Overcoming the Supply Inconsistencies of Tidal Current Energy Conversion Devices

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DECLARATION OF ORIGINALITY

SEPTEMBER, 2010

The substance of this thesis is the original work of the author and due reference and acknowledgement has been made, when necessary, to the work of others. No part of this thesis has been accepted for any degree and is not concurrently submitted for any other award. I declare that this thesis is my original work except where otherwise stated.

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Abstract

The adoption of a sustainable approach to meeting the energy needs of society has recently taken on a more central and urgent place in the minds of many people. There are many reasons for this including ecological, environmental and economic concerns. One particular area where a sustainable approach has become very relevant is in the production of electricity. The contribution of renewable sources to the energy mix supplying the electricity grid is nothing new, but the focus has begun to move away from the more conventional renewable sources such as wind and hydro. The necessity of exploring new and innovative sources of renewable energy is now seen as imperative as the older forms (i.e. hydro) reach the saturation point of their possible exploitation. One such innovative source of energy currently beginning to be utilised in this regard is tidal energy.

The purpose of this thesis is to isolate one specific drawback to tidal energy, which could be considered a roadblock to this energy source being a major contributor to the Irish national grid. This drawback presents itself in the inconsistent nature in which a tidal device generates energy over the course of a 24 hour period. This inconsistency of supply can result in the cycling of conventional power plants in order to even out the supply, subsequently leading to additional costs.

The thesis includes a review of literature relevant to the area of tidal and other marine energy sources with an emphasis on the state of the art devices currently in development or production.

The research carried out included tidal data analysis and manipulation into a model of the power generating potential at specific sites. A solution is then proposed to the drawback of inconsistency of supply, which involves the positioning of various tidal generation installations at specifically selected locations around the Irish coast. The temporal shift achieved in the power supply profiles of the individual sites by locating the installations in the correct locations, successfully produced an overall power supply profile with the smoother curve and a consistent base load energy supply. Some limitations to the method employed were also outlined, and suggestions for further improvements to the method were made.

Acknowledgements

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1.1 Introduction

The introduction has been separated into three sections. The first section outlines the author’s motivation for selecting the thesis topic. This includes the reasons behind selecting the general area of tidal energy and also the reasons for choosing the specific problem addressed in this thesis. The second section presents the objectives of the thesis. The six objective outlined in this section are revisited in the concluding chapter in an attempt to decide whether or not the thesis successfully attained its goals. The last section of the introduction outlines how this thesis document is structured by providing a very brief indication of what is covered in each chapter.

1.2 Thesis Motivation

The motivations for choosing tidal energy as the subject matter of this thesis were twofold. Firstly, it was apparent to the author that, due mainly to concerns over the energy security of the country, it will become increasingly important to expand the existing knowledge base on renewable energy sources. Secondly, the main focus of development in the renewable energy sector of electricity production in this country has been on wind energy. This source will reach a saturation point in its exploitation, due to the inevitable reduction in available installation sites. Consequently it seems prudent that focus be moved away from this already well developed technology towards a technology still in a very early stage of its development, tidal current energy conversion. Wind is still a very important contributor to renewable electricity production, but the renewable energy mix is likely to grow more diverse with time, and tidal energy will also have its place within this mix.

As regards the motivation for selecting the specific problem addressed in the thesis, it was considered an important limitation to the large scale development of tidal energy in Ireland. Ireland is often mentioned when analysts are espousing the virtues of tidal and wave energy, due to the favourable marine conditions around the island. This potential energy source will remain just that, a *potential* energy source, unless a way is found to harness it efficiently. On the one hand this can refer to making the conversion devices more efficient whereby they produce more energy per wave, or per tidal cycle, however on the other hand there is the consideration of how useful the energy is when produced. Energy produced at the wrong time of day or with an undesirable profile over time can become more of a negative influence when supplying an electricity grid than a positive one. Tackling the problems of ensuring the supply of energy, once produced, has the characteristics of supply required by an electricity grid can present just as big of a challenge as that faced in developing the energy conversion mechanisms, and can produce just as big of a benefit if successful.

These were the main factors which contributed to the choice of topic selected in this thesis, and it was hoped that these factor would maintain the focus of research throughout the course of the thesis.

1.3 Thesis Objectives

The renewable energy sector is growing steadily and, as a result, the challenges to overcome to ensure the continued growth in this area are many and varied. It was decided at a very early stage of research that the formation of a thesis around tidal energy should be concentrated on a specific problem encountered in this field. Tidal energy is still at a vary early stage in its development but with the surmounting of issues such as the one addressed in this thesis the potential for vast growth in the years ahead can clearly be seen. The objectives which it is hoped will be attained in the completion of this thesis are outlined in the six following points,

1. Analyse the reasons behind any possible transition away from conventional fossil fuels and towards renewable sources of energy in the generation of electricity.
2. Ascertain what place marine, and in particular tidal, energy has in the renewable market for electricity generation in Ireland, and what benefits are offered by tidal energy over other renewable sources.
3. Focusing on the specific problem of consistency of supply over a 24 hour period, propose a solution to this issue. This is not by any means the only issue with tidal energy, or indeed renewable energy as a whole, but it is an important one to solve before tidal energy can be seen as a major player in the renewable energy sector.
4. Simulate the proposed solution mentioned in point three using data for the tidal displacement at various sites around the Irish coast.
5. Analyse the simulation model to decipher if it works (i.e. would implementation successfully mitigate against the undesirable characteristics of tidal energy identified in this thesis).
6. Suggest how the proposed solution could be improved upon. Select the three main perceived limitations to the solution and suggest ways of navigating around these issues.

1.4 Thesis Structure

The chapters in this thesis are structured as follows:

Chapter 1: This chapter provides an introduction to the thesis. The motivation for selecting the topic is detailed here as well as the objectives which it was hoped would be achieved by completing this thesis. This introductory chapter also contains an overview of how the thesis was structured (this section).

Chapter 2: Provides a detailed literature review based on material relevant to the thesis. This includes a review of the drivers involved in deciding energy policy (climate change, global fossil fuel reserves and the energy security situation of Ireland), background to wave and tidal energy, in depth analysis of tidal energy systems and state of the art tidal energy devices.

Chapter 3: This chapter presents the core elements of the thesis. A description of the specific problem related to tidal current generation devices and addressed by the thesis is provided here. This is followed by a thorough explanation of the data used and the methods of analyzing\modelling this data. The proposed solution is outlined and simulated using the models generated and some perceived limitations to the solution are investigated. Suggestions are made on how to mitigate against the limitations outlined and finally there is a discussion of the key points made in the chapter.

Chapter 4: This final chapter attempts to bring together the conclusions drawn from the previous two chapters in order to ascertain how successfully the project work completed achieved the objectives from chapter one. Finally some suggestions are given for possible further research based on the work done in this thesis.

Chapter Two: Literature Review

2.1 Introduction

As with any movement away from the conventional standard of operation, the use of renewable energy must be considered to be necessary for clear and viable reasons. These reasons can be termed ‘Energy Policy Drivers’. The first section in this chapter looks at a number of these drivers and explains how they have formed the basis of the transition from fossil fuel sources towards more sustainable sources such as wind energy, bio-fuels and marine energy.

The second section of this chapter looks at marine energy as a background to the main subject matter of this paper. An overview is given of wave energy as a source of electrical power generation and greater detail is provided on the use of energy derived from tidal sources, as this is the specific area of interest of this paper.

The third section takes a closer look at the state-of-the-art devices, whether currently in development or commercially operational, used to produce electricity from tidal sources. These consist of devices which use barrages to store the potential energy in the tidal waters using a dam-like effect and devices which extract the kinetic energy from a tidal current.

The chapter concludes with a consideration of the effectiveness of the energy policy drivers and the place of tidal and wave energy extraction devices in the future of the energy sector.

2.2 Energy Policy Drivers

2.2.1 Climate Change

Climate change has been a contentious issue since it moved into the mainstream of debated topics after a meeting of the World Meteorological Organisation in Geneva in 1979 (World Meteorlogical Organisation, 2010). The purpose of this meeting was to decide if there was a climate change problem and, if so, whether it was serious enough to call a world conference of scientists to discuss it. The agreed answer to the two questions was a resounding ‘Yes’, and so began the search for proof of anthropogenic climate change on one side of the argument, and the search for other ways to explain observed climate phenomena on the opposite side of the argument.

Since 1978, the general consensus within the scientific community has been that climate change is occurring and that anthropogenic forcing is, to some degree, responsible(Hansen, 2003). However, there is still a minority who either do not accept that climate is changing, or believe that, if it is changing, it is nothing to do with the influences of mankind.

The climate in recent years has proven to be remarkable when examined alongside data from the last two centuries, and the instances of very extreme weather conditions, both in Ireland and worldwide, have increased in regularity and intensity in the last twenty years. An investigation is therefore required in order to explore whether this behaviour can be explained by climate change, and if not, what other explanations could suffice.

The Greenhouse Effect

Central to the debate on climate change is an examination of the greenhouse effect. The greenhouse effect is a term, coined by Nobel laureate Svante Arrhenus, used to describe how CO_2 and other chemical compounds trap heat in the Earth’s atmosphere.

Greenhouses are structures designed to retain heat from the sun in order to maintain suitable conditions for the growing of vegetables, fruits, etc. In a similar way, the greenhouse effect is responsible for making the earth’s climate suitable for sustaining life as we know it. It has been calculated that, without the greenhouse effect, the global average temperature would be in the region of 33°C cooler than it is today (US Environmental Protection Agency, 2010). The Earth Policy Institute in Washington DC quotes the global average temperature for the decade 2000 - 2009 at 14.52°C (The Earth

Policy Institute, 2010), therefore without the greenhouse effect this would be somewhere in the region of -18°C. So, the greenhouse effect is a positive thing for the earth's ability to sustain life, but what happens if the concentration of greenhouse gases in the earth's atmosphere reaches a level whereby they cause excessive warming? This is a situation that could result in what is known as a 'runaway' greenhouse effect.

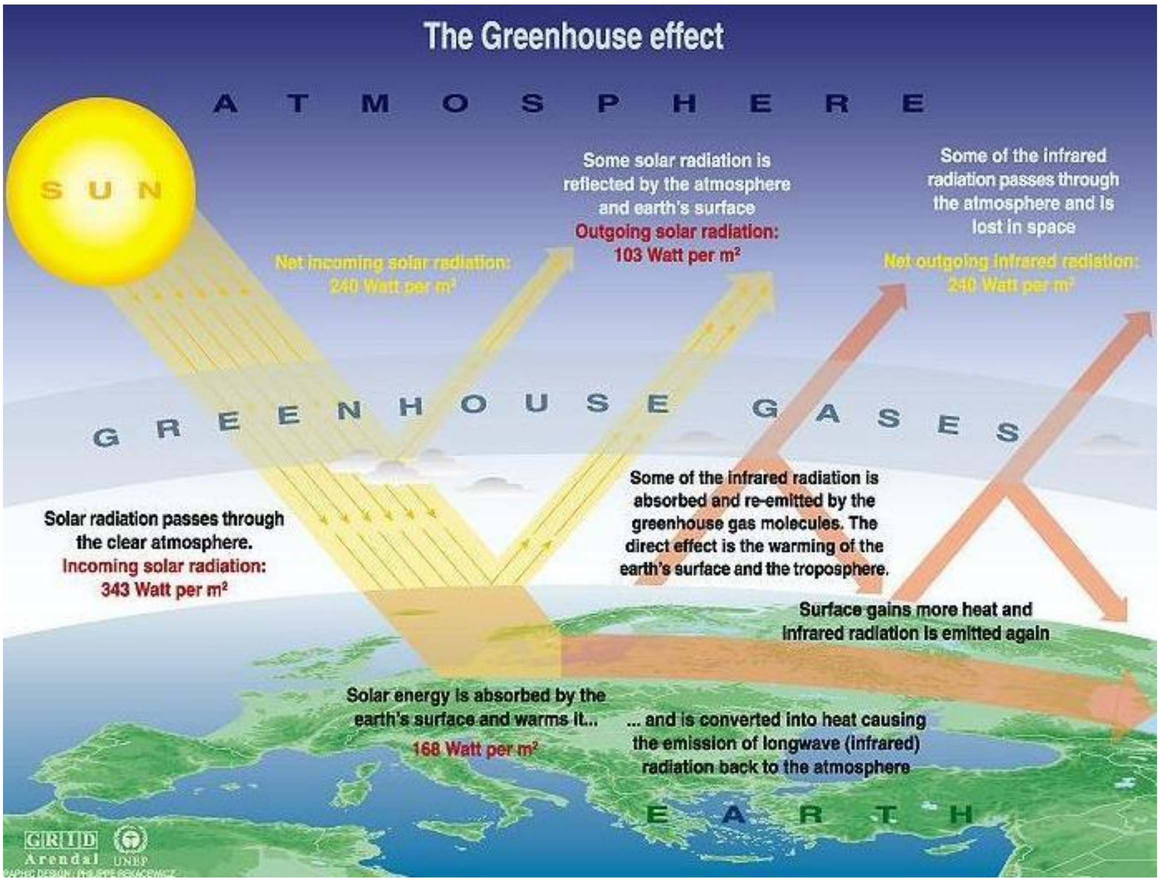

Figure 2.1: The Greenhouse Effect (Adapted from: Williamstown Cool Committee)

Figure 2.1 (Williamstown Cool Committee, 2010) describes how the greenhouse effect works. The solar radiation passes through the earth's atmosphere, the atmosphere and the earth's surface reflect some of this radiation and the remainder is absorbed by the earth's surface. When a substance, in this case the surface of the earth, absorbs energy and converts it into heat, infrared radiation is emitted. This infrared radiation is emitted back into the atmosphere and would pass through and be lost in space were it not for greenhouse gases, whose molecules absorb and re-emit the infrared radiation. This leads to further warming of the earth's surface and troposphere; the surface gains more heat and as a result emits more infrared radiation, and so on.

Therefore these greenhouse gases act as an “insulating blanket” to the earth’s surface, resulting in a cumulative warming effect. The greenhouse gases with the most significant effect on global warming are Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and the group of gases known as F-Gases. While some of these (CO_2, CH_4 and N_2O) are important because they are present in the atmosphere (and are still being emitted) in large quantities, others (F-Gases) are important because of their high global warming potential (GWP). Table 2.1 below lists the GWP, relative to CO_2, and the lifetime of the greenhouse gases discussed in his section (Department of the Environment, Heritage and Local Government, 2007). There are other greenhouse gases such as ground-level ozone and aerosols but they are less significant as they have a far shorter lifetime, of the order of days to weeks. Water vapour has a significant influence as a greenhouse gas; however as there is no possibility to directly influence atmospheric water vapour concentration, the GWP for water vapour is not calculated.

Table 2.1: Global Warming Potential and Lifetime of various Greenhouse Gases

Greenhouse Gas	Lifetime (years)	GWP (Over 100 years)
CO2	100	1
CH4	12	21
Nitrous Oxide	114	310
HFC-23 (hydrofluorocarbon)	270	11700
HFC-134a (hydrofluorocarbon)	14	1300
Sulphur hexafluoride	3200	23900

As this “insulating blanket” gets “thicker”, the earth radiates less energy to space than it absorbs from the sun, resulting in an energy imbalance. According to James Hansen of NASA, this energy imbalance currently stands at about 1 W/m^2 and because of the long time it takes the oceans to warm this could take ~100 years to balance out, during which time additional forcings would have led to a further imbalance. It is further estimated that the amount of energy required to raise sea level by one metre is about 12 watt-years. This implies that if the current energy imbalance estimate of 1 W/m^2 is correct it would take only 12 years for the sea level to rise by a metre. This is a very worrying statistic as in countries such as Bangladesh one metre of sea level rise would engulf 100km of coastline (Hansen, 2003).

Evidence of Climate Change

Many of the most convincing arguments that climate change is really happening have been outlined in the IPCC Climate Change report from 2007. In this report we are told that eleven of the last twelve years rank in the top twelve warmest years since 1850, and average temperatures in the northern hemisphere in the last 50 years were likely higher than in any 50-year period in the last 1300 years. It also states that rising sea level is consistent with warming. Sea level has risen since 1961 at a rate of 1.8 mm/year and since 1993 at a rate of 3.1 mm/year, and the oceans are becoming more acidic (average decrease in pH of 0.1 units since 1750) (Intergovernmental Panel on Climate Change, 2007).

The report suggests that decreases in snow and ice are also consistent with warming. Arctic sea ice has shrunk by 20% since 1979 (see Figure 2.2), mountain glaciers and snow cover have both declined, and the number and size of glacial lakes has increased. Precipitation has increased in some regions since 1900, while areas affected by drought have increased since the 1970’s (Intergovernmental Panel on Climate Change, 2007).

