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Investigating the Potential for Tidal Energy Development in Dumfries and Galloway

By

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Declaration of Authors Rights

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Abstract

The waters off the coast of Dumfries and Galloway are known to possess a significant tidal current resource and Scottish Enterprise has indicated a willingness to ensure that the potential for development of tidal power in the area is maximized. The tidal power industry is in the early stages of development and much more research is required if tidal power is to make a significant contribution to electricity generation in the UK, but even at this early stage it is important to investigate the potential of the various sites which have been identified with significant tidal flow. This project was commissioned to investigate further the tidal resource off the coast of Dumfries and Galloway and to make recommendations as to how it can best be exploited.

Initial questions were raised as to the potential suitability of the site to accommodate a test centre facility, similar to the existing one in Orkney, but in less extreme conditions. It was thought that this could be a useful facility for testing devices at the early stages of development, in relatively benign conditions. Therefore the resource in the area is analysed on a fairly broad level in order to assess the suitability of the region to this kind of application. All the various constraints are considered in order to rule out unsuitable areas and make suggestions of potentially suitable sites.

The resource is analysed in more detail at its most intense point, off the tip of the Mull of Galloway, in order to make a detailed evaluation of the potential for electricity generation on a commercial scale in the region. This is important as any commercial generation would be likely to require the strengthening of the electricity distribution and transmission networks in the area.

Initial findings are that there is an area south of Luce Bay that may be suitable for future development as a test site although further research will be required to confirm this. Among the many constraints identified, possibly the most significant is the local wave climate, which may be reasonably severe given the sites exposure to prevailing winds. It was also found that the resource round the Mull of Galloway could, in future, make a significant contribution to the electricity network with the benefit of being entirely predictable.

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1.0 Introduction

1.1 Background

As the United Kingdom Government continues its drive to reduce carbon emissions and sets long term targets to achieve, the need to exploit new and previously untested energy sources takes on greater prominence. Tidal stream energy is one such resource which although untried offers great promise for providing a base load electricity supply.

The government has set targets to generate 10% of the UK's electricity supply from renewable energy by 2020, compared to 5% in 2006 (Department for Trade and Industry (DTI), 2006), while in Scotland the target is 40% given the large proportion already generated by hydro-electric schemes (The Scottish Executive, 2003). With the exception of the long established hydro plant across Scotland the most prominent form of renewable energy is wind power, which has now become tried and tested technology, although the very nature of the resource makes it both unreliable and unpredictable. However if government targets are to be met, it is essential that all possible resources are considered and investigated, giving rise to essential research into harnessing tidal energy.

Generating energy from the motion of the tides is still very much in its infancy and it is only in the last few years that significant steps have been taken to quantify the potential for generating electricity in this manner. The Carbon Trust, the DTI and a number of universities have all carried out studies into the potential resource which could be exploited in the UK; while there have been a number of developers coming forwards with different kinds of generating technology.

In this climate of relatively immature development one of the main requirements is for adequate test facilities, both for the development of technology and in order to discover what kind of impact that energy capture has on the tidal flow and the local environment. Also full scale tests provide the opportunity to evaluate the power quality of these devices prior to launching full scale commercial projects.

Prior to the construction of the European Marine Energy Centre (EMEC) in Orkney, no such facility existed anywhere in the world and EMEC's development has undoubtedly been a big step forward for the industry. However, it is possible that there may, in the short to medium term, be the potential demand for the development of further test sites. A particular gap which has been identified is the lack of any test facilities in a much less harsh and more accessible location in order to facilitate the development of new technology, particularly in the earlier stages of design.

As discussed later in this report, the Carbon Trust's studies into the potential resource in the UK identified the tidal flow round The Mull of Galloway in Dumfries & Galloway as an area of particular interest (see Section 1.4) and Scottish Enterprise are keen to make the most of any potential development in the area.

1.2 Project Objectives

The main objective of this project was to investigate the potential for locating a test centre off the coast of Dumfries & Galloway in what is a much less harsh environment than that experienced at the EMEC site in Orkney. Initially, this involves assessing whether or not there are any suitable sites for such a development, taking into account issues such as the nature of the resource, the local bathymetry and the local infrastructure.

If it transpires that the area does lend itself to hosting a tidal test centre then the question arises of what this will involve, what changes or improvements will have to be made locally to accommodate it and what kind of impact it would have, both environmentally and economically.

This project seeks to address these issues at this early stage and provide a conclusion regarding whether or not there is potential for pursuing this development and to provide recommendations regarding the geographical areas that would be suited to it. It also aims to provide recommendations on what steps must be taken in both the immediate future and long term to ensure that the potential for exploitation of the tidal resource in the region on a commercial scale is maximised.

Therefore, as well as assessing the potential for testing in the region, this project looks to evaluate the resource in the most promising locations and make judgements of how much electricity this could be expected to yield given the technology which is being developed. Early appreciation of the possibilities will help to ensure that the necessary steps are taken now to maximise its exploitation.

1.3 Tidal Stream Energy

Tides are a familiar concept and can be defined as 'the periodic rise and fall of the waters of the ocean and its inlets, produced by the attraction of the moon and sun, and occurring about every 12 hours. (Dictionary.com, 2007)' The primary force which drives the tides is provided by the moon in its orbit around the earth and this force is essentially the moon's gravitational pull, coupled with the centrifugal force experienced by the water as it rotates around the earth's axis. This has the effect of creating tidal bulges on both the side of the earth facing the moon and the opposite side, as shown in Figure 1.

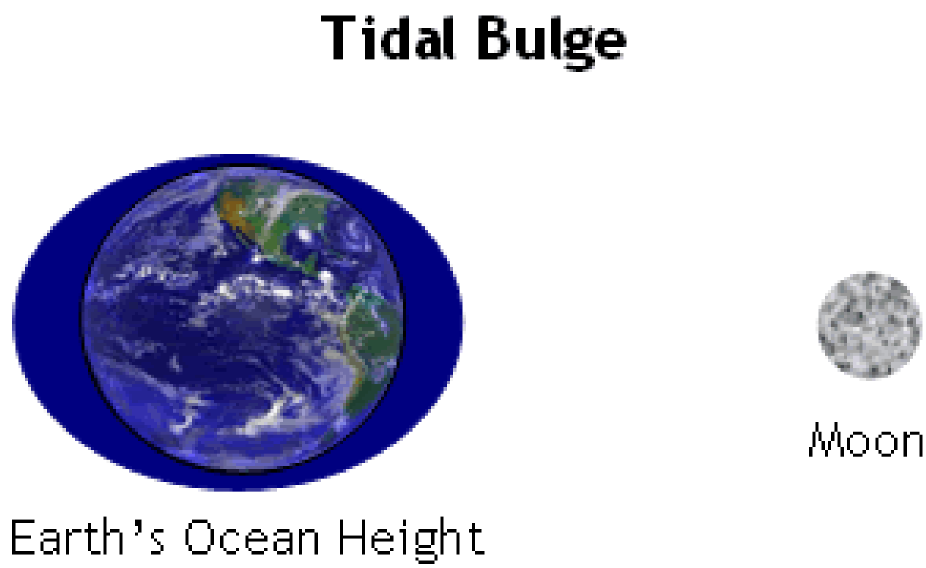


Figure 1: Tidal Bulge (Image Courtesy of RTS Weather Centre)

Similarly, the sun exerts a gravitational pull over the earth's waters but its massive size is compensated for by the great distance between it and the earth resulting in the sun's influence on the tides being about 0.46 that of the moon (The University of Edinburgh, 2006). This contribution is significant however, and this is illustrated by the difference between spring and neap tides (greater than average tidal flow and lower than average tidal flow respectively).

Spring-tides, occur when the moon is either new or full, i.e. the sun, moon and earth are all in line, and so their respective gravitational forces complement each other. Neap-tides, however, occur at half moon, when the forces of the sun and moon are acting at right angles to each other and have the effect of canceling each other out, to an extent (RTS Weather Centre, 2006).

This results in massive horizontal movements of water as the tides ebb and flow and where flow is particularly dense, such as through channels and round headlands, velocities are high. Flows such as these are known as tidal currents and in these locations flow is predictable and bi-directional, as opposed to open seas where flows are more complex.

Where such flows exist it is possible to harness the energy to generate electricity and it is in this particular form of tidal energy that the main thrust of activity exists at the moment.

1.4 The Tidal Resource in the UK

The United Kingdom is considered to have one of the most significant tidal resources in the world with the extractable energy initially estimated to be around 22,000 GWh/year (Black & Veatch Ltd, 2005). For the study which came up with this figure, 57 sites were considered and it was found that 80% of the UK's tidal resource existed at the top ten sites, as shown in Table 1. Further investigation of this however, revealed that the potential resource had been significantly overestimated. Research carried out by Black & Veatch for the Carbon Trust (2005) found that limitations on the amount of energy extractable from any given site had more of an impact than was previously expected.

These limitations came to be known as the Significant Impact Factor (SIF). The SIF was defined by Black and Veatch as 'the percentage of the total kinetic energy resource at a site that could be extracted without significant environmental or economic effects'. While this was initially estimated to be around 20% for all sites (the figure which spawned the 22,000 GWh/y estimate) it was later found that this could vary significantly with some sites having a SIF as low as 8%. The SIF for the Mull of Galloway was estimated to be 12%, meaning that 12% of the tidal energy present should be extractable with marine energy devices.

As with all the sites, the Mull of Galloway was initially estimated to have a SIF of 20%, this translates to an extractable 383 GWh/year from the total energy present of 1915 GWh/year. This was later revised to 12%, giving 230 GWh/year of extractable energy. The Phase II UK Tidal Stream Energy Resource Assessment also identified an additional 3 sites which are worthy of further consideration at Islay, Carmel Head & the Isle of Wight. The distribution of the tidal power resource around the UK can be seen in Figure 2, and it is clear that there is a lot of potential for future development of tidal power in order to exploit this vast energy resource.

Ranking	Site Name	Contribution		
		Individual (%)	**Cumulative (%)**	**GWh/y**
1	Pentland Skerries	17.9	17.9	4526
2	Stroma, P. Firth	12.7	30.6	2114
3	Duncansby Head P. Firth	9.3	39.9	1699
4	Casquets, Channel Islands	7.6	47.5	418
5	S. Ronaldsay P. Firth	7.0	54.5	1030
6	Hoy, P. Firth	6.3	60.8	714
7	Race of Alderney, Channel Islands	6.3	67.1	365
8	S. Ronaldsay, P. Skerries	5.3	72.4	964
9	Rathlin Island	4.0	76.4	408
10	Mull of Galloway	3.7	80.1	383
	Total top 10 Sites	**-**	**80.1**	**9,542**
	Total UK Sites	**-**	**100**	**13,814**

Table 1 –Initial top ten tidal site estimates (Black & Veatch Ltd, 2005)

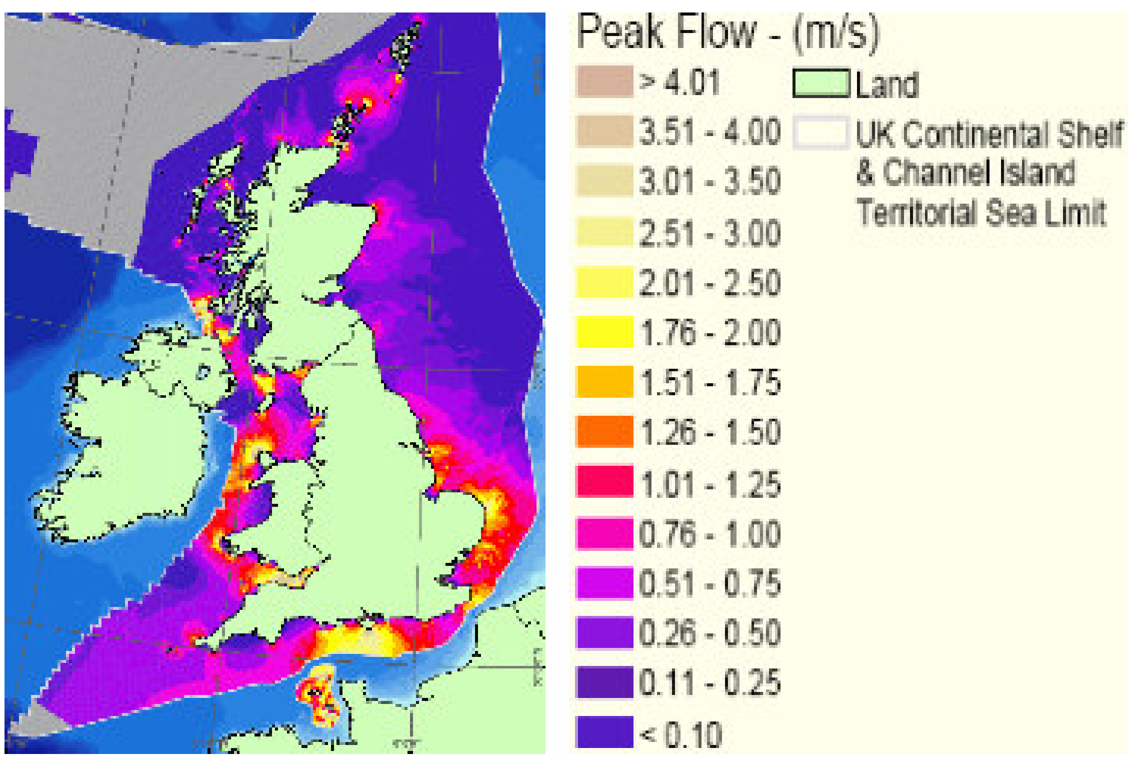


Figure 2: Atlas of Marine Renewable Energy Resource (DTI, 2004)

It is important to note, and indeed fairly obvious, that a very high concentration of the UK tidal resource is in Orkney, with the Pentland Firth possessing around 58% of the entire UK resource. It is likely that the resource in Orkney is even greater as this figure does not consider other areas with significant tidal flow, such as the site at Eday, the location of EMEC's tidal test site. 6% of the extractable energy is in the Channel Islands, 3% at Rathlin Island and 2.7% at the Mull of Galloway.

Whilst these figures provide a useful starting point for identifying the areas where the resource is most potent, this study is very general and so should be treated with some scepticism when considering individual sites. As shall be explored further, later in this report, there are many issues to be taken into account when assessing the resource at any given site which must be done on a site by site basis. This means that the findings of studies such as the Black & Veatch one, although initially helpful, are of limited use once a project reaches the site specific stage.

Section 4.0 looks to investigate the magnitude of the resource in the area in as much detail as possible to provide a site specific representation of the amount of energy available for capture. This figure is then compared with the Black & Veatch figure and should help to assess the value of the Phase II UK Tidal Stream Energy Resource Assessment.

1.5 Current State of Development

Compared to other forms of renewable energy such as wind and hydro power, marine power in general and tidal stream power in particular is very much in its infancy. There are few developers with technologies much beyond the concept stage and it will be some time before the first commercial tidal 'farm' is up and running.

There are only a few devices at the stage of full scale testing in the open seas at present. These include Marine Current Turbines Ltd's (MCT) Seagen turbine and Open Hydro's Open Centre Turbine, both of which are covered in more detail later in this report. Lunar Energy have also tested their Rotech Tidal Turbine, a seabed mounted device capable of energy extraction in deep (i.e. >50) water while Hammerfest Strøm AS have deployed their turbine off the coast of Norway. These two devices are shown in Figures 3 & 4 respectively.

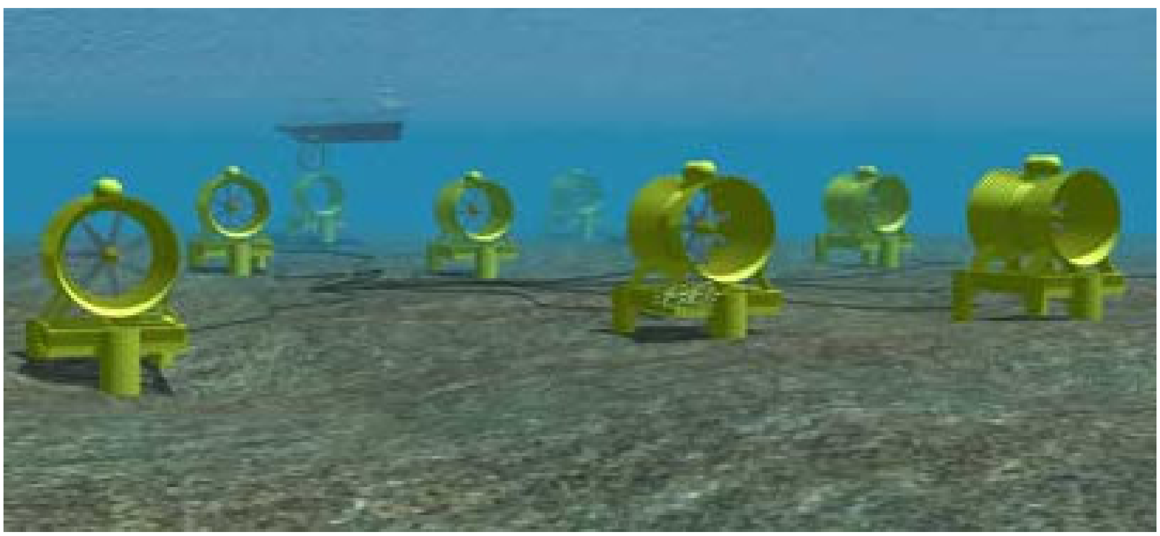


Figure 3: Artists impression of a 'sea farm' of Rotech Tidal Turbines (Lunar Energy, 2007)

There is another device: The Stingray Tidal Stream Generator developed by The Engineering Business Ltd which had been tested at full scale. This is the only hydrofoil device to have been tested in the open sea but this project has since been shelved due to financial constraints (The Engineering Business Ltd., 2007).

As the contribution made by renewable electricity generation increases, issues regarding their connection to the grid become more significant. There are several problems with renewable energy concerning intermittent supply and how this is balanced but there is also a problem arising regarding the location of many renewable generation sites.

Figure 4: Hammerfest Strøm AS tidal turbine being deployed (Hammerfest Strøm AS, 2007)

The north of Scotland has by far the highest concentration of renewable resources from hydro, wind and marine energy in the UK. However, it also has the least well developed grid network in the country and is ill equipped to transmit this electricity to the energy demanding south. To this end there has been the proposal of the well documented Beauly – Denny Line which is at present subject to a public enquiry and will take years to complete if and when it gets the go-ahead (Scottish Executive, 2007).

This fact automatically gives any site with a potential tidal resource nearer to capable grid connection an automatic advantage over a northern counterpart, at least in the short term and it is with this in mind that the tidal resource off Dumfries and Galloway is being considered by Scottish Enterprise as having potential for development.

2.0 Current Experience in Tidal Energy Testing

2.1 Introduction

In the development of any new technology it is important to build on the experience gained previously in the area and given the relatively limited scope of work which has been carried out developing tidal stream energy to date, this is all the more important .

There are two obvious candidates for more detailed consideration for this project, both being pioneers in their respective fields. Marine Current Turbines (MCT) are the market leaders in tidal turbine technology and are unique in that they have been testing a device for several years and are now looking to progress to the next stage of development (Fraenkel, 2006). The European Marine Energy Centre in Orkney, meanwhile, is the world's only dedicated marine energy test facility (EMEC, 2007).

This section presents brief case studies on both the experience gained by MCT in their tests to date and the recent development of EMEC.

2.2 Marine Current Turbines Ltd Case Study

The current leaders in terms of technology development are Marine Current Turbines Ltd in Bristol. MCT was formed from its parent company, the Intermediate Technology Development Group, specifically to develop tidal turbine technology in October 2000.

They have had a 300kW test turbine running off the coast of Devon since 2003 and have gained enough useful data to move their development on to the next stage: a commercial scale test, with a 1.2MW system due to be installed in Strangford Lough in Northern Ireland in August of 2007. It is likely that, for tidal stream energy to become commercially viable systems would have to be at least this size and MCT are market leaders, given that they already have 4 years testing experience under their belt.

Since MCT are the only tidal power developers to have undergone extended testing in the open sea the following is a case study of both the experience gained from the test off Devon and the plans for the second installation in Northern Ireland.

The concept of the MCT device is simple: An underwater, single rotor turbine which operates in exactly the same way as a conventional wind turbine when placed in a tidal current stream. Figure 5, below, shows both the installation which has been operating of Devon since 2003, known as the Seaflow project (with the rotor in its 'raised' position), and an artist's impression of the second generation, Seagen, with twin rotors. This is the system due to be installed in Northern Ireland this year (Fraenkel, P.L., 2005).

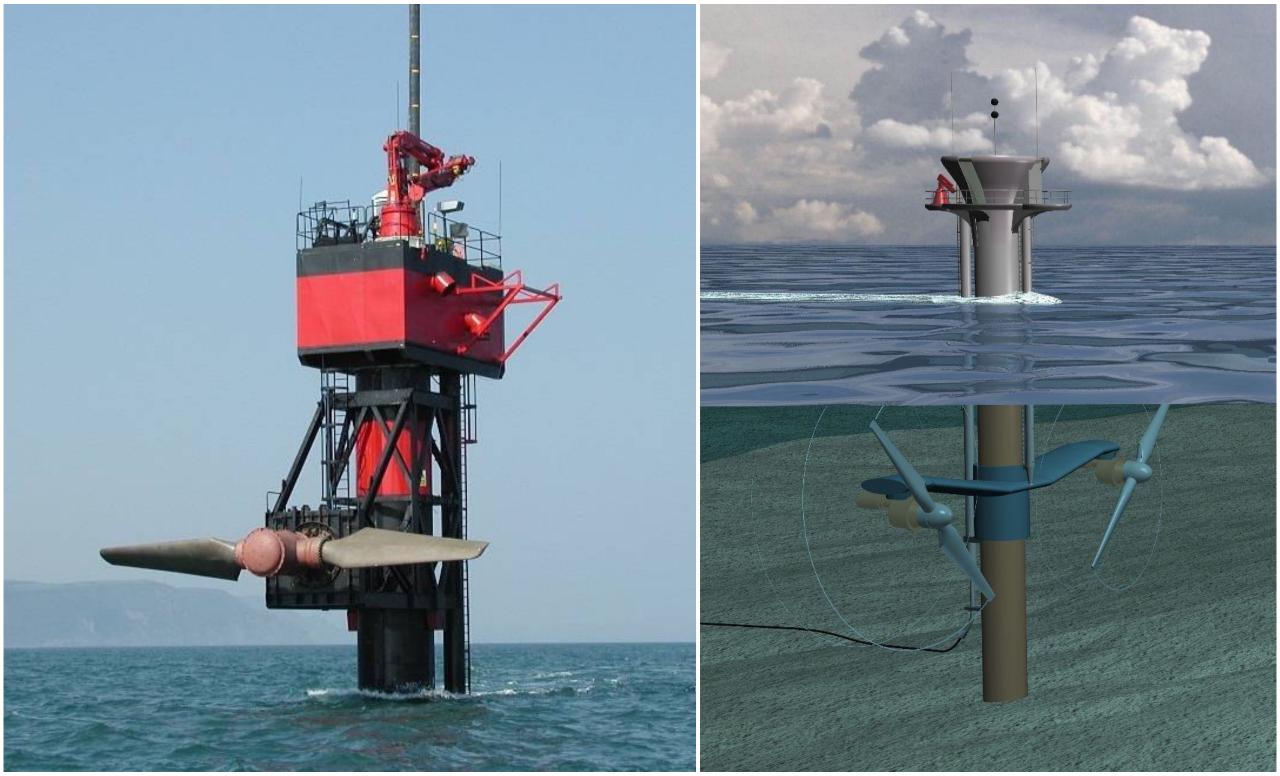


Figure 5: MCT's Seaflow Device & Artists impression of Seagen (MCT, 2007)

2.2.1 Seaflow

MCT has been successfully testing their Seaflow device on a site for 4 years with only minor teething troubles but no major technical difficulties, allowing them to amass a wealth of useful data. The Seaflow system, as stated, is a 300 kW single rotor turbine with a rotor diameter of 11m and full span pitch control. The rotor and power train are mounted on a tubular steel pile which is set in the seabed and rises above the surface of the water. As the picture of the Seaflow turbine shows, the whole rotor assembly can be raised above the surface for maintenance to be carried out. This is achieved by using hydraulic rams to drive the assembly up the pile.

The pile is a tubular steel column consisting of a series of 6 metre 'cans' welded together. The total length is 52 metres with an outside diameter of 2 metres. The pile reaches 18 metres below the seabed in a water depth of 24 metres.

The rotor assembly itself houses the gearbox and generator, mounted in sequence direct to the rotor. The gearbox is similar to what would be found in a standard wind turbine, using a planetary first-stage drive with spur intermediate and high-speed stages. The gearbox ratio is 57:1 meaning that when the rotor is turning at its rated speed of 17.4 rpm the output from the gearbox is at around 1000 rpm. The main difference from a wind turbine gearbox is that the tidal version requires no subsidiary cooling as its immersion in seawater in a sealed casing provides perfectly adequate passive cooling. A compressor in the above-water housing pressurises the gearbox to match the equivalent pressure at the operating depth.

The generator is mounted behind the gearbox as shown in the schematic below (Figure 6) and the whole assembly is in itself separate to the pile mounted on a steel collar structure. As can be seen from the diagram, the generator is slightly offset from the axis of the rotor allowing for cables to be fed through the centre of the main shaft. The purpose of these cables is to provide power and control to the servo motors on the hub. These motors control the pitch of the rotor, providing full pitch variability which in turn enables the power coefficient to be maximised.

While, in theory it would be possible to operate the turbine bi-directionally (i.e. to capture energy from both ebb and flow tides), it was decided that this would not be carried out in practice on the Seaflow project. This was mainly to avoid the issues which would arise from the turbine being directly downstream of the pile and therefore in its wake.

With the exception of the gearbox and generator, all other components used in the running of the turbine are located in the above water housing, which is 6m x 3m x 3m in size. In the case of this test device these other components include a small diesel generator to provide power for maintenance procedures and also to meet parasitic loads at start up, a small crane, hydraulic lifting gear and electronic converter and transformer. There was also a fan cooled air heater in the housing.

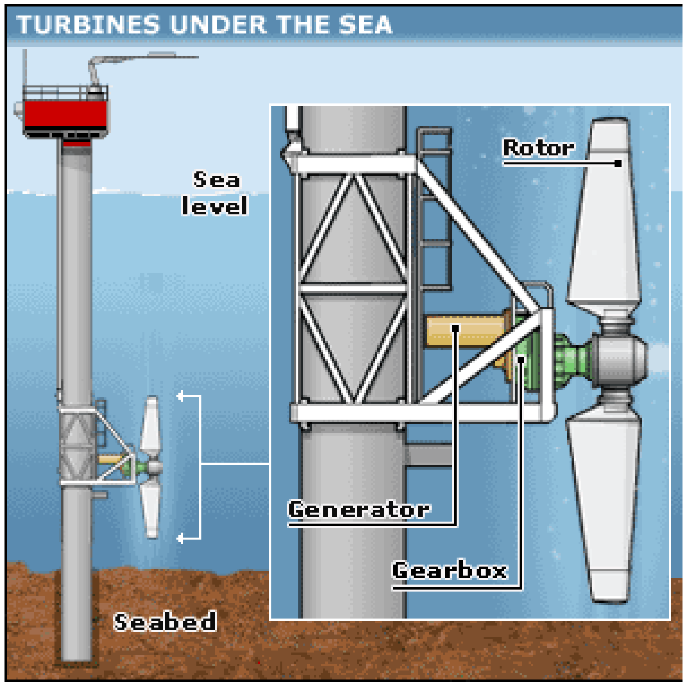


Figure 6: Seaflow Schematic Diagram (MCT, 2004)

The generator and the air heaters were unique to the test device and would not be required on any commercial project, simplifying the installation considerably. The reason for their inclusion here is that due to the large distances involved to the nearest suitable grid connection point (around 3 kilometres) it was decided not to grid connect given the large costs involved and the corresponding limited benefit. In the absence of grid connection there were two areas that had to be addressed. Firstly, the lack of a power supply for any auxiliary systems (met by the diesel generator) and also the lack of grid connection created the need for a dump load to absorb the generated power. This is the function of the fan cooled air heater.

