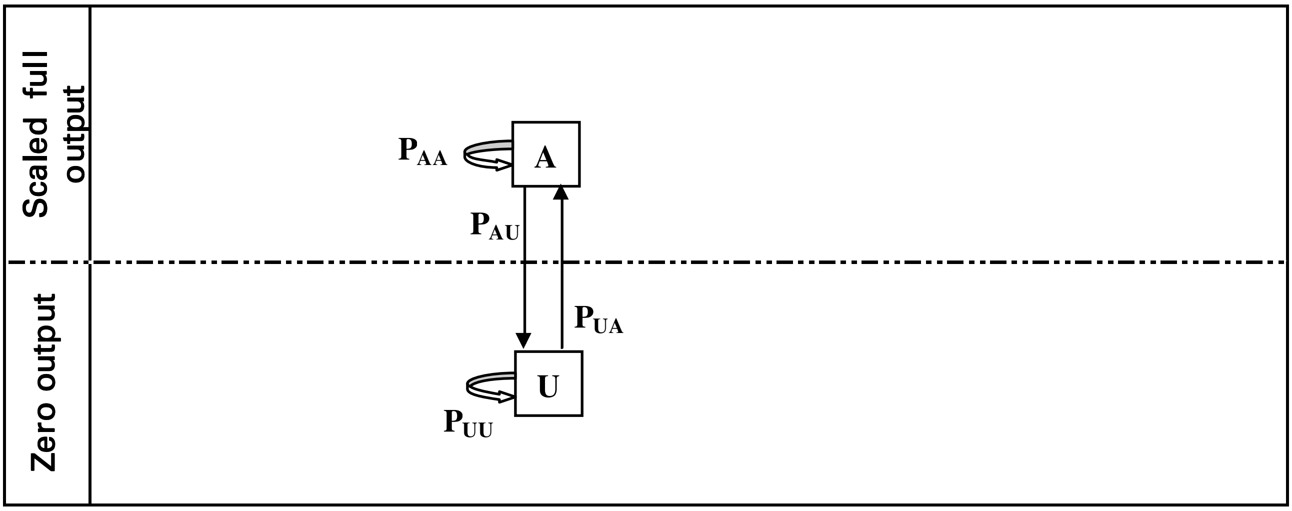


Figure A4 Two-state model

Again, P_{VW} V=W represents the probability that the machine will remain in its present state. Probabilities of transitions between the various states are also shown in the table below.

For this model, P_{AU} (failure probability per time increment) may be constant, or could in principle be a function of some other variable. For example, P_{AU} could be a function of elapsed time chosen to simulate general wear and deterioration or perhaps to replicate the well-known 'bathtub' failure rate curve.

		Final state	
		A	U
Initial state	A	P_{AA} (=1-P_{AU})	P_{AU}
	U	P_{UA}	P_{UU} (=1-P_{UA})

Table A5

P_{UA} is perhaps best represented as a function of elapsed time. It may then represent the effects of bad weather precluding access to the device for part of the year.
For much of the work conducted in support of this study, P_{UA} was modelled as:
$P_{UA} = P_{UAmax} - (A_1[\sin(2\pi(A_4 t + A_3)/T_T)]^M)$
where
P_{UAmax} = maximum value of P_{UA} allowed for the given series of experiments
A_1 = Arbitrary constant, controlling the minimum value of P_{UA} for the series of experiments
A_3 = Arbitrary constant, controlling the ‘phase shift’ of the P_{UA} curve
A_4 = Arbitrary constant, controlling the period of the P_{UA} curve
t = Elapsed time
T_T = Total time (in ‘periods’)
M = Exponent (positive integer) Note that the value of A4 differs by a factor of 2 for a given P_{UA} curve period, according to whether the exponent is even.

This function was chosen to give a reasonable degree of control over the form of the P_{UA} curve without the user having to input a large number of arbitrary constants.
For example, the idea was considered of allowing the user to input a separate P_{UA} for each period of the experiment, or at least for a recurring subset of the experimental periods, so allowing (for example) repair probabilities to be defined for each calendar month. This would add seven degrees of freedom to the model (versus the sinusoidal model described above), but would not necessarily clarify the results.
Reference 11 was used to estimate a range of access probabilities for a notional device in likely UK locations. Correspondence between the ‘power-sine’ P_{UA} function incorporated in the Monte Carlo simulation and the access probabilities calculated from Reference 11 over the course of a calendar year varied; in some cases a close match was obtained whilst in others the ‘power-sine’ formulation could replicate the maximum and minimum or the mean values, but did not otherwise display good correspondence with the Reference 11 function.