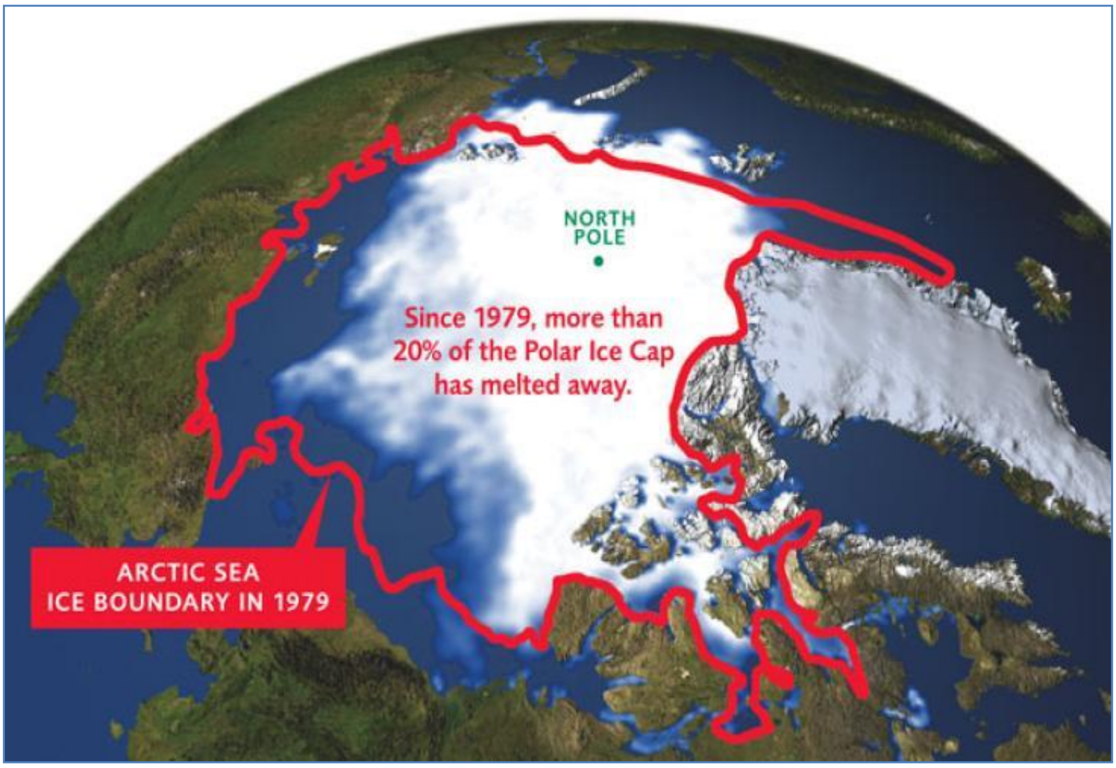

Figure 2.2: Arctic Ice Reduction Since 1979 (Adapted from: IPCC Report 2007)

This evidence strongly suggests that gradual warming is happening and that the rate of warming is becoming more pronounced. Perhaps the most compelling evidence in support of anthropogenic climate change is illustrated in Figure 2.3 below. The graph on the top illustrates how atmospheric CO_2 concentrations have grown since 1850 (Hansen, 2003). The graph on the bottom (Intergovernmental Panel on Climate Change, 2007) shows the corresponding rise in global average surface temperature. The correlation is undeniable and shows that as the population has increased and societies have become more industrialised, CO_2 and other GHG emissions have also increased and global warming has resulted.

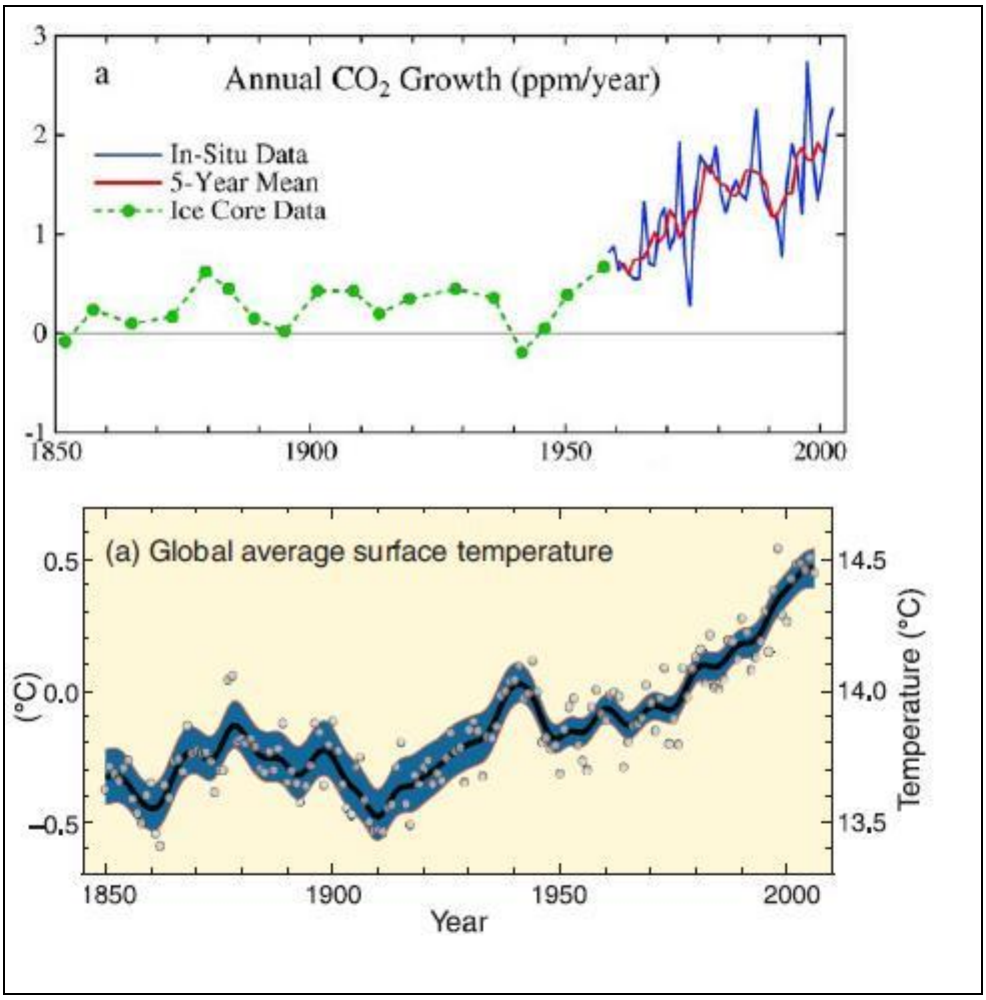

Figure 2.3: CO2 and Average Global Surface Temperature Correlation Since 1850

All this evidence points to climate change being a very real and serious issue and as such must be considered one of the main drivers behind a global move towards more sustainable sources of energy. This driver is largely considered to be one of an environmental nature and taken on its own lacks any fiscal element. There are however various economic mechanisms such as carbon taxes and carbon trading markets which are directly linked to the problem of climate change.

The following section explores further energy policy drivers which have a more direct financial impact on global economies as well as on individuals.

2.2.2 Fossil Fuel Reserves

In the preceding section the concept of climate change as a driver for the transition to renewable forms of energy was explored. This is a valid and necessary reason for the use of renewables but it is not universally accepted as the proof presented by scientists and environmentalists that climate change is manmade is still debated and strongly contested in some quarters. There is also the fact that even if it was proven beyond doubt that climate change was directly linked to anthropogenic effects, the consequences are widely regarded as environmental and as such not considered a priority by large sections of society.

Taking this last point into account, the next driver for renewable energy development to consider is one with more of an economic basis. This driver is the state of the world's fossil fuel reserves and their likely availability in the years and decades to come.

Oil can be taken as an indicative example of fossil fuels as it has the same characteristics as others (coal, natural gas, etc), such as long natural formation time and large scale global utilisation. Many may argue that there is plenty of oil for the foreseeable future and therefore there is no need to worry about supply. However, others (Campbell and Laherrere, 1998) suggest that it is not simply the amount of oil left in the ground that needs to be considered when analysing probable future supply but also the production profile over the lifetime of the individual oil well or oilfield. Campbell et al use the argument first put forward by M. King Hubbert that the amount of oil produced in any region starts to fall after about half the crude has been pumped. This results in a bell shaped production curve for an oil well, oilfield or oil producing region. This bell shaped curve model is then extended by Campbell et al to encompass all the oil producing areas and the world as a whole (see Figure 2.4).

The prediction here is that, as the current rate of oil field exhaustion far exceeds the current rate of oil discovery, the rate of production will soon begin to fall off as the large oil fields pass the half way point in their reserves. Therefore, even though there may be plenty of oil left in the oil fields around the world, the rate of production will slow down and it is this rate of production (and not the reserves of oil in the ground) that dictate the price of oil to the end consumer. This will ultimately decide how long oil will remain affordable and, as such, a viable option as an energy source.

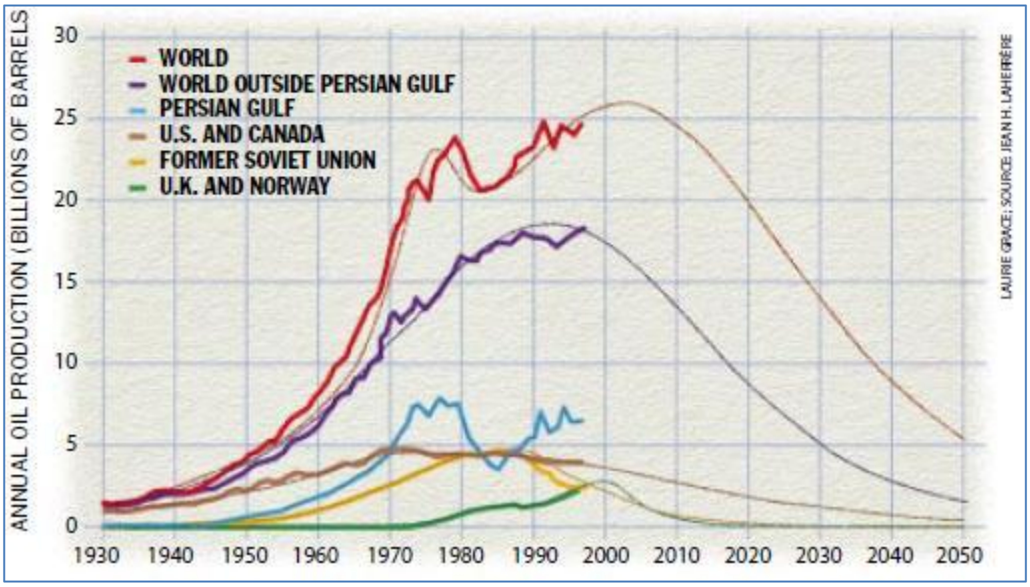

Figure 2.4: Projected Global Oil Production (Adapted from: Campbell and Laherrere)

In his article addressing the likely timeframe within which peak oil production will occur (Doyle, 2004), Rodger Doyle puts the estimate anywhere from the next year or two to the year 2112 depending upon whether one is what he terms an oil optimist or an oil pessimist. He does make the key point about the risks involved with failing to err on the side of caution however, stating *"the difference between oil optimists and oil pessimists is crucial, for if the pessimists are correct, there will be insufficient time for an orderly transition to alternative energy sources"* (Doyle, 2004).

This last point by Doyle is an important one. It is obvious that a global over-dependence on oil (and other fossil fuels) has developed due to the cheap nature of obtaining this resource. However the real risk is in allowing this over-dependence to continue until the fossil resources are no longer easily affordable. This leads to the question of how we can replace fossil fuels in an "orderly transition". Huber et al suggest that any replacement energy sources must be able to 'compete' with oil at $60 a barrel (Huber and Dale, 2009). At the time of writing the price of oil was nearer $75 a barrel but we can take his point. Any renewable sources of energy with pretentions of replacing fossil fuels monopoly in the energy sector must be able to compete economically with oil and the other fossil sources. The only way this is achievable is by investing in research and development now, so that when the time comes when the fossil sources become less attractive, economically, renewable sources will be ready to compete as a replacement option.

2.2.3 Energy Security for Ireland

The final driver for the exploitation of renewable energy sources will be taken specifically from an Irish perspective. This is the issue of energy security and, while this issue concerns every country in the world, it has a special significance for Ireland. The problem for Ireland with respect to its energy security can be split into two separate factors:

1. Ireland has very few fossil fuel reserves of its own. The main one currently used for electricity production is peat which accounted for 8.5% of the overall fuel mix in 2006 (Tuohy et al., 2009). This does not take into account the natural gas reserves off the coast of the country, as the rights to these are not owned by the Irish state but rather by international energy companies such as Shell. They therefore do not contribute in a positive way to the energy security position of the country. Of the other non-renewable sources in the electricity production fuel mix, coal and oil are imported in the same way as natural gas (see Figure 2.5) (International Energy Agency, 2010b). Therefore we can say that of the fossil fuel elements in the mix only peat contributes to the energy security position of the country and its influence is steadily declining as reserves diminish and generation stations transfer to natural gas.

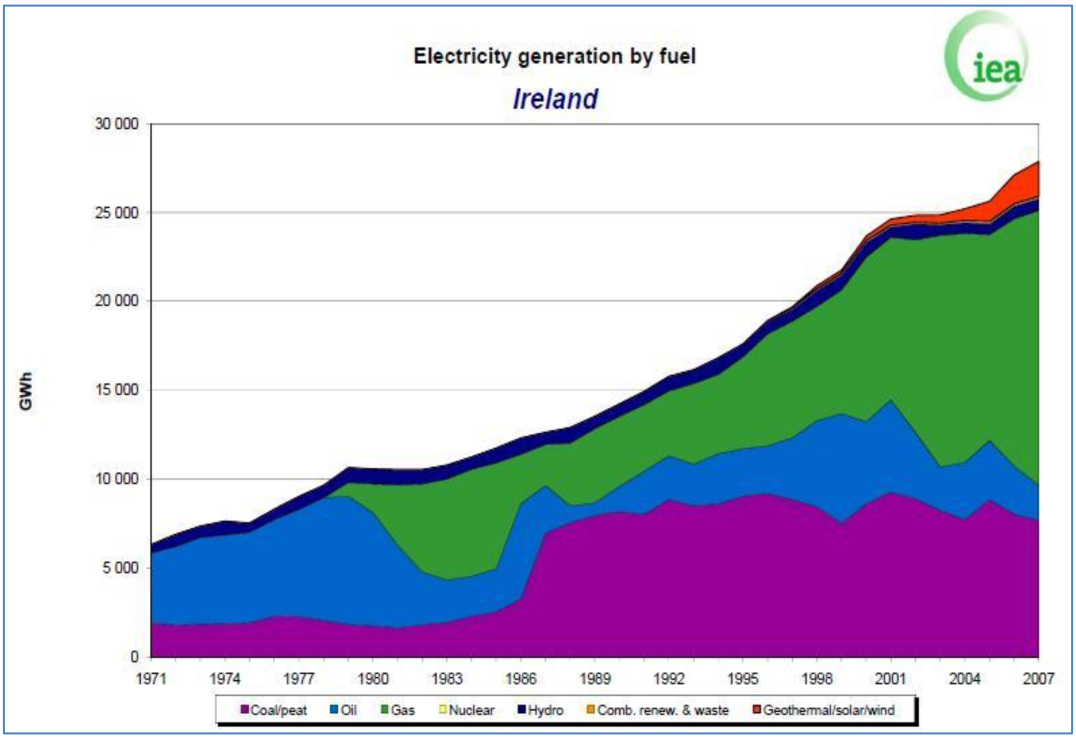

Figure 2.5: Ireland's Electricity Generation by Fuel up to 2007 (Adapted from: IEA)

2. Ireland imports over 90% of its primary energy needs (Tuohy et al., 2009). This in effect means that, as we do not have the fossil fuel reserves here and we persist in maintaining generation stations which run on fossil fuels (i.e. oil, natural gas and coal), we will always be dependent on other countries for our energy supply.

This is a major driving force behind the increasing move towards renewable ways of producing electricity. If Ireland wants to improve its position with regard to energy security then the fact that fossil fuel energy sources are not available on the island of Ireland means that there are only two viable options:

1. Nuclear Power: This is highly unlikely to ever receive the necessary backing due to concerns over the health risks posed by these types of plants. The various campaigns and controversy in this country surrounding Sellafield nuclear power plant show that the chances of such a plant being constructed here are very slim.
2. Renewables: This is the only really viable alternative to conventional fossil fuel powered plants. The electricity production statistics for March 2010 (International Energy Agency, 2010) show that of the 2,407 GWh of electricity produced indigenously only 245 GWh came from renewable sources. These renewable sources were listed as geothermal, solar, wind and other. Consequently there is plenty of scope for improvement in the more established renewable sources such as solar and wind but the as yet largely untapped tidal resource could represent the biggest area for expansion in the renewable sector.

In the following sections this tidal resource will be examined more closely with a view to ascertaining which of the methods of extracting energy (barrage or tidal current) is the most likely to be practical for a small island nation such as Ireland. The various devices developed to generate electricity from the tides will also be investigated with a view to establishing the practical pros and cons of such a process.

2.3 Marine Energy Solutions

The main types of renewable energy sources for the production of electricity are outlined in Table 2.2. This table also includes a summary of the elements upon which the resource is dependent.

Table 2.2: Sources of Renewable Energy and Their Dependence on Climate etc.