There were many unknown aspects upon commencement of this project, given that it was the first of its kind in the world. Due to this, design of Seaflow was approached with a degree of caution and the device was more robust than it needed to be. This was understandable however, given the pioneering nature of this particular project and the desire to ensure it was a success.

The end result of this project was convincing proof that this kind of system is technologically sound and is capable of generating electricity in the harsh marine environment with surprisingly few problems and only minor maintenance required. However, this is just the first step on the road to commercial generation using marine current turbines, whilst the technology has now been tried and tested the prospect of cost effective generation is still to be explored in depth. In order to move in this direction MCT have begun the development of the Seagen turbine, a move towards larger scale tidal stream electricity generation (Fraenkel, 2005).

2.2.2 Seagen

Seagen, the next generation of MCT tidal stream devices is largely the same as Seaflow in principle, there are however a few marked differences. The most obvious of these is (as can be seen in Figure 5) that it consists of two turbines instead of one, each mounted on either end of a dihedral cross-arm wing mounted on the pile (which is now 3m in diameter). This has a number of implications for the design of the rest of the device, presenting both advantageous opportunities and a few problems to be worked round.

The actual generating equipment itself is identical in principle to Seaflow, just on a bigger scale. The rotors are 16m in diameter and they each drive a generator with rated power of 600 kW. The rotor/gearbox/generator assembly is mounted on the bottom of the wing and, when raised above water, allows for a barge to come underneath and the whole assembly to be unbolted off the wing and replaced. This is clearly much more accessible than having to carry out maintenance under water, providing the opportunity for the most complicated parts of the turbine to be taken onshore for essential maintenance work.

Further to this, the layout of the rotors means that bi-directional generation is much more feasible, since they are clear of the pile. The wing has an elliptical design designed to leave minimum turbulence in its wake so further facilitating bi-directional generation. In order to maximise the potential for generating electricity in both directions the rotors are fitted with the same 180º pitch control as the Seaflow system, with a control system to ensure that the blades are pitched to keep the turbine generating as close to rated power as possible.

This configuration does present challenges however, particularly in the form of the loads experienced where the wing is attached to the pile. Velocity shear from the tidal flow and passing waves exert force on the structure causing massive moment forces to develop. These forces put strain on the mechanism which must be accounted for in the design.

A significant development with this device will be its grid connection. Instead of absorbing the generated power on the device, power conditioning equipment will be housed on the structure above water. The turbine will be connected via an 11kV sub-sea cable to a local substation and onto the distribution grid.

Dry testing of the Seagen system is currently ongoing, with installation in Strangford Lough due to be completed in August 2007. It is hoped that this arrangement of 2 turbines on one pile will provide significant savings on cost relative to electricity generated. Early estimates are that when compared to the Seaflow project, Seagen should provide three times the amount of electricity for twice the cost. It is also hoped that once the Seagen project has been operational for sufficient time to prove itself that an array of turbines will be installed at another location off the UK coast, with a similar installation in the United States helping to drive prices down with economies of scale (Fraenkel, P.L., 2005).

2.3 The European Marine Energy Centre (EMEC) – A Case Study

At the international forefront of development in marine energy technology is the European Marine Energy Centre (EMEC) in Orkney. The centre is the first of its kind anywhere in the world and offers a unique opportunity to test and develop the various fledgling marine energy technologies in what is a relatively harsh environment. While considering other opportunities to develop testing facilities for marine renewables (such as the potential of a test centre in Dumfries & Galloway) it is important to consider the work already being done in Orkney in order to look to complement it and build upon it. This section shall therefore present a case study of the EMEC test centre in Orkney.

2.3.1 The Location

EMEC Orkney currently occupies facilities on two sites on the Orkney Islands, off the North coast of Scotland, at Stromness and Eday, as shown in Figure 7 on the following page. The main reason for situating this site in Orkney is because of the nature of the marine resource there. In terms of wave energy, the wave site has uninterrupted exposure to waves of up to 15m whereas the tidal site experiences spring tide peak flows of 4 m/s, amounting to a significant resource in a relatively sheltered area in terms of wave climate, which is also important.

The location in Orkney also has other benefits that made it attractive for the development of a test centre. It offers relatively good access to grid connection compared to other more remote locations and this is always an issue with renewable energy supplies. Also, the location in Stromness is close to the local infrastructure and considerable local expertise. It also is easily accessible from the mainland, with Stromness being the main port for sailings from Scrabster (up to 4 times daily) and with the airport in Kirkwall, 15 miles away.

There are inherent advantages to developing both tidal energy technology and the associated expertise in Orkney. Given that such a high percentage of the total UK resource (nearly 60%) is located there, it makes some sense that, from the very earliest of stages, Orkney should receive the majority of attention and funding to pioneer this type of renewable energy, despite the remote location.

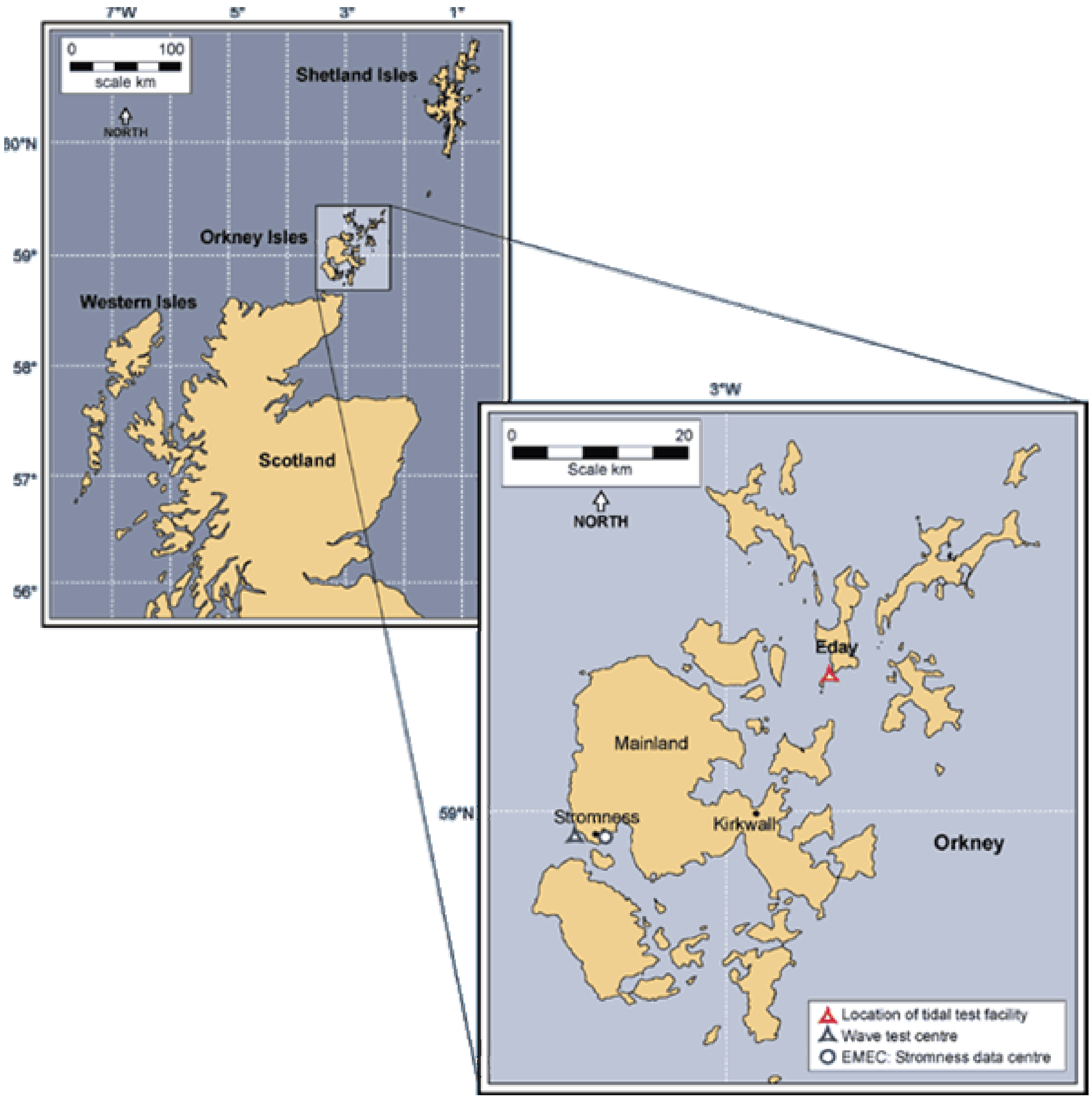


Figure 7: EMEC Location map (Image courtesy of EMEC)

The biggest problem with the location is how remote it is from the large population centres in the UK. This presents challenges, not just in respect to the accessibility of the site and the availability of local resources and expertise, but also, in the longer term, when thinking about how to transmit any commercially generated electricity.

The north of Scotland has a weak grid with little capacity to absorb electricity generation of any significant scale locally. This is currently being discovered with the much more advanced wind power industry. This means that any significant quantities of generated electricity must be transmitted to other parts of the country where demand is higher. Development of this is ongoing, as discussed later, with the proposed Beauly – Denny line attracting a lot of attention.

2.3.2 The Wave Site

The test centre is divided into two sections; the wave site at Stromness, and the tidal site on Eday. The wave site is the more developed of the two, having been fully operational since October 2003 with 4 test berths situated about 2 km offshore at Billia Croo. The four berths are located on the 50m deep contour line and are connected to the national grid through the centre's substation onshore.

The conditions on site are continuously monitored by two Datawell Directional Waverider buoys at the test berths. These buoys are cannected via radio link to the EMEC data centre where their half hourly readings are recorded. This arrangement enables EMEC to amass a comprehensive datset of conditions on site and is available to all developers who use the site. There is also comprehensive monitoring of weather conditions in the area and measurement of factors relating to power quality at the substation.

All off this serves to provide valuable realtime data for any device being tested on site, with the potential to evaluate how differing weather conditions and wave types translate into electrical power, usable or otherwise. This kind of information is vital in developing new technology, giving an opportunity to make alterations in order to maximise potential.

The wave test centre has already seen some success stories, most notably the Pelamis system, pioneered by Ocean Power Delivery, which began testing at Billia Croo in August 2004. This venture saw Pelamis become the first grid connected wave power generation system in the world and there are plans for it to enter commericial service in the UK with the world's first wave farm, with a generating capacity of 3 MW, expected to be up and running in Orkney by summer 2008. The device has also been exported to Portugal where a 2.25 MW array of three Pelamis devices was trialed in 2006 (EMEC, 2007).

2.3.3 The Tidal Site

In comparison with the wave facility, the tidal site on Eday is very much in its infancy. It is located off the southern tip of the island in an area known as the Fall of Warness and consists of five test berths in an area of around 2 km by 3.5 km. Each berth, as with the wave centre, is connected to the grid via a substation onshore, while there is a separate communications link with the test centre headquarters in Stromness to relay telemetry from test devices.

The tidal site was completed in spring 2007 and became operational soon after. Depths vary between berths from the shallowest at 25m up to a 50m limit. As with the wave centre there is continuous monitoring of conditions with Acoustic Doppler Current Profilers (ADCPs) deployed at the berths, offering comprehensive data regarding the tidal resource.

The first device to be deployed there was the Open Centre turbine, developed by Open Hydro in Dublin (Open Hydro, 2007). This is a 250 kW rated system mounted on two pillars as shown in Figure 8, below.

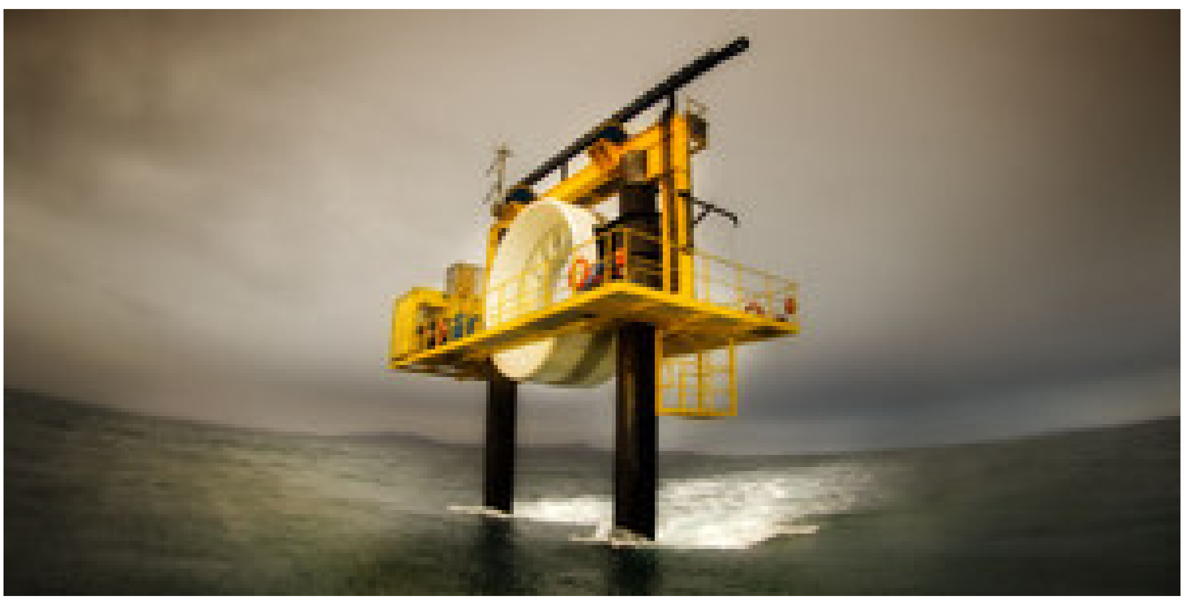


Figure 8: Open Centre Turbine (Image courtesy of Open Hydro)

2.3.4 Funding

The majority of funding for EMEC has come from a group of public sector organisations convened by Highlands & Islands Enterprise. This group consists of the Department of Trade and Industry, The Carbon Trust, The Scottish Executive, The European Union, Orkney Enterprise & Scottish Enterprise. The total budget is £14.5 million (EMEC, 2007).

3.0 A Test Centre in Dumfries and Galloway

3.1 Introduction

Since Dumfries and Galloway is home to a significant tidal resource consideration must be given to how this can best be exploited, and what action, if any, should be taken in the first instance. As has been discussed previously, the main concentration of tidal resource is up in Orkney (about 60%) and the Mull of Galloway accounts for only 3.7% of the UK total (Black & Veatch, 2005). While this goes some way to explaining why the main thrust of current activity is in Orkney it does not rule out development at other locations, even at this early stage.

Scottish Enterprise Dumfries and Galloway (SEDG) have indicated their commitment to ensuring this opportunity for future development is not missed and commissioned this report to investigate the feasibility of developing an alternative test centre at the Mull of Galloway to act as an instigator for increased development of tidal technologies in the near future and to provide a valuable service to developers.

This initiative was borne out of the realisation that the Dumfries and Galloway region had a number of inherent advantages over the only other tidal test centre in Orkney. Obviously, there is the issue of accessibility, with Orkney being an inconvenient location well out of the way whereas Dumfries and Galloway is much more central. Furthermore, the resource and general environment of the Orkney site is among the most extreme. It has been speculated that there may be an opportunity for a test centre offering less searching conditions, the area off the coast of Dumfries and Galloway certainly seems to fall into this category. Finally the potential advantages of the location for grid connection were identified as a possible instigator for commercial development in this region although this has yet to be investigated in-depth.

3.2 Offshore Site Selection

The primary aim of this report was to scope out the potential for developing a test centre in the Dumfries & Galloway region and this section focuses on the task of identifying specific offshore sites which could potentially be suitable. This involves considering all factors which may influence site selection and hence ruling out unsuitable areas.

There are however some issues which take precedent over others and so should be considered as primary constraints on site selection. Primary constraints are any characteristics of a site, or the presence of ordinances that makes situating a test centre or tidal array there impossible. Secondary constraints are those which should be avoided if possible but do not absolutely rule out development on a given site if due mitigation is carried out.

3.2.1 Primary Constraints

3.2.1.1 The Bathymetry of the Area

Off fundamental importance when considering the offshore aspect of any tidal current development is the bathymetry of the area. The term bathymetry refers to the nature of the seabed, specifically the depth and its variations. At the present time any area where the depth exceeds 50 metres can be excluded from consideration and any area where the depth was less than 20 metres would generally be deemed too shallow. For a test centre it is desirable to have berths at various depths within this range to allow for testing on different scales and there may even be instances where shallower water could be considered.

The waters off the coast of Dumfries and Galloway generally appear to be very favourable for tidal development, at least in the area east of the Mull of Galloway. The North Channel (the area to off the west coast of the Rhinns) can be discounted as depths there exceed 250 metres however on the approach to the Solway Firth it becomes much shallower with depths generally between 40 and 50 metres with only minor variations. Closer to the mouth of the Solway Firth it becomes much shallower, with depths as low as 10 metres. This is also the case in the areas close to the shore and in the various bays. Most of Luce Bay is less than 20m deep as is Wigtown Bay. Kirkudbright Bay is less than 10 metres deep (United Kingdom Hydrographic Office (UKHO), 2005). Appendix A shows the Admiralty Chart for the Area in more detail.

This suggests that the most suitable areas in terms of depth would be either around the edge of Wigtown or Luce Bay, or up towards the Solway Firth so that a range of depths would be available. However should this ultimately prove unfeasible it will be possible to consider other areas with less of a variation in depth.

3.2.1.2 The Tidal Resource in the Region

The tidal resource characteristics can actually be considered both a primary and secondary constraint. It is primary in the sense that there must be significant tidal flow to provide adequate conditions for testing devices and so any 'slack' water where flow is negligible can be discounted. It is however of secondary importance what the magnitude of the flow velocity is when considering a test centre. What this means is that since the objective of the Dumfries & Galloway test centre project is to provide testing facilities in what would be considered intermediate conditions it is not necessary for the site to be located where the tidal resource is most intense.

Figure 9: Distribution of Tidal Data in the Region (UKHO, 2005. Image courtesy of Google Earth, 2005)

Figure 9 shows the distribution of tidal current velocity data for the area and it can be seen from this that there is a wide distribution of tidal current flow, typically with peak spring tide flow of 2m/s and so there is little in the way of primary constraints from this aspect. Appendix B shows the data for each of the tidal diamonds.

3.2.1.3 Military Activities

The presence of both military exercise areas and munitions dumping grounds are significant in the selection of any site, and play a prominent part in the area being considered here. The brown hatched areas in Figure 10 show military exercise sites while the shaded red parts indicate areas under byelaw review and danger areas (Faber Maunsell, 2007a). Byelawed areas can be considered no-go areas when thinking about tidal current developments given the large amount of disruption this would cause to the military activities (Ministry Of Defence (MOD), 2007).

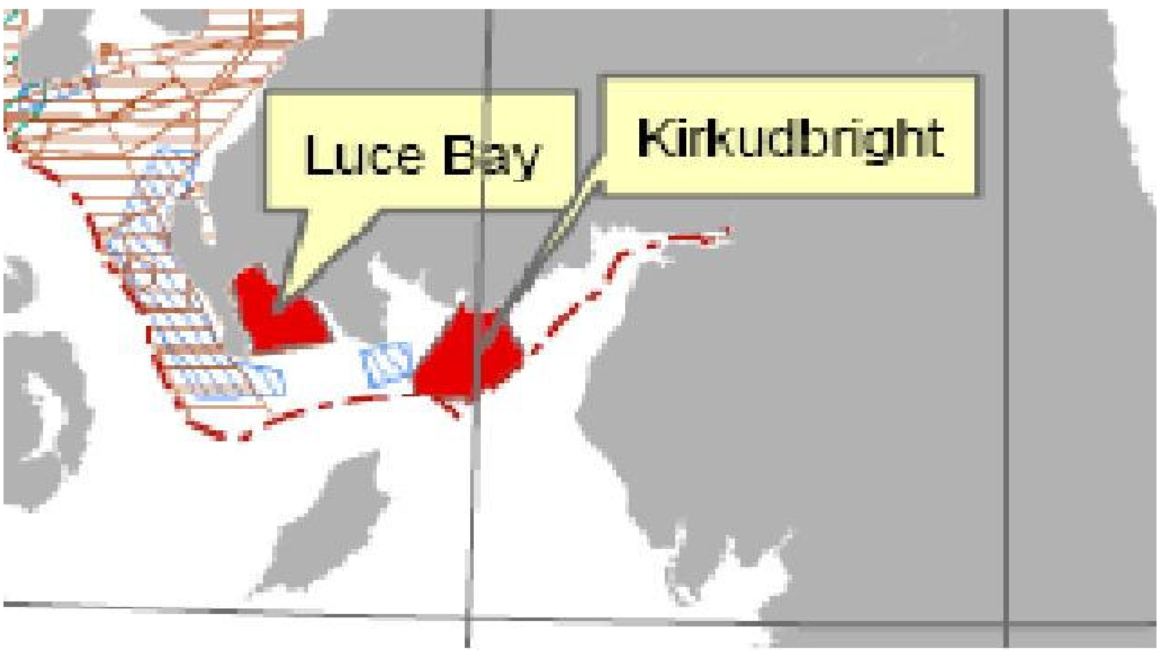


Figure 10: Military Activities in the Area (Faber Maunsell, 2007a)

The blue hatched areas in Figure 10 indicate areas with a significant tidal resource and they can be seen to be outwith these no-go areas. However it is likely that any development in this region would require extensive consultation with the (MOD). Whilst the location of any test centre berths in the no-go areas would be unworkable, it should be possible, were it required, to run cables through these areas as these would cause minimum disruption and have few long term effects to any activities on these sites.

It should be noted that the byelaws governing these sites are currently under review by the MOD and the relevant local authorities (MOD, 2007). There is little information regarding this process available at the present time but its main purpose was with a view to extending these areas, as opposed to reducing them. It is important therefore that if the decision is made to progress with the development of a tidal test centre in this region, that consultation with the MOD is embarked upon at the earliest possible opportunity to ensure that key areas are not needlessly lost.

Out-with the byelawed areas it is likely that the extent to which military activities would be disrupted could be kept to an acceptable minimum although there should be a definite preference for areas which would have the minimum impact. Sites close to high activity areas should be avoided if at all possible.

3.2.1.4 Dumping Grounds

There are a number of dumping grounds around the Scottish coast, some frequently used and some very rarely. There are two categories of site that must be considered. Disposal areas and Munitions dump sites and both are present off the Dumfries and Galloway coast. The disposal grounds in the region are shown in Figure 11, below, and all of them are used only for the disposal of silt, sand, gravel or rock (Faber Maunsell, 2007b).

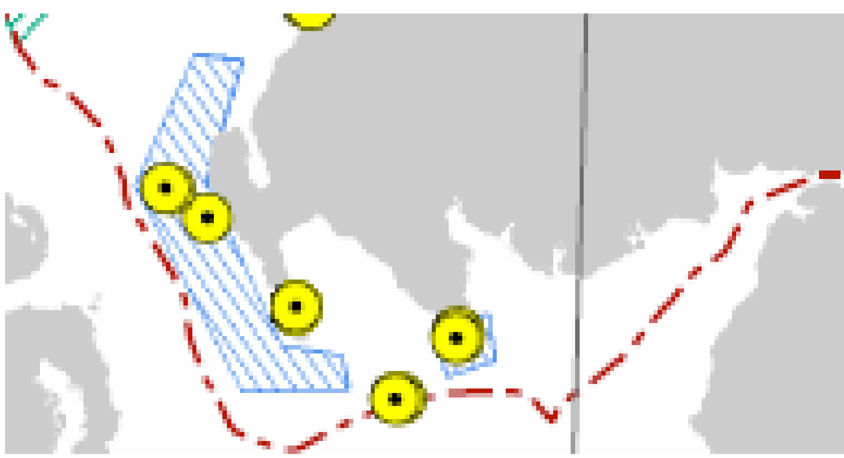


Figure 11: Disposal Sites in the Region (Faber Maunsell, 2007b)

It is not clear how frequently these sites are used but no developments should be considered within 500 metres of these facilities. The only other possible effect of dumping grounds is that if very large amounts of material are dumped it could have an impact on the local flow characteristics. This would however require further investigation. Apart from this restriction there is little impact made by these disposal sites on the potential of developing a test centre in the area.

Munitions dump sites are of a greater significance given the nature of the material being considered. The main issue with these sites is that although they are relatively harmless when dormant, if disturbed there is a risk of explosion from previously unexploded munitions. The result of this could be environmentally catastrophic and so any such area can be written off as a site for wither a test centre, or for future commercial development involving tidal arrays.

The main dump site off the coast of Dumfries & Galloway, and so worthy of consideration here, is Beaufort's Dyke in the North Channel, the location of a large amount of dumping after the Second World War and still in use up to the present day. It is thought that Beaufort's Dyke is the only chemical weapons dump site off the Scottish coast (Martin & Smith, 2007). While this site is in the deep water of the west coast of the Rhinns of Galloway and so, is not currently an area where tidal development would be considered, its presence here should still be noted as significant, both when thinking about future development and in the immediate future.

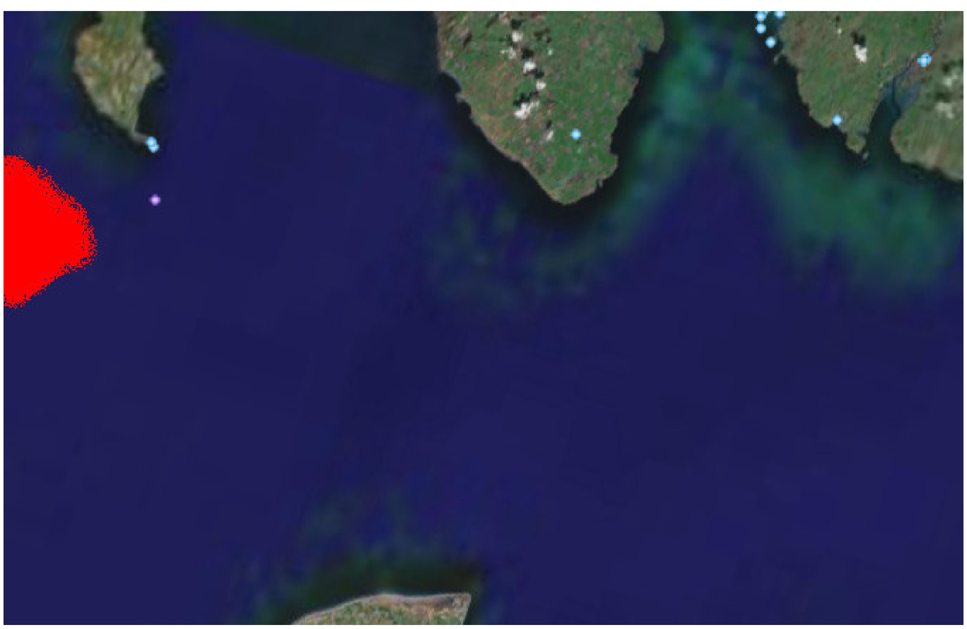


Figure 12: Explosives Dumping Ground (UKHO, 2005. Image Courtesy of Google Earth, 2005)

There is some evidence that some munitions intended to be dumped at Beaufort's Dyke actually ended up being dumped in the area immediately south of Luce Bay in water with a depth less than 50 metres (Martin & Smith, 2007). This is unconfirmed but the speculation is significant, given that this would otherwise be an attractive area for the test centre. There is no hard evidence regarding the exact location of this dumping activity and so further seabed surveys would be required which could eliminate further areas. The Admiralty Charts also indicate that the explosives dumping ground stretches round the tip of the Mull of Galloway which could be significant in the future if the most potent resource is to be exploited. The shaded red section in Figure 12, above, shows the extent of the area which must be avoided due to the explosives dumping.