APPENDIX B: CASES ASSESSED

The various cases assessed are summarized in the table below. The complete run plan (and results, when available) was populated into a spreadsheet containing full details of assumed costs etc. In general, all run inputs matched those for Case 1.0 unless otherwise specified, with the main exceptions that overall device availability and expected number of failures vary according to failure rate, accessibility and (for those cases modelling 'no unscheduled maintenance') maintenance interval.

For all runs, equipment was ordered so as to produce maximum farm output as soon as possible, and automatic re-ordering of all equipment except mountings was permitted, so each run modelled a farm generating for a twenty-five year period within an overall run duration of thirty years, including decommissioning of all installed mountings (but not including any other site decommissioning cost element). Note that the individual cases were not calculated in the order listed in **Table B1** below.

List of Cases Assessed		
Case	**Description**	**Remarks**
1.0	Baseline case, two LRU per mounting, mean failure rate. Variable speed for both types.	P_{UA} represents Reference 11 node 16357 [50.413°N, 1.650°W English Channel] for $H_{sig} = 1m$
1.1	As 1.0, but maximum failure rate	
1.2	As 1.0, but minimum failure rate	
2.0	Alternative case, two LRU per mounting, mean failure rate. Fixed speed for both types.	Questionable whether this assumed specification would be acceptable for connection to the UK grid.
2.1	As 2.0, but maximum failure rate	
2.2	As 2.0, but minimum failure rate	
3.1	As 1.0, but four LRU per mounting	Changes in mounting and SBE cost to reflect four LRU per mounting. Farm capacity limited to 30MW installed, to retain comparison basis. Mounting order quantities changed.
3.2	As 1.0, but one LRU per mounting	Changes in mounting and SBE cost to reflect one LRU per mounting. Farm capacity limited to 30MW installed, to retain comparison basis. Mounting order quantities changed.
4.1	As 1.0, but 50% of initial farm cost	
4.2	As 1.0, but 200% of initial farm cost	
4.3	As 1.0, but 50% of FLCE cost	
4.4	As 1.0, but 200% of FLCE cost	
5.1	As 1.0, but 50% of LRU life	Results reflect the changed number of replacement LRUs needed (calculated by model)

5.2	As 1.0, but 200% of LRU life	Results reflect the changed number of replacement LRUs needed (calculated by model)
6.0	As 1.0, but no unplanned maintenance, 1 year planned maintenance interval	′
6.1	As 6.0 but two year maintenance interval	Cost results should be regarded as OPTIMISTIC, as failure rate underestimated for this specific circumstance by calculation process
6.2	As 6.0 but maximum failure rate (Case 1.1 assumptions apply)	Case not calculated as other Case 6 runs indicated this situation would be uneconomic
6.3	As 6.1 but maximum failure rate (Case 1.1 assumptions apply)	Case not calculated as other Case 6 runs indicated this situation would be uneconomic
6.4	As 6.0 but minimum failure rate (Case 1.2 assumptions apply)	
6.5	As 6.1 but minimum failure rate (Case 1.2 assumptions apply)	
7.0	As 1.0 but maintenance by DSV	Same location as 1.0 but H_{sig}= 4m to reflect DSV capability and intervention fixed fee £150000 (normally £1500)
7.1	As 1.1 but maintenance by DSV	As 7.0
7.2	As 1.2 but maintenance by DSV	As 7.0
8.0	As 1.0 but worse access probability	P_{UA} represents Reference 11 node 14824 [59.579°N, 4.315°W West Shetland Shelf] for H_{sig} = 1m. P_{UA} function chosen overestimates access probability for about 55% of year but preserves overall average. May not be sensible to use RIB in this location.
8.1	As 1.1 but worse access probability	As 8.0
8.2	As 1.2 but worse access probability	As 8.0
9.0	As 1.2 but 50% annual running cost	
9.1	As 1.2 but 50% initial farm cost	
9.2	As 1.2 but 50% FLCE cost	
9.3	As 1.2 but 50% initial farm cost & 50% FLCE cost	
9.4	As 1.2 but 50% initial farm cost & 50% annual running cost	
9.5	As 1.2 but 50% FLCE cost & 50% annual running cost	
9.6	As 1.2 but 50% initial farm cost, 50% FLCE cost & 50% annual running cost	
9.7	As 1.2 but 50% LRU cost	Maintenance cost allocation preserved by doubling percentage maintenance allocation.

Table B1 Cases assessed