Source	**Dependence**
Hydro	Dependent on the hydrological climate cycle.
Wind	Dependent on climate.
Solar	Dependent on climate.
Wave	Dependent on climate.
Tidal	Dependent on the movement of the moon around the earth and, to a lesser extent, the movement of the earth around the sun.

As illustrated in Table 2.2, all the main sources of renewable energy are dependent on climate and weather conditions except tidal which is completely predictable as it is dependent on astronomical movements which vary very little from predicted orbits.

The rise and fall of the earth's seas and oceans over the short term (waves) and longer term (tides) represents a vast and as yet relatively untapped energy source. As the issues addressed by this paper deal exclusively with tidal energy systems, only a brief overview of wave energy will be given here with a more detailed analysis being reserved for tidal energy.

2.3.1 Wave Energy

Physical Principles

The energy contained in a wave is provided by the effects of the wind acting on the water. The wind skims the surface of the water with the streams of air closer together over a crest. This causes the air to move faster over the crest, reducing the pressure increasing the amplitude. This creates the wave, and as this wave crest collapses the displacement of neighbouring water occurs. This is how a wave propagates (The Open University, 2004b).

It can be shown that the total energy (E) of a surface wave per unit width of wave front and unit length of wave propagation is given by:

$$E = \frac{1}{2}\rho g a^2$$

where ρ = the density of the water
g = the acceleration due to gravity
a = the amplitude of the wave

The mathematical derivation of this relationship will not be covered in this paper but is clearly laid out in the reference material (The Open University, 2004b). For the purposes of this paper, the main characteristic to be taken from this equation is that the energy in a propagating wave is proportional to the square of its amplitude.

Wave Energy Extraction

As the energy supplied by a wave is proportional to the square of the amplitude, from the point of view of extracting usable energy from the wave it follows that the greater the amplitude the better. This information is of benefit as it is known that the waves of largest amplitude occur before they break on the shore. This is important as it means that any devices used to extract wave energy can be located nearer the shore, where it is cheaper and more efficient to deploy and maintain them. However there can also be a downside to this characteristic of wave energy. As the energy supplied can increase dramatically with an increase in wave amplitude, the challenge presented is to extract the energy in a usable fashion without exposing the extraction device to any potential damage caused be the large amount of energy involved.

The devices used to extract the energy from waves are usually referred to as ‘Wave Energy Converters’ and there are many design types broadly categorised into one of three main groups:

1. Oscillation water columns
2. Spill-over devices
3. Floating devices

Of these, the oscillating water column devices are the most widely known. This type of device consists of a chamber with a bottom open to the sea. The waves oscillate up and down the chamber, pushing air out through a turbine on the device platform on the upsurge of the water and sucking air in through the turbine when the water recedes. The turbine is designed to generate with bi-directional air flow.

Examples of this type of device include the Wavebob device produced by Wavebob Limited (Wavebob Ltd., 2010) and OE Buoy produced by Ocean Energy Limited (OceanEnergy Ltd., 2010). Both of these companies are based in Ireland.

An example of a spill-over device was developed by Norwegian company, Norwave. The device, known as the TAPCHAN (Tapered Channel) device, must be located at a cliff face with a small tidal range (of the order of one metre). The device consists of focusing the incoming wave through a constructed tapered channel. Tapering the wave increases its amplitude as it approaches the shoreline forcing it to over-spill over a wall to a reservoir. The water in the reservoir is then released back to the ocean via a hydro turbine which generates electricity in the conventional manner. These types of devices are easier to maintain and operate than the oscillating water column devices but are restricted to very specific installation sites (Da Rosa, 2005).

The Pelamis device is an example of the last category of device; the floating wave energy converter device. This is a long, cylindrical device which floats on the surface of the water. It is made up of segments connected together with hinges and pointed towards the incoming waves. As the waves pass along the length of the device the hinged segments rock back and forth acting on hydraulic rams which in turn operate hydraulic motors generating electricity (Pelamis Wave Power Ltd., 2010).

2.3.2 Tidal Energy

Physical Principles

Tides are primarily caused by the gravitational pull of the moon on the earth's surface waters. This movement is most noticeable along the coast of a land mass (such as the west coast of Ireland). The rotation of the earth causes the tide to rise and fall by a coast line roughly twice in a 24 hour period; that is, two high tides and two low tides.

The existence of a single high tide at a particular location is easily explained by referring to Figure 2.6. As the earth rotates, the 'bulge' of water, caused by the gravitational pull of the moon, is propagated around the earth's surface. The corresponding areas indicated as locations of 'low tide' are such due to the displacement of water from these locations to the 'water bulge'.

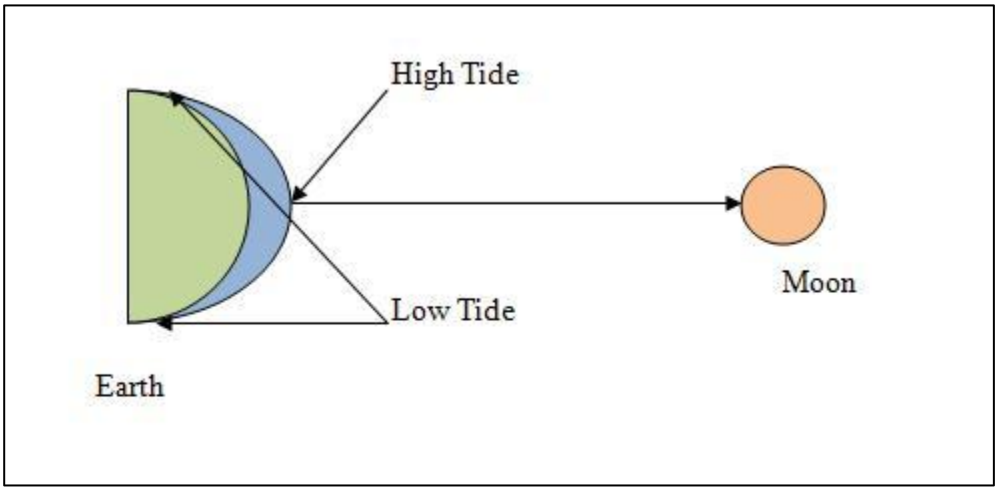

Figure 2.6: High Tide Due to the Gravitational Pull of the Moon

This does not however explain why there is a second high tide within a 24 hour period. If the 'bulge' is propagated by the rotation of the earth about it own axis then this should only occur at a specific location once in a 24 hour period. Therefore there must be a second force acting on the water to produce this secondary high tide. This second force is a centrifugal force caused by the fact that the earth and the moon rotate around one another about their common centre of gravity (The Open University, 2004). See Figure 2.7.

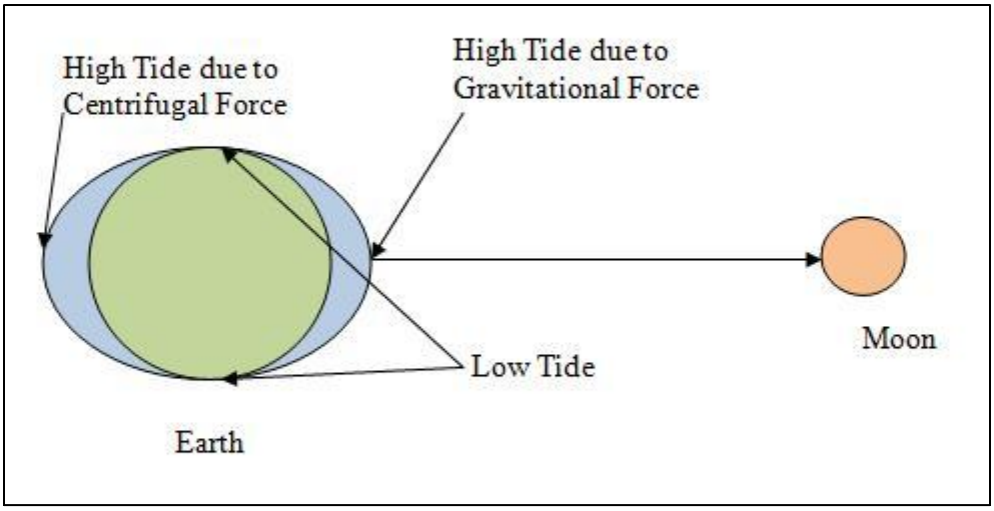

Figure 2.7: Centrifugal and Gravitational Forces Acting in Unison

The range of the tide can be defined as the measurement between the level of a high tide and the level of a low tide. This range is governed in a consistent and unchanging way by the topography of the location in question, but it is also dependent in a changeable fashion on the gravitational pull of the sun. This variation in the tidal range caused by the sun's gravitational pull gives rise to cyclical phenomena known as 'spring' and 'neap' tides.

The gravitational force between two bodies of mass M_1 and M_2 and a distance d apart is given by:

$$Force = \frac{GM_1M_2}{d^2}$$

Equation 2.1

where G is the gravitational constant.

This equation can be combined with Newton's Second Law to ascertain the relative net forces (gravitational and centrifugal) the sun and moon have on the earth and as such what the proportional role of each is to the tides. The following equation results from this combination (Bowditch, 1995):

$$Force_{net} = \frac{GMR}{d^3}$$

Equation 2.2

Where M is the mass of the moon or sun, R is the radius of the earth and d is the distance between the moon and earth or the sun and earth.

The following values were obtained from Young's University Physics (Young, 1992):
Mass of the Moon: 7.35×10^{22} kg
Mass of the Sun: 1.99×10^{30} kg
Gravitational Constant (G): 6.67×10^{-11} $\mathrm{Nm^2kg^{-2}}$
Radius of the Earth: 6.4×10^{6} m
Distance between the Moon and the Earth: 0.38×10^{9} m
Distance between the Sun and the Earth: 1.49×10^{11} m

When these values are input into Equation 2.2, the following results are obtained:

$$Force_{Moon} = \frac{(6.67 \text{ x } 10^{-11}\ \mathrm{Nm^2kg^{-2}})(7.35 \text{ x } 10^{22}\ \mathrm{kg})(6.4 \text{ x } 10^{6}\ \mathrm{m})}{(0.38 \text{ x } 10^{9}\ \mathrm{m})^3}$$

$$= 5.72 \text{ x } 10^{-7}\ \mathrm{N}$$

$$Force_{Sun} = \frac{(6.67 \text{ x } 10^{-11}\ \mathrm{Nm^2kg^{-2}})(1.99 \text{ x } 10^{30}\ \mathrm{kg})(6.4 \text{ x } 10^{6}\ \mathrm{m})}{(1.49 \text{ x } 10^{11}\ \mathrm{m})^3}$$

$$= 2.57 \text{ x } 10^{-7}\ \mathrm{N}$$

This shows that the net gravitational and centrifugal force of the sun on the earth is about half that of the moon. This is as a result of the sun being much further away than the moon and the force being inversely proportional to the *cube* of this distance. The much larger mass of the sun compared to the moon does not have as great an effect as the force is directly proportional to the mass (see equation 2.2).

The net effect of the sun and moon on the earth's tides depends on their relative orientation (The Open University, 2004). When the sun, moon and earth are all aligned, the gravitational force acting on the water is at its greatest, and this results in a very high tide known as a 'spring' tide. This spring tide occurs whether the sun and moon are aligned on the same side of the earth or not (see Figure 2.8 and Figure 2.9).

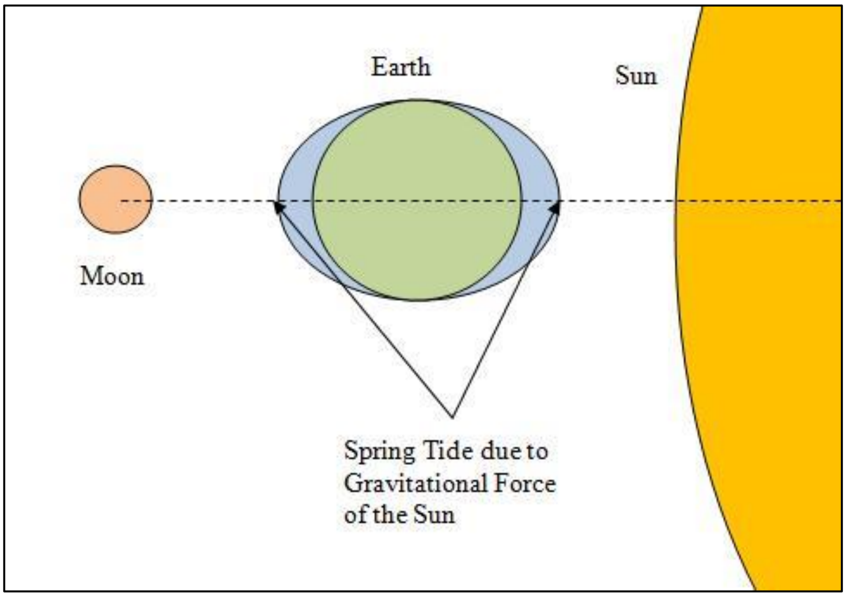

Figure 2.8: Sun and Moon Aligned on Opposite Sides of the Earth

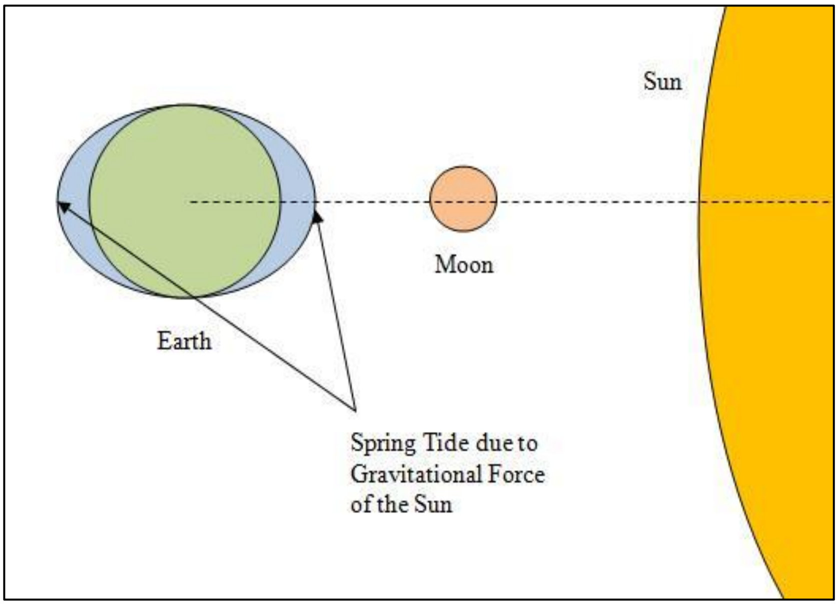

Figure 2.9: Sun and Moon Aligned on the Same Side of the Earth

When the sun and moon form an angle of 90° with each other relative to the position of the earth a diminished high tide occurs (see Figure 2.10). This is known as a neap tide. The period between successive spring and neap tides is approximately 14 days (that is, in a 28 day period there would be two spring and two neap tides in a given location).

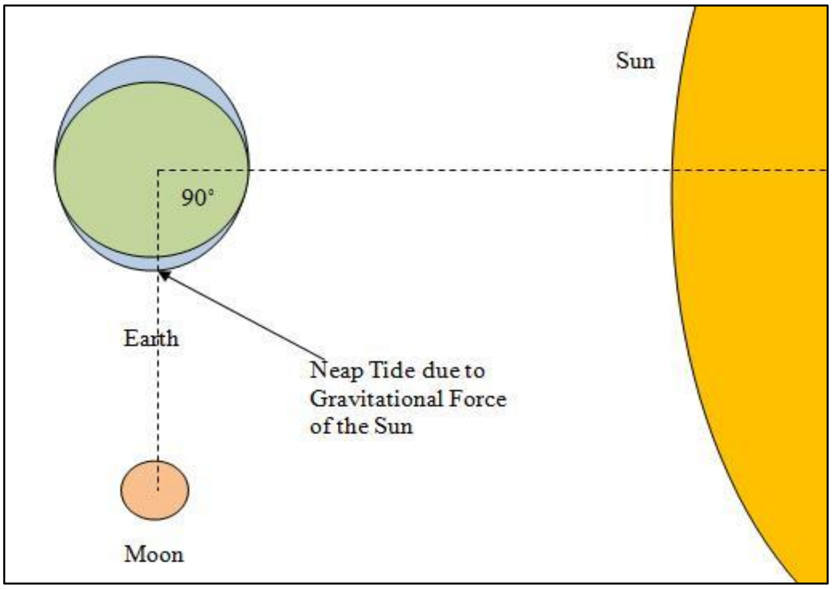

Figure 2.10: Sun and Moon at a 90 Degree Angle With Respect to the Earth

Tidal Energy Extraction

It has been illustrated in this section that the tides are controlled by the orbits of the moon around the earth and the earth around the sun. This huge displacement of water across the surface of the earth represents a massive amount of energy which can theoretically be converted into usable forms.

When it comes to converting the energy from tides into electrical energy, there are two main categories for the different technology designs. The first category is the barrage-type which uses the potential energy of the water trapped behind a barrage at high tide to generate electricity. The second category uses the kinetic energy in the tidal current to rotate a turbine in much the same way as wind energy operates. This latter kinetic type is generally regarded as the preferable method as it is not as intrusive (aesthetically and environmentally) as the barrage type.