3.2.1.5 Protected Sites

There are many environmental issues to be taken into account when considering tidal current development but the only one that could be considered a primary constraint is the location of specially protected sites. The Scottish Marine Renewables: Strategic Environmental Assessment carried out an extensive study on a wide range of environmentally sensitive sites and there are a number of those found off the coast of Dumfries & Galloway. However the only protected site is near the shore in Luce Bay, the area small area shaded yellow in Figure 13 below.

It is worth noting that the shaded pink areas are Special Areas of Conservation (SAC's) under the Nautra 2000 European Network (Faber Maunsell, 2007c). Any development in these areas would involve extensive mitigation but given that the whole of Luce Bay is an MOD no-go area (see Figure 10) it is unlikely that it would be considered.

Protected sites can be considered out of bounds for development and also for the routing of cables unless absolutely necessary. Running cables into Luce Bay should therefore be avoided.

Figure 13: Protected Sites and Special Areas of Conservation (Image Courtesy of Google Earth, 2005)

3.2.1.6 Cables and Pipeline

It is important that any tidal test centre development steers clear of any pipelines or cables in order to avoid the problems which could arise were they to be disturbed. Whilst there are several cables nearby running through the North Channel and reaching as far as Canada, the only ordinances present in areas which may be considered for a test centre are the two gas interconnector pipelines linking Scotland and Ireland (Faber Maunsell, 2007d). These are shown in Figure 14 as the green lines which come ashore at the mouth of Kirkudbright Bay (UKHO, 2005).

Figure 14: Gas Pipelines (Image Courtesy of Google Earth, 2005)

It is recommended that any tidal current developments be limited to a distance of 500 metres from these pipes in any direction and so a 1.5-2km strip along the length of the pipelines can be considered out of bounds for future development. It is also worth noting that the pipelines run through the middle of an area which may otherwise be considered a potential site for commercial generation.

3.2.1.7 Outcome of Primary Constraints

The outcome of the information in sections 3.2.1.1 – 3.2.1.6 is that vast areas of the areas of the coast of Dumfries and Galloway can be written off as unsuitable for the development of a tidal test centre. These unsuitable areas are displayed in Figure 15, shaded red.

Figure 15: Unsuitable Areas for Development (Image Courtesy of Google Earth, 2005)

These areas are discounted on the basis of unsuitable depth, having problematic ordinances or being out of bounds due to MOD activities. Some areas such as Luce Bay are ruled out for all three of those reasons. This leaves only one area, the unshaded triangle south of Luce Bay in the above figure which has an area of about 310km². This does not however take into account the speculated presence of weapons dumping in this area and further surveys will be required to clarify which areas, if any are unsuitable due to this.

3.2.2 Secondary Constraints

The following sections deal with issues which influence site selection within the predefined potentially suitable area from Figure 15. It therefore should not be considered as an assessment of all the impacts or factors surrounding a tidal test centre development, rather an evaluation of the factors which would be expected to vary within this area.

3.2.2.1 Resource Distribution

Having identified a potentially suitable area for development (Figure 15) it is then important to consider the resource data for that area in order to determine if there may be any local variations which would render one location more favourable than another. The Admiralty chart offers data for the points shown in Figure 16, below. The velocities given are peak spring and neap tide velocities as displayed on the charts, Diamonds C and E refer to tidal diamond data for these points whilst point 1 refers to the data from British Oceanographic Data Centre (BODC) records.

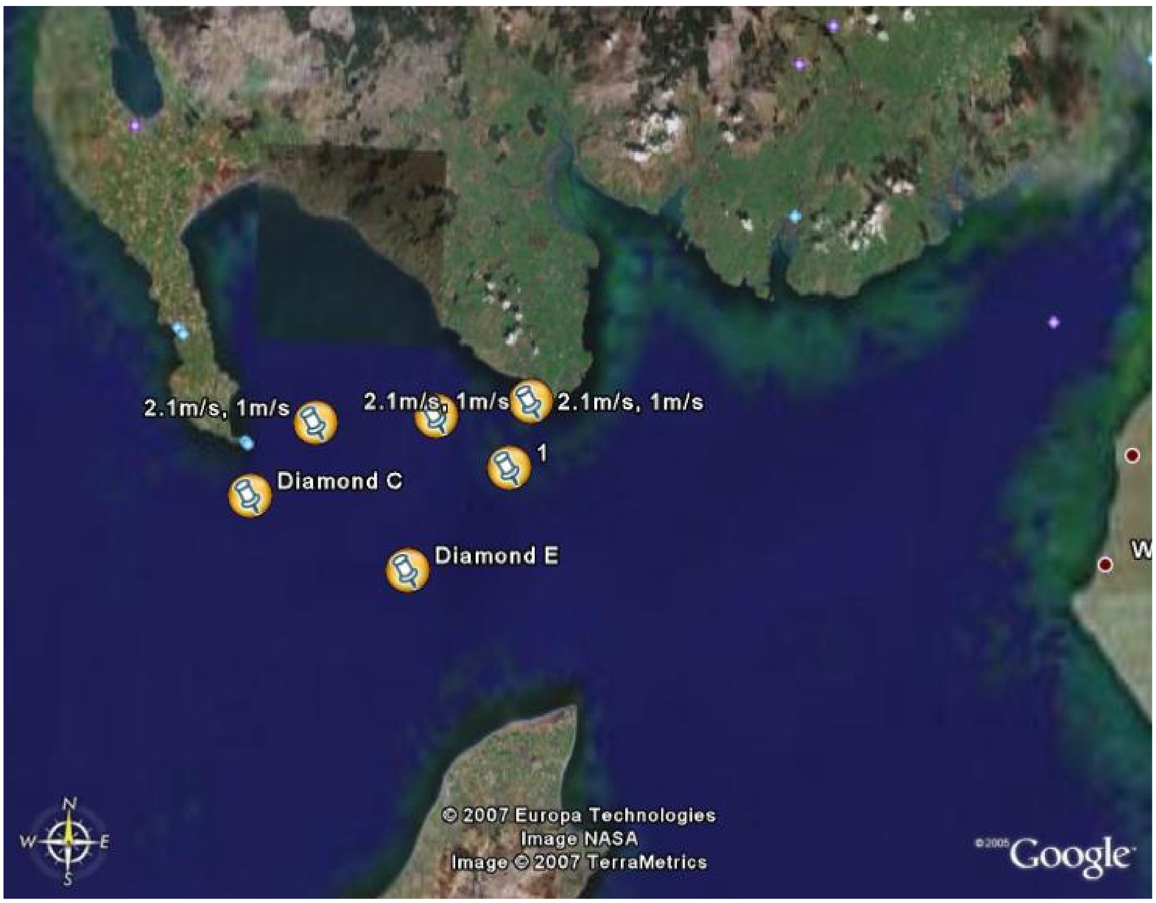
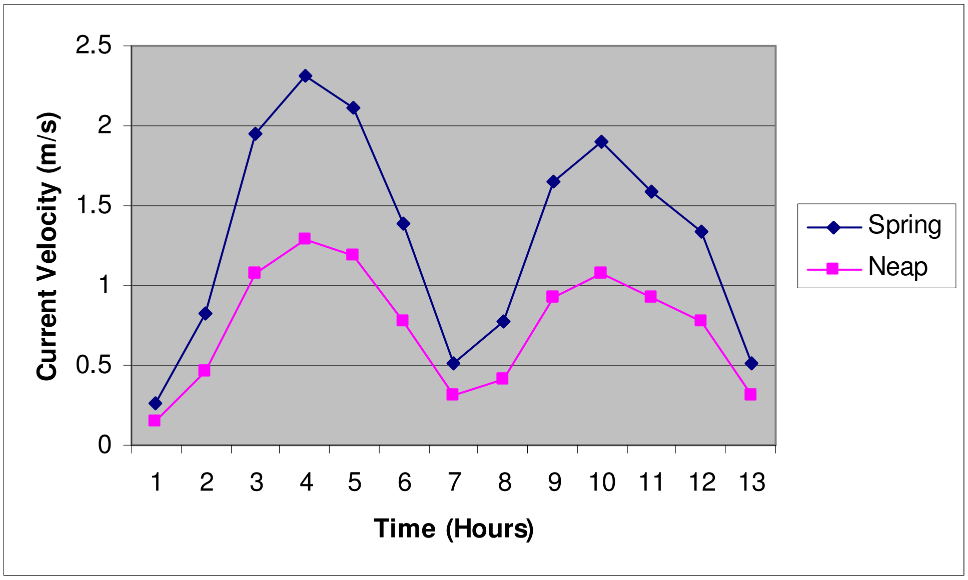
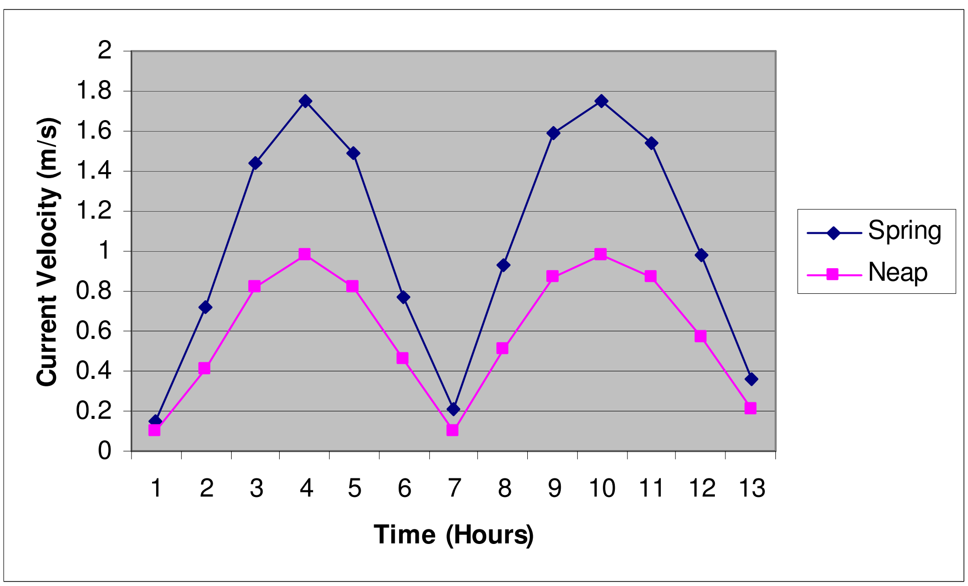


Figure 16: Tidal Flow Data for Potentially Suitable Area (Image Courtesy of Google Earth, 2005)

Graphs 1 & 2 below show the tidal current velocities for diamonds C and E respectively.

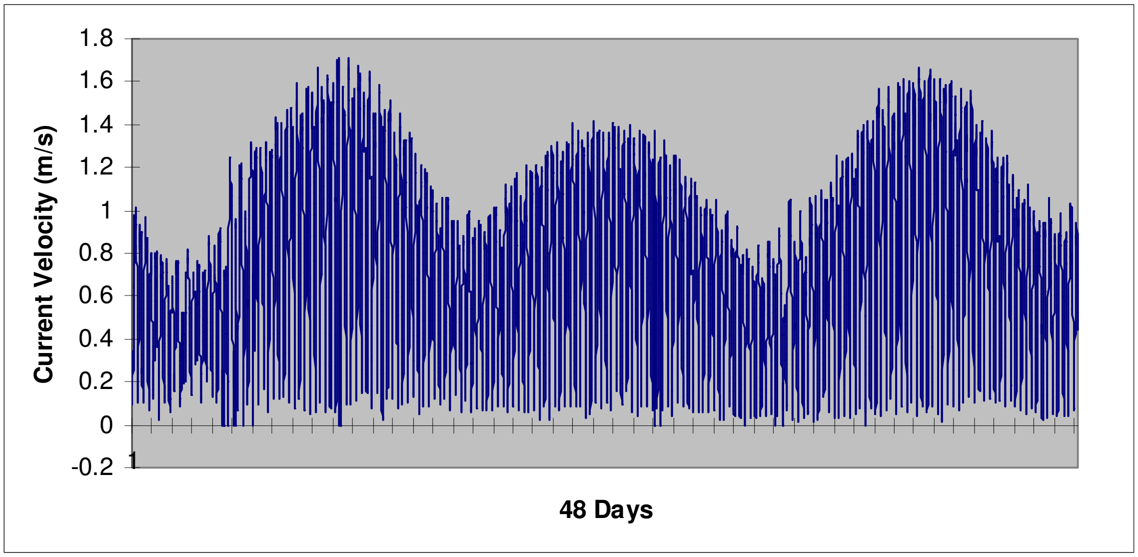


Graph 1: Tidal Current Velocity at Diamond C



Graph 2: Tidal Current Velocity at Diamond E

The BODC data for point 1 is displayed in graph 3 representing tidal current measurement at a depth of 16m in an overall sea depth of 52m for a period of 47 days.



Graph 3: BODC Tidal Current Data for Point 1 (BODC, 2007)

As would be expected given the information in the DTI's Atlas of Marine Renewable Energy Resource and Phase II UK Tidal Stream Energy Resource Assessment, the velocity increases significantly close to the peninsula, as shown by Diamond C. However it can be seen from Diamond E and the BODC data that further out into the channel velocities are lower. It should also be noted that velocity increases again close to Burrow Head.

It would seem that from the available data for the area, velocity conditions throughout the suitable area present themselves as favourable to the intermediate kind of test centre and so there are no secondary constraints from velocity that would strongly influence selection of one site over another.

It was identified that one favourable velocity characteristic for a tidal test centre is extended periods of 'slack' water or very low velocity in order to aid the inevitable maintenance on prototype devices. Closer inspection of the BODC data shows that even at periods of peak spring tidal flow the current velocity is below 0.2m/s for 30-40 minutes and below 0.5m/s for at least an hour. This would require further exploration but indicates that conditions could be quite favourable in the area.

3.2.2.2 Shipping

Clearly the presence of large amounts of shipping traffic and a tidal energy development are incompatible, and it is important when considering this kind of development to investigate the shipping density of the site. In the case of the area being considered here, it appears that any development would cause minimum disruption to shipping in the region.

The North Channel is a major shipping route and is governed by a traffic separation scheme to organise the flow of traffic through the region, such is the level of traffic both along the channel and between Scotland and Northern Ireland. This is further exacerbated by the high speed crafts which operate between Cairnryan and Larne and Stranraer and Belfast which require additional monitoring. However, in the area to the east of the Mull of Galloway, the area considered suitable for a test centre, there is very little traffic (Faber Maunsell, 2007e).

Of particular interest is the amount of traffic which passes through the channel between the Mull of Galloway and the Isle of Man as this is most likely to be affected by a test centre in the area. Appendix C shows maps of shipping traffic around the coast of Scotland compiled for the Scottish Marine Renewables SEA report. The information in these maps was obtained from the Marine and Coastguard Agency (MCA) and shows all shipping traffic with a weight of over 300 gross registered tonnes which are required to carry Automatic Identification System (AIS) equipment. Data was gathered for two 14 day periods: One during January 2006 and the other in August 2006 in an attempt to represent possible seasonal representations.

Type Of Vessel	January 2006	August 2006
Tankers	Occasional	None
Dry Cargo Vessels	Frequent	Occasional
Passenger Vessels	Very Frequent	Very Frequent
Fishing Vessels	None	None
Other Vessels	Occasional	None

Table 2: Shipping Traffic In the Area (Faber Maunsell, 2007e)

The amount of traffic for various vessel types through this channel is represented in Table 2. It should be noted that the very frequent passage of passenger vessels, whilst passing through the defined channel is far enough south to mean it is unlikely to be affected.

In terms of lighter traffic there is limited information available. The SEA study did gather information from the Royal Yachting Association and this is displayed in Figure 17. It can be seen from this map that the area of interest for the test centre and the RYA sailing areas are in clear conflict.

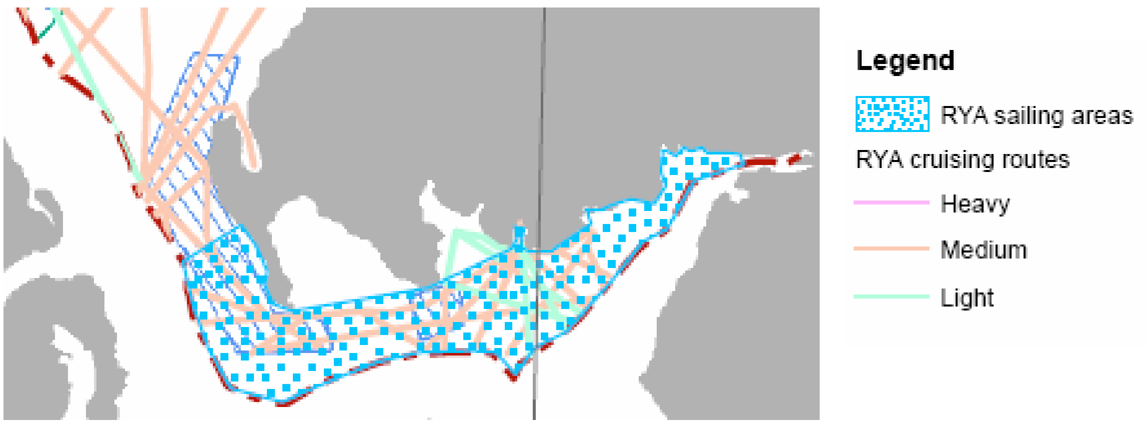


Figure 17: RYA Activity in the Area (Faber Maunsell, 2007e)

In terms of specific site selection, it is therefore advisable to locate a test centre as far north as possible in order to minimise impact on commercial shipping. This would have the effect of avoiding the vast majority of the known traffic in the area and hence avoiding extensive disruption. It is advised that a 500 metre exclusion zone should be implemented around any tidal energy device and this should be implemented here.

It would seem that avoiding RYA activities completely is impossible, and so extensive consultation would be required to optimise the location of the test facility to ensure minimum disruption to their activities. This is outlined further in Section 3.5.1.

3.2.2.3 Wave Climate

It is highly desirable when considering potential sites for a tidal test centre to find locations where the sea is generally the calmest. Information regarding variations on such a local scale, as is required here, is difficult to come by without actual site surveys however it is possible to make some assumptions.

The biggest influence on the local wave climate will be the effect of land masses in the area. Long stretches of open sea offer the chance for waves to accumulate with the prevailing wind and so, as a general rule, it is desirable for a test centre to be sited in a location that is well sheltered by land. Initial observations indicate that the area being considered off the coast of Dumfries and Galloway could prove problematic.

In the UK the prevailing winds are westerly (swinging from north-westerly to south-westerly) and the area being considered is particularly exposed to waves which build up across the Irish Sea on a north-westerly passage as is displayed by the arrow in Figure 18. A further indication of this is the presence of sheer cliff faces on the west coast of the Machars Peninsula which indicates a harsh wave climate with relatively severe erosion.

Whilst this does require further research and may not rule out siting a development in the area, early indications are that this could prove to be the largest obstacle which must be overcome.

Figure 18: Prevailing Winds (Image Courtesy of Google Earth, 2005)

3.2.2.4 Local Wildlife

Other factors which should be taken into consideration are the concentrations of local wildlife throughout the area. Seabirds, fish and marine mammals will be affected by the presence of tidal energy converters at all stages of development and there presence in the area needs to be taken into account.

The Mull of Galloway is home to a RSPB (Royal Society for the Protection of Birds) reserve and any development close to this would create issues (RSPB, 2007). Seabirds are particularly sensitive to the noise which would inevitably be involved with device installation and diving birds could also be affected by devices during operation. There is a risk of collision with devices and their effect on the birds feeding habitat (i.e. on the local fish population) could be significant.

It is difficult to quantify such issues but detailed surveys of the local wildlife will be required before a specific site is settled on. There is also a significant presence of dolphins and grey seals in the area that could be affected by the presence of devices and the marine noise that they generate (Faber Maunsell, 2007f,g).

These factors are unlikely to be restrictive in terms of ruling out sites absolutely given the absence of any protected sites but in order to minimise the environmental impact it is important that they are considered.

3.2.3 Suitable Sites

Having taken into account all of these aspects it is possible to make recommendations of suitable sites for the offshore part of a tidal test centre. An arbitrary area of 25 km² (5 km by 5 km) was used in order to give some kind of boundaries but this should not be perceived as a limitation. Theoretically test berths could be situated over a wider area in order to incorporate a variety of depths or tidal current speeds, however this would result in more complications defining the boundaries of the site in terms of where shipping traffic could pass and so it is sensible to keep in a more concentrated area.

So with this precondition three possible sites are suggested here. These sites are shown in Figure 19 and although they are in relatively close proximity of one another they offer different options, mainly in terms of water depth.

In order to define these sites more accurately, the coordinates of the centre of each site is given as follows:

- Site 1 - 54°38’50N 4°35’30W
- Site 2 - 54°36’70N 4°28’80W
- Site 3 - 54°34’30N 4°39’00W

Figure 19: Suggested Potential Sites (Image Courtesy of Google Earth, 2005)

Site 1 is the shallowest with depths ranging from just 16 metres up to a maximum of 35 although it is more sheltered, being just inside the bay. It is likely that the shallower water makes it the least attractive site for development, as the majority of tidal current developers are creating devices that require larger depths. However it could offer an ideal location for testing smaller scale prototypes.

Site 2 offers the most variation, being situated on an undulating section of the seabed. With depths ranging from 20 metres to 63 metres, although the deeper points are in relatively small 'dips' in the seabed, which is likely to have significant effects on the flow. The plateau in the area is at a depth of 34 metres. Both sites 1 & 2 are closer to the shore than Site 3 but the distance is still significant at about 8km.

Site 3 is the most consistent of the three with a more or less constant depth of 40 metres. It is also the most exposed. The uniform characteristics of the seabed are likely to offer favourable flow conditions, with fewer disturbances caused by the bathymetrical changes of the area. It is also the furthest out from the shore which could prove attractive when considering the impact on the coastal wildlife and also on the visual impact; at a distance of 15km from the nearest shoreline at the Mull of Galloway this would be minimal.

3.3 Onshore Site Selection & Infrastructure

3.3.1 Introduction

Having identified suitable offshore locations for a test centre, the next step is to look at the onshore aspect. In terms of actual onshore construction a test centre essentially requires very little. A building housing a substation for grid connection including all the hardware required to regulate this, along with a communications link to a control centre is all that must be on the shoreline. A control centre could be situated just about anywhere. However, there will be benefits to be gained from it being nearby, and the location of an 'onsite' control centre should not be ruled out completely.

There are two obvious choices when it comes to selecting a point to come onshore. These are the southern part of the Machars Peninsula, and the area near the mouth of Kirkcudbright Bay. These are shown in Figure 20 along with the suggested offshore sites. Whilst Kirkcudbright Bay is obviously some distance further away from the offshore sites than the Machars Peninsula, this is counteracted by its increased onshore accessibility from the main local infrastructure. There may also be a possibility of coming on shore somewhere in Wigtown Bay in between the two if another option is required

There are many issues which could influence the exact location of the onshore part of a test centre but the most significant of these is likely to be the aspect of connection to the National Grid. The area that is the most attractive for grid connection is at an instant advantage over the other. This section looks in depth at the advantages and disadvantages both these areas offer in order to evaluate which is the best option for onshore development.

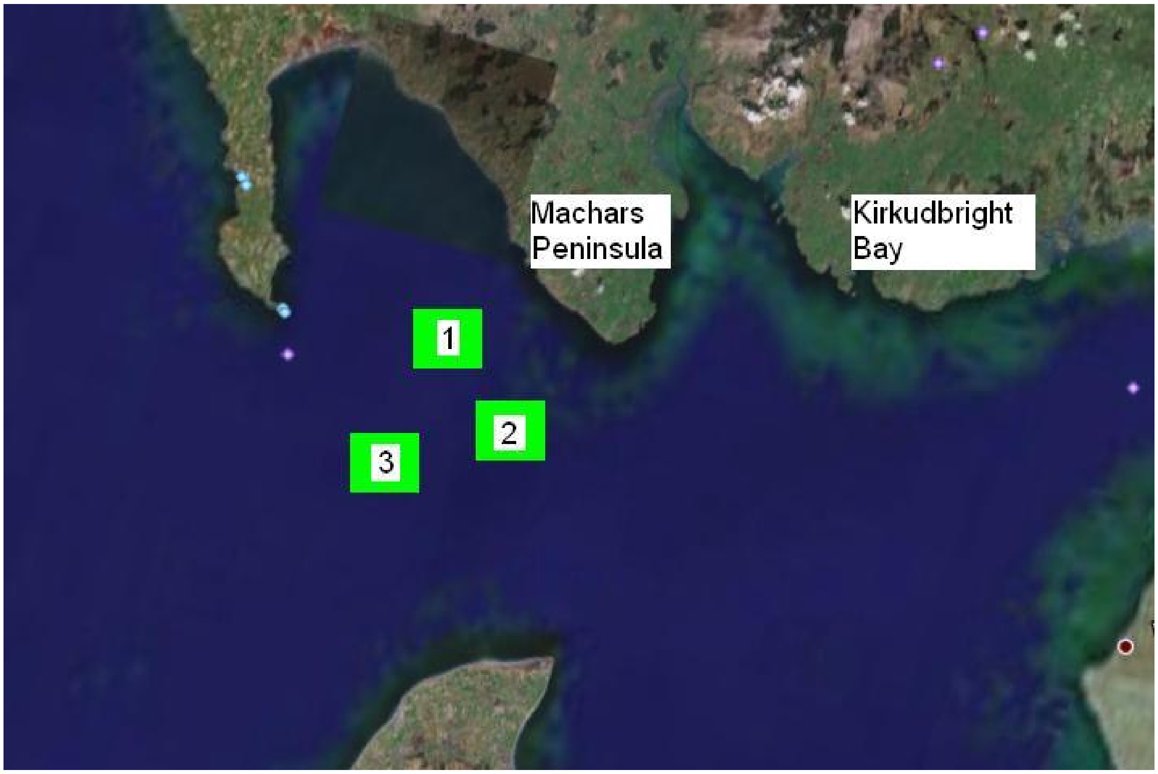


Figure 20: Potential Sites with Onshore Possibilities (Image Courtesy of Google Earth, 2005)

3.3.2 Local Substations

It is highly desirable, although notably not essential, that the test centre has a grid connection. The experiences of MCT indicates that early testing can be useful without connection but it is sensible to make every effort to ensure that any new development offers the option of connection.

As already stated the locality of grid connection is likely to play a large role in defining suitable onshore sites. Given that the local area is rural in nature the opportunities for connecting at existing substations are limited with only a couple of viable options presenting themselves. Figure 21 shows a schematic layout of the local 33kV distribution network with the substations denoted by red circles and grid supply points (GSP's) by red squares and from this it is apparent that Tongland, near Kirkudbright may be, at least initially, a more attractive option than Sorbie on the Machars Peninsula given the location of a substation close to the shore (Scottish Power, 2006). It is however 2-3 times the distance from the proposed sites which more than counters the onshore advantages of closer grid connection and increased accessibility. There could also be potential for connecting just next to Fleet Bay at Gatehouse of Fleet or at Glenluce should further options be required. Although there would be numerous issues to address when considering running cables through Luce bay given the MOD activities and environmental sensitivities.