2.4 Tidal Energy Systems

In the following section, a brief summary will be given on the barrage type method used to extract energy from the tides. As the main subject matter dealt with in this paper concerns the tidal current systems, a much greater level of detail will be reserved for this type of device.

2.4.1 Barrage Type

Until relatively recently, references to tidal energy systems typically meant barrage tidal energy systems. This is a system whereby a barrage (or barrier) is built across waterway, generally an estuary, and electricity is generated by utilising the difference in head across this barrage. The concept is not new, with the first commercial installation of such a system being opened in Rance, France in 1966 (see Figure 2.11).

Figure 2.11: Rance Tidal Barrage, France **(Wikipedia, 2010)**

There have being very few installations since this 240MW rated system however, as they are expensive to construct and can have a severe impact on the local environment (land and marine plant and animal species). Amongst the only other sites where tidal barrages have been successfully commissioned are the Annapolis River in Nova Scotia (20 MW) and Kislaya Guba in Russia (1.6 MW) (Tidal Electric Inc., 2010).

All of these installations operate what is referred to as ebb generation, meaning that they start to generate electricity when the tide is going out.

The operation of an ebb generation tidal barrage is straight forward (Xia, Falconer and Lin, 2009):

1. When the tide is on its way in, the sluice gates open allowing the water to flow in shore side of the barrage.
2. At, or near, high tide the sluice gates are closed. The tide turns and begins to go out and the water is contained behind the barrage creating a difference in head between the water on either side of the barrage.
3. The turbine gates remain closed until the tide has dropped sufficiently for the appropriate head difference for electricity generation to occur, then the turbine gates are opened allowing the water to pass through the turbines and generate electricity.
4. Electricity is generated until the water level behind the barrage drops so low that the difference in head either side of the barrage is no longer sufficient for electricity generation. The turbine gates are then closed and the sluice gates are opened ready for the next flood tide and the cycle repeats.

As well as the currently commissioned sites mentioned, there is also a proposal to construct a tidal barrage in the Severn estuary in south-west England. The proposed barrage would be constructed as in the Figure 2.12 below (Xia, Falconer and Lin, 2010). However, environmental concerns mean the Severn project may never get past the proposal stage. This is one of the reasons why tidal current installations are generally favoured over tidal barrage installations.

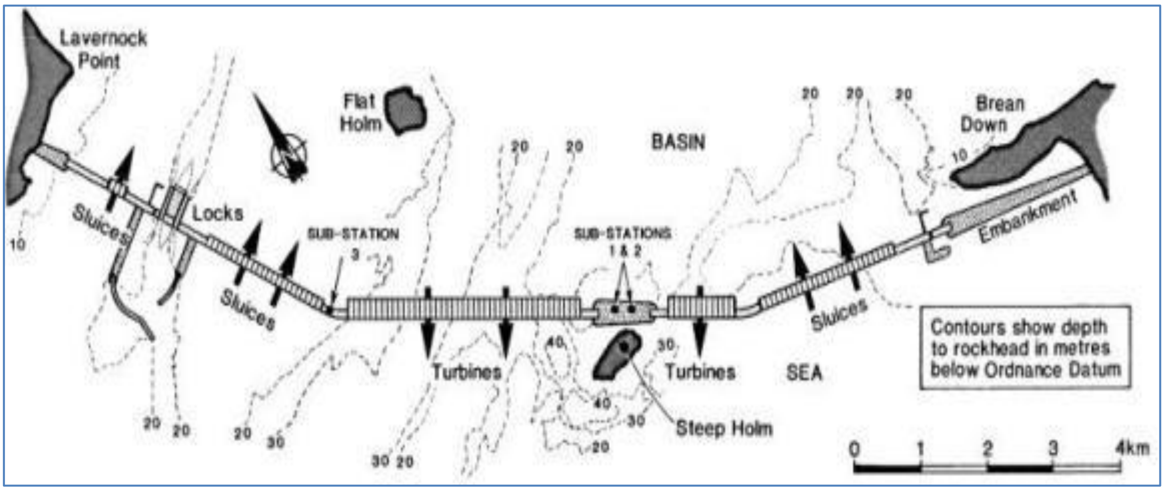

Figure 2.12: Proposed Configuration for the Severn Estuary (Adapted from: Xia et al)

2.4.2 Tidal Current Type

Devices designed to extract the kinetic energy from the moving waters in a tidal stream as the tide comes in (flood tide) and goes out (ebb tide) are termed tidal current generators. These devices generally operate in an analogous fashion to wind turbines and as such come in Horizontal Axis (rotor blades rotate around a horizontal axis parallel to the direction of fluid flow) and Vertical Axis (rotor blades rotate around a vertical axis perpendicular to the direction of fluid flow) configurations. Wind turbines extract energy from a wind stream with an available power given by:

$$P = \frac{1}{2}\rho A v^3$$

Where ρ = the density of the wind stream
A = the cross sectional area of the wind stream (i.e. the turbine)
v = the velocity of the wind stream

This equation can also be used for water streams (Clarke et al., 2006). In the case of tidal current devices, the velocity (v) of the water stream may be generally less than for a wind stream but the density (ρ) will be far greater. Young's University Physics lists the value for the density of air to be 1.2 kg/m^3 and for the density of water to be 1000 kg/m^3 (Young, 1992). Therefore the density of water is about 833 times that of air and so the associated power in a stream of water would be 833 times greater than for a stream of air travelling at the same velocity. This greater density also allows the tidal current turbine to have a lower cut-in fluid velocity which results in power generation at lower fluid stream velocities.

The following paragraphs outline the state-of-the-art horizontal axis devices and vertical axis devices with an emphasis on the power capacity and suitability for commercial deployment.

DeltaStream Turbine

The DeltaStream device (see Figure 2.13) is currently being developed by Welsh based company Tidal Energy Limited. These devices consist of a triangular structure with a horizontal axis turbine located at each of the three angles. The triangular structure provides stability in the harsh ocean environment and reduces the risk of overturning. This configuration also allows the device to rest on the sea bed without anchoring as the tubular structure can be flooded on deployment. The three turbines can rotate to the direction of tidal flow allowing power generation for both flood and ebb tides. A prototype is scheduled to be deployed this year (2010) off the Welsh coast at Pembrokeshire. The prototype is expected to have a rating of 1.2 MW and a commercial array deployment of 10 MW is planned for late 2013.

The design of the DeltaStream device has been kept deliberately simple in order to reduce the development and deployment costs. This approach has resulted in the expected costs of development and installation being in the region of one third that of the commercial installation of the Marine Current Turbine in Strangford Lough (Tidal Energy Limited, 2010).

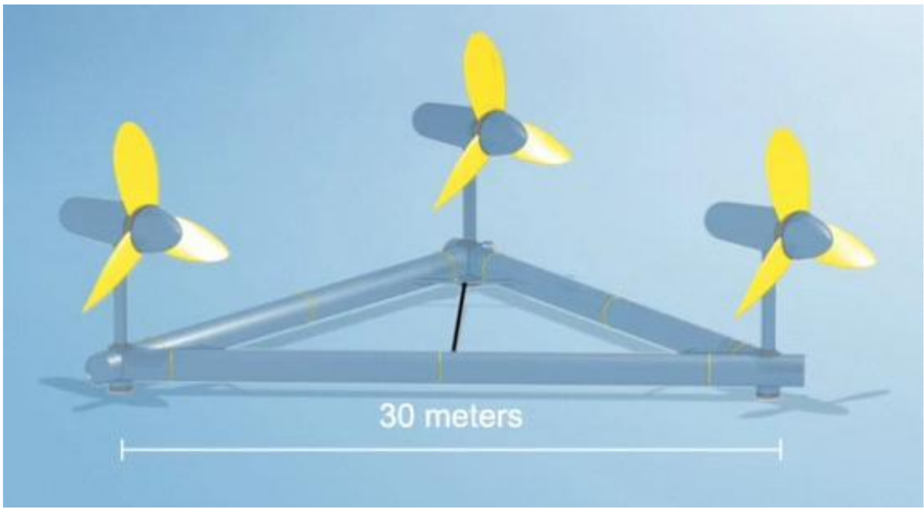

Figure 2.13: DeltaStream Device by Tidal Energy Limited

Evopod Tidal Turbine

The Evopod tidal turbine, produced by Ocean Flow Energy, (see Figure 2.14) is currently in the testing phase of its development. The Tyne and Wear based company have deployed a 1/10 scale model in the Strangford Narrows in Northern Ireland. The full scale model will have a rated capacity of 35 kW and will most likely be utilised in stand-alone off grid applications. The design incorporates a horizontal axis turbine at the base of the partially submerged floating unit, which is tethered to the sea bed in such a way that it always faces into the tidal current allowing power generation during flood and ebb tides.

The company are also in the early stage of development of a twin turbine system based on the same floating structure. The turbines would have an individual rating of 1.2 MW each, giving the unit an overall rating of 2.4 MW. This would make the configuration more viable for grid connection due to its larger power generating capacity (Ocean Flow Energy, 2010).

Figure 2.14: Evopod Device by Ocean Flow Energy

Free Flow Turbines

The New York based Verdant Power have had six Free Flow turbines (see Figure 2.15) commissioned in the East River in New York between 2006 and 2008. This deployment constituted the first ever grid connected array of tidal turbines in the world. The six full scale horizontal axis turbines (5 metre diameter) operated for over 9000 hours between these dates. Their operation was fully automatic and unattended and supplied over 70 MWh of electricity to the grid from the 35 kW rated turbines.

The company have further projects planned in China and Canada and are aiming to complete a megawatt scale build out by 2012 (Verdant Power, 2009).

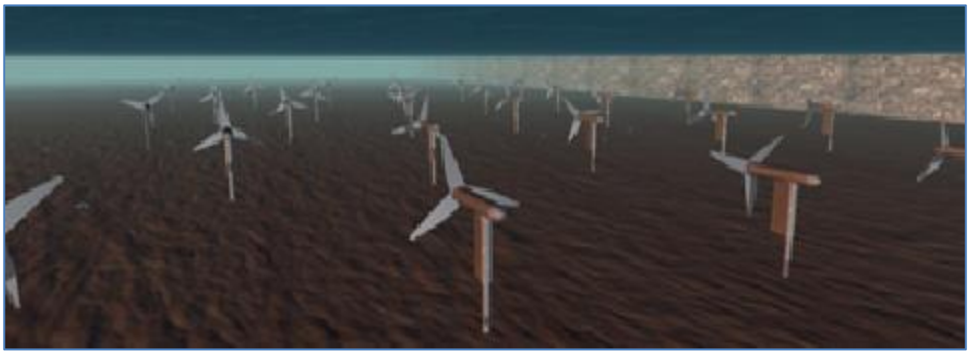

Figure 2.15: Free Flow Turbine Array Developed by Verdant Power

Gorlov Helical Turbine (Vertical Axis)

The Gorlov Helical turbine (see Figure 2.16) was developed by US based GCK Technology Inc. This is a three blade vertical axis turbine based on the Darrieus wind turbine. Amongst its main benefits is the ability to generate power at low current speeds (≈ 0.7 m/s) and to rotate regardless of current flow direction (ebb or flood) (GCK Technology Inc., 2010).

Figure 2.16: Gorlov Turbine Developed by GCK Technology

Rotech Tidal Turbine

The Rotech Tidal Turbines are developed by Lunar Energy Ltd. which is based in Glasglow, Scotland. The focus of the company is keeping the design of their turbines robust, simple and economically viable. With this is mind the Rotech turbine was developed with its main system components removable for maintenance, therefore negating the need for offshore maintenance. Figure 2.17 shows the 1 megawatt version of the turbine which is bi-symmetrical in design (allowing for generation in flood and ebb conditions) and is housed in a venturi duct. This structure uses the gravity base to anchor it to the seabed which allows for deployment at greater depth (> 40m) as there are few bathometric requirements. This reduces the obtrusive nature of its installation keeping it clear of shipping lanes, etc. The company have signed a deal with the Korean Midland Power Company to install 300 of these one megawatt turbines off the coast of South Korea. This project is due to start supplying electricity to the grid in 2015 (Lunar Energy Ltd., 2010).

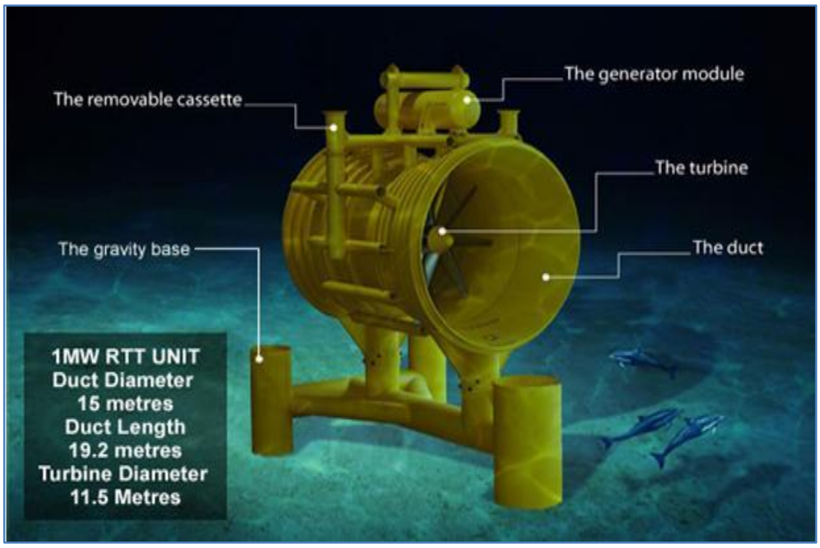

Figure 2.17: Lunar Energy's 1MW Rotech Turbine

AK1000 Tidal Turbines

The latest offering, in the tidal market, from Singapore based company Atlantis is the AK1000, horizontal axis twin rotor turbine (see Figure 2.18). This device follows up from earlier technology produced by Atlantis such as the Nereus and Solon devices. The AK1000 is the high end of the company’s devices with ratings of 1 megawatt and 2 megawatts. This device has unique twin fixed pitch rotor blades which allow generation to occur in either ebb or flood conditions without the need to rotate the turbine housing. One turbine is simply designed to generate when flow is in one direction and the twin turbine generated when flow is in the opposite direction. This feature cuts down on maintenance requirements and reduces operational downtime (Atlantis Resources Corporation, 2010). A commercial installation of a 1 megawatt AK1000 took place on the 24th August 2010 in Orkney, off the Scottish coast. This is the world’s largest tidal turbine generator installation (Faversham House, 2010).

Figure 2.18: AK1000 Tidal Turbine from Atlantis Corporation

Open Centre Turbine

Irish firm OpenHydro Limited are the manufacturers of the Open Centred Turbine pictured in Figure 2.19. This turbine is a departure from the designs which have been looked at up to this point. All the designs presented thus far could be considered expansions of the two main types of wind turbine. Most of these are based on the horizontal axis turbine and the Gorlov, which was based on the vertical axis wind turbine. The turbine from OpenHydro is not based on either of these prototypes, but consists of a circular turbine six metres in diameter. The water flows through the device acting on the rotors to slowly rotate the turbine. OpenHydro say that the open centre and slow moving rotor minimise the effect of the turbine on marine life. The turbine is also designed to sit on the seabed out of the way of ships and away from the view of the public (Openhydro Group Ltd., 2010).

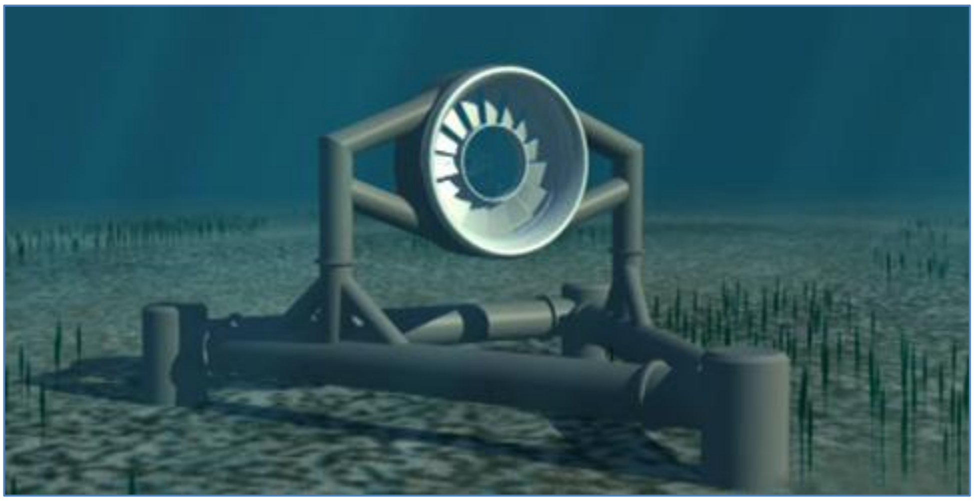

Figure 2.19: Open Centre Turbine from OpenHydro

This device was the first ocean current device to connect commercially to the UK national grid, and the company are due to connect to the French electricity grid in 2011. The initial installation will consist of up to ten Open Centred Turbines with further connections planned on an ongoing basis (OpenHydro Press Release, 2008).