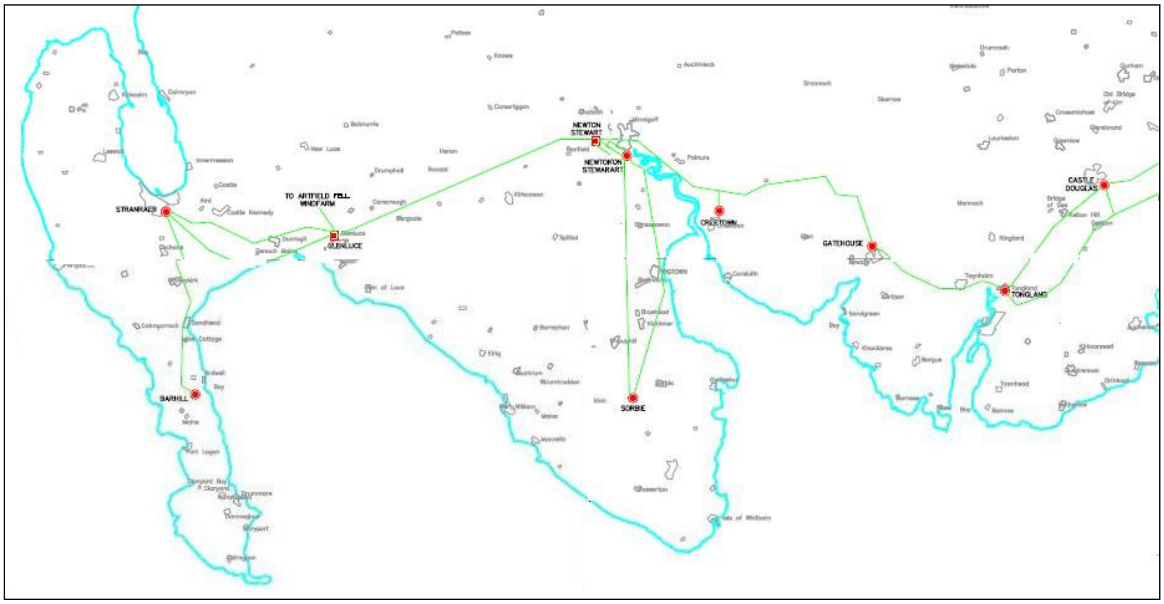


Figure 21: Local 33kV Distribution Grid & Substations (Scottish Power, 2006)

In financial terms it is desirable to connect to the national grid as close to the shore as possible, given the obvious cost of a purpose built connection. This is countered by the cost of laying cables on the seabed which will obviously increase if the test centre berth cables come on shore further away. Given the nature of the local grid network and the magnitude of generation likely to come from the test site the electricity will in all probability be distributed and absorbed locally (embedded generation) as opposed to being transmitted over long distances. Early indications are that the grid could comfortably cope with the load.

For completeness, the following section describes how both of the possible locations, the Machars Peninsula and Kirkcudbright, fit into their local surroundings. It should be noted that the grid connection at Tongland is much stronger than at Sorbie with Peak Make fault level of 74kA compared to 8.36kA and so may be more suitable (Scottish Power, 2006). This is generally a good indication of the strength of the local network.

3.3.3 The Region

Dumfries and Galloway is one of the most sparsely populated regions in the UK with an area of 4300 square miles but a population of just 148,000. Agriculture, forestry and tourism have traditionally played a prominent role in the local economy and indeed still do although there has been an increase in the presence of digital telecommunications companies thanks mainly to the development of business and enterprise parks. There are numerous small towns and villages scattered throughout the regions with only two towns with populations of over 10,000: Stranraer and Dumfries (South of Scotland Labour Market and Economic Intelligence (SSLMEI, 2007).

Dumfries

Dumfries is the larger of the two with a population of 31,000. This sets it up as the ‘capital’ of the region and as such it has a wide range of services and businesses and is the focal point for much of the development of enterprise in the area. Figure 22 below shows the breakdown of employment sectors in Dumfries from the 2001 census which indicates that about 56% of the local working population are employed providing local services (SSLMEI, 2005a).

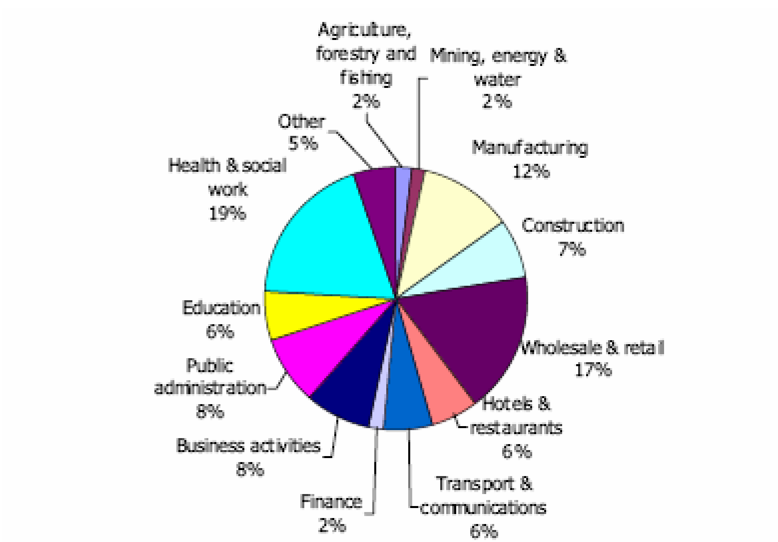


Figure 22: Employment Sectors in Dumfries (SSLMEI, 2005a)

Dumfries lies 64 miles from Port William on the Machars Peninsula, a drive of about 1½ hours. Kirkcudbright meanwhile is just 27 miles and a ½ hour drive away.

Stranraer

Stranraer has a population of 11,000 and is relatively isolated with no other sizeable settlements within 50 miles. Its dominant feature is the harbour which provides links with Northern Ireland and presents itself as being of some interest to this study. Again, Figure 23 displays the breakdown of employment and this shows that a high 66% of the working population is concerned with the service industry with a relatively small manufacturing sector (SSLMEI, 2005b).

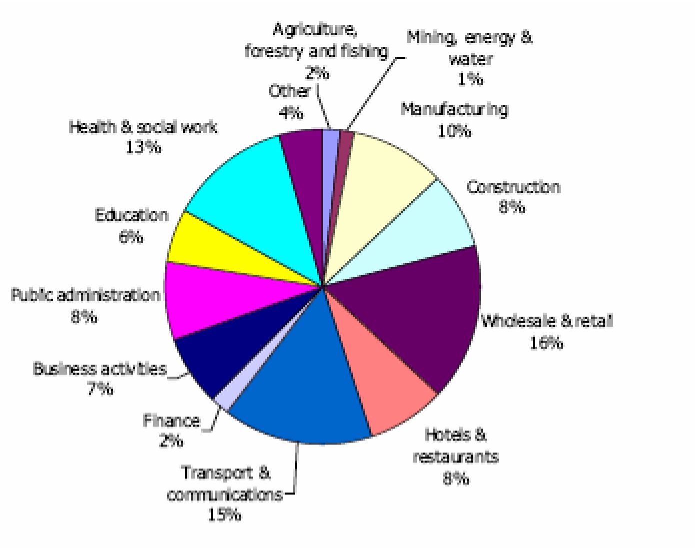


Figure 23: Employment Sectors in Dumfries (SSLMEI, 2005b)

Stranraer lies 22 miles from Port William, a drive of about 40 minutes due to the poor roads in the area while Kirkcudbright is an hours drive, about 50 miles away.

A massive benefit for the development of a tidal energy test centre in the region would be the presence of local expertise in offshore activities that could be put to use here. Given that much of the previously existing expertise originates in the oil and gas industries it is unlikely that such existing infrastructure will be found locally as it had been in Orkney, since there is no connection between the oil and gas industry and the Dumfries and Galloway region.

There may however be potential for involving the local economy and getting local businesses on board where suitable. This should be strongly encouraged as the success of any such venture will be dependant on the local economy being supportive and making a contribution.

3.3.4 The Local Area

The two areas under consideration for the onshore part of the site have are very similar in nature, although the Machars is more isolated and has no significant population centres. The two main settlements are Wigtown and Whithorn with the village of Port William being the only one on the west coast of the peninsula. The coast of the whole peninsula is dominated by spectacular cliffs interspersed with sandy beaches. In terms of the inland infrastructure there is one A-class road which runs south from Glenluce along the coast before cutting in to Whithorn and running up the east coast to Newton Stewart. There are various B-roads and other minor routes but it should be noted that the road standard, even on the A-road is not particularly high.

The main industry in the area is agriculture although tourism also makes a significant contribution to the local economy, and probably generates more income. There is no manufacturing industry in the area and no significant ports. Port William is a small fishing town with a population of 460 and it could possibly used as an access point for maintenance of devices (Whithorn, 2007).

The area round Kirkcudbright is again rural in nature although the town of Kirkcudbright itself is a much more significant settlement with a population of 3700. It is also a small harbour town which could be used for accessing the devices for maintenance, albeit from a greater distance. The surrounding area is sparsely populated with a few small hamlets and tourist facilities such as campsites (Kirkcudbright, 2007). There is also a 33 MW hydro power station up the river Dee at Tongland, where the electric substation linking to the grid is located (Scottish Power, 2006. Gazetteer for Scotland, 2007).

3.3.5 Accessibility

Accessibility to the area, both nationally and internationally, is an important aspect. One of the key benefits of Dumfries and Galloway over Orkney at a strategic level is its central location. On a national level Dumfries and Galloway is very accessible as can be seen in Figure 24.

As was outlined in Section 3.3.3 the two nearest towns of significant size are Dumfries to the east and Stranraer to the west. Stranraer offers ferry links to Northern Ireland and lies about 90 miles south of the nearest city, Glasgow, which can be reached by road or rail and has an international airport which also has a shuttle service to London Heathrow, the busiest international airport in the World.

Figure 24: Map of Scotland (Rotary International, 2007)

Dumfries lies 13 miles off the M74, the main motorway link between Scotland and England and consequently the main link to Glasgow, again the nearest city, a distance of 76 miles away. There is also a rail link. The main road between Dumfries and Stranraer is the A75 (the distance between the two is 70 miles). This is the main road that would be used to access either site and is a good single carriageway route (The Automobile Association (AA), 2007).

3.4 The Test Centre

3.4.1 Offshore Aspects

It is obviously important to consider what a new marine energy test centre could and should involve were it to progress in this case. This will involve learning from the experiences of others who are further down the road in terms of development and also looking to improve on those experiences, looking for the potential to provide services which are currently not available to facilitate the development of marine energy in Scotland.

3.4.1.1 Number of Test Berths

The recommendation in Section 3.2.3 is for a site of an area of 25 km². This is a fairly vague assertion and it is worth considering further the reasoning behind it. In order to make the test centre an attractive option for testing a wider variety of devices of various concepts and sizes it is necessary to include within the scope of the test centre as wide a variety of conditions as possible.

This is countered by the need to keep the area affected as compact as possible to limit the environmental impact and the disruption it will cause to local activities such as sailing. For this reason a limit of 5 km by 5 km was decided on giving the opportunity to offer a variety of conditions in a clearly defined area which can be easily marked off above water and avoided by other users of the area. As the project progresses this may be altered to include the necessary conditions over the area that is deemed suitable. It is important however that the site is not sprawled over too wide an area.

There is also the question of how many test berths to install in the area. This may largely be dictated by demand as more berths will equate to higher capital costs which will only be justifiable up to a point. It is probably too early in the process to make final decisions about the particulars of these types of questions but some general guidelines can be set out.

A key part of this will involve surveying the developers of tidal energy devices and taking on board their input on the level of demand for such a system, and the kind of conditions they are looking for. Other than the demand and capital cost issue, there would seem to be no upper constraint on the number of possible berths aside from what could be fitted within the geographical space, taking account of the disturbance each device would cause to the flow.

Continuing with the theme of offering as many options as possible to developers it is worth considering installing both AC and DC berths to accommodate different types of generating equipment. Clearly, were DC berths to be offered, grid connection would require inverter hardware onshore.

Also, whilst there is a definite desire to have grid connection capabilities it may also be beneficial to offer berths that are connected to the onshore facility and are fully monitored but which, rather than being grid connected, dissipate the supply through some local load. This would be similar in principle to the heating element used by MCT on the Seaflow device. Whether this would require a dedicated berth or the hardware onshore could be set up so that it could be switched between the two would require further analysis and should be investigated.

The reason for this is that since this facility is to be targeted to developers at the early stage of the development process the devices may not be suitably refined to be connected to the grid or may be too unreliable. The opportunity to test a device in ‘real’ conditions though, and monitor it effectively, at these early stages could prove highly attractive.

3.4.1.2 What Each Berth Should Include

The berths themselves are relatively simple in terms of what they would have to include. Basically they would be made up of an 11 kV cable running along the seabed with a suitable underwater connection at the berth end and a connection to the necessary hardware onshore. The undertaking of connection of devices to the berth would be expected to fall to the developers rather than the test centre operators so full information of the type of connection and the requirements for connection would need to be made available to developers.

Other than the above, the only other inclusion would be a surface locator buoy which would be connected to the test berth in order to locate it easily.

3.4.1.3 Site Monitoring Equipment

One of the most important things the test centre can offer the developer is in depth monitoring of the site conditions and this should be done thoroughly. Acoustic Doppler Current Profilers should be deployed at various points throughout the entire site. These provide measurement of the current velocity and direction at various depths whilst also monitoring variations in the water depth. They also monitor water temperature. These profilers would need to have a data link to the control centre where the variations in conditions could be monitored.

As well as monitoring the flow characteristics it is advised that the weather and wave conditions of the site are monitored to MET office standards. This could be done by mounting the required equipment to measure air temperature, humidity, and wind speed etc on one of the locator buoys. Waverider buoys could be used to monitor the wave climate accurately and this would offer the opportunity for developers to see how waves affect device performance.

This kind of site monitoring would be valuable to developers as it would allow them to determine how their device behaves and responds in different conditions and how the electrical output is affected. It is crucial that all these things are well understood before any device is deployed commercially, in order to ensure the success of any project.

3.4.2 Onshore Aspects

The onshore aspects of a marine energy centre will be threefold. Firstly there will be a requirement for purpose built shore side housing in which all the necessary hardware will be located along with the transformers for Grid connection should they be required, in effect making a small substation. Secondly there will be a control centre where all the data from the site is monitored. Thirdly there is an obvious requirement for harbour access for the deployment of vessels as well as perhaps more local access for maintenance.

3.4.2.1 Shore Side Housing

A building will have to be constructed on the shore to connect the marine cables to the national grid and to house all the necessary hardware and monitoring equipment. This will in turn be connected to the nearest substation and onto the National Grid. In terms of the transmission of the power generated there are two options. The centre can either connect to the grid at 11 kV or 33 kV. The nearest substations are in the same locations for both, at Sorbie on the Machars Peninsula and Tongland and Gatehouse of Fleet near Kirkcudbright (Scottish Power, 2006). Connection at 11 kV is significantly cheaper than at 33 kV and if the local network can handle it then this should be pursued. The costs of equipment and cable connections are shown in Table 3.

	11kV	**33kV**
Connection Equipment	£20,000-£60,000	£120,000-£150,000
Overhead Lines	£15,000 - £30,000/km	£20,000 - £35,000/km

Table 3: Costs Associated with Grid Connection (BWEA, 2007)

As well as the equipment to connect from undersea cables to onshore ones there will be other pieces of hardware required such as approved power monitoring equipment and the necessary safety equipment.

The building itself will obviously have to comply with local planning regulations and should be as unobtrusive as possible to the local (likely rural) landscape. Consideration during specific site selection should be given to access to the site and the routing of power lines and local stakeholders should be involved in this process from the earliest opportunity (see Section 3.5.1).

3.4.2.2 Control Centre

The test centre will obviously require an office where all the recorded data is collected and analysed and where the soft aspects of the test centre such as marketing and research would be based. The location of this however is not really constrained by the exact site of the test centre and it could be located remotely, perhaps in Dumfries or Stranraer where it would be more accessible but still relatively local to the site.

3.4.2.3 Harbour Access

An important part of the day to day running of a test centre would be local access to the devices being tested. It is likely that, particularly for prototypes in the early stages of development, teething problems will be relatively frequent and the devices will require attention on a regular basis. It is also important that there is a port of significant size nearby to facilitate the installation of devices, particularly the larger ones. As has been touched on previously, there are small ports on the

Dumfries and Galloway coast near to the proposed onshore sites that would be ideal for maintenance access such as Port William and Kirkcudbright. It is likely however that the deployment of larger devices would be from Stranraer, or another larger harbour suitable for docking ships of the size required.

Whilst access from the area is important it is not essential that it is on site, as it were. It is perfectly acceptable for the nearest port or harbour to be several miles away; although obviously the closer the access is the more convenient for the developers.

3.4.3 Grid Connection

As has been outlined in Section 3.3.2 having a connection to the National Grid would be very attractive. There are a number of complicated issues involved with connecting to the Grid and these have been the subject of increased interest in recent years as the role played by renewable energy has increased.

The National Grid was originally designed to cope with constant inputs of large quantities of electricity from coal and gas power stations which could then be transported via the transmission network to the areas where there was high demand. This set-up is ill suited to the rise in renewable energy generation where the electricity generated is often small in comparison and tends to be inconsistent. This has lead to an increase in research into how demand can be matched with this new kind of supply and how the fluctuations can be accommodated to maintain a stable grid.

One of the main problems with the renewable energy resource in the UK is that it tends to be located in rural areas where the grid system is weakest and least able to cope with large volumes of electricity generation. This is particularly true in the North of the country such as the Highlands of Scotland but it also the case in much of Dumfries and Galloway and has an effect on how the tidal resource in general and the test centre in particular should be approached.

The transmission network in the region is such that there is little capacity for further generation of electricity to be exported nationally as is outlined in the National Grid Seven Year Statement and displayed in Figure 25 (National Grid, 2007). Given this scenario it would appear that there is only capacity for localised embedded generation where the local load will absorb the extra input of electricity.

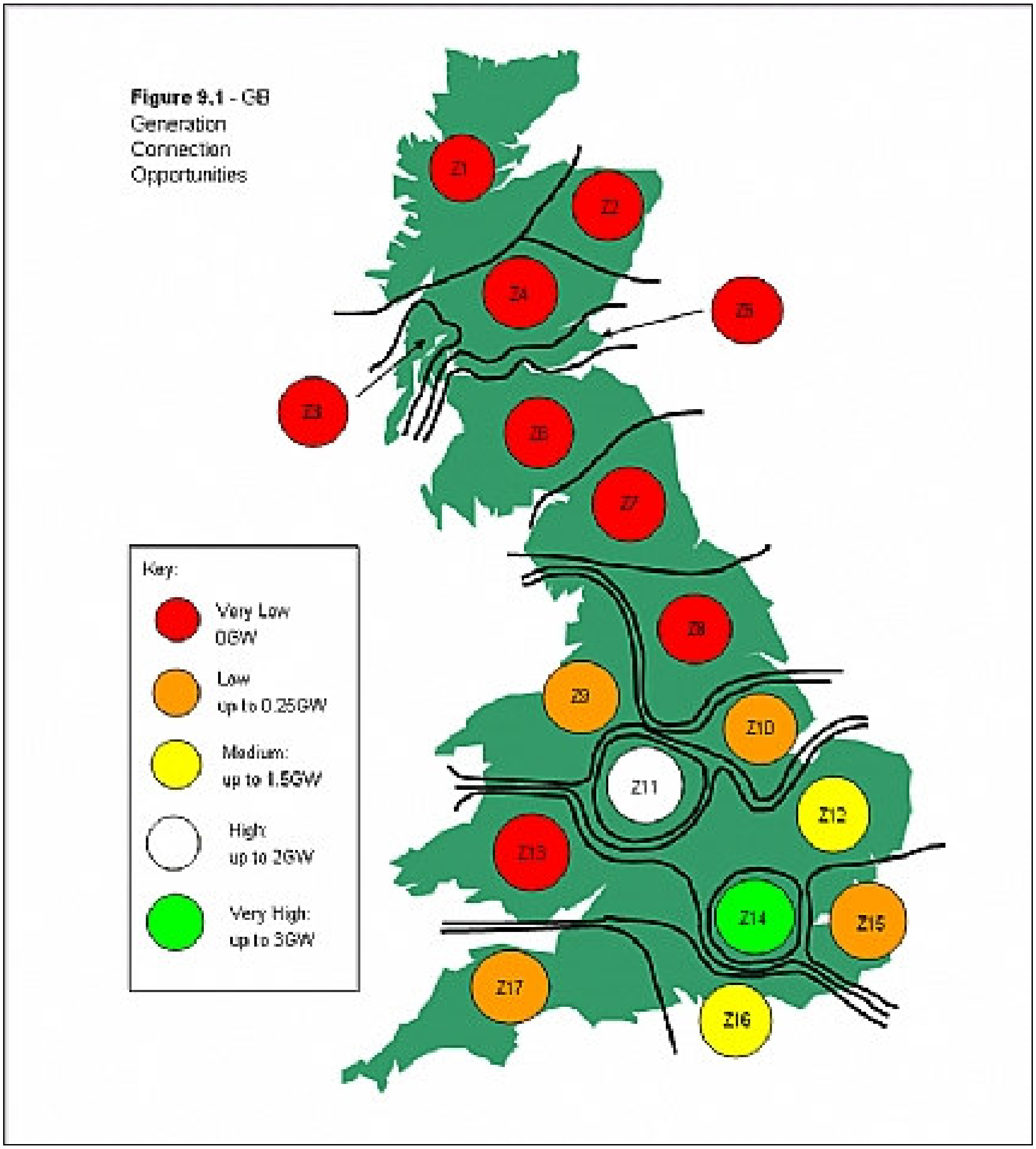


Figure 25: Capacity of the Transmission Network for Further Generation (National Grid, 2007)

From the point of view of developing a test centre this is not much of a hindrance since the output would be generally low but with a longer term view it is worth noting that the local transmission is likely to require substantial reinforcement if the tidal resource were to be exploited commercially.

It is recommended that an upper limit of 5 MW at 11 kV is put on the grid connected output of the test centre as this would be easily absorbed by the local network and would avoid the more stringent regulations. As a minimum, generators under 5 MW and 20 kV must comply with the requirements of Engineering Recommendation G59/1 “Recommendations for the Connection of Private Generating Plant to the Electricity Board’s Distribution System” as opposed to the more stringent Engineering Recommendation G75, “Recommendations for The Connection of Embedded Generating Plant to the Public Electricity Suppliers’ Distribution Systems Above 20 kV or with Outputs Over 5 MW” (Scottish Power, 2006).

3.5 Initiating Test Centre Development

3.5.1 Local Consultation

An important part of ensuring that any development is a success, and that it has a positive impact on the local community is the consultation process which must be embarked upon throughout the planning and construction phases. This can be initially defined as including 3 stages as follows:

- Identifying all the relevant stakeholders
- Providing them with required information in an accessible form
- Engaging with stakeholders to allow concerns to be raised and ideas taken on board.

It is important that this is understood from the outset of a project in order to avoid complications further down the line. Openness regarding both the positive and negative effects of the development of a test centre will contribute to smoother progress and help avoid unnecessary antagonism.

Stakeholders can be categorised into three separate groups. These are: Statutory Consultees, Strategic Stakeholders and Community Stakeholders. Statutory Consultees are organisations or groups that must be consulted by law for the any development to go ahead. Examples of this kind of body relevant here are the Department for the Environment, Food and Rural Affairs (DEFRA), The Scottish Executive & the Ministry of Defence (MOD).

Strategic Stakeholders are representatives of organisations whose opinion, whether positive or negative, of the project is likely to prove influential and organisations that offer expertise which is vital to the development of the project. For example Friends of the Earth, The Association for the Protection of Rural Scotland (APRS) & the Royal Society for the Protection of Birds (RSPB).

Finally Community Stakeholders, as the term suggests, are groups or individuals who live in the local area, and who are most likely to be directly affected by the development of a test centre in the area. Some examples of such groups are local sailing clubs, fishermen's organisations and Community Councils. More comprehensive lists of the organisations and groups which should be consulted, both at a national level and locally are included in Appendix D (British Wind Energy Association (BWEA), 2002)

Whilst these categories are useful to help define the stakeholders at an early stage, the respective labels should not be carried too far into the consultation, as some stakeholders could be defined by one or two of these categories. Also, it is worth noting that special consideration should be given to community stakeholders as there is a higher chance of missing someone out here than in the other categories where the bodies are more prominent. As a general rule it is wise to err on the side of caution and include more rather than less potential stakeholders.

In order to embark on a consultation process it is important first to fully understand the nature of the development, what it will involve, and who it will affect. This will involve detailed consideration of the Environmental Impact of the project (see Section 3.5.2) and a clear structure of what the process should involve. The British Wind Energy Association (BWEA) has published a guidance note for offshore wind farms, which will have many of the same aspects.

3.5.2 Environmental Impact

An important part of the progression of any offshore project, and so a key factor here, is the completion of an Environmental Impact Assessment (EIA) for the specific site and activity being considered. The Scottish Marine Renewables: Strategic Environmental Assessment (SEA) makes a good across the board critique of many of the issues involved and provides information on a strategic level, as its name would suggest, but it is crucial that a site specific EIA is carried out thoroughly and completely in the early stages of the development and design, in order to minimise the disruption and impact, and to aid the consultation process (BWEA, 2002., Scottish Natural Heritage (SNH), 2003)

The SEA offers a good framework from which this should be approached indicating all the aspects which should be considered. These are:

- Bathymetry of the site
- Geology, seabed sediments & sediment transport
- Marine and coastal processes
- Seabed contamination and water quality
- Protected sites and species
- Benthic ecology
- Fish and shellfish
- Marine birds
- Marine mammals
- Commercial fisheries and mariculture
- Archaeology
- Cables and pipelines
- Military activities
- Disposal areas
- Shipping and navigation
- Recreation and tourism
- Noise
- Electric and magnetic fields
- Seascape
- Grid impacts
- Decommissioning

(Faber Maunsell, 2007h)

Some of the more intrusive of these have been considered here during site selection to eliminate unsuitable areas and aid site selection, but in order to make more informed choices about the specific locations (both on and offshore) all must be considered in more detail. It is therefore of utmost importance that detailed environmental assessment be made at an early juncture.

The environmental impact of a test centre, or any tidal development, will be threefold. There is the impact of the installation process, which is likely to be particularly intrusive, the impact during operation, and the impact during decommissioning. The nature of this kind of development means that installation and decommissioning will occur more frequently than with a commercial project and also the kind of device and its operation may vary. It is therefore recommended that further EIA's should be carried out on a device by device basis so as the impact of each device that is tested is assessed thoroughly. This is the case at EMEC where specific guidelines have been drawn up (EMEC 2005).

4.0 Potential Commercial Generation at the Mull of Galloway

4.1 Introduction

Having outlined the opportunity available for another test centre in the area, it is wise to consider the further potential for generating electricity commercially. Many of the same issues arise here but the size and nature of the resource is of even more importance and therefore takes prominence. This section focuses on the potential for commercial generation, by quantifying the resource in as much detail as possible and considering the local grid capacity for the likely output of a tidal farm.

As mentioned previously, it is estimated that the Mull of Galloway is home to the tenth most potent tidal stream resource in the UK. What is less clear however, is just how accurate this figure is given that it is based mainly on Tidal Atlas data along with broad estimates of how much of the energy present will be extractable. While this does give a good general indication there are many other factors that must be taken into account in order to effectively evaluate the resource and assess its suitability both as a test site and for commercial generation.

The Phase II UK Tidal Stream Resource Assessment indicated that most significant tidal resource in the region is focussed round the tip of the peninsula. This is best illustrated by the DTI's tidal resource atlas as shown in Figures 24 & 27, below (DTI, 2004). This section therefore concentrates on this area as it is highly likely that any commercial development in Dumfries and Galloway would be located here.

This is not to say that this area is automatically suitable for extraction, and given the discovery of the munitions dumping ground and the other environmental issues there will clearly need to be further investigation of site suitability. This should be taken as an early attempt to make a detailed resource assessment in order to begin to quantify the kind of energy yield which may be expected.

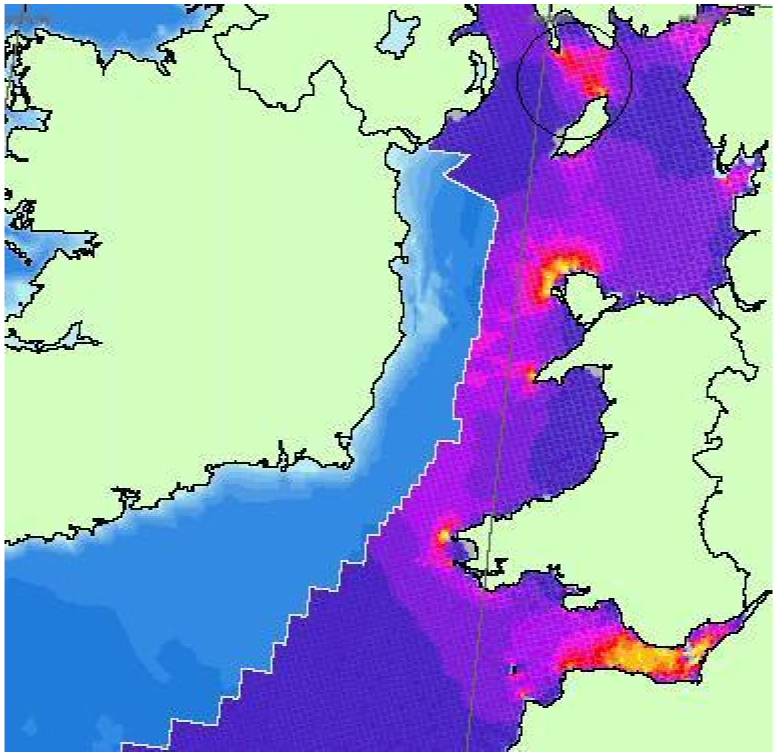


Figure 26: Area of highest energy density in flow-1 (DTI, 2004)

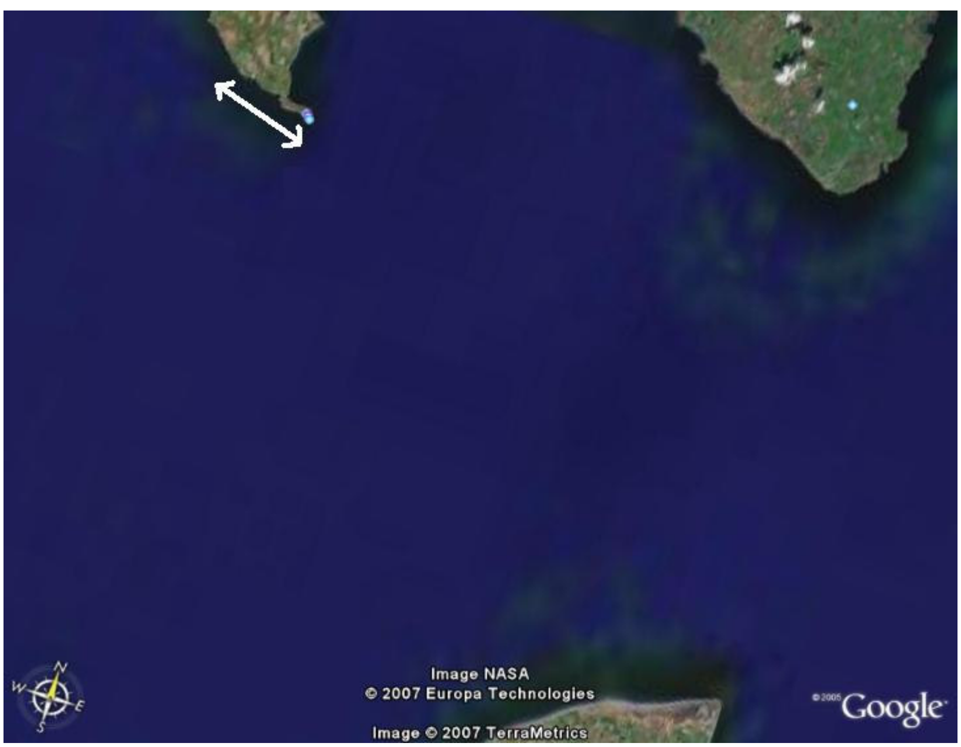


Figure 27: Area of highest energy density in flow (2)(Image Courtesy of Google Earth, 2005)

While this is a useful starting point for selecting sites for the development of tidal generation, this prediction offers no guarantee that the site is suitable. There are many other issues which must be considered on a site by site basis including the bathymetry of the site, the local distribution of the tidal flow, the environmental impact of any development and local infrastructure.

In order to gain a fuller picture of the potential for future development off the coast of the Mull of Galloway it was necessary to carry out as full an analysis as possible on the site, using all the data available at present.

Most of the research which has been carried out on potential capture of tidal stream power has focused on flow through narrow channels, such as the Pentland Firth. Clearly, this is not the case here where we have flow round a headland. However, given that this particular assessment is very much in its early stages; many of the same techniques were used to assess the resource round this peninsula.

It is tempting to bracket tidal currents with the well developed wind methods when it comes to resource assessment; however it is not that simple. Standard practice involves using the Betz limit to quantify the maximum amount of energy extractable from a given wind resource but the constraints on extractable tidal energy are somewhat more encroaching. The Betz limit assumes an unconstrained, incompressible flow with infinite boundaries whereas this is clearly not the case for tidal streams, given the obvious constraints on flow by the free surface and the sea bed, as well as any additional boundaries such as a channel or headland (Bryden et al, 2006). Therefore a more detailed assessment of the flow is required in order to develop a reasonable estimate of extractable power.

This section gives as in depth an analysis of the actual resource at the Mull of Galloway as is possible with the data available. This involves analysis not only of the tidal stream velocity in the simplest terms (i.e. near surface known velocity) but also analysing how this flow varies with depth, and the effect that extraction will have on the resource.

4.2 Resource Quantification

It is the intensity of the energy in tidal flow which helps to make it such an attractive resource. The energy flux in a tidal stream moving at 3 m/s is 14 kW/m² rising to as much as 175 kW/m² in rapid flows of 7 m/s such as in the Pentland Firth. This is explained by the relationship between kinetic energy flux and the velocity flow which is given by the following equation:

$$P = \frac{1}{2}\rho\int_A (U^3 dA), \qquad [1]$$

where:

ρ is the water density (kg/m³)

A is the cross sectional area of the channel (m²) and

U is the component of velocity perpendicular to the cross section of the channel (Bryden & Couch, 2005).

What this means is that the cube of the velocity, at any given point in the cross sectional area of the channel being considered is directly proportional to the power in that section of flow. While this appears a relatively simple relationship, it is somewhat complicated by the fact that tidal flow is known to vary considerably through a given column of water, laterally as well as from surface to seabed. There can even be variations through the swept volume of a turbine and clearly, this makes an accurate assessment of the energy available at any give site much more complex.

The biggest influencing factor for tidal current flow near the seabed is the bathymetry of the area, and the effect that the seabed has on the flow across it. There are a number of complex factors involved here, such as the boundary layer which develops and its characteristics along with the seabed roughness and the effect that this has along with other factors relating to both the physical nature of the channel, and the dynamic nature of the flow.

The estimates which lead to the ‘tenth most significant UK resource’ statement do not take this into account in any meaningful way other than to make across the board generalisations, nor do they consider the issues surrounding how energy extraction using a turbine or other device will affect the flow. This is generally accepted to be more significant than in wind applications and has an obvious implication when considering successive banks of turbines extracting energy from the one stream (Bryden et al, 2006).

4.2.1 Evaluating Variations in Velocity within the Water Column

In order to make reasonable estimations of the extractable energy present in the flow it is important to make a realistic evaluation of the velocity of the flow through the swept area of any given turbine. There has been a considerable amount of work carried out to develop expressions of how the velocity varies in a water column in a tidal stream and it is now common for the longitudinal component of flow velocity, U_x, to be expressed as:

$$U_x = Const\left(\frac{\xi}{h}\right)^{(1/w)} \qquad [2]$$

where:

ξ is the vertical distance above the seabed,

h is the water depth and

w is the power law coefficient

(Bryden et al, 2006)

In the analysis of a turbine's performance ξ can be used as the height of the hub and it has in the past been assumed that the velocity at this point is a reasonable approximation for that across the entire swept area. It is however preferable to obtain an average value over the swept area and it has been found that this can reasonably be expressed as

$$\overline{u} = \frac{4}{\pi D^2}\int_{-(D/2)}^{+(D/2)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u(y+z_0)\,dy \qquad [3]$$

where:

D is the turbine diameter,

y is the horizontal distance perpendicular to the flow direction and

z_0 is the height of the turbine hub above the seabed.

This expression can be further developed to take into account the cubic nature of the relationship between velocity and energy flux which takes the form:

$$\left[\overline{u}^{3}\right]^{(1/3)} = \frac{4}{\pi D^{2}}\int_{-(D/2)}^{+(D/2)}\cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right]u^{3}\times(y+z_{0})dy \qquad [4]$$

In order to utilise this expression boundary conditions for the channel were developed and all available data regarding tidal flow velocity was compiled in order to make the most accurate assessment possible (Bryden et al, 2006).

4.2.2 Boundary Conditions

In order to carry out a meaningful analysis of the flow round the peninsula at the Mull of Galloway it is first necessary to define the area being considered more explicitly. With simple channels this is intuitive, given that the flow is constrained on either side by the defining land masses. In this case however, where flow round a headland is being considered, it requires a little more thought.

Figure 28, below, shows the admiralty chart for the area, with the depth of the channel displayed by contour lines and individual values. There is also some information on current velocity. Considering the information in the DTI's tidal resource atlas (Figure 2) and the information in this chart assumptions can be made for a hypothetical 'channel' round the peninsula.

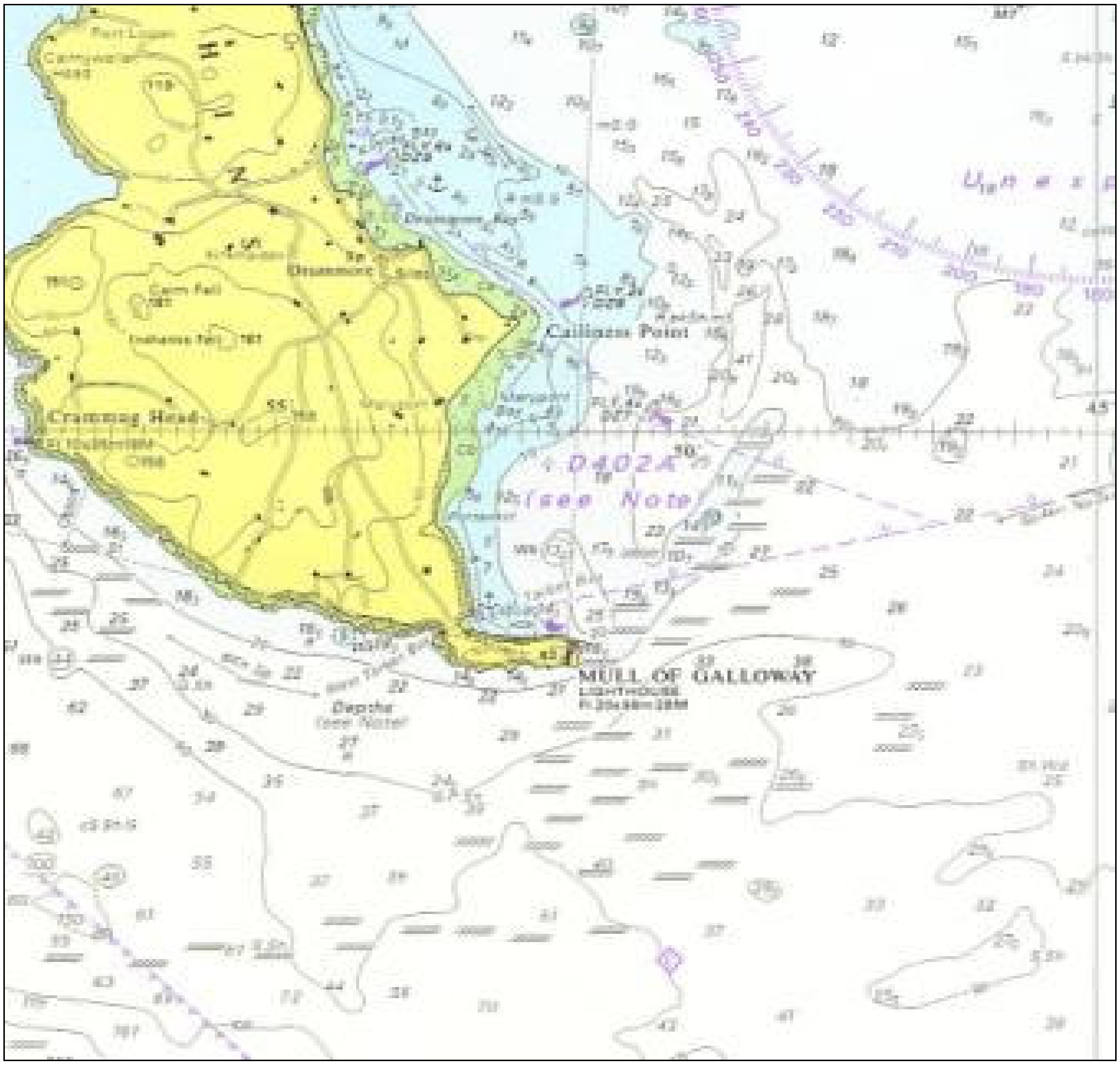


Figure 28: Admiralty Chart for Mull of Galloway Area (UKHO, 2005)

What this shows most clearly is that the site off the Mull of Galloway has a fairly uniform depth which only exceeds 50 metres in isolated locations. This means that the site is attractively wide, with tidal current velocity still significant up to and over 5 kilometres from the shoreline. Figure 29 gives an idea of what this looks like proportionally at 6 cross sections taken at 1 km intervals along the headland.

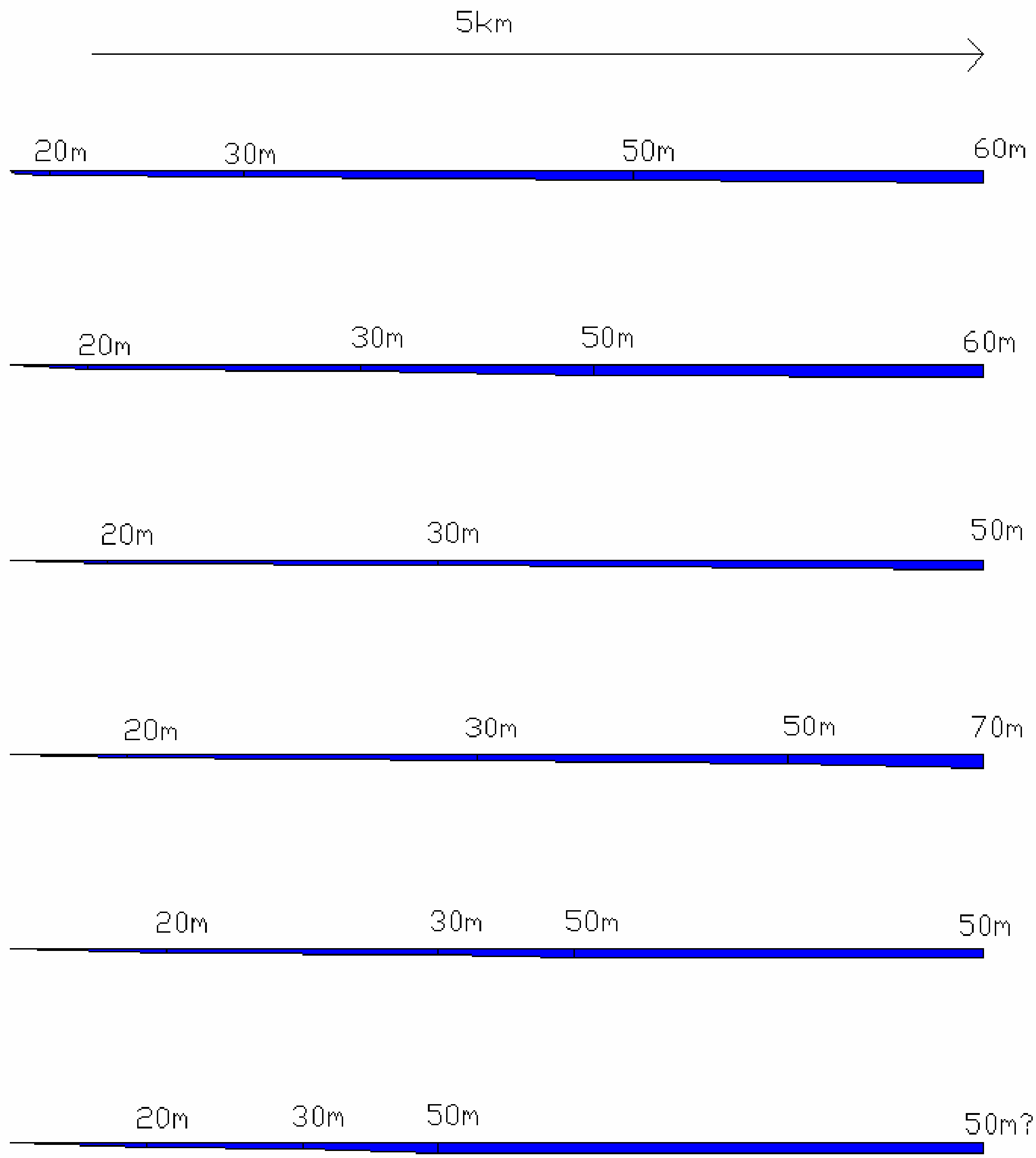


Figure 29: Bathymetry Cross-sectional profile

Of primary interest in this case is the area where depths are between 20 and 30 metres, with depths of up to 50 metres being of secondary importance for the tidal site. This channel has an area of about 12-13 km².

At this early stage it is necessary to make a simplification of the situation in order to implement mathematical analysis. It was decided that the 'channel' round the headland between the 20 and 30 metre contours be used for analysis, given that it is likely to contain the most significant flow. This area was greatly simplified to be considered as a cuboid 1000 metres wide and 25 metres deep. Since the south side of this channel is exposed to what can reasonably be considered open sea it is possible that this simplification could even yield an underestimation of the available extractable power, as it may recover more quickly than flow in a more constrained channel.

4.2.3 Available Data

Having established the boundaries of the area being considered, all available data regarding the nature of the flow must also be evaluated. Tidal data for this study was available in three main forms. Firstly, the Admiralty Tidal Stream Atlas for the region (UKHO, 1992), giving values for directional flow taken 6 metres below the surface, secondly, the in depth bank of tidal current data available from the BODC (BODC, 2007) and finally the data displayed in the Admiralty Chart for the area (UKHO, 2005).

4.2.3.1 Atlas Data

The tidal atlas data available from the Admiralty is the primary source of any tidal stream information and is of some use here. The tidal atlas records current velocity at two useful locations round the Mull of Galloway and these can be seen in Figure 30, below. The comma in between the two numbers (speed in knots for spring and neap tides) indicates the point of measurement.

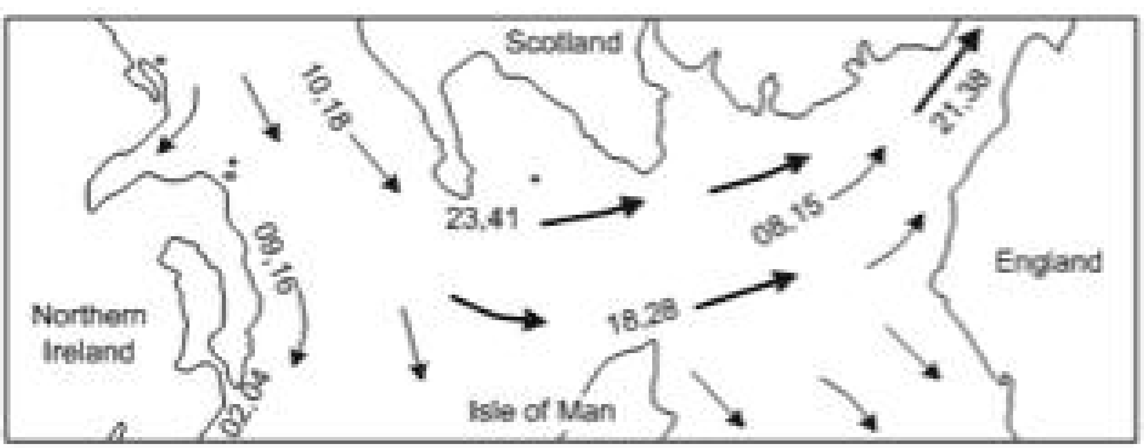
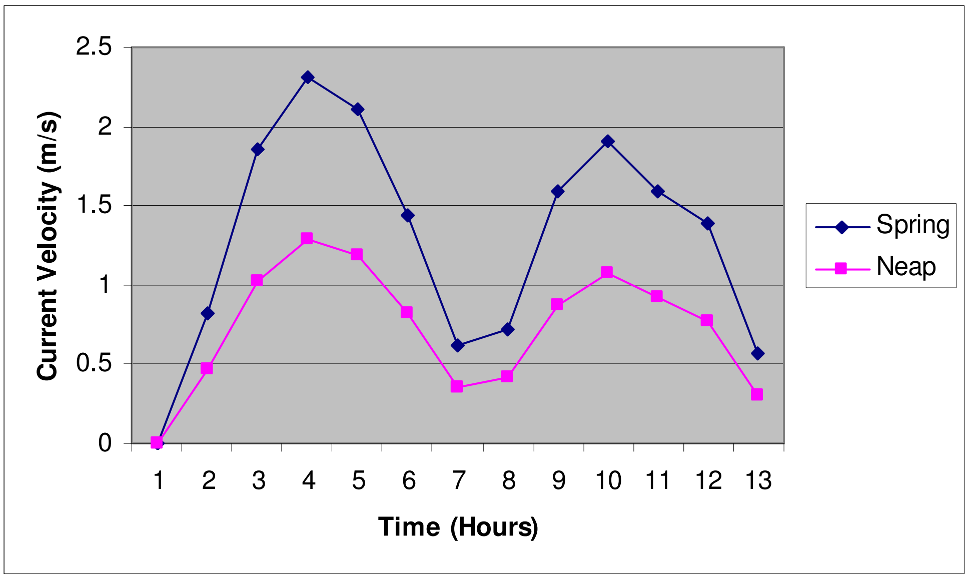


Figure 30: Admiralty Tidal Stream Atlas for Area (UKHO, 1992)

The values for tidal current velocity indicate the mean values over the measured period. Clearly, given the area considered, the point just off the tip of the headland (about 2km from the shore) is the most useful here, although the measurements 2-3km off the west coast may also help with this analysis.

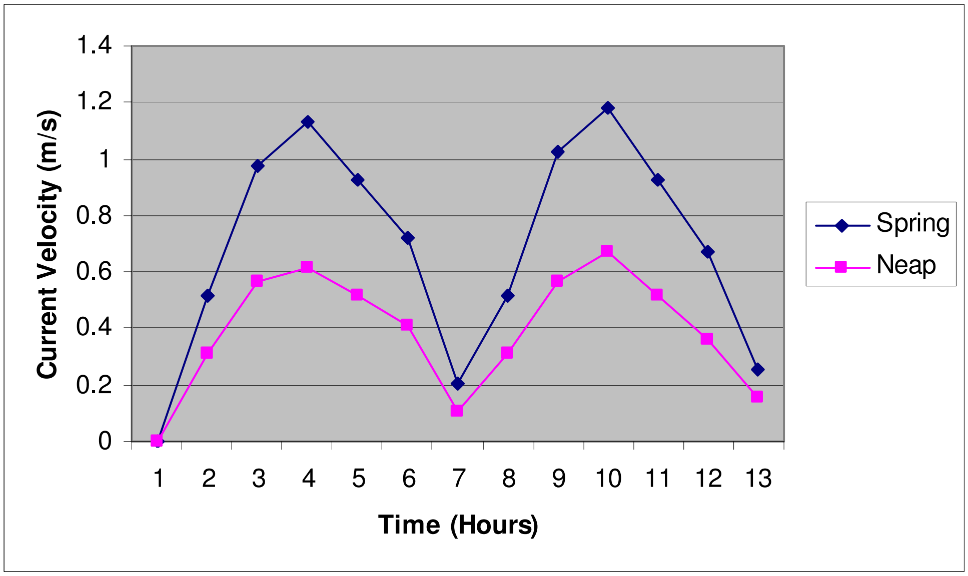
The data from the atlas, given in knots, is taken and converted to metres per second by using a multiplication factor of 0.514. Graph 4 shows a graphical representation of the surface tidal current recorded at the point off the tip of the peninsula for spring and neap tides in m/s.



Graph 4: Tidal Current Velocity from Atlas Data (Point 1)

As can be clearly seen, the spring tide peak flow is significantly larger when the tide is moving in towards the Solway Firth (2.3 m/s) than when it is on its way out (1.9 m/s). The difference is less dramatic when it comes to neap tides with 1.3 m/s on the way in and 1.1 m/s on the way out. These figures give a good indication of the marked difference in peak flow between spring and neap tides, in this case a drop of 43%.

On the west coast of the peninsula, the current speed is significantly less as shown in Graph 5, where the spring peaks are 1.1 m/s and 1.2 m/s with neap peaks of 0.6 m/s and 0.7 m/s. This indicates a similar variation of peak velocity of about 45%.

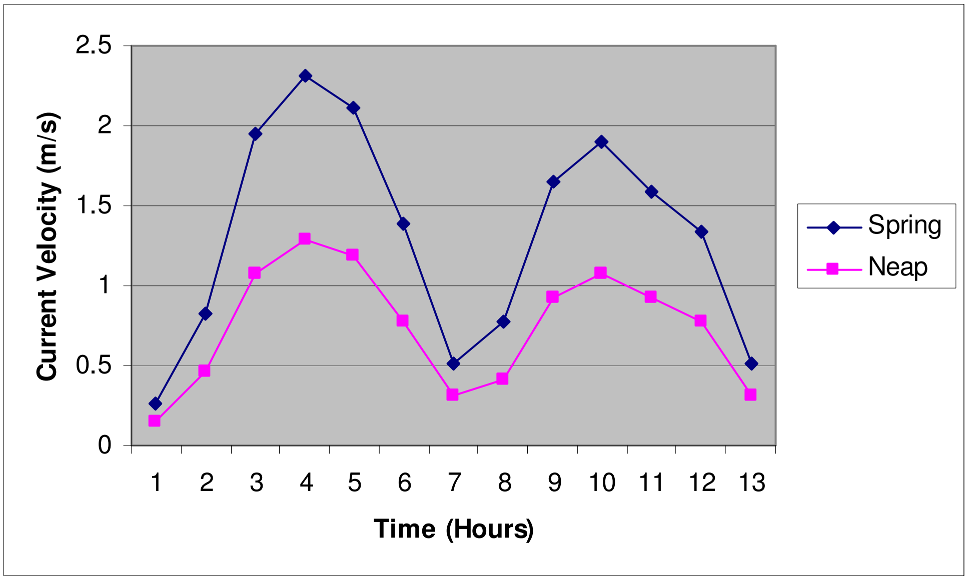


Graph 5: Tidal Current Velocity from Atlas Data (Point 2)

4.2.3.2 Admiralty Chart Data

The Admiralty Chart data for the region is shown in Section 3.2.1.2 and there are a couple of pieces of information that are useful here. These are the assertion that the mean peak tidal current velocity at spring tides is 3.1 m/s and the information from tidal Diamond C. The diamond data is represented in Graph 6.