The turbine is rated at 250kW and are currently designed and manufactured at the company’s premises in County Louth in Ireland.

SeaGen

Another device which is currently supplying the UK grid is the SeaGen device (see Figure 2.20) designed and manufactured by Marine Current Turbines also based in the UK. The installation at Strangford Lough in Northern Ireland consists of a single SeaGen device which has a rated output of 1.2 megawatts at a water velocity of 2.4 m/s. The turbine at Strangford Lough has regularly produced electricity at its rated capacity and can produce about 6,000 MWh per year, which Marine Current Turbines claim is the equivalent to the yearly production of a 2.4 megawatt wind turbine (Marine Current Turbines Limited, 2010). This is due to the consistent nature of tidal energy compared to that of wind energy.

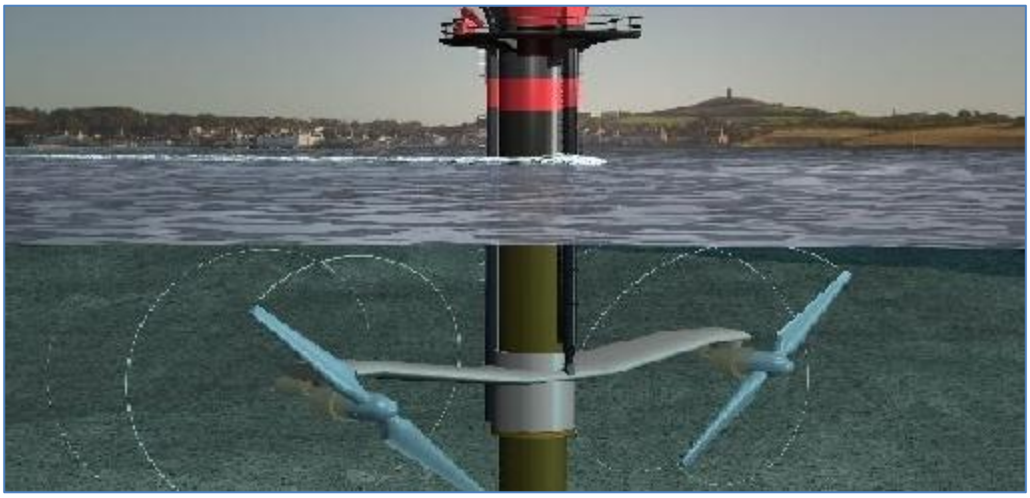

Figure 2.20: SeaGen Tidal Device by MCT

The device itself consists of twin turbines which, unlike the AK1000 twin turbines, operate in ebb and flood flow directions. This allows a single device to generate 1.2 megawatts which is the largest rated power of a single device to have been encountered by the author to date.

The other interesting feature of this design is that, unlike the other horizontal axis turbines, the rotation of the whole turbine hub between ebb and flood tides is unnecessary. The device designers have developed a system whereby only the blades of the turbine need to rotate to allow generation in the opposite flow direction. This feature cuts back on the maintenance of the device and also on the cost of maintenance and repair, as the moveable parts are smaller and less expensive (Marine Current Turbines Limited, 2010).

Tidal Fence Davis Hydro Turbine (Vertical Axis)

The Tidal Fence design (see Figure 2.21) currently being proposed by Canadian company Blue Energy Limited is effectively a barrage consisting of a number of Vertical Axis Turbines. The individual turbines used are the Davis Hydro Turbines which operate in a similar way to the Gorlov Helical Turbine mentioned earlier. The main differences between the Davis turbine and the Gorlov is the number of hydrofoils (four for the Davis compared to three for the Gorlov) and the fact that the Davis hydrofoils are straight compared to the helical Gorlov hydrofoils. The company are still in the development phase of their product and are currently attempting to raise funds for a 200 megawatt commercial project. (Blue Energy Limited, 2009).

Figure 2.21: Tidal Fence by Blue Energy Ltd.

Time will tell if this innovative take on tidal energy systems will prove viable. The obvious benefit of having a large scale production installation on a single site may well be offset by the growing importance of marine ecology impact concerns of such an installation.

TidEl Stream Generator

The TidEl Stream Generator (see Figure 2.22) was developed by the UK based company SMD Hydrovision Limited. There is nothing different about the power producing turbines on this device compared to the others outlined above other than one important feature. Instead of the device structure being anchored to the seabed in the conventional manner, this device is buoyant and tethered to the seabed. This arrangement allows the device to self-align with the direction of water flow, therefore reducing the amount of serviceable parts and saving on operation and maintenance costs (Department of the Environment, Heritage and Local Government, 2007).

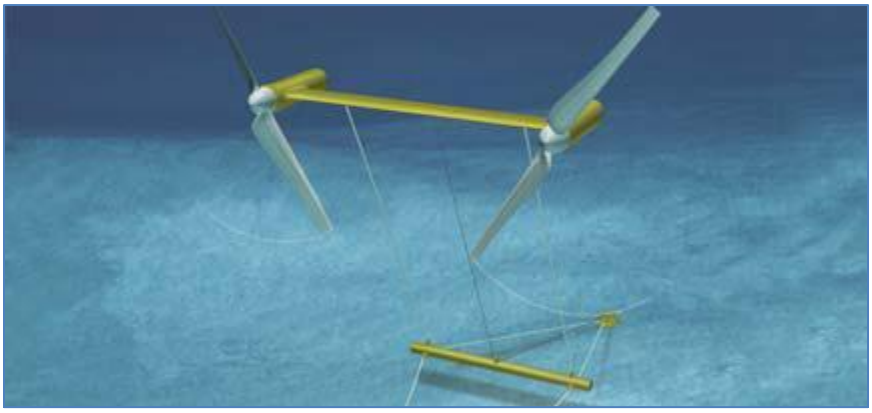

Figure 2.22: TidEl device from SMD Hydrovision Ltd

Two of these buoyant turbines, each rated at 500kW are connected together with a crossbeam giving a total device rating of 1 MW (Department of the Environment, Heritage and Local Government, 2007).

Tidal Stream Turbine

The HS1000 tidal current turbine (see Figure 2.23) uses the same technique as the SeaGen device for generating in flow from either tidal direction. This allows the device to be rigidly anchored to the seabed without the need for a rotating turbine hub. The device has been developed by Norwegian company Hammerfest Strom, who espouse the devices ability to meet the structural demands of the harsh environment for which the device is designed. The turbine is currently in a pre-commercial stage of its development with the company hoping to have a commercial connection to the UK national grid by 2011. The HS1000 has a rating of 1 megawatt (Hammerfest Strom, 2010).

Figure 2.23: HS1000 Tidal Energy Device from Hammerfest Strom

2.5 Conclusions

Amongst the primary global drivers for a move away from conventional methods of generating electricity are climate change, the precarious nature of fossil fuel reserves and energy security. For a small island nation such as Ireland the latter of these three drivers could be seen to be the most relevant. The reason for this is that as a nation with limited fossil resources anyway, the global reduction in these resources does not effect us as much, or more correctly, it was always an issue so nothing has really changed in this respect. Subsequently if we, as a nation, decided to prioritise our poor energy security situation and commit ourselves to tackling it, we would have also addressed the former two drivers in the process. We import 90% of our primary energy requirements, the majority of which are in the form of fossil fuels. Therefore if we looked for alternatives in the shape of indigenous renewables we would not only have addressed the energy security driver, but also the fossil fuel reserves driver as we would no longer have use for them, and the climate change driver as the use of renewables in electricity production would decrease the greenhouse gas emissions drastically. The only other viable alternative would be large scale nuclear energy which would be unlikely to ever get the popular support it would require.

Given that it is beneficial on many fronts (both environmental and economic) to transition towards renewables, the next question is what type of renewable energy should be exploited? The quick answer to this is all of them, but some may have a wider scope for increasing the level of exploitation. For example, hydro energy has been successfully utilised for decades in Ireland but there is a general consensus that it has been taken as far as it can go. There simply are not any more suitable sites for large scale hydro generation. Wind energy has also been utilised heavily and, while there is still room for further expansion, it will become more and more difficult to find sites with suitable wind conditions and low levels of local resistance for wind farm installations. This leaves solar, which due to the climate in Ireland will never be as heavily utilised here as it will in, say, Portugal.

The only remaining, largely untapped, renewable source of electricity is the ocean around the island. The ocean can provide electricity generation capacity in two main ways, wave conversion and tidal conversion. Neither of these conversion types have been exploited anywhere near their potential. The main drawback to wave generation is the same problem voiced by many opponents to other renewable sources, the unpredictability of supply. This is indeed a valid drawback, and not only effects wave energy but also wind and solar energy. Tidal energy however is completely predictable years into the future. This is because the tide is caused by the relative movements of the sun, moon and earth around one another whereas waves, wind and incident solar intensity are governed by the climate which is notoriously changeable in Ireland.

Tidal energy has traditionally been extracted by what are known as tidal barrages. Similar to large scale hydro installations, these are now seen as practically exhausted in terms of future available sites and, in addition, tend to have a serious impact on the environment around where they are installed. In more recent times, tidal energy development has become centred on tidal current devices. These operate in an analogous fashion to wind turbines where the medium of air is replaced by water. The greater density of water compared to air allows generation to occur at much lower flow speeds, resulting in rated generation comparable to a wind turbine of vastly greater size.

There are many different types of devices which convert the kinetic energy in a tidal current into electricity, but the vast majority are based on the horizontal axis turbine design. These are considered efficient and are easily adaptable to ensure that generation occurs during both ebb and flood tides. Designs based on the vertical axis turbine are also prevalent and can generate in both flow directions without any adaptation at all. In a departure from designs adapted from various types of wind turbines, Irish company OpenHydro have developed a tidal energy conversion device called the Open Centre Turbine.

As to which of these devices proves to be the most effective at generating electrical energy from the tides remains to be seen. These devices are in various stages of development and each will score differently in robustness, efficiency, ease of installation, cost of installation and operation, ease and cost of maintenance and environmental impact. It is likely that no one device will ‘win out’ but rather the selection of which device to install will be based on the relative importance of each of these factors for the installation in question and will therefore be very much site specific.

Chapter Three: Tidal Base Load Supply

3.1 Introduction

As demonstrated in the previous chapter the supply of electrical energy obtainable from tidal sources should have a high degree of predictability. This is in contrast to many other renewable sources of energy, such as wind and solar, which only produce electricity when the appropriate weather conditions prevail.

This predictability, however, is not the only consideration that must be taken into account when ascertaining if the supply of electricity is suitable for connection to the grid. Another significant consideration is the level of consistency in the supply. The following section in this chapter outlines the difficulties associated with connecting a supply to the grid which varies in magnitude over the course of a 24 hour period. This is the central problem addressed by this paper. The next two sections outline the method behind, and the results from, a proposed solution to this problem of inconsistent supply using data from various coastal sites around Ireland to test the viability of the solution.

The last two sections introduce some of the limitations associated with the proposed solution and suggest improvements which could be implemented to mitigate the effects of these limitations.

It should be noted that the following analysis at all times assumes that the tidal device to be deployed is a tidal current device as apposed to a barrage type or other design. In addition, it is also assumed that the device can generate in either flood or ebb conditions (e.g. the SeaGen device outlined in section 2.4.2).

3.2 Base Load Supply Problem

3.2.1 Overview

Electricity generated from tidal sources is amongst the most predictable of the renewable sources. It is easy to switch on a gas turbine generator whenever electricity is required. This is a luxury not present with renewable sources of electrical power generation as they generally have to generate when the weather is favourable and cannot generate when it is not. This predictability of tidal generated power must not be confused with consistency of supply. It can be predicted to a high degree of accuracy what times of the day the tidal device will generate and what times it will not, but there is no guarantee it will generate when power is needed by the grid.

As will be demonstrated later in this chapter, the profile of power generated from a tidal current system is not consistent but rather has regularly spaced peaks and troughs (see Figure 3.2 in section 3.3 of this paper). This can result in problems for a grid connected supply as explained in the following section.

3.2.2 Cycling of Conventional Plants

When electricity generated from tidal or other renewable sources is added to the grid it may or may not coincide with times of peak demand. This can result in oversupply during times of low demand and as such require the conventional power plants supplying electricity to the grid to be temporarily shut down.

This cycling of power plants takes place regardless of whether there are renewable sources connected to the grid or not, as more power is required from the grid at 5pm in the day than at 5am in the morning. However the inclusion of renewable sources supplying to the grid can increase the frequency of this cycling dramatically. The total cost associated with cycling a plant can arise from any of the following (Denny, 2009):

- Operation and maintenance payments caused by higher thermal and pressure stresses due to variable operation
- Increased fuel use during start up
- Shortening lifetime of parts
- Increased human error due to greater amount of manual interaction

Depending on the type of plant and the type of fuel used, Denny estimates that the cost of a single cycle can range between €200 and €500,000 (Denny, 2009).

Looking at Figure 3.2 it can clearly be seen that there are four times during a 24 hour period when peak power production occurs from a tidal current generator. This could therefore result in the cycling of a conventional power plant on the grid up to four times a day depending on when the peaks happened to occur and whether or not they coincided with times of peak demand.

The cycling requirements on conventional power plants can therefore have a big impact on the economic viability of adding this type of electricity generating source to the grid, as the benefits of saving on fuel (tidal energy constituting an energy source that is essentially ‘free’) can quickly be offset by the cost associated with the conventional plant cycling requirements.

Therefore the problem addressed in this paper can be summarised as follows:

1. Tidal power added to the grid is predictable but not consistent over the course of a 24 hour period of generation.
2. The power generating profile from a typical tidal current system will consist of four peaks of power generation and four corresponding troughs.
3. This type of power generation profile can result in an increase in the frequency of conventional power plant cycling.
4. The associated cost of the additional cycling of conventional power plants on the grid can offset some or all of the savings gained by adding the renewable source to the grid.

It is therefore clear that in order for tidal sources to play an important role in the supply of energy to the Irish grid, a way must be found to smooth out the power generation profile of the tidal current systems being used. This removal of the peaks and troughs of generation would ensure that the tidal sources provide a consistent, or near consistent, supply over a 24 hour cycle and therefore not only constitute a good environmental energy solution but also a good economic one.

3.3 Method

The solution suggested here to the problem outlined in the previous section involves the simultaneous commissioning of several tidal systems at points around the coast of Ireland. The reasoning being that if the sites are a suitable distance apart and all systems generate with a power profile as described by the graph in Figure 3.2 then the distance between the sites should provide a phase shift in the profile. The cumulative effect of all these systems supplying the grid at the same time would therefore provide a consistent base load to the grid as each site will produce at a maximum slightly later than the previous site.

3.3.1 Data Collection

The initial step in verifying if this was indeed a viable solution involved obtaining tidal data from a range of sites around the island of Ireland. After contacting the Marine Institute in Galway, it became apparent that tidal current speed data was not recorded around the Irish coastline. The only data that was extensively recorded and readily available was the tide height over time (The Marine Institute, 2010). This data was therefore collated and tabulated for the fourteen available sites. The sites for which data was available are listed in Table 3.1 below.

Table 3.1: Sites with Tidal Data Available

Site	Site
Aranmore	Killybegs Port
Ballyglass	Kish Bank
Castletownbere	Malin Head
Dublin Port	River Dodder
Dundalk	River Liffey
Galway Port	Skerries Harbour
Howth Harbour	Sligo

The tidal data obtained for these fourteen sites was initially for just one day (January 1st 2010 was selected as a random choice).

3.3.2 Converting Data

As only the tide height data was available and not the tidal current speed data, a method was required to convert this data to something representing the available power at each site. To this end, it is convenient to introduce a parameter termed the ‘power potential’ of the site. The power potential of a site can be defined as the quantity of power that the site has the potential to produce at a given point in time over the lunar cycle.

The following is an excerpt from the American Practical Navigator: *“At any one place the speed of the current at strength of flood and ebb varies during the month in about the same proportion as the range of tide, and this relationship can be used to determine the relative strength of currents on any given day.”*(Bowditch, 1995)

From this statement it is reasonable to say that if the current strength varies in the same proportion over a flood and ebb cycle as does the range of the tide, and the power that can be drawn from the current is proportional to the current strength, then the ‘power potential’ at a given site will vary with the range as well.

In order to understand more fully how the power potential varies with the tidal range we need to look more closely at the data from our sites.

When the tide is fully in (at its highest level) or fully out (at its lowest level) the tidal current will have a speed of zero and therefore a power generating potential (power potential) of zero. Accordingly the current speed, and its power generating potential, will be at its greatest when the half way point between low and high tides is reached. The power generating potential will increase gradually from low tide up to this point and decrease gradually again after this point until high tide is reached. Figure 3.1 and Figure 3.2 use the data from Galway Bay (The Marine Institute, 2010) to illustrate this point. When the tide is at its greatest displacement above or below the datum level (Figure 3.1), the power generating potential (Figure 3.2) is at a minimum. Conversely, when the tide is exactly at the datum level (Figure 3.1) the power generating potential (Figure 3.2) is at a maximum. This is the behaviour that provides four supply peaks and troughs in a 24 hour period.

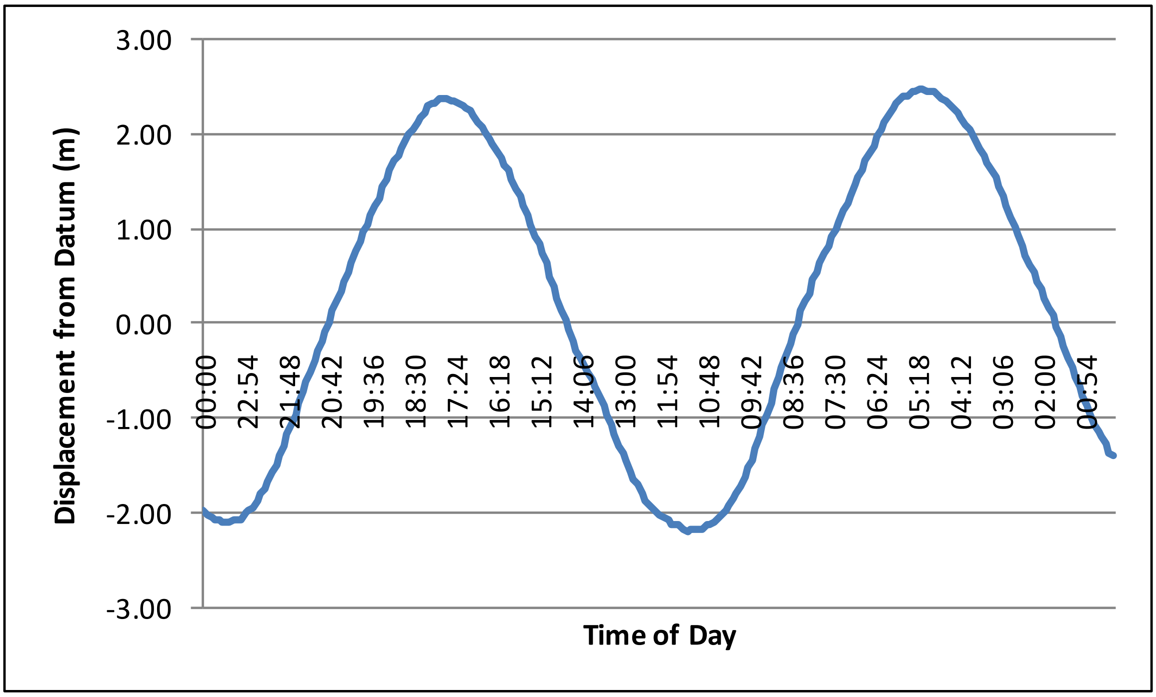

Figure 3.1: Tide Level in Galway Bay over a 24 Hour Period

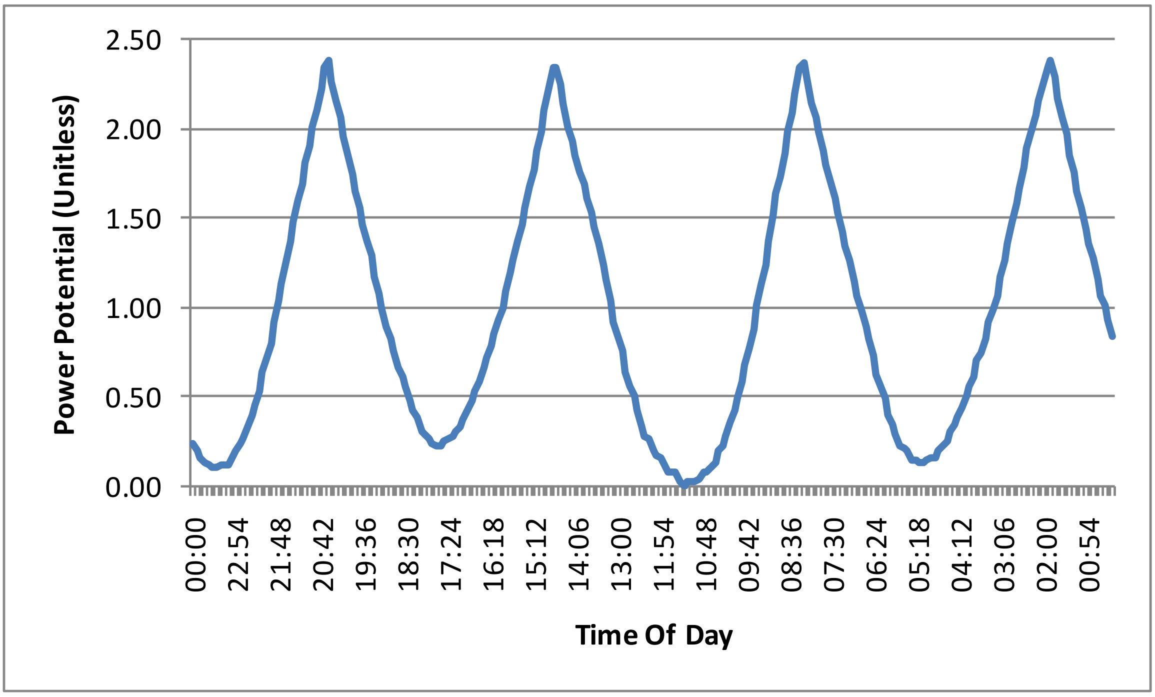

Figure 3.2: Power Potential for Galway Based on Water Displacement from Datum

Conversion Procedure

The following method was used to convert the tidal range data into power potential data (i.e. to get from the graph in Figure 3.1 to the graph in Figure 3.2):

1. The tidal range data for each of the fourteen sites was tabulated and copied to Microsoft Excel.
2. The average value was calculated for the dataset. This value was taken as the datum.
3. Each value in the dataset was checked to see if it was greater or less than the datum.
4. If the value was less than the datum, then this value was subtracted from the datum.
5. If the value was greater than the datum, then the datum was subtracted from the value.
6. Steps 4 and 5 were executed in order to calculate how far the tide was from its datum level. This gives a value that is large when the tide is at full flood or full ebb and gets gradually smaller as it approaches the datum. From the analysis above, it can be seen that this is the opposite of what is required to model the power potential. Therefore the last step was to ‘invert’ the data calculated in steps 4 and 5. This was achieved by calculating the maximum value in this dataset and subtracting each element in the dataset from this value.

So looking again at the graphs, at about 11:00 and 23:30 we can see that the water level is at a minimum (Figure 3.1) and this corresponds to a minimum in the power potential (Figure 3.2) and at about 05:30 and 18:00 the tide is at its maximum level and this also corresponds to a minimum in the power potential as the tide is turning at all these points and therefore the flow rate is at a minimum.

Similarly the peaks in power potential which occur at 02:00, 08:30, 15:00 and 20:30 (Figure 3.2) correspond to the times when the tide is at, or near its datum level (Figure 3.1) and is therefore in ‘full flow’ either in or out.

3.3.3 Data Analysis

At this stage, only one day’s data was required for each site. This was because the next step was to ascertain which of the sites were the most out of phase as regards the time of their peak energy production and therefore most suitable for inclusion in the more detailed analysis. The data obtained for all fourteen sites available is contained in the AllTideData.xlsm file on the CDROM accompanying this thesis. The data for the four sites which were chosen for further analysis is tabulated in Appendix A. For each of these datasets the conversion procedure outlined above was executed using Microsoft Excel and graphs were plotted for the power potential of all sites.

At this point it was deemed useful to create some macros to add and remove data for each site to a single graph and to assign them to buttons in Excel. This allowed the addition of the data from a particular site to the graph at the click of a button and the removal of data in the same way. This proved very helpful in ascertaining the most out of phase sites. This macro based tool used for creating and removing datasets from the graph can be found on the ‘Macro’ tab in the AllTideData.xslm file on the CDROM accompanying this thesis.

3.4 Results

3.4.1 Chosen Sites

Upon completion of the data analysis described in section 3.1.3, four sites were chosen for further analysis. Figure 3.3, Figure 3.4 and Figure 3.5 and the previously displayed graph for Galway Bay (Figure 3.2) show the power potential graphs for the four sites which were deemed to be the most out of phase due to their location. The other ten power potential graphs, deemed unsuitable for further analysis, can be found in Appendix B. These four sites were decided upon after checking each combination using the macro tool described previously.

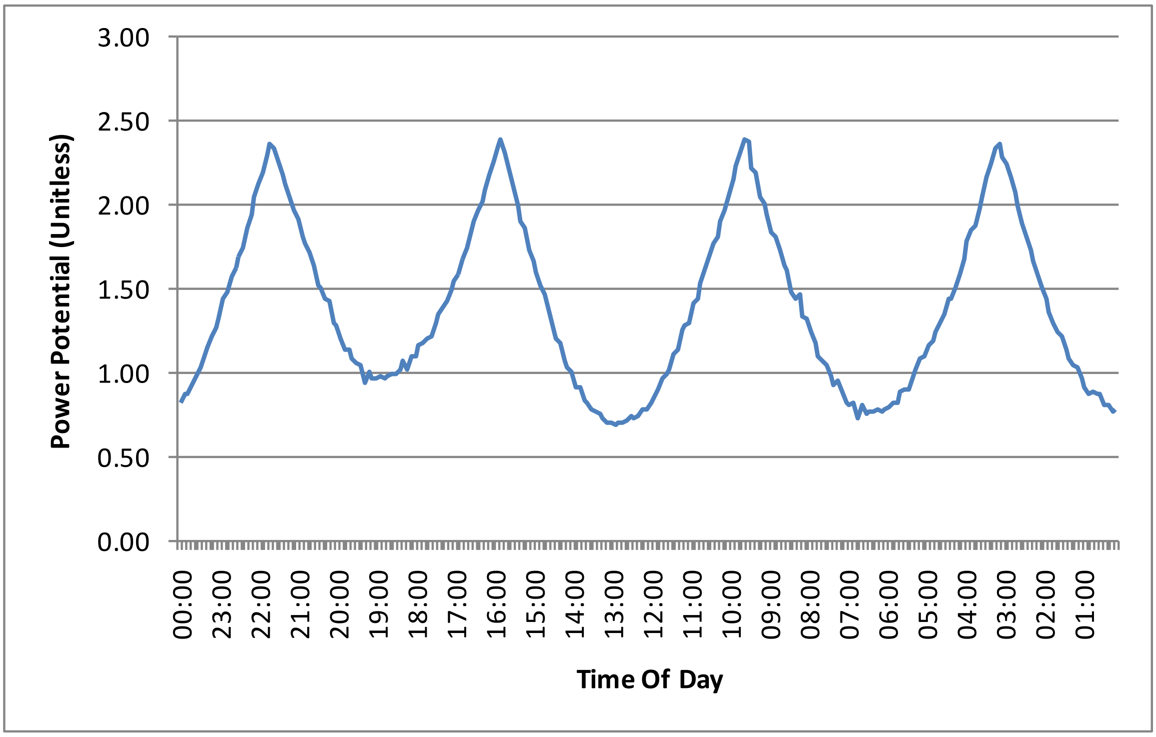

Figure 3.3: Power Potential for Malin Head for a 24 Hour Period

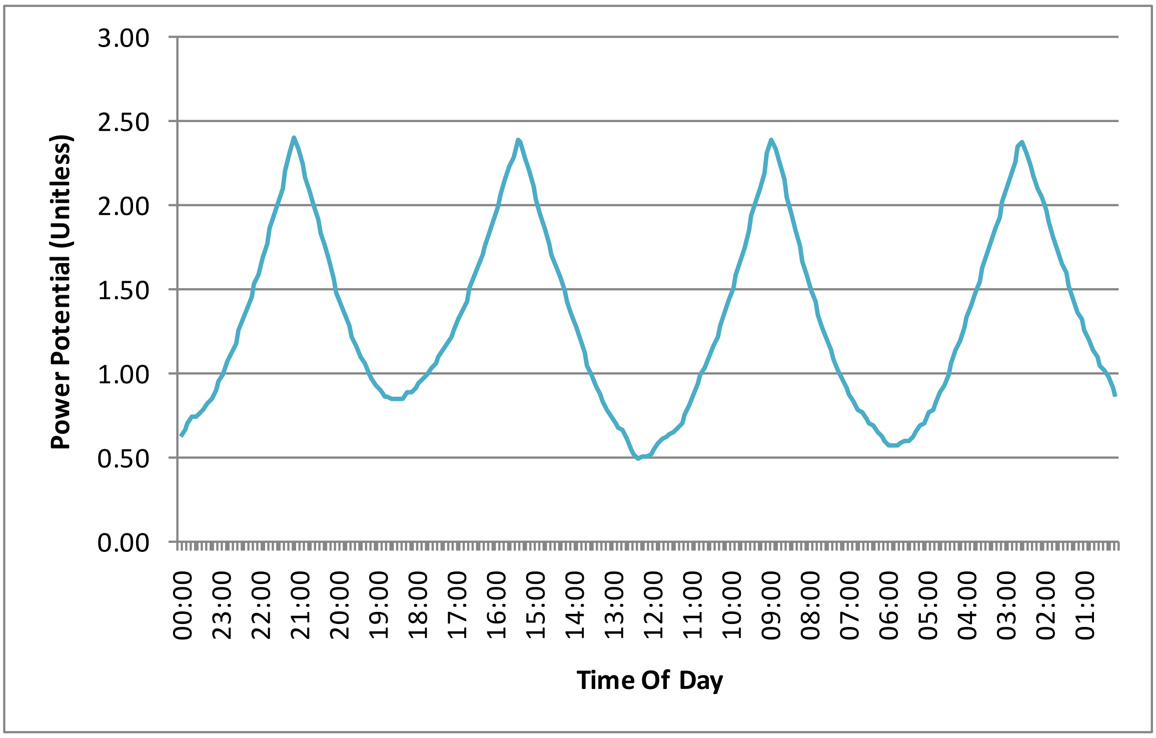

Figure 3.4: Power Potential for Sligo for a 24 Hour Period

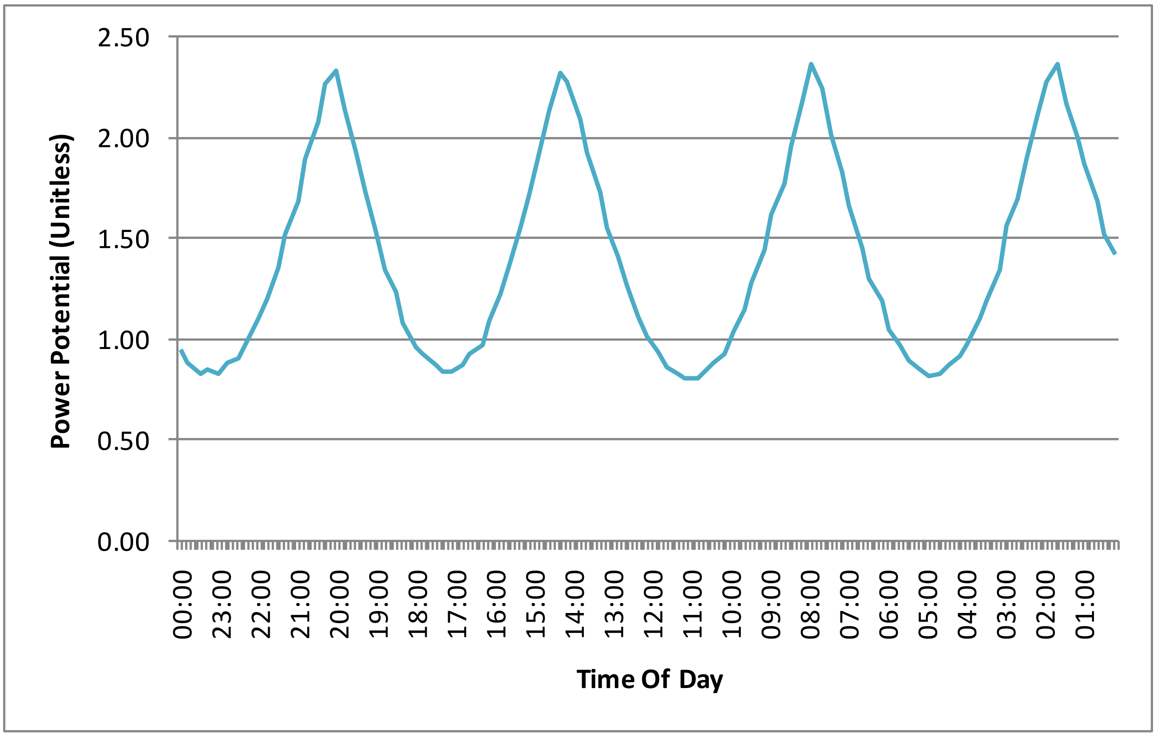

Figure 3.5: Power Potential for Castletownbere for a 24 Hour Period

The four sites chosen, as depicted in Figure 3.6, were Malin Head, Sligo, Galway and Castletownbere. The other sites for which data was gathered are indicated by the red markers, but are not labelled. As can be seen on the map, the distances between the four sites are roughly equal. That is to say the distance between Malin Head and Sligo is roughly equal to the distance between Sligo and Galway and between Galway and Castletownbere. This characteristic, along with the fact that Malin Head and Castletownbere have just about the greatest spatial separation possible between any two sites on the island of Ireland, ensures that the maximum possible time delay occurs between flood tides (and ebb tides) between these four sites.