It can be seen that Graphs 4 & 6 are almost identical, indicating that the two sources corroborate one another.



Graph 6: Data from Tidal Diamond C (Admiralty Chart)

4.2.3.3 BODC Subsurface Data

Whilst the tidal atlas provides good data for near-surface flow, it is necessary to consider how this may vary throughout the depth of the water column. The best readily available data was from the BODC's vast bank of marine measurements over the last 40 years and so all available readings for round the Mull of Galloway were obtained.

Unfortunately there is no data available just off the end of the headland or anywhere in that vicinity. There is however, fairly comprehensive data for the area off the west coast of the peninsula and this serves to illustrate the nature of tidal flow clearly. Figure 31, below, shows the distribution of available tidal data on the west coast of the Mull of Galloway. Comparing the image with the Tidal Atlas in Figure 30 it can be reasonably assumed that data points 12, 13, 16, 17 & 23 offer the most attractive option for comparison with surface data, in order to evaluate how the flow velocity differs throughout the water column.

Figure 31: Available tidal data (Image Courtesy of Google Earth, 2005)

Many of the tidal current records held by the BODC are fragmented and of limited use but of the most applicable points, 23 offered the most comprehensive data. The depth around this point is between 260m and 265m and there is a range of data available for periods of between 25 and 50 days at depths around 20m, 130m and 260m below the surface. The period over which measurements were taken is particularly important as it must be over 30 days in order to cover a full cycle from spring to neap tides and back to spring again.

The peak velocities recorded at 23 can be seen in Table 4. There are three separate periods of measurement labeled A, B & C.

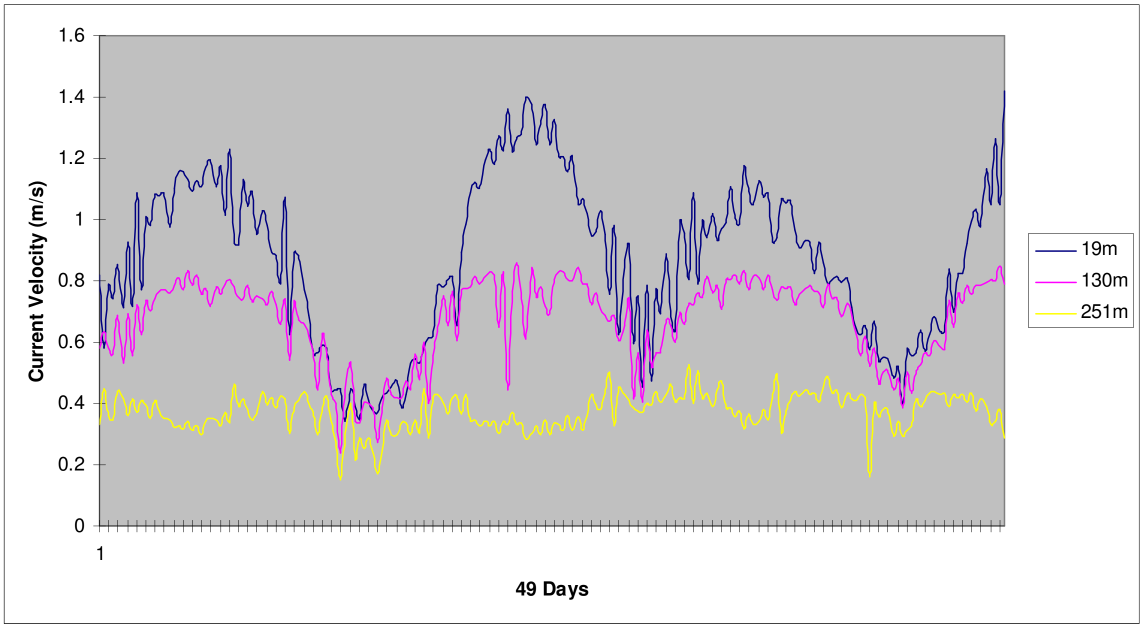
	Period	**At 20m**	**At 130m**	**At 260m**
A	25 days	1.2514m/s	0.9652m/s	0.5662m/s
B	50 days	1.2907m/s	0.9521m/s	0.624m/s
C	48 days	1.4193m/s	0.9022m/s	0.6476m/s

Table 4: BODC data for selected points

At present there are no devices in operation that would be able to be deployed in water this deep, but it is likely that developments will lead towards energy capture in deep water, given that this is where the majority of the global tidal resource is to be found. This information gives a good indication of the characteristics involved with tidal currents at various depths.

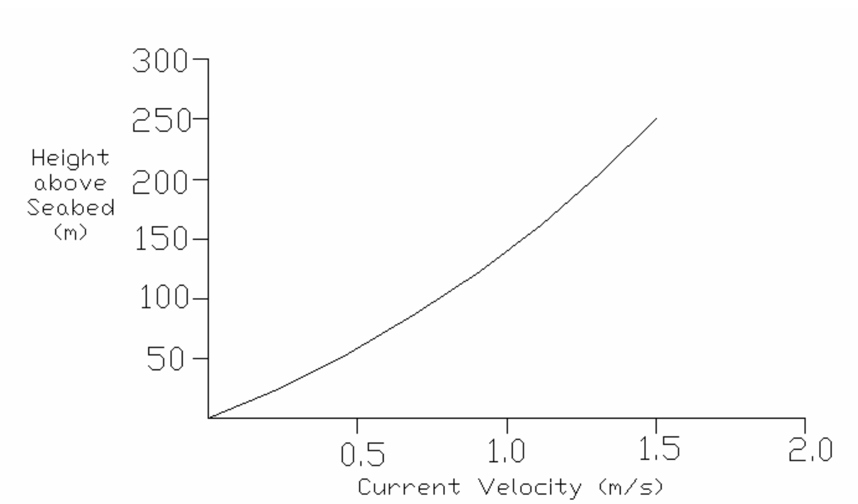
Comparing Table 4 with the surface information available from Graph 4 it can be reasonably assumed that there is little reduction in flow rate below the surface up to depths of 20 or 30 metres when the overall depth is much deeper. This indicates that the information obtained from the BODC is consistent with that available from the Admiralty Tidal Atlas.

To give a clear representation of what this means over a full cycle, Graph 7 shows plots of peak tidal flow over a 50 day period for the 3 depths measured at point 23. From this graph it can be clearly seen both how tidal flow varies with depth and how it varies over time following a sinusoidal pattern.



Graph 7: Variation of Tidal Current Velocity with Depth 1 (260m Seabed Depth)

It is clear from this data that tidal current flow is strongest near the surface and reduces with depth and this has implications when considering exploiting the available resource. As mentioned previously, it is not yet possible to exploit the tidal resource in areas where the sea is this deep although, as the industry develops it is likely that energy capture projects will become much more ambitious. This data allows the development of the plot shown in Graph 8, which illustrates how tidal current velocity has an almost linear relationship with depth at peak spring tide velocity.



Graph 8: Variation of Current Velocity with Depth 2 (260m Seabed Depth)

As has been previously illustrated, at the location of the peak resource round the Mull of Galloway the depth of the seabed is less than 50m and in this case the relationship between velocity and sea depth takes on a rather different form. While there was no data available for the exact location, there were data sets available for areas of similar depth within the vicinity, further up toward the Solway Firth and these prove useful as they provide data sets for tidal velocity over similar depths to those being considered. Figure 32 shows this with Point 4 providing the most comprehensive data set.

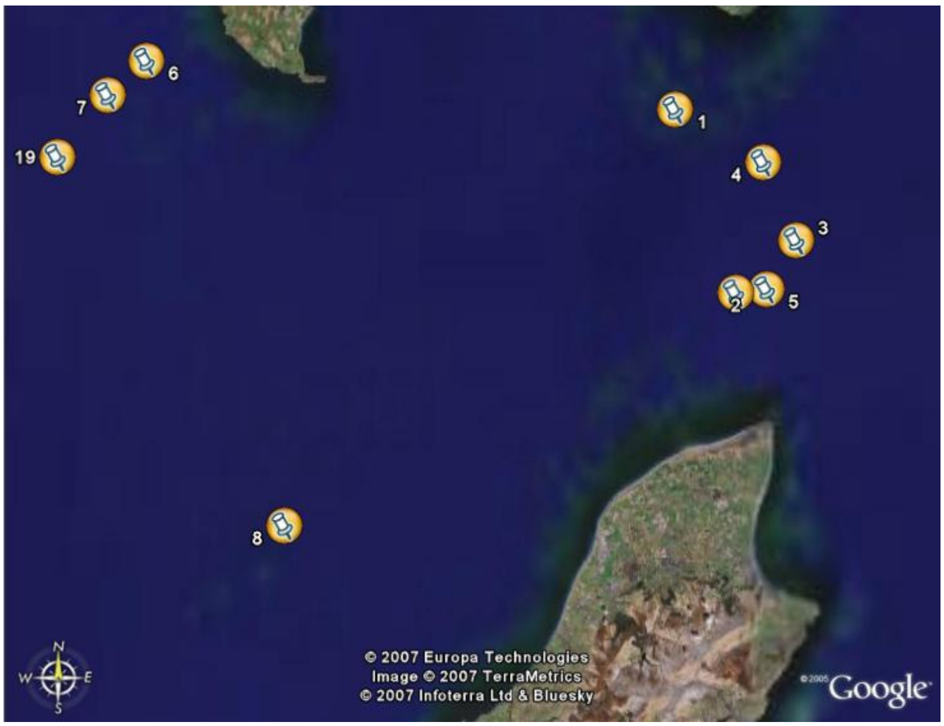
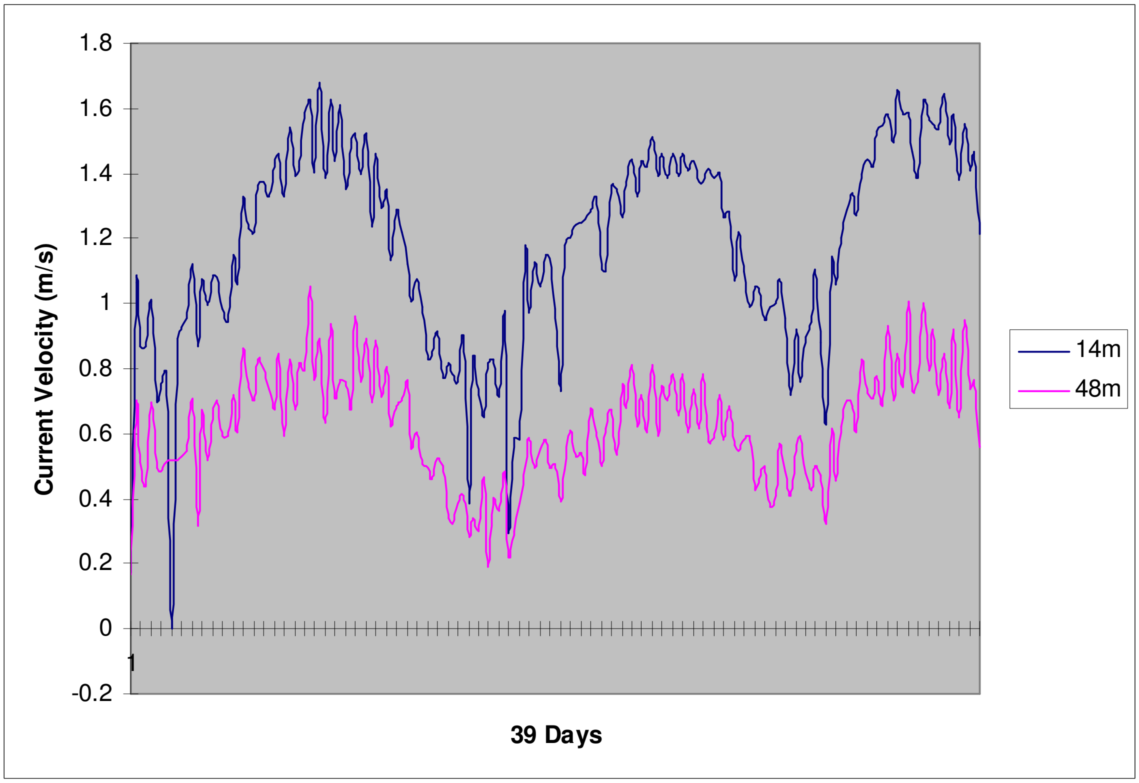


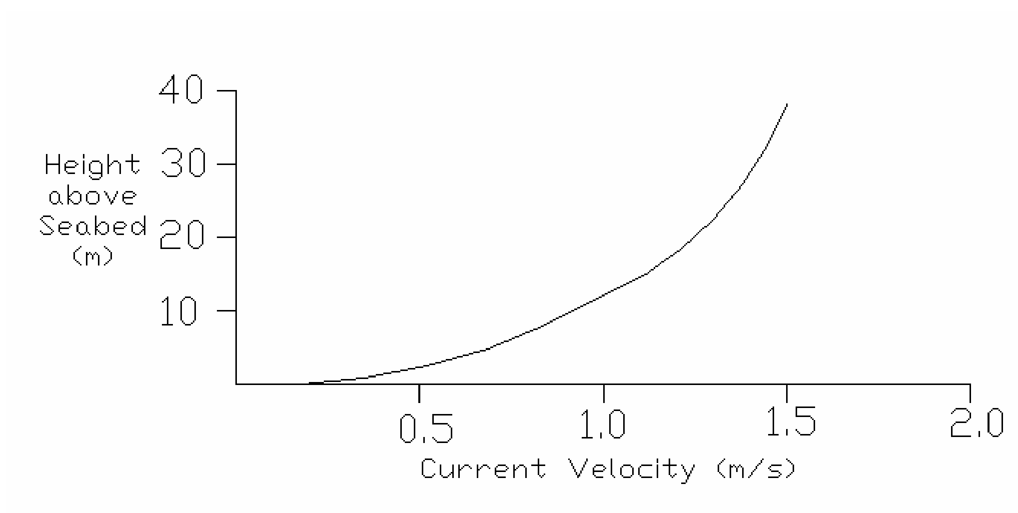
Figure 32: BODC Data (Image Courtesy of Google Earth, 2005)

The readings at point 4 give a good demonstration of how the shallower water leads to a reduction in flow rate near the sea bed with the peak values at a depth of 48m being about 29% less than at 14m in a total sea depth of 53m. Graph 9 shows this tidal cycle over a period of 54 days. This data can reasonably be compared with the tidal atlas data further up toward the Solway Firth as shown Graph 9.



Graph 9: Variation of Tidal Current Velocity with Depth 3 (50m Seabed Depth)

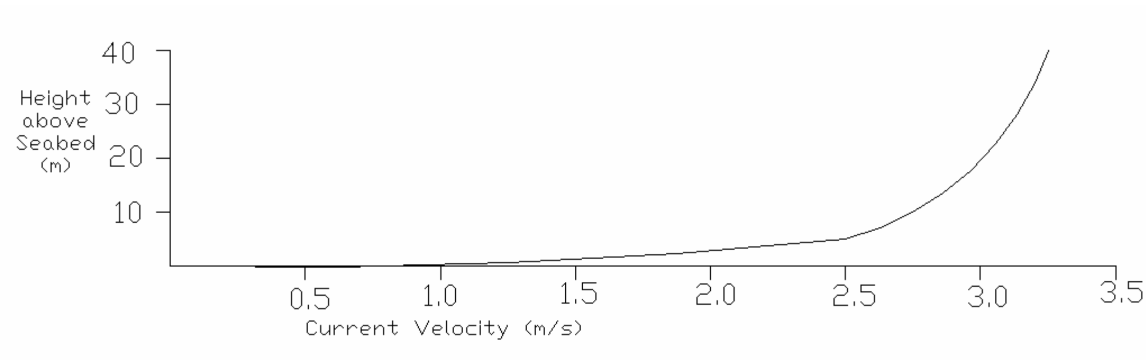
All this data was used to develop a relationship between current velocity and position within the water column and is represented in Graph 10, below. This is however a somewhat crude depiction given the presence of only two data points. It is worth noting that even at a depth of 48m of an overall depth of 53m the flow is still significant.



Graph 10: Variation of Tidal Current Velocity with Depth 4 (50m Seabed Depth)

4.2.4 Initial velocity Calculations

Research carried out to date has shown that basing energy flux estimations in tidal current flow can produce gross overestimation of the energy available. Models based on a 1/7th power law are commonly used however the data from the BODC shows that, in slower flows at least, this is not accurate (Bryden et al, 2006). However, as Graph 11 shows, a 1/7th power law assumes a slightly different relationship between the current velocity and depth than the BODC measurements for this point display (Graphs 8 & 10).



Graph 11: 1/7th law variation of current velocity with depth (Bryden et al, 2006)

Furthermore, the current velocity increases significantly closer to the peninsula to double the velocity recorded by the BODC and so it can reasonably assumed that the profile will be close to that shown in Graph 11.

Using this as a starting point it is possible to further evaluate equation [2] and calculate a relevant value for the constant:

$$U_x = Const\left(\frac{\xi}{h}\right)^{(1/w)}$$

In this case it is known that at a depth of 6 metres in an overall sea depth of 25m the velocity is 3.1 m/s. So,

$$3.1 = Const\left(\frac{19}{25}\right)^{(1/7)}$$

This gives a constant of 3.22 for this particular column of water. With this number is possible to calculate the velocity at any given point in the water column.

In order to evaluate the flow over the swept volume of a turbine it is necessary to make some assumptions regarding the placement of the turbine. In this instance it was assumed that the turbine hub would be situated 13 metres above the seabed and would have a diameter of 16 metres. Using Equation [2]:

$$U_x = 3.22\left(\frac{13}{25}\right)^{(1/7)}$$

$$= 2.93\text{m/s}$$

Taking this value and the given diameter of the turbine it is then possible to use Equation [4] as follows to calculate the average velocity across the swept volume as follows.

$$\left[\overline{u}^3\right]^{(1/3)} = \frac{4}{\pi D^2}\int_{-(D/2)}^{+(D/2)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u^3 \times (y + z_0)\,dy$$

This equation can be solved for the given values (D=16, Z_0=13 & U=2.93) hence the value of the average velocity over the swept area of the turbine ($\overline{u}$) can be found to be 2.73 m/s.

As the surface current velocity was defined as being 3.1 m/s, it can be seen that there is a drop of 0.37 m/s or 12% over the initial value. A relatively small amount, but significant when considering generation over a whole year at a given velocity.

4.2.5 Channel Characteristics

Further to simple velocity considerations, it is known that extraction of energy is likely to cause a head drop through the channel in addition to the head drop that naturally exists. An expression showing the ratio, B, between these two head drops has been developed giving the relationship (Bryden et al, 2006):

$$B = \frac{f}{1 + {}^{2gLn^2}\!\big/_{R^{(4/3)}}} \quad [5]$$

Where f is the fraction of kinetic flux being extracted, n is the Manning friction coefficient and g is the acceleration due to gravity. L is the length of the channel and R is the hydraulic radius which in this case can be taken to be the ratio between the cross-sectional area of the channel and the wetted perimeter. This relationship is significant in that it shows that the sensitivity of a given channel to energy extraction is directly related to its physical characteristics, specifically its depth, length and boundary roughness.

This relationship can be applied to our hypothetical channel at the Mull of Galloway and applying the values for this area gives the following:

$$B = \frac{0.2}{1 + {2 \times 9.81 \times 4000 \times 0.035^2} / {24.39^{(4/3)}}}$$

$$B = 0.085$$

Indicating that were 20% of the kinetic flux to be extracted there would be an additional 8.5% head drop in the channel. This could be expected to have a significant affect on the flow characteristics further down the channel.

4.2.6 Implications of extraction on unrestricted flow

Having considered how the velocity of the flow, and therefore the energy flux present in the flow, varies with the depth, and the impact that energy extraction in the channel will have on the flow downstream, there is one other inhibiting implication of energy extraction which must be considered.

In their paper on tidal current resource assessment, Bryden et al (2006) outlined how energy extraction has an impact on the unrestricted flow in a given channel. This was illustrated by modelling flow along a channel with an island in the centre and evaluating how the flow responded if there was energy extraction on only one side of the island. Figure 33 shows an illustration of what this would look like in practice.

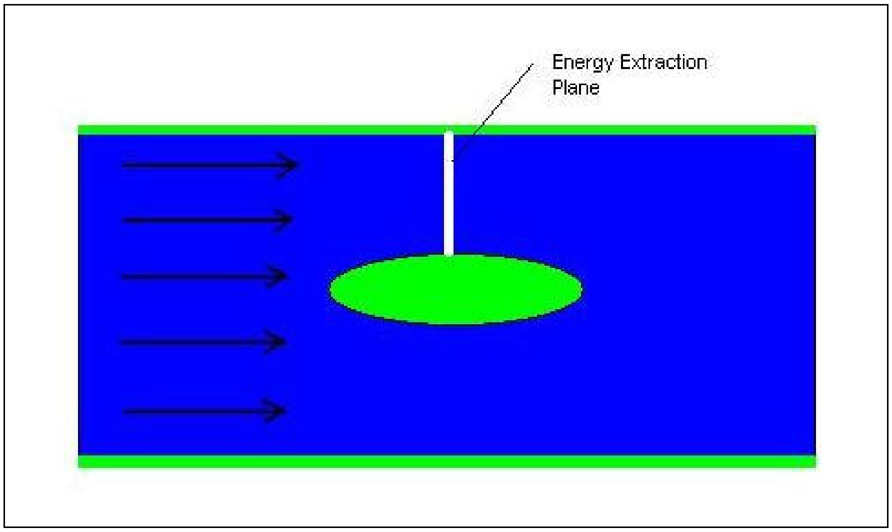


Figure 33: Energy Extraction in part of a Channel

It was found that the presence of the energy extraction in the northern channel had a significant impact on the flow through both channels. The resistance offered by the energy extraction meant that the flow developed a preference to go down the unrestricted channel as opposed to passing through the energy capture devices. Naturally, the flow takes the path of least resistance. In the case considered the velocity of the flow in the northern channel was found to decrease by around 25% from 1.75 m/s to 1.31 m/s at a depth of 38m.

While this is worthy of consideration when addressing flow through channels, it is even more significant when thinking about flow round a headland, as at the Mull of Galloway. Given the lack of constraint on the south side of the hypothetical channel which is being considered here, it can reasonably be expected that the impact of energy extraction could be even more significant leading to an even larger reduction in the resource before any of it has been extracted.

4.3 Estimate of Potential Resource

4.3.1 Energy Present

Having considered these different factors which affect the amount of extractable energy from the tidal current flow it is possible to make a more detailed assessment of the resource at a given site, in this case at the Mull of Galloway, with some significant assumptions.

It has already been shown that the velocity 12 metres below the surface in our 25 metre deep channel can be taken to be 2.93 m/s. Equation [4] further develops this so that the average velocity over the swept area of a 16m diameter turbine at peak spring tide is shown to be 2.73 m/s.

Taking the findings of the effect of extraction on the velocity of the undisturbed flow it can be assumed that this will experience a drop in velocity of at least 25% (Given the findings for flow in a channel), translating to an actual velocity at the first bank of turbines of 2.19 m/s. It is important to note that this could be even more significant given the lack of boundaries constraining the flow and should only be considered an initial estimate. This figure can then be used to calculate the flux in the channel, making the broad estimate that this velocity can be taken as a reasonable average over a harvestable range (i.e. not including less than 4m above the seabed).

The relationship between the velocity, U, and kinetic flux density, P, has been shown to be

$$P = \frac{1}{2}\rho\int_A \left(U^3 dA\right)$$

For the velocity at a depth of 12m in this case translates to give us:

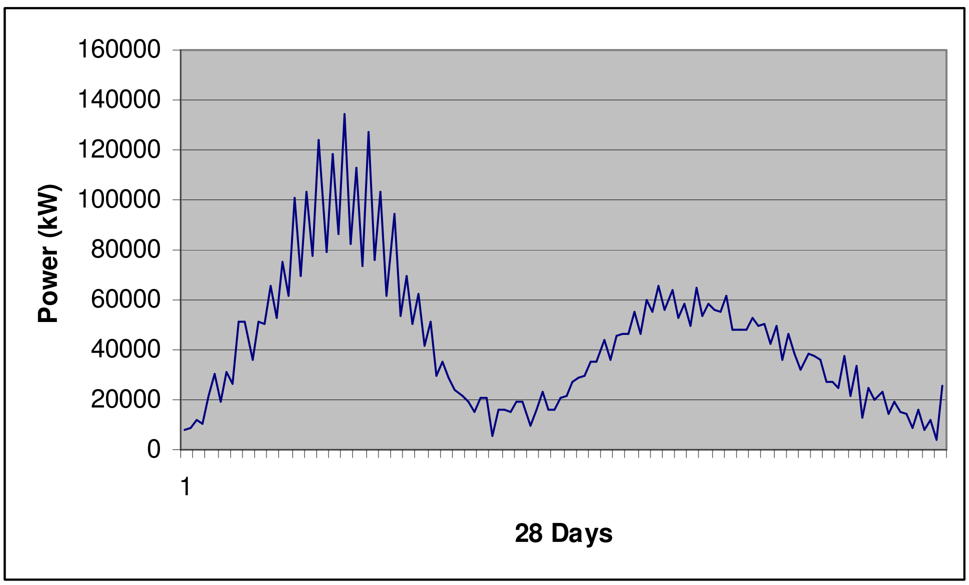
$$P = \frac{1}{2}\times 1023\int_A \left(2.19^3\, dA\right)$$

$$\therefore P = 5.4 \text{ kW/m}^2$$

This illustrates the dramatic fashion in which flux density varies with velocity, since a velocity of 3 m/s gives a flux density of 14 kW/m² which of course to be expected given the cubic relationship. The simple channel being considered here has a cross sectional area of 25,000 m² which, taking this velocity as a reasonable mean, corresponds to an initial total flux in the channel of 135 MW at peak spring tide velocity.

However, given the cyclic nature of the tides it is important to also consider the flux present at neap tides in order to gain as full a picture as possible of the energy available at his location. Give that the mean peak neap tide velocity is in the region of 1.75 m/s it is possible to go through the same process as before which gives a value for the flux in the channel of 18.2 MW at peak neap tidal velocity.

BODC data was used to develop a full data set for a full months cycle for velocities of this magnitude and Graph 12, below, shows the instantaneous kinetic flux in the channel at peak tidal current velocity throughout the period.

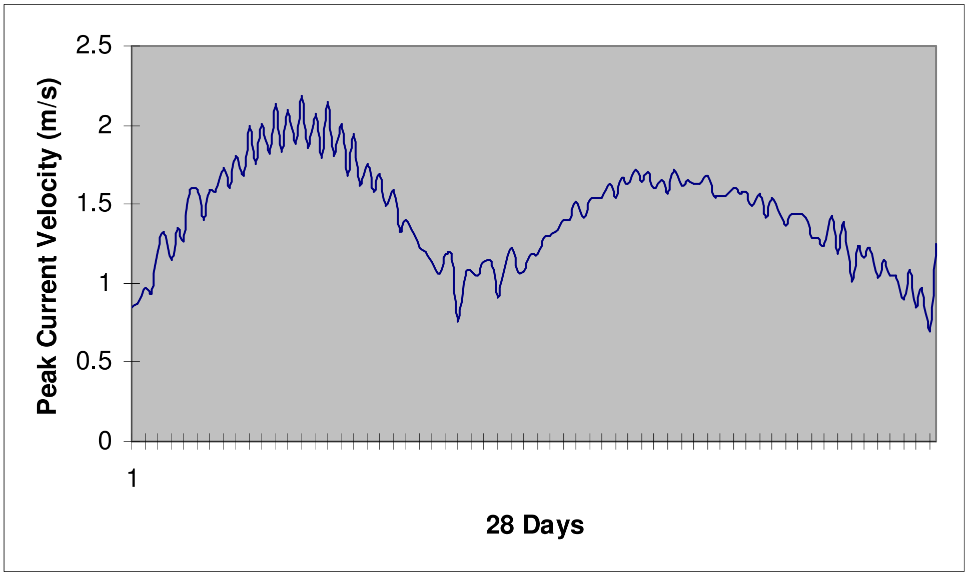


Graph 12: Kinetic Flux in hypothetical 'Channel'

This data was then evaluated to estimate the total present energy at the sight over a whole year using the relationship shown in Equation [6]:

$$\int P dt = \int_{t_1}^{t_2} (\tfrac{1}{2} \rho V_{\max}{}^3 \sin^3 \omega t) dt \quad [6] \quad \text{(Grant, 2006)}$$

Where $V_{\max}$ is the peak velocity for each 12½ hour tidal cycle. A plot of the peak velocity for each 12½ hour cycle over a month is shown in Graph 13. It was found that for the channel being considered the total energy present was 341 GWh/year.



Graph 13: Peak Tidal velocity per 12½ hour cycle

4.3.2 Extractable Energy

It is possible to use this data to make an estimation of the amount of energy which could theoretically be captured by a simple turbine device placed in a tidal stream of this speed using some mathematical equations. These calculations were undertaken for the tidal data shown above.

This mathematical process involves calculating the electricity generated over an entire cycle (from slack tide to slack tide) given the maximum velocity for that cycle. The outworking of this formula is shown below.

Generally, the instantaneous power produced by a turbine is given by:

$$P = \tfrac{1}{2} C_p \rho \pi R^2 V^3 \quad [7] \qquad \text{(Grant, 2006)}$$

Since tidal flow follows a sinusoidal pattern, as the graph shows, it is necessary to integrate In order to calculate the power generated over a full cycle. This is done using the following equation:

$$P = \int_{T_1}^{T_2} \tfrac{1}{2} C_p \rho \pi R^2 V_{\max}^3 \sin^3 \omega t + P_{rated}[186.25 - T_2] \quad [8] \qquad \text{(Grant, 2006)}$$

Which gives the power delivered for a quarter cycle and hence, when multiplied by four, for an entire 12½ hour full cycle.

In this formula C_p is the power coefficient, ρ the density of water, R the radius of the rotor, $V_{\max}$ the peak velocity for the cycle. $T_1 \& T_2$ are the cut in time and the time when rated power is reached respectively. The angular velocity is given by $\omega = \frac{2\pi}{T}$, where T is the period of the cycle.

The cut in time can be calculated using the formula $V_{cutin} = V_{\max} \sin \omega t$, with the resultant time for t representing T_1. Similarly, the time where rated power is reached is found from $V_{rated} = V_{\max} \sin \omega t$, the resultant t representing T_2.

In order to give a benchmark for the potential electrical generation from one Seagen twin turbine device this formula was used on the data obtained from the BODC and shown in Graph 14. Basically this means calculating the power output for every point on the graph as each point represents the peak velocity for a full cycle. The data covers a full neap – spring tidal cycle and so from this the potential annual energy capture can be calculated fairly accurately.

The values for the Seagen turbine are as follows:

$$V_{rated} = 1.6m/s$$

$$V_{cutin} = 0.7m/s$$

$$\rho = 1025kg/m^3$$

$$C_p = 0.45$$

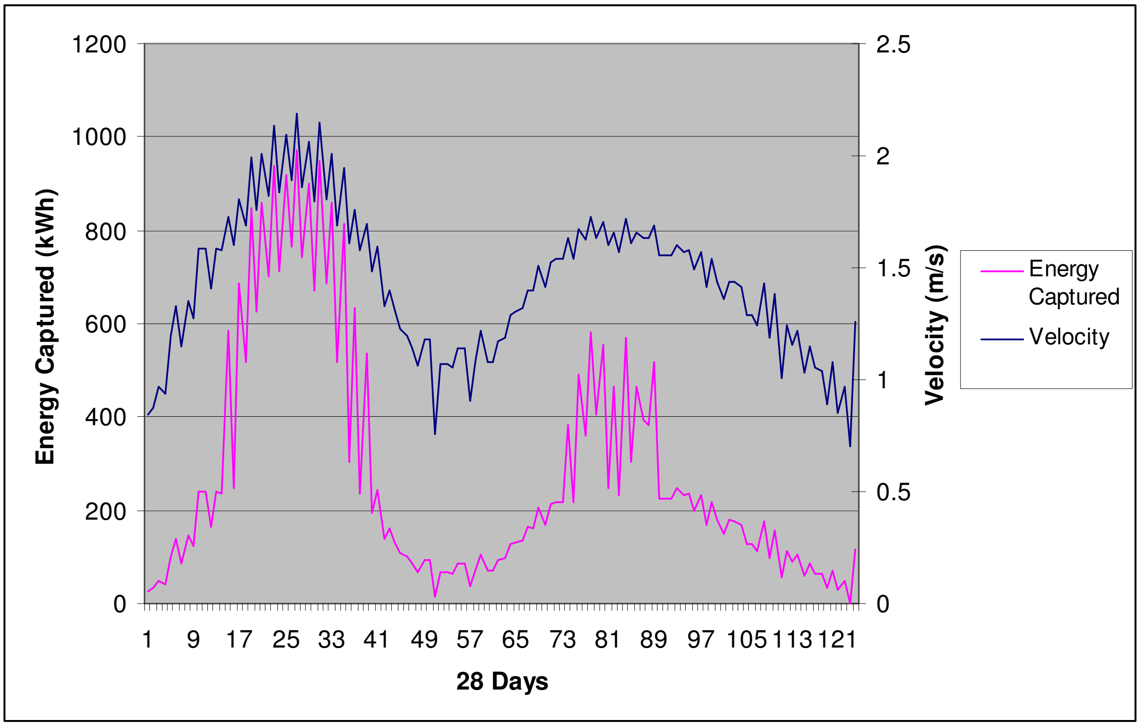
$$R = 8m$$

$$T = 745\min$$

$$\omega = \frac{2\pi}{T} = \frac{2\pi}{745} = 0.0084338rad/\min$$

$$P_{rated} = 600kW$$

Using an Excel spreadsheet, (Appendix E) $T_1 \& T_2$ were calculated for each peak tidal flow value, with the consequent value for P being the output for a single turbine. Since the Seagen device has twin turbines this is simply doubled to give the total power generated. Taking the sum of all the calculated values for an entire tidal cycle it is possible to estimate the amount of energy which could be generated over a given period, in this case for a year.



Graph 14: Current Velocity with Energy Captured

Graph 14 shows how energy captured varies with tidal stream velocity, over a full cycle period of 30 days. This data gives a value for the total energy generated for each 12½ hour cycle which, when totalled up gives the value for a full 30 day cycle which then repeats itself throughout the year about 12 times. Table 5 shows the amount of energy captured over these periods.

Cycle Period	**Total Energy Captured per Turbine**
30 days	68.6 MWh
1 Year	823 MWh

Table 5: Total Energy Captured by Turbine

So, this data indicates that a single Seagen device located at the Mull of Galloway site could generate approximately 1.65 GWh per year.

Assuming that these turbines could be located in an array across the channel at a pile to pile separation of 50m, it would be possible to install rows of around 200 turbines. This kind of arrangement would yield energy extraction of 16.46 GWh which corresponds to about 5% of the energy in the flow. Using this percentage in Equation [5] it is possible to estimate the effect this will have on the energy in the flow over a distance of 1 km.

$$B = \frac{f}{1 + {2gLn^2}/{R^{(4/3)}}}$$

$$B = \frac{0.05}{1 + {2 \times 9.81 \times 1000 \times 0.035^2}/{24.39^{(4/3)}}}$$

$$B = 0.037$$

Indicating that energy extraction of this magnitude would contribute an additional head drop of around 4%. Assuming this would lead to a similar drop in velocity it is possible to follow an iterative process to determine the effect of energy extraction at successive intervals along the channel.

Taking this approach for 6 locations along the channel, it would theoretically be possible to extract 67 GWh over a year, 19.6% of the total energy in the flow. This figure is the significant impact factor (SIF) described in Section 1.4 and can be seen to be significantly higher than the Black & Veatch estimate for the Mull of Galloway site of 12% (Black & Veatch, 2005). This is mainly due to the fact that these calculations only take the hypothetical channel and not the entire resource present in the area.

It should be noted that this figure is only 16% of what was estimated to be available at the Mull of Galloway in the Phase II UK Tidal Stream Energy Resource Assessment. Again, this is due to the boundary conditions set out to consider only the hypothetical channel, and not the entire area.

4.4 Summary of Results

This limited resource assessment serves to corroborate the estimations of the tidal current resource round the Mull of Galloway. Taking an imaginary channel at the peak of the resource it has been shown that there will be significant reductions in velocity due to several factors.

The velocity at the depth of energy capture is likely to be significantly below that at the surface and the average velocity over the swept area will be lower still. Given the cubic nature of the relationship between velocity and power output this serves to have a drastic effect on the amount of energy present in the flow.

Furthermore, it has been demonstrated that the placement of energy capture devices is likely to incur a reduction in flow of at least 25%, given the added resistance that is created and the lack of channel constraints on the south side. Indeed, this could prove to be the most significant limiting factor on large scale energy capture.

However, most encouraging is that initial calculations suggest that as much as 20% of the energy in the flow could be extractable.

5.0 Conclusions & Recommendations

5.1 Conclusion

There are many driving factors behind the growth in renewable electricity generation which make it an attractive market to be in at the present time. Tidal energy is a particularly vibrant part of that market and is fast developing along lines that could one day make it a significant contributor to energy generation not just in the UK, but worldwide.

The UK is the world leader in tidal energy, and given the location of the main resources, the main thrust of activity is in Scotland and there is a strong desire at all levels to maintain the nation's place at the forefront of development. This means that any potential for further improvement of the facilities for this development if pitched correctly is likely to receive support from the highest level of government.

The idea to investigate the potential of a second test centre for tidal energy converters off the coast of Dumfries and Galloway could prove an inspired one, and the investigation carried out here certainly indicates that there is potential for this to happen. However, how this is approached politically will be fundamental to its success. As has been identified, the majority of the focus of development to date has been on the Orkney site, which has attracted a lot of funding from both the Scottish executive and the DTI and if a development in Dumfries and Galloway was to be perceived as being in competition, rather than complementary, problems could arise which may hinder funding and hence stall the development.

This study did not concern itself with the political aspects that any such project would inevitably take on and so no meaningful correspondence with potential supporters was carried out and consultation with these groups, with developers and with EMEC is an important aspect which should be approached early on in the life of this project.

While this report has demonstrated that a test centre is physically possible and attractive, there is still no guarantee that there is the demand in the short term, and an investigation into the economical viability of this project is essential.

Focussing on the physical aspects however, it is possible to draw more definite conclusions. This study has shown that the resource in the area of the coast of Dumfries and Galloway is suitable for the desired application, with peak current velocities of 2m/s at spring tides. This obviously makes for a much less harsh environment than the site in Orkney, where the current velocities are double this and where the general climate is much more hostile. Furthermore, the bathymetry of the area is also suitable for testing of the current generation of energy capture devices with depths not exceeding 50 metres. Also, there should be few problems in connecting to the National Grid with the kind of capacity likely to be generated by test devices.

An area free from any local limiting factors which would rule out development has been identified with a high likelihood of specific sites being found which are usable. A test centre would also add a new aspect to the local economy and present the possibility of new industry in the area. The lack of any real local expertise in this kind of offshore engineering is a factor, but should be seen as an opportunity rather than a prohibiting factor.

In terms of the physical characteristics of the area, the local wave climate has been identified as potentially the biggest constraint on the development of a test centre in the region. Early indications are that the site is exposed to the prevailing winds and this is not desirable. Further work will need to be carried out to identify just how severe this proves to be and if it could be fatal to the project.

The potential for commercial generation has also been addressed and a quantification of the resource in the area has been made. This shows that a significant contribution could be made by tidal power in the area with an expected yield of over 400 MWh. This could well increase as technology evolves. This does however throw up some further issues regarding the strength of the National Grid in the region which at present would not be able to support this kind of input. It is worth taking note of this at an early stage so that the necessary arrangements can be put in place were commercial generation in this area to become a reality.

5.2 Recommendations for Further Work

This investigation has uncovered several opportunities for further work to be carried out on this project. The main ones, which should be pursued in the first instance, are:

- Consultation with stakeholders in the area and with developers and supporters should be initiated in order to facilitate as smooth a process as possible, and to tap into another resource of potential expertise regarding both local issues which may affect the development, and industry specific issues which should be taken on board. This will inevitably touch on the more political aspects of the project.
- Detailed surveying of the area must be carried out in order to identify the optimum location of a test site. This should involve seabed surveys in order to identify any unrecorded ordinances below the surface. Also, detailed profiling of the resource in the area should be carried out using Acoustic Doppler Current Profiler's (ADCP's). These surveys should be carried out over periods of 30 days for each location, in order to provide data on a full tidal cycle. Also of paramount importance is an early assessment of the local wave climate.
- An Environmental Impact Assessment should be carried out for the test centre in order to further advise the optimum location of the specific test site, both onshore and offshore taking into consideration all the aspects outlined in Section 3.5.2.

Once these steps have been taken and if favourable results have been obtained throughout, design of the centre itself can begin, taking into account the more technical issues concerned with generating electricity and connecting to the National Grid.

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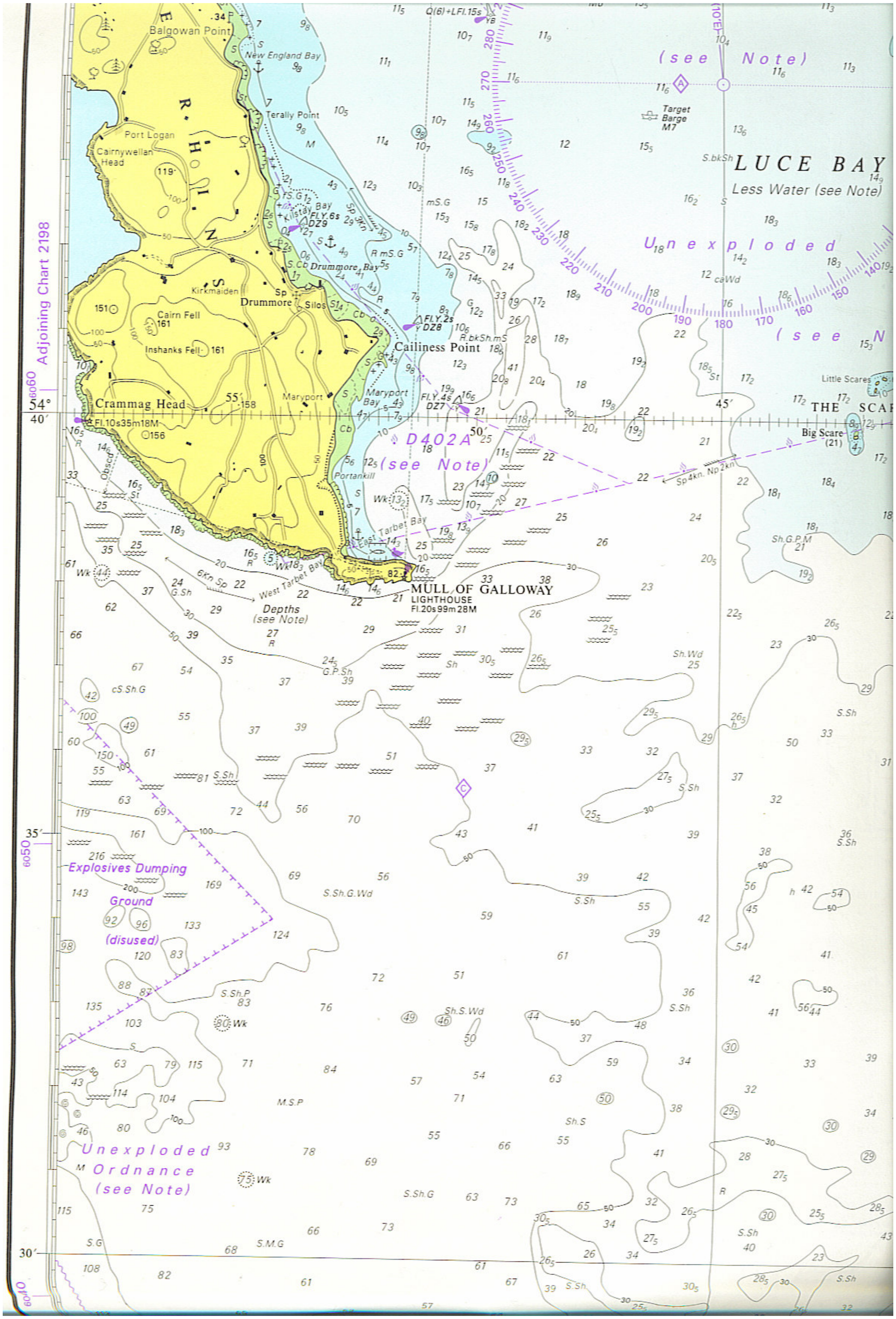
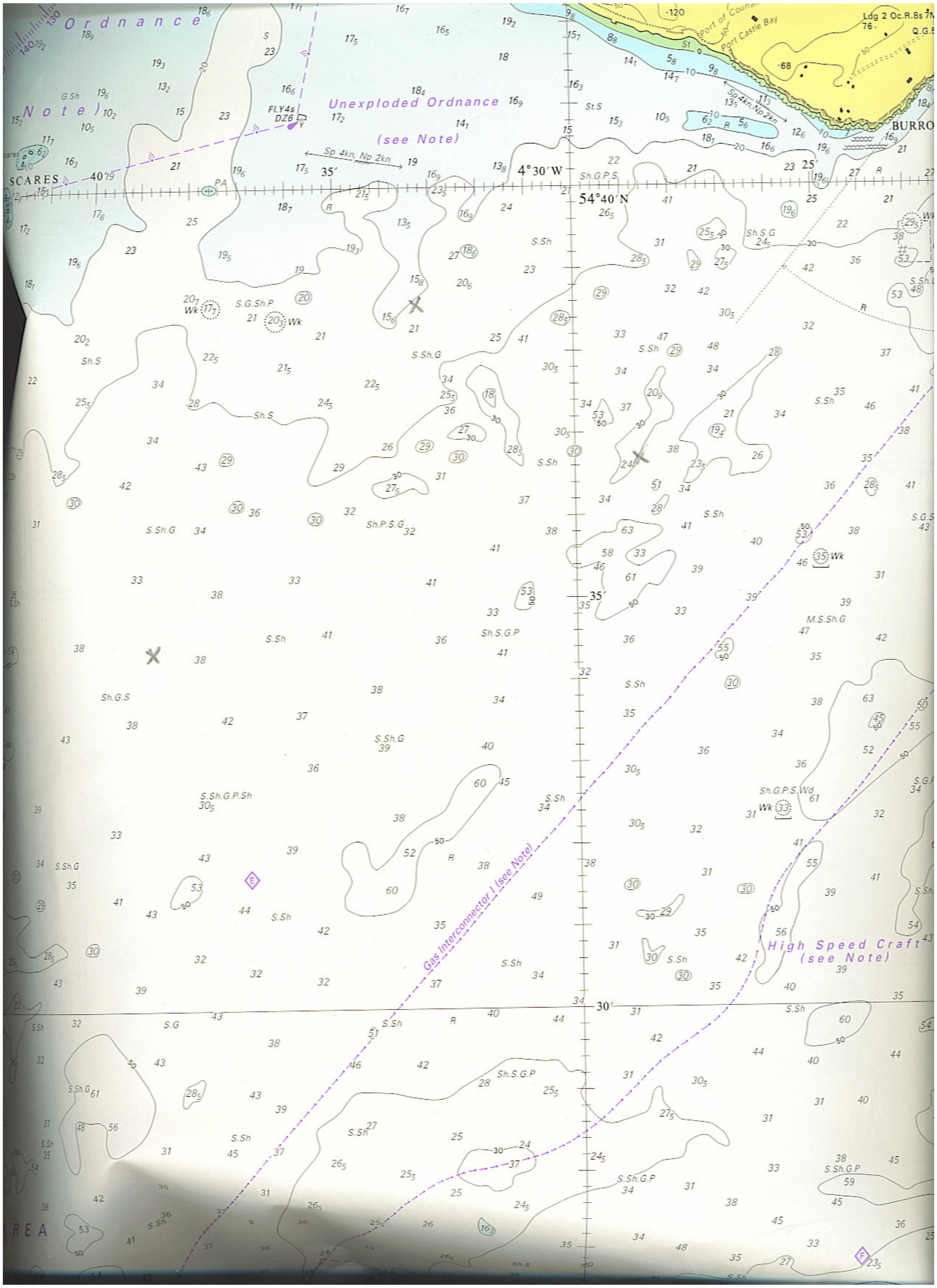
APPENDIX A:
Admiralty Chart for Area of Interest


Adjoining Chart 2198
Balgowan Point
New England Bay
Terally Point
Port Logan
Cairnywellan Head
Kirkmaiden
Drummore
Cairn Fell
Inshanks Fell
Crammag Head
Maryport
Cailiness Point
Portankill
Tarbet Bay
West Tarbet Bay
MULL OF GALLOWAY
LIGHTHOUSE
LUCE BAY
Less Water (see Note)
Target Barge M7
Unexploded
(see Note)
D402A
Little Scares
THE SCAR
Big Scare
Depths (see Note)
Explosives Dumping Ground (disused)
Unexploded Ordnance (see Note)

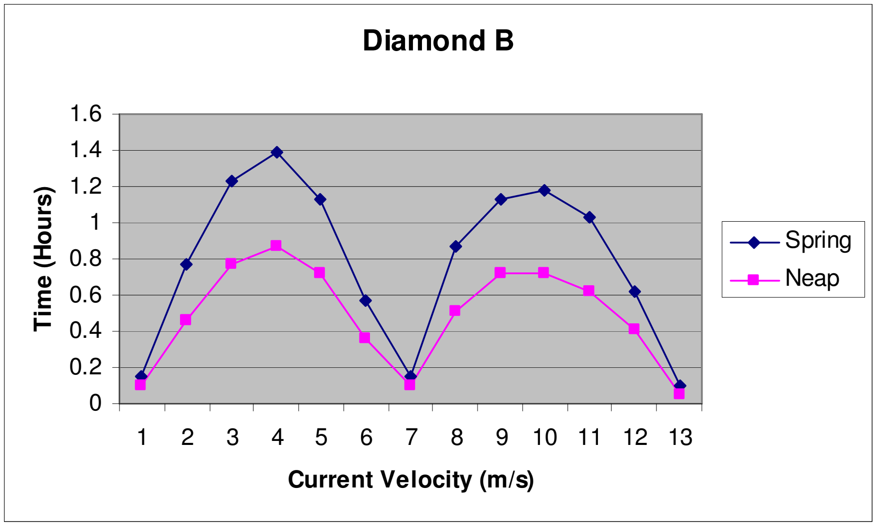


Source: UKHO, 2005

APPENDIX B:
Tidal Diamond Data

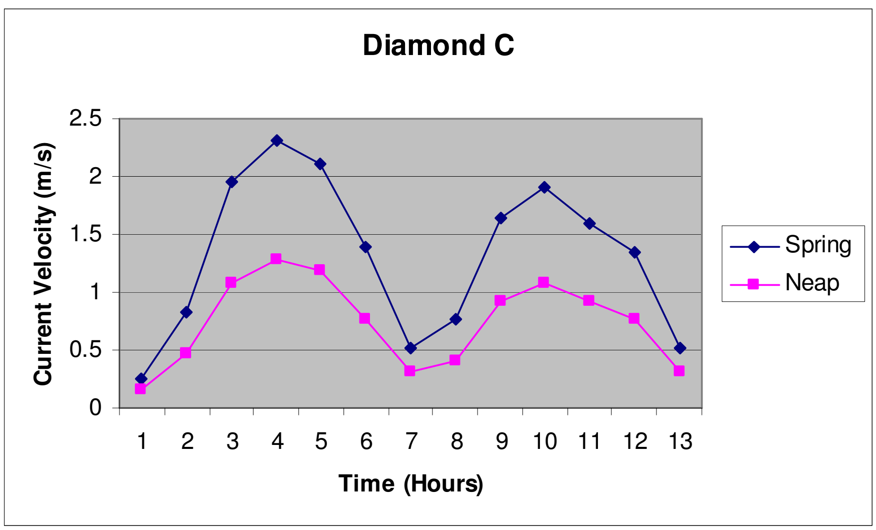
Diamond B
Velocity (m/s)

Spring	Neap
0.1542	0.1028
0.771	0.4626
1.2336	0.771
1.3878	0.8738
1.1308	0.7196
0.5654	0.3598
0.1542	0.1028
0.8738	0.514
1.1308	0.7196
1.1822	0.7196
1.028	0.6168
0.6168	0.4112
0.1028	0.0514



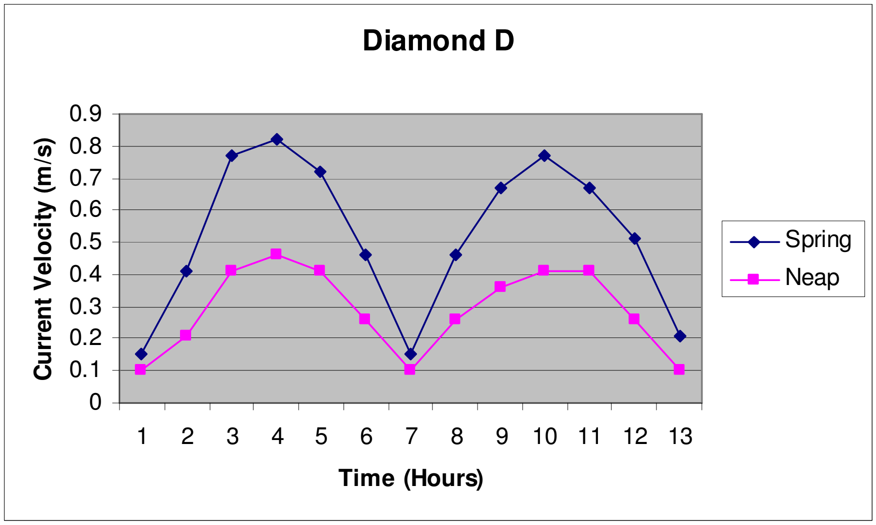
Diamond C
Velocity (m/s)

Spring	Neap
0.257	0.1542
0.8224	0.4626
1.9532	1.0794
2.313	1.285
2.1074	1.1822
1.3878	0.771
0.514	0.3084
0.771	0.4112
1.6448	0.9252
1.9018	1.0794
1.5934	0.9252
1.3364	0.771
0.514	0.3084



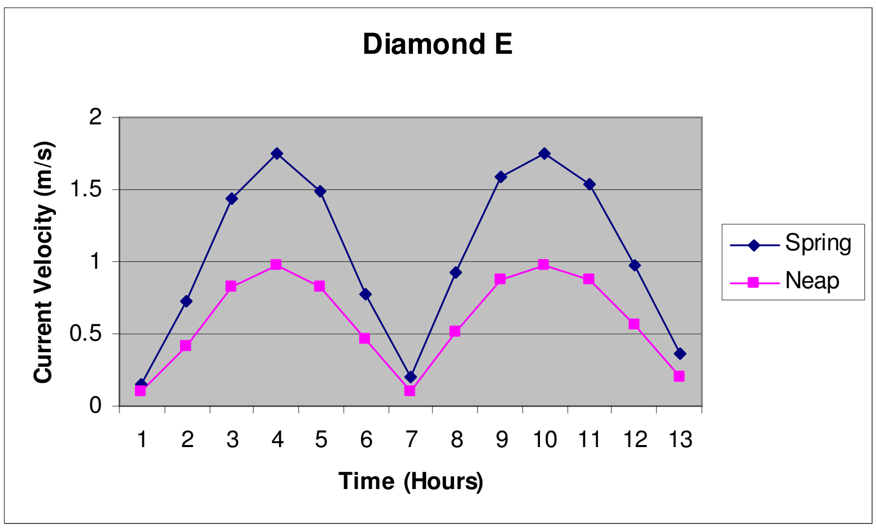
Diamond D
Velocity (m/s)