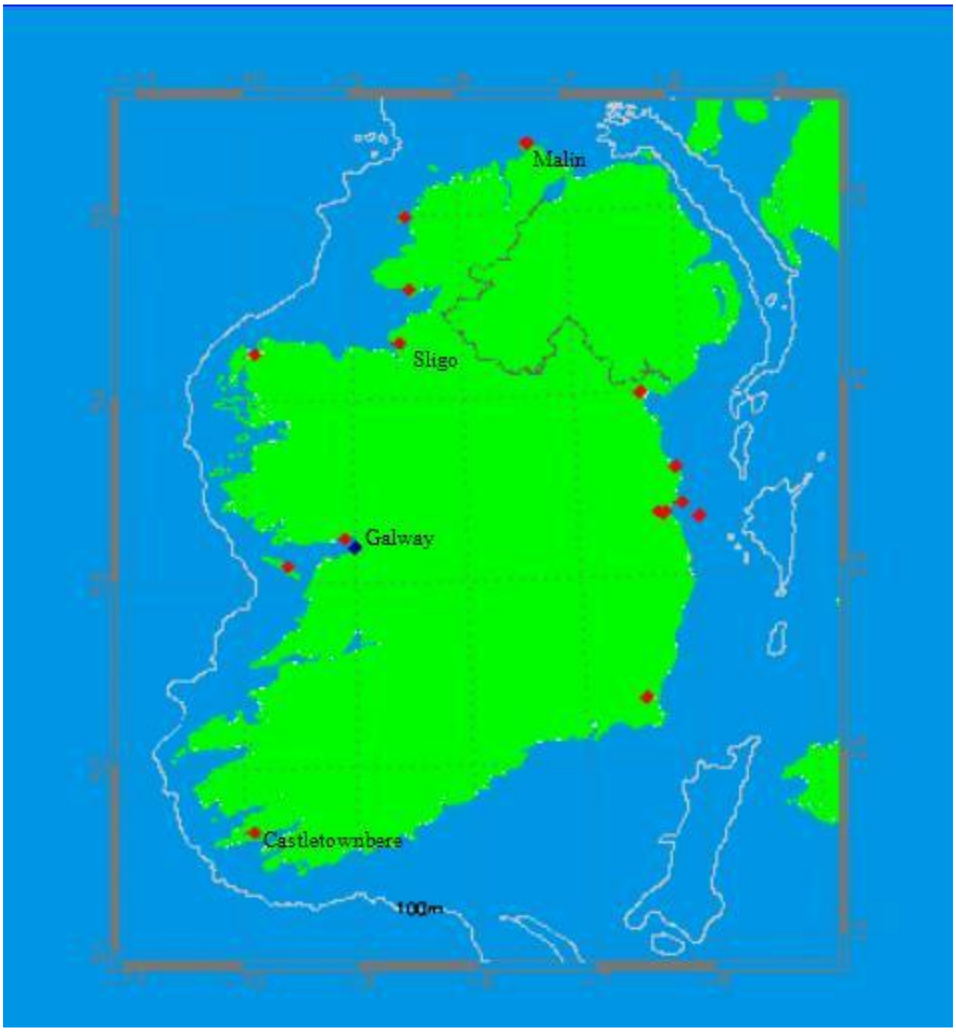

Figure 3.6: Location of Chosen Sites

3.4.2 Total Power Potential

Up to this point only the individual sites and their power potential in isolation from the other sites have been considered. Now we will look at the power profile curve which we could expect from the cumulative data of all four of our sites. Figure 3.7 shows the power potential curves which were displayed earlier on the same graph (the four lower curves). Displaying these curves on the same graph gives a much clearer representation of the degree to which they are out of sync. The blue curve on the top of the graph is the total power potential for all four sites over a one day period. While it can be clearly seen that this cumulative power curve is not consistent throughout the day, it is also clear that the relative power potential does not drop below about 2.5 at any time of the day.

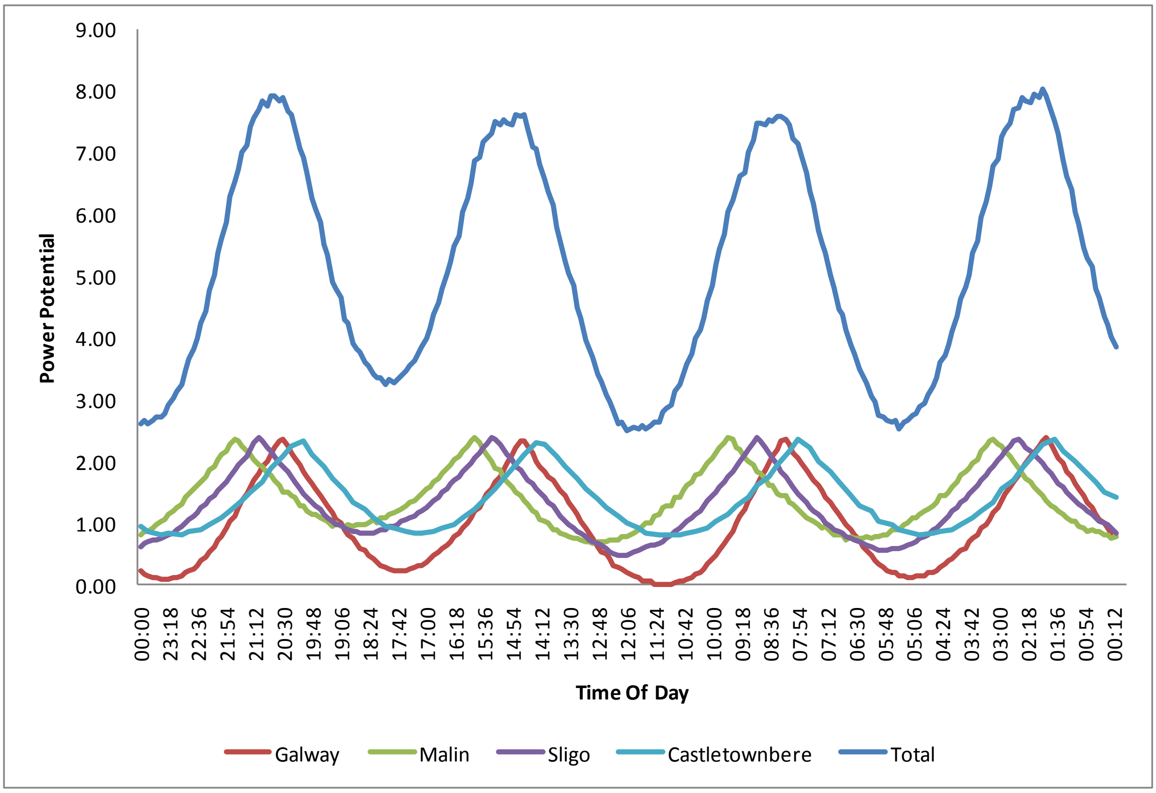

Figure 3.7: Daily Power Potential of the Four Chosen Sites and Total Power Potential

If we take a closer look at the individual site curves we can see why this is the case. The individual peak for a site occurs roughly 30 minutes after the previous sites peak. This has the effect of broadening the peaks of the total cumulative curve. This same 30 minute interval occurs between the troughs for each site and this has the effect of not only broadening the total cumulative trough but also ensuring that the minimum of the total will never reach zero. This last point is due to the fact that when one site is producing at its minimum capacity, none of the others will be.

We have now decided on the four sites we want to investigate more closely and have also shown that using four properly located sites can provide a base load (the total curve in Figure 3.7 never dropping below 2.5). The next step therefore was to ensure that this characteristic held true over an entire spring - neap cycle. The following two subsections continue the analysis over the spring - neap cycle time period.

In order to illustrate more clearly the reason why the other ten sites were omitted from further analysis, we will take a look at one of their power potential profiles alongside one of the sites that was chosen for inclusion.

As shown in Figure 3.8 the power potential profile of the Galway Bay site coincides almost exactly with that of the Howth site (the peaks occur at the same times of the day and the troughs occur at the same times of the day).

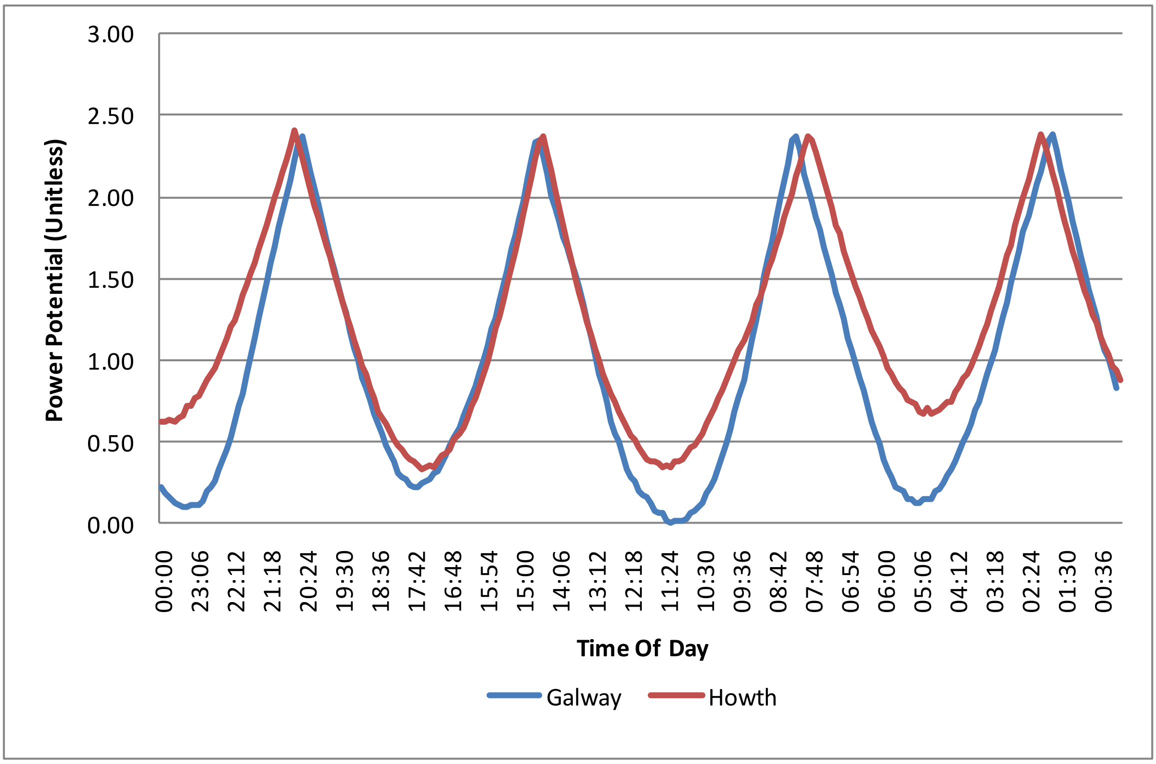

Figure 3.8: Power Profiles for Galway Bay and Howth

When the cumulative data from the two sites is graphed (see Figure 3.9) it is apparent that there is very little difference in the overall profile of the total compared with the profiles of the individual sites.

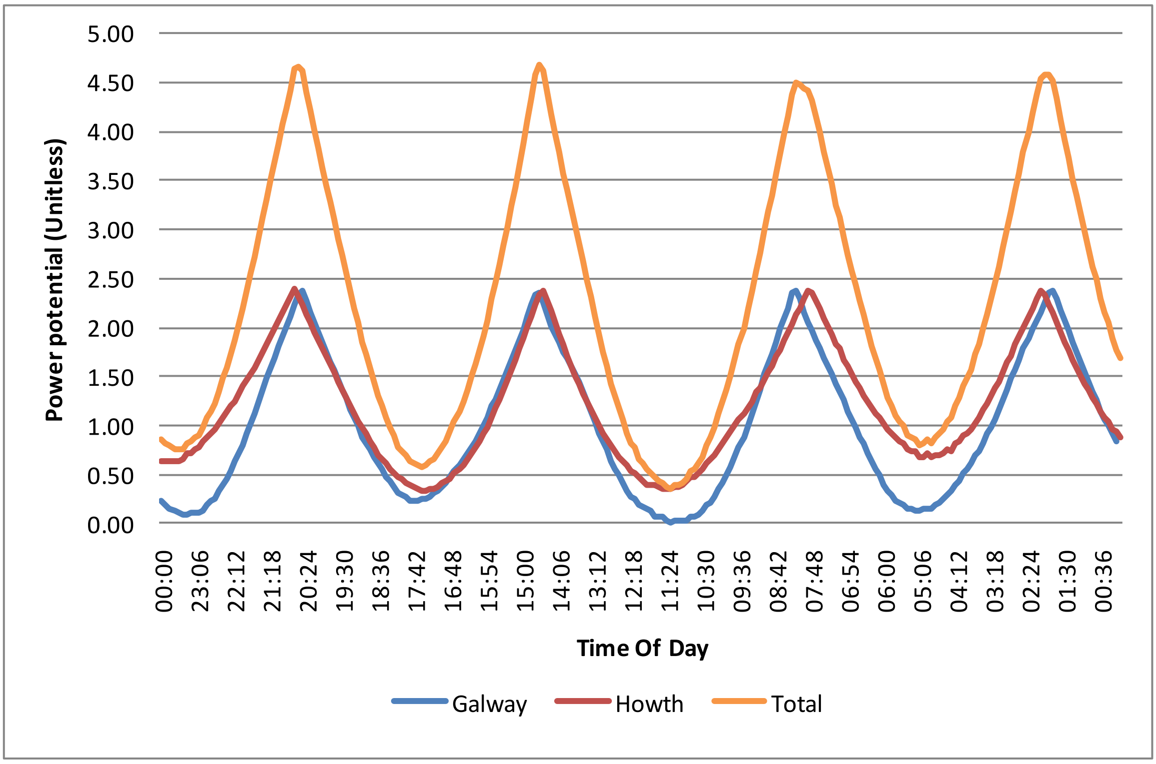

Figure 3.9: Power Profile of Galway Bay and Howth with Total

The addition of all fourteen sites would certainly supply more power to the grid but if the peak power times coincide too closely with one of the sites already included then the benefit in smoothing out the supply profile is lost. In this case the effect of having widely dispersed peaks and troughs in the total power profile of all sites (as in Figure 3.9) becomes more pronounced and would lead to the possibility of more frequent cycling of the conventional power plants instead of the desired reduction in this action. This is the reason that sites such as Howth and others were omitted, as they matched an existing profile (Galway's profile in the case of Howth) too closely.

3.4.3 Spring - Neap Tide Cycle

It has been demonstrated in the previous sections how the tide height, and therefore the power potential, of the four sites varies over the course of a single 24 hour period. However, we have already seen in section 2.3.2 of the previous chapter that the moons gravitational pull is not the only force acting on the surface waters of the earth. There is also the gravitational force of sun which causes an unusually high tide (Spring Tide) when the moon, earth and sun are aligned and an unusually low tide (Neap Tide) when the moon and sun form a 90 degree angle with the earth.

Taking this into account it is clear that analysing the data for a 24 hour period is insufficient. Data is required for an entire spring – neap cycle in order to ensure that the behaviour of our chosen sites as presented in Figure 3.7 extrapolates in a consistent manner over the whole cycle.

The spring – neap cycle is repeated just over every 14 days. Data was therefore obtained from the Marine Institute for 15 consecutive days for each of the selected sites(The Marine Institute, 2010). Once again an arbitrary date range was used for this data collection, the first 15 days in February 2010.

The data for the 15 day period for each of the four sites was quite large and as such is not tabulated either in the main text or in the appendices. The data can however be found in the following files on the CDROM which accompanies this thesis:

Table 3.2: Filenames Containing Site Data on CDROM

Data	**FileName**
Castletownbere Data	Castletownbere_February2week.xlsx
Galway Bay Data	Galway_February2week.xlsx
Malin Head Data	Malin_February2week.xlsx
Sligo Data	Sligo_February2week.xlsx

In order to produce a model of the power potential over a spring – neap cycle, it was necessary to convert the displacement data in a more rigorous way than when dealing with a single day’s data. The following section outlines why this was so, and the procedure followed to convert the data.

3.4.4 Data Conversion Procedure

The procedure used previously to convert the tidal displacement data into power potential data (see section 3.3.2) used data for a 24 hour period. This procedure was sufficient as the amplitude of the displacement data waveform (see Figure 3.1) did not vary significantly for this dataset. Using this method, the power potential could be modelled sufficiently well (the peaks in Figure 3.2).

However, as this method depended on i) how far the data element was from the datum and ii) the maximum value in the entire dataset, it did not lend itself as readily to the situation where the amplitudes varied widely.

When it was attempted to use this same method to model the 15 day dataset (see Figure 3.10) a problem resulted whereby the data within the lower amplitude areas of the waveform (the neap part of the cycle) were giving skewed results.