Spring	Neap
0.1542	0.1028
0.4112	0.2056
0.771	0.4112
0.8224	0.4626
0.7196	0.4112
0.4626	0.257
0.1542	0.1028
0.4626	0.257
0.6682	0.3598
0.771	0.4112
0.6682	0.4112
0.514	0.257
0.2056	0.1028

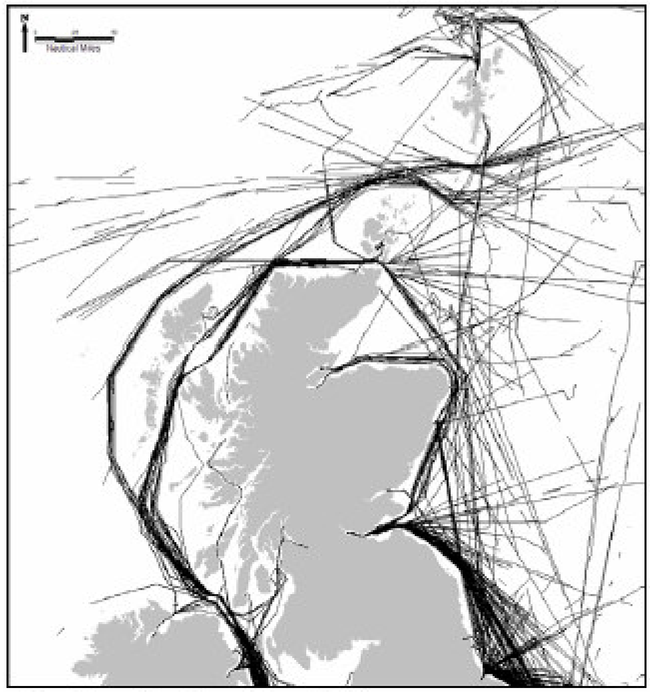


Diamond E
Velocity (m/s)

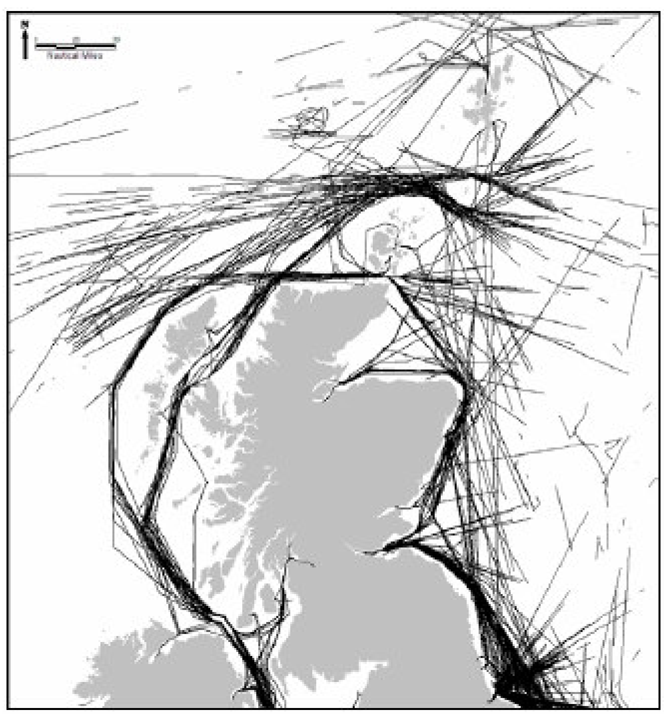
Spring	Neap
0.1542	0.1028
0.7196	0.4112
1.4392	0.8224
1.7476	0.9766
1.4906	0.8224
0.771	0.4626
0.2056	0.1028
0.9252	0.514
1.5934	0.8738
1.7476	0.9766
1.542	0.8738
0.9766	0.5654
0.3598	0.2056



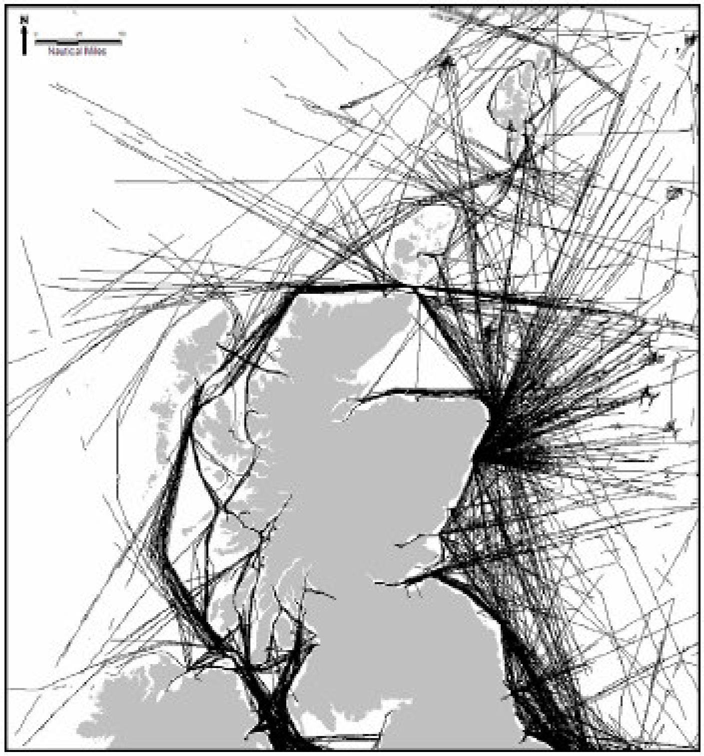
APPENDIX C:
Shipping Maps



Tracks of Tankers (Jan 2006)

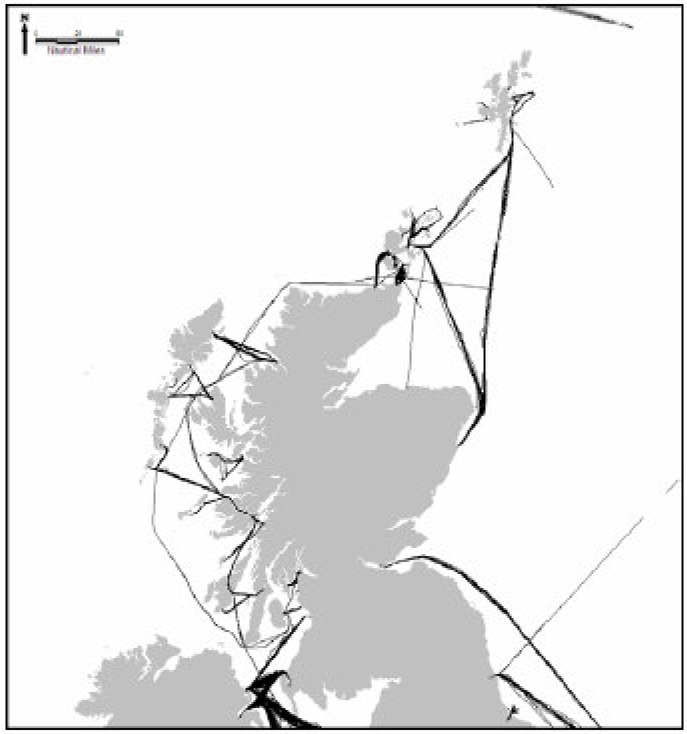


Tracks of Tankers (Aug 2006)

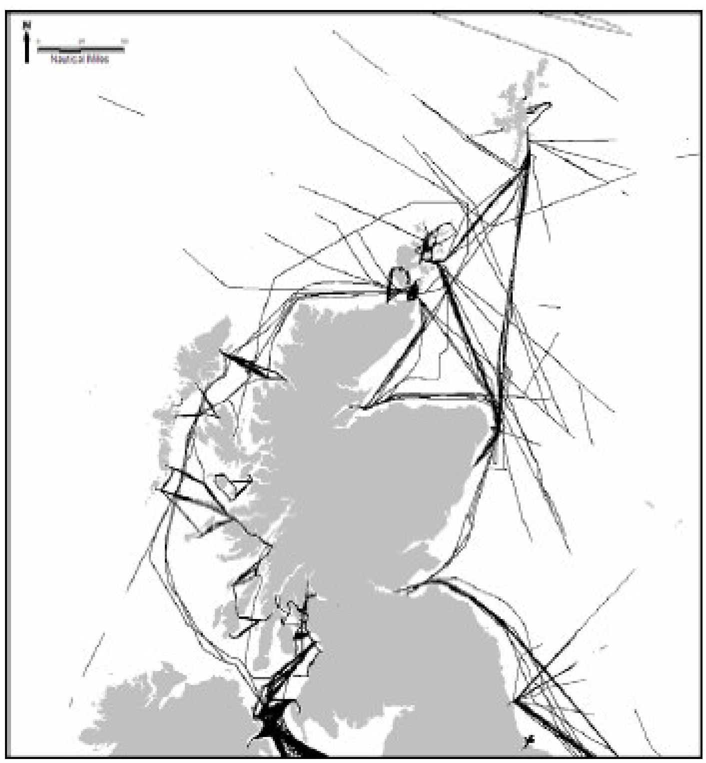


Tracks of Dry Cargo Vessels (Jan 2006)

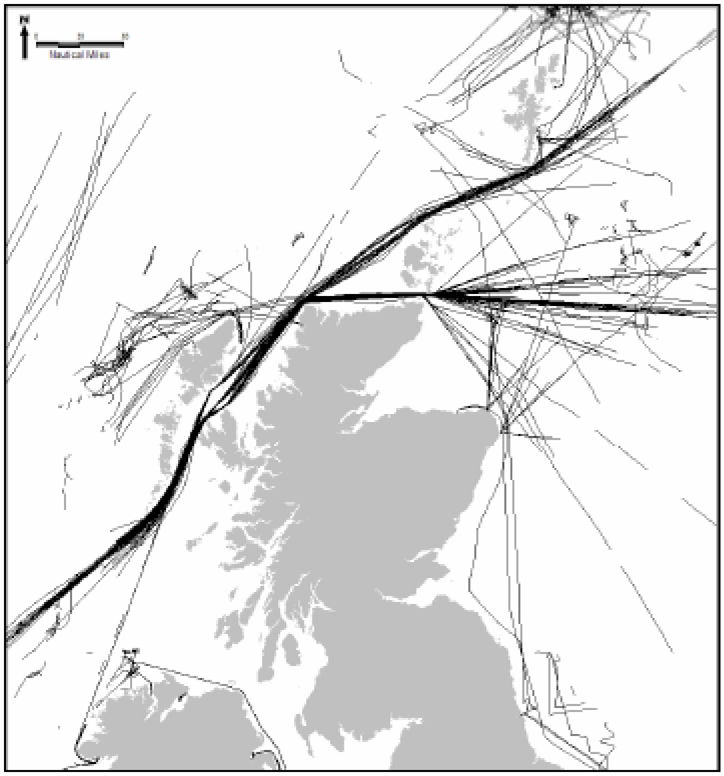
Tracks of Dry Cargo Vessels (Aug 2006)



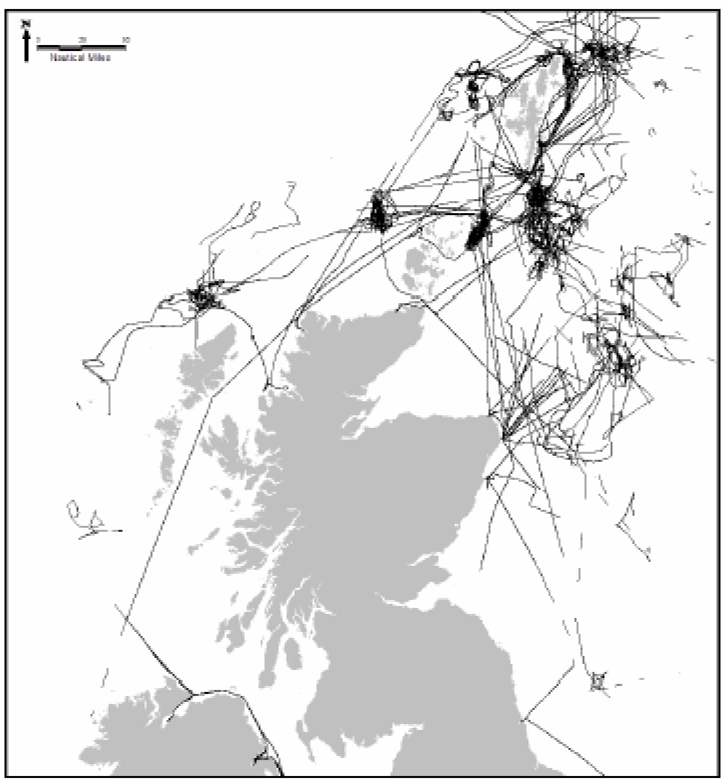
Tracks of Passenger Vessels (Jan 2006)



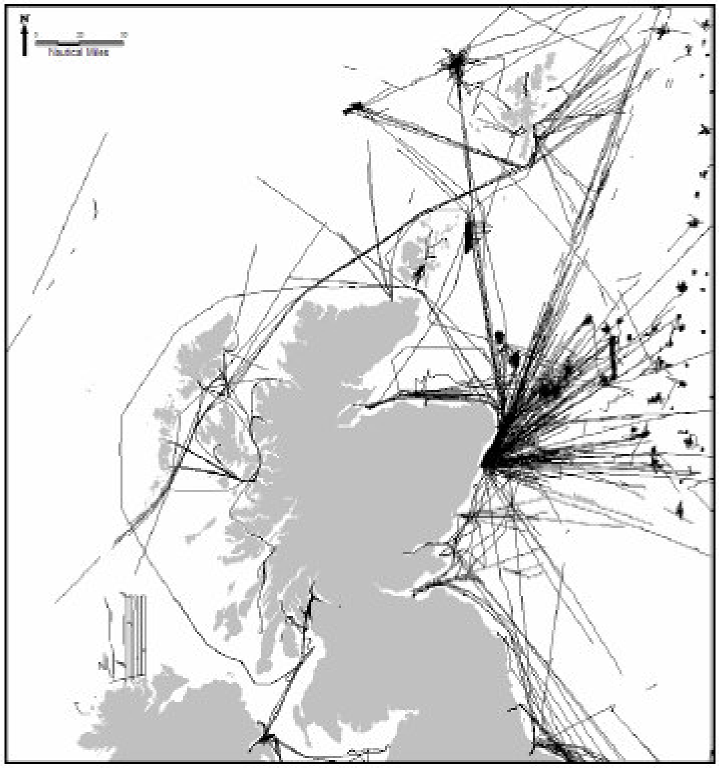
Tracks of Passenger Vessels (Aug 2006)



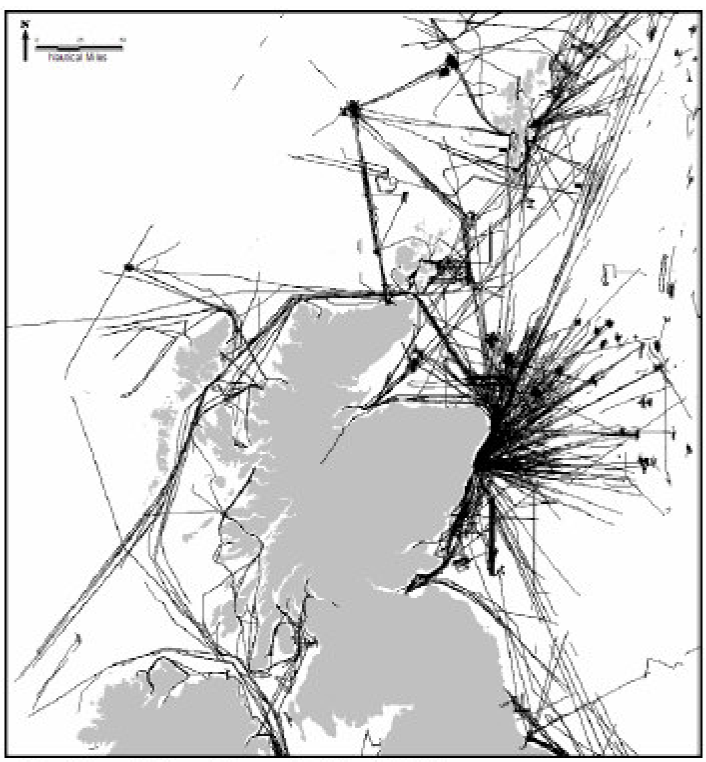
Tracks of AIS Equipped Fishing Vessels (Jan 2006)



Tracks of AIS Equipped Fishing Vessels (Aug 2006)



Tracks of Other Vessels (Jan 2006)



Tracks of Other Vessels (Aug 2006)

Source: Marico cited in Faber Maunsell (2007e)

APPENDIX D:
List of Potential Stakeholders

Statutory Consultees/Regulators

- Centre for Environment, Fisheries and Agriculture
- Civil Aviation Authority
- Countryside Agency
- Department for Culture, Media & Sport
- Department for the Environment, Food & Rural Affairs (DEFRA)
- Department of Trade and Industry (DTI)
- Department of Transport, Local Government and the Regions
- Dumfries and Galloway Council
- Environment Agency
- Health and Safety Executive
- Historic Scotland
- Maritime Coastguard Agency
- Ministry of Defence (MOD)
- National Parks authorities
- Radio Communications Agency
- Scottish Enterprise Dumfries and Galloway (SEDG)
- The Scottish Government

Strategic Stakeholders

- Association for the Protection of Rural Scotland
- Friends of the Earth
- Greenpeace
- Joint Nautical Archaeology Policy Committee (JNAPC)
- Marine Archaeological Interests
- Marine Conservation Society
- National Farmers Union (NFU)
- National Fisherman's Organisation
- National Trust for Scotland
- Nautical Archaeology Society
- Ramblers Association
- Regional Coastal Fora
- Royal Society for the Protection of Birds (RSPB)
- Royal Yachting association (RYA)
- Sea Fishery Committees
- The Wildlife Trust
- Trade Unions
- WWF

Potential Community Stakeholders

- Church groups
- Community Council
- Educational Interests
- Individuals
- Local Companies/businesses
- Recreational groups
- Residents associations

Source: BWEA, 2002

APPENDIX E:
Energy Capture Calculation Spreadsheet

					Rated Speed:	1.61	m/s
					Cut in Speed	0.7	m/s
					Period:	745	mins
	Cut in:	**Max**	**(W/mins)**		**Density:**	1025	kg/m³
Vmax	**T1**	**T2**	**Power for cycle**	**kWh**	**Cp:**	0.45	
0.84508	115.7377	186.25	1664725.118	27.74541863	**Diameter**	16	m
0.87468	110.0077	186.25	1941992.82	32.366547	**Angular Velocity:**	0.008433806	rad/min
0.97088	95.47738	186.25	2929127.864	48.81879773	**Rated Power**	600000	
0.93536	100.2642	186.25	2547109.47	42.4518245	**Total data**		
1.19732	74.03953	186.25	5978228.019	99.63713365	**TOTAL GENERATED:**	34,551.98	kWh
1.32904	65.77209	186.25	8331643.076	138.8607179	**2 Turbines:**	69,103.95	kWh
1.14552	77.95051	186.25	5176996.512	86.2832752			
1.34828	64.72656	186.25	8715787.632	145.2631272	**Full Cycle**		
1.27724	68.7755	186.25	7349763.231	122.4960538	**TOTAL GENERATED:**	34,551.98	kWh
1.58804	54.12552	186.25	14461648.39	241.0274732	**2 Turbines:**	69,103.95	kWh
1.58804	54.12552	186.25	14461648.39	241.0274732			
1.40748	61.71984	186.25	9966226.744	166.1037791	**Full Year**		
1.58804	54.12552	186.25	14461648.39	241.0274732	**Power Generated:**	829,247.41	kWh
1.57768	54.50818	186.25	14174405.97	236.2400995		0.83	GWh
1.72568	49.52401	142.5887	35105813.98	585.0968997			
1.60432	53.53537	186.25	14920561.65	248.6760274	**GRAND TOTAL:**	3,378,466.49	kWh
1.80412	47.24575	130.7405	41064092.91	684.4015485		3.35	GWh
1.68424	50.82188	150.9141	31020130.43	517.0021739	**arrays of 20**	67	GWh
1.9906	42.60663	111.7065	50909957.94	848.4992991			
1.75528	48.63811	137.6694	37560961.25	626.0160208			
2.00688	42.24552	110.3936	51599170.42	859.9861737			
1.8204	46.7997	128.6788	42115750.91	701.9291818			
2.13268	39.65285	101.4406	56327921.96	938.7986994			
1.83224	46.48071	127.2432	42850370.14	714.1728356			
2.09716	40.35138	103.779	55088231.13	918.1371856			
1.887	45.06171	121.1911	45967248.33	766.1208054			
2.1904	38.56887	97.90413	58208472.13	970.1412022			
1.86184	45.70246	123.8616	44588078.04	743.1346341			
2.0646	41.01417	106.0453	53889780.28	898.1630047			
1.79376	47.53419	132.1105	40367539.9	672.7923316			
2.14896	39.34086	100.4117	56874340.05	947.9056675			
1.80708	47.164	130.3576	41259085.47	687.6514246			
2.00392	42.31071	110.6293	51475371.24	857.9228539			
1.68424	50.82188	150.9141	31020130.43	517.0021739			
1.94324	43.69404	115.7778	48780211.03	813.0035171			
1.6132	53.21908	178.7805	18205291.77	303.4215295			
1.7612	48.46485	136.7597	38017992.88	633.6332146			
1.58064	54.39827	186.25	14256096.77	237.6016128			
1.6946	50.49085	148.6259	32133699.19	535.5616532			
1.48444	58.22485	186.25	11752611.09	195.8768515			

1.591	54.01721	186.25	14544400.43	242.4066738			
1.32608	65.93615	186.25	8273491.594	137.8915266			
1.39712	62.2245	186.25	9739806.04	162.3301007			
1.3098	66.85433	186.25	7958127.944	132.6354657			
1.22692	71.99079	186.25	6466542.062	107.775701			
1.19732	74.03953	186.25	5978228.019	99.63713365			
1.14256	78.18783	186.25	5133202.176	85.55336959			
1.06116	85.41343	186.25	4008925.307	66.81542179			
1.18104	75.22161	186.25	5719214.24	95.32023733			
1.18104	75.22161	186.25	5719214.24	95.32023733			
0.75776	139.6552	186.25	871345.4345	14.52242391			
1.07152	84.41093	186.25	4143692.788	69.06154647			
1.07152	84.41093	186.25	4143692.788	69.06154647			
1.05228	86.29454	186.25	3895265.791	64.92109652			
1.1396	78.42675	186.25	5089618.525	84.82697542			
1.1396	78.42675	186.25	5089618.525	84.82697542			
0.90724	104.4969	186.25	2259809.475	37.66349125			
1.07744	83.84994	186.25	4221761.867	70.36269778			
1.21952	72.49134	186.25	6342334.398	105.7055733			
1.07744	83.84994	186.25	4221761.867	70.36269778			
1.07744	83.84994	186.25	4221761.867	70.36269778			
1.17068	75.99563	186.25	5557853.002	92.63088337			
1.18696	74.78702	186.25	5812626.607	96.87711012			
1.2876	68.15148	186.25	7540135.03	125.6689172			
1.30388	67.19504	186.25	7845312.408	130.7552068			
1.32016	66.2669	186.25	8157940.92	135.965682			
1.40008	62.07942	186.25	9804164.514	163.4027419			
1.39712	62.2245	186.25	9739806.04	162.3301007			
1.5096	57.17059	186.25	12377648.16	206.294136			
1.4134	61.43534	186.25	10097080.87	168.2846811			
1.52292	56.62847	186.25	12716960.63	211.9493439			
1.5392	55.98031	186.25	13139683.53	218.9947255			
1.5392	55.98031	186.25	13139683.53	218.9947255			
1.62948	52.64919	167.8975	23021350.14	383.689169			
1.5392	55.98031	186.25	13139683.53	218.9947255			
1.67092	51.25415	154.134	29466154.52	491.1025754			
1.62356	52.85495	170.9148	21658111.63	360.9685271			
1.72272	49.61443	143.1198	34842468.1	580.7078017			
1.6354	52.44509	165.3253	24198790.66	403.3131776			
1.70644	50.11796	146.1964	33323972.91	555.3995485			
1.59988	53.69499	186.25	14794486.08	246.574768			
1.65908	51.64485	157.3374	27936184.13	465.6030688			
1.57176	54.72938	186.25	14011929.45	233.5321575			
1.7168	49.79632	144.2069	34304536.22	571.7422704			
1.6132	53.21908	178.7805	18205291.77	303.4215295			
1.65908	51.64485	157.3374	27936184.13	465.6030688			
1.63244	52.54693	166.5674	23628518.79	393.8086464			

1.62948	52.64919	167.8975	23021350.14	383.689169			
1.68424	50.82188	150.9141	31020130.43	517.0021739			
1.55252	55.46142	186.25	13492163.65	224.8693941			
1.55252	55.46142	186.25	13492163.65	224.8693941			
1.55252	55.46142	186.25	13492163.65	224.8693941			
1.59988	53.69499	186.25	14794486.08	246.574768			
1.5688	54.84069	186.25	13931142.56	232.1857093			
1.57472	54.61855	186.25	14093017.06	234.8836177			
1.49036	57.97313	186.25	11897823.76	198.2970627			
1.5688	54.84069	186.25	13931142.56	232.1857093			
1.41044	61.57724	186.25	10031519.64	167.191994			
1.53624	56.097	186.25	13062165.66	217.7027611			
1.44	60.1904	186.25	10698385.41	178.3064236			
1.36	64.10683	186.25	8955069.888	149.2511648			
1.44	60.1904	186.25	10698385.41	178.3064236			
1.4356	60.39265	186.25	10597403.96	176.6233993			
1.41044	61.57724	186.25	10031519.64	167.191994			
1.29056	67.97542	186.25	7595072.285	126.5845381			
1.29056	67.97542	186.25	7595072.285	126.5845381			
1.24172	71.01182	186.25	6719276.733	111.9879455			
1.43264	60.52951	186.25	10529811.05	175.4968508			
1.184	75.00362	186.25	5765810.287	96.09683812			
1.3838	62.88632	186.25	9453471.202	157.5578534			
1.0064	91.20236	186.25	3334434.274	55.57390456			
1.24172	71.01182	186.25	6719276.733	111.9879455			
1.15884	76.90196	186.25	5376696.958	89.61161596			
1.21952	72.49134	186.25	6342334.398	105.7055733			
1.03304	88.2769	186.25	3654769.73	60.91282883			
1.14848	77.71478	186.25	5221002.234	87.0167039			
1.05228	86.29454	186.25	3895265.791	64.92109652			
1.04192	87.34913	186.25	3764796.898	62.74661496			
0.89096	107.1613	186.25	2099044.841	34.98408068			
1.0804	83.5726	186.25	4261087.798	71.01812997			
0.84804	115.1281	186.25	1692029.992	28.20049987			
0.97088	95.47738	186.25	2929127.864	48.81879773			
0.70004	184.9825	186.25	20162.39123	0.336039854			
1.25504	70.15503	186.25	6951717.115	115.8619519			