This problem highlighted the need to find a better way of modelling the power potential data based on the relative amplitude magnitudes of each section of the waveform (from the higher amplitude spring tide sections to the lower amplitude neap tide sections). This proved a very difficult problem to overcome and after many attempts, the following procedure was used, which depends on the amplitude of the waveform local to the particular data point.

Conversion Procedure

1. Check if each data point in the tidal displacement dataset is greater than zero or less than zero.
2. If it is less than zero, leave it.
3. If it is greater than zero, make it a negative value without changing its magnitude (i.e. if the value is 3.21, make it -3.21).
4. All elements in the dataset are now negative.
5. Split the tidal displacement dataset into sections of one period in length. One period was calculated to contain 120 data points.
6. Add each element in the negative dataset to twice the minimum value in each one period section. This gives a large minimum value when the amplitude of the displacement profile is large and a small minimum value when the amplitude of the displacement profile is small. The values will then increase as the displacement approaches zero. This is the reason why it was necessary to convert the dataset to negative values.

Spring - Neap Tide Cycle Results

The results of this conversion can be seen in Figure 3.11 below for the Galway Bay site. Figure 3.10 shows the raw data for the displacement of water obtained from the Marine Institute used to generate Figure 3.11. The power potential graphs for the other three sites can be found in Appendix C.

As shown in Figure 3.11 the power potential profile for each one day section of the graph (e.g. between day two and day three) is similar in form to the one day graph in Figure 3.2. However the difference over the spring – neap cycle can be seen when the whole 15 days are viewed together.

If this data is looked at in sections, it is clear that this model predicts the expected results throughout the spring – neap tide cycle.

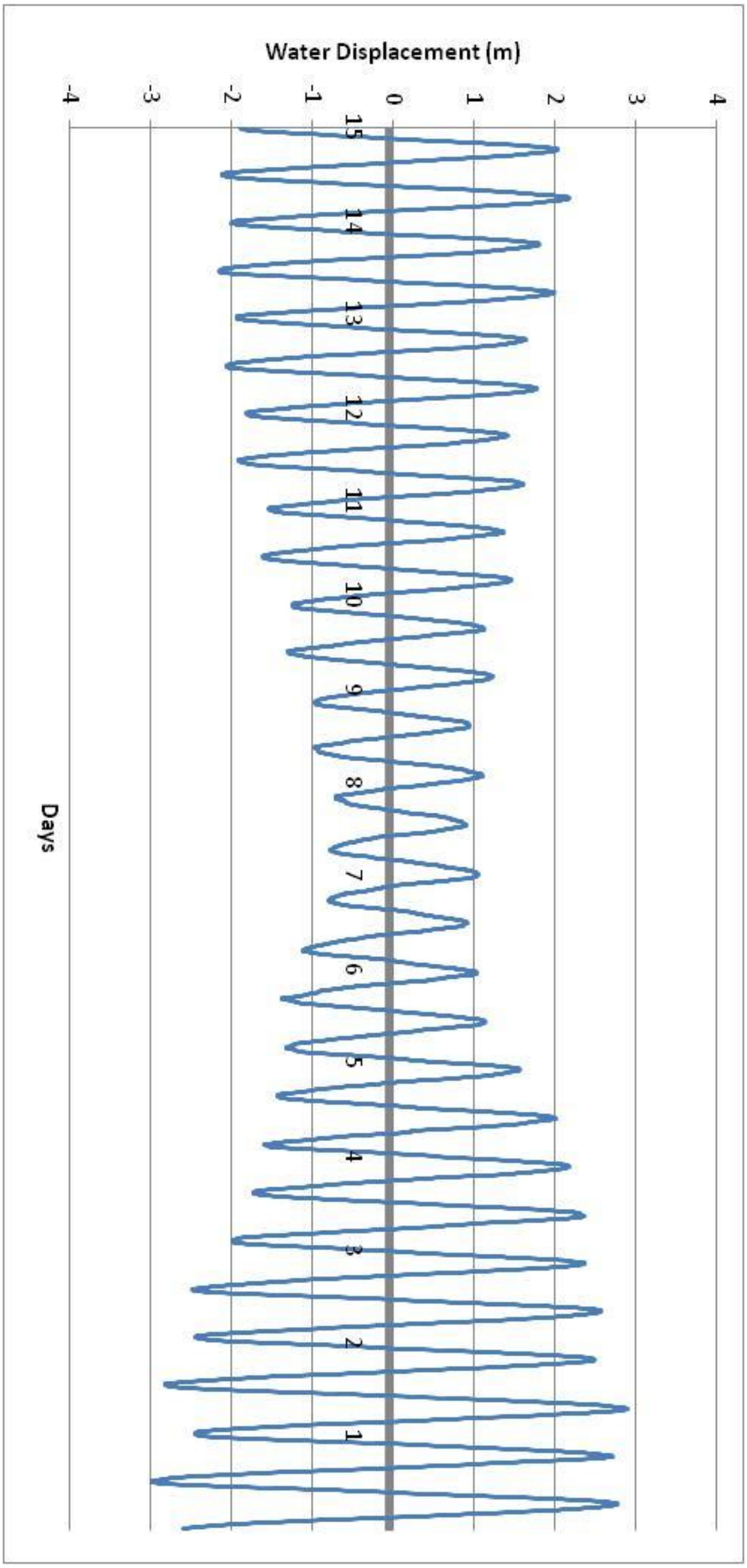

Figure 3.10: Water Displacement from Datum for Galway Bay Site

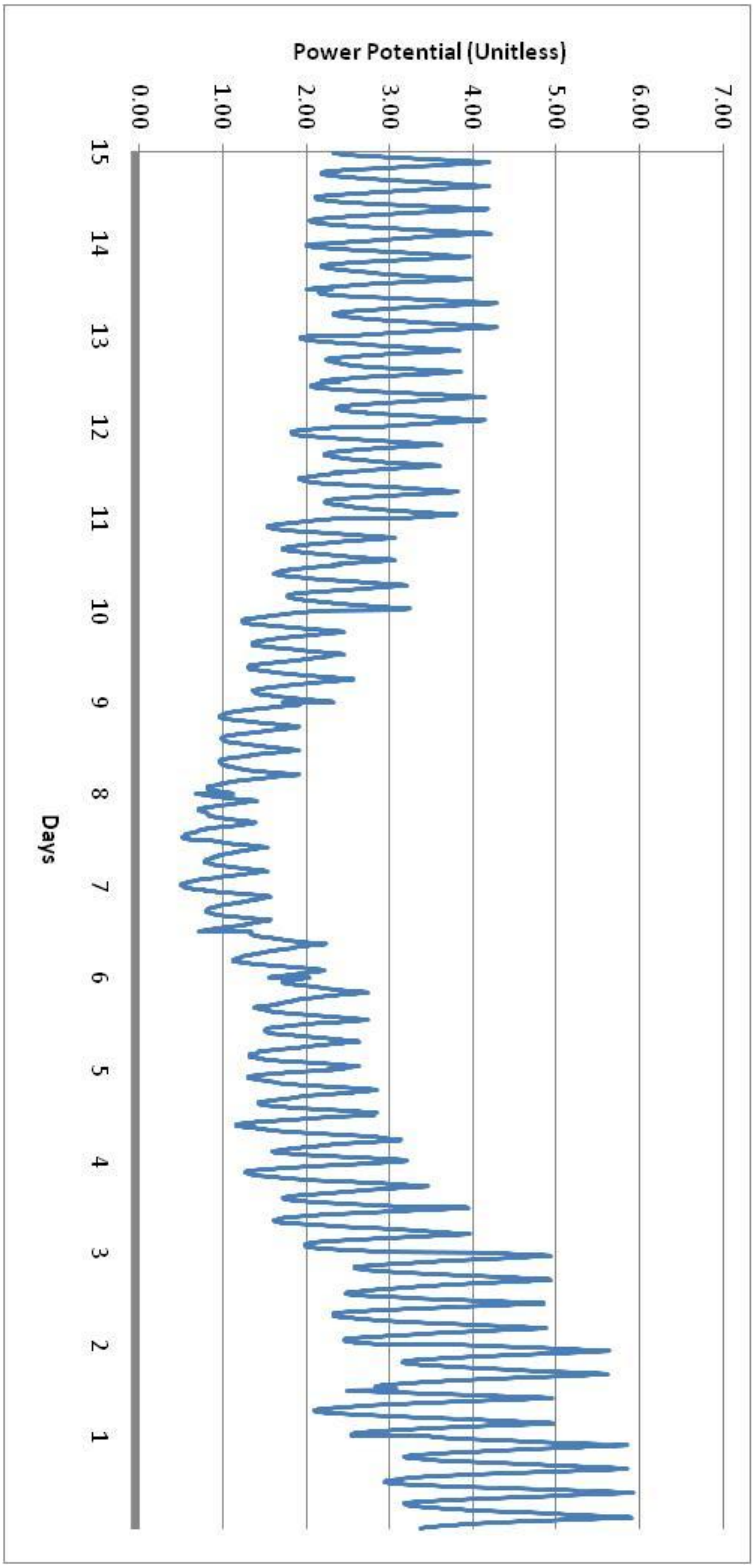

Figure 3.11: Power Potential (Galway Bay) over Spring - Neap Cycle

Section 1 (Day 0 – Day 3): This section of the graph displays the data from, and near, the spring tide in Galway Bay. There is a large variation in the power generating potential over the 1 day time frame with four peaks and four troughs as seen before. However the general power generating potential in this section is much higher than for the next section, which displays the data for the neap tide.

Section 2 (Day 4 – Day 11): This section of the graph displays the data as we move away from the spring tide in Galway Bay and through the neap part of the cycle. There is still a large variation in the power generating potential over the 1 day time frame with the four peaks and four troughs. However, the general power generating potential in this section is now much less than for section 1 of the graph. This again is as expected as the overall mass of water which flows in and out during this phase of the cycle would be far less than during the spring tide. Therefore we see a gradual decrease in the overall power generating potential at the site as the neap tide is approached and then a gradual increase back towards the next spring tide.

Section 3 (Day 11 – Day 15): This section of the graph displays the data as we move towards the next spring tide.

The whole graph represents a single period of the waveform which will then repeat as we go through successive spring – neap cycles. This is the reason fifteen days of data was chosen, as it is reasonable to assume any characteristics encountered during power generation at an individual site would be captured in this repeating cycle.

3.4.5 Total Power Over a Spring - Neap Cycle

The data from the other three sites (Sligo, Malin Head and Castletownbere) was processed in the same way as for Galway Bay and the graphs are provided in Appendix C. These graphs display the same characteristics as the Galway Bay data in Figure 3.11, with the relatively low minimum values and the sharp peaks. These are the characteristics which describe the inconsistent nature of supply over a 24 hour period and make the possibility of additional conventional power plant cycling more likely.

This data was then cumulated to give the total predicted power supplied by the four individual sites. The results of this calculation can be seen in Figure 3.12. The relative differences between the minimum power production times of the sites (similar to the one day data shown in Figure 3.7), causes the total power profile to have generally larger minimum values. This has the effect of supplying a greater base load of energy to the grid than one individual tidal device, even if all the individual devices have the same minimum production values. In this way the commissioning of four devices located at strategic positions around the coast of Ireland can generate a consistent base load of greater magnitude than, for example, a farm of tidal devices located at the same site.

Although it is more difficult to see on the graph in Figure 3.12 (due to the necessity of having fifteen days data on this graph), the same differences between peak power production times of the sites results in broader peaks. This effect can be seen more clearly in the one day data from Figure 3.7. The fact that these peaks only show a small amount of broadening, and therefore only provide a small improvement in the consistency, or levelling off, of the supply, is indeed a problem with this proposed solution to the problem introduced in 3.2.2. This issue is investigated in more detail in section 3.5.2 and 3.6.2.

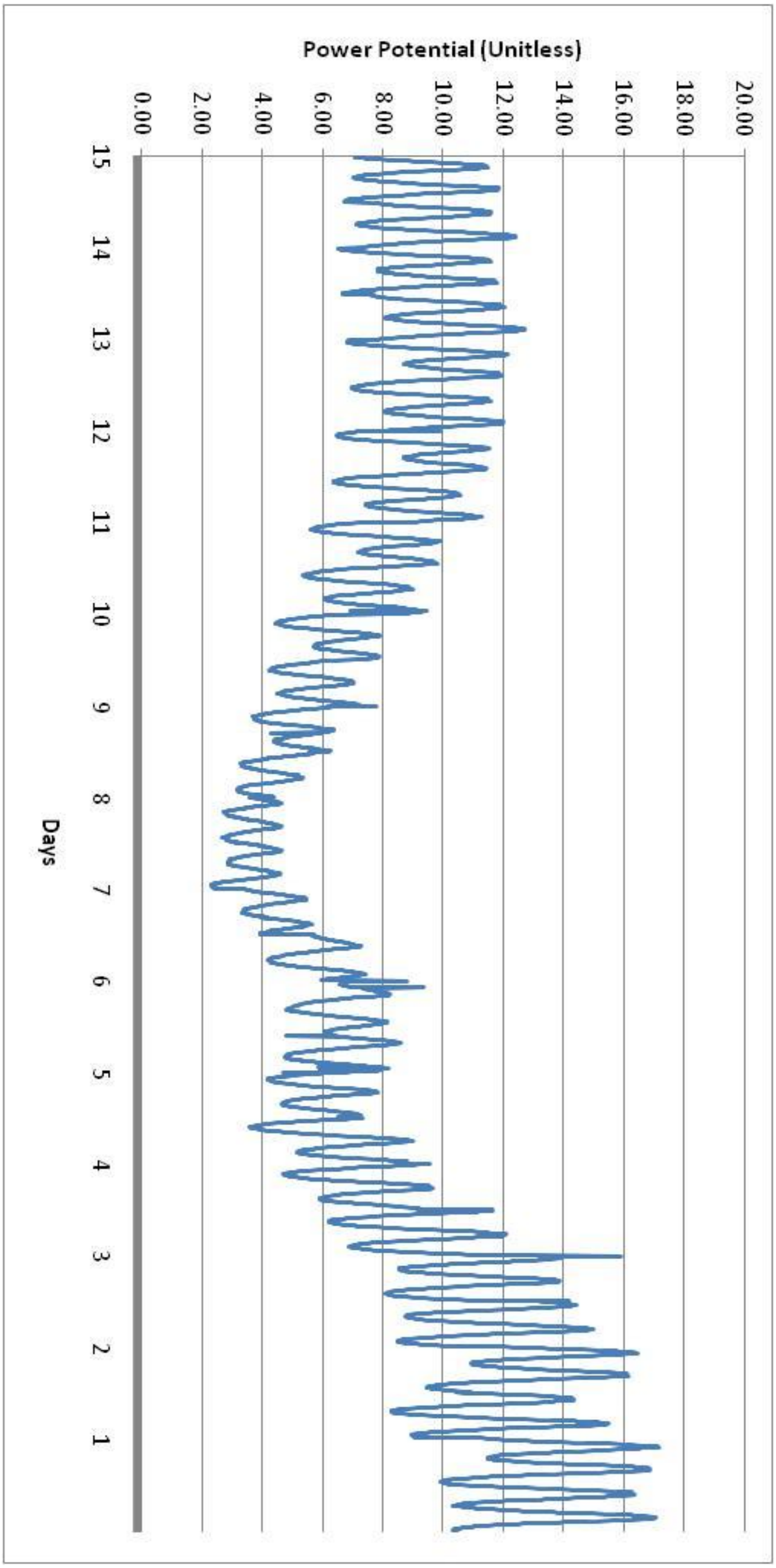

Figure 3.12: Total Power Potential for the 4 Sites over Spring - Neap Cycle

3.5 Solution Limitations

In this section a description is provided of the main potential problems associated with the solution presented above. The problems are presented here as they were envisaged by the author, with no attempt made to ascertain if the problem has any real foundation at this stage. This will be dealt with in section 3.6 when a closer look is taken as to whether the problem has any basis in fact, and if so, if there is a viable solution to it.

There were three main problems identified which it was deemed required further investigation.

3.5.1 Spring – Neap Cycle Fluctuations

The first problem that became evident upon looking at the graph in Figure 3.12 was that the power produced from the tidal device would not only fluctuate between a maximum and minimum value over the course of a day, but the power generated per day would also fluctuate over the course of the 15 day spring neap cycle.

The solution outlined earlier in this chapter helps to provide a consistent base load by synchronising power generated by tidal devices located a suitable distance from each other, therefore smoothing out the power production curve and helping to alleviate the problem caused by the increased conventional power plant cycling (due to the four times daily fluctuation from maximum to minimum power). However this solution does not do anything to prevent the wider fluctuations over the 15 day cycle as shown in Figure 3.12 where the maximum power is produced during spring tides and the minimum power is produced during neap tides.

If this larger time scale fluctuation in power produced also contributed to the additional cycling of conventional power plants then this proposed solution only goes half way at best.

3.5.2 Supply Peaks

Looking again at Figure 3.12 it is clear that while some levelling of the profile has occurred, with the base load production being significantly higher than the individual sites, there still exists power production peaks. These could cause the additional cycling of the conventional plants which is the main characteristic to be avoided.

This can be seen most clearly when the daily total power for all four sites is displayed as in Figure 3.13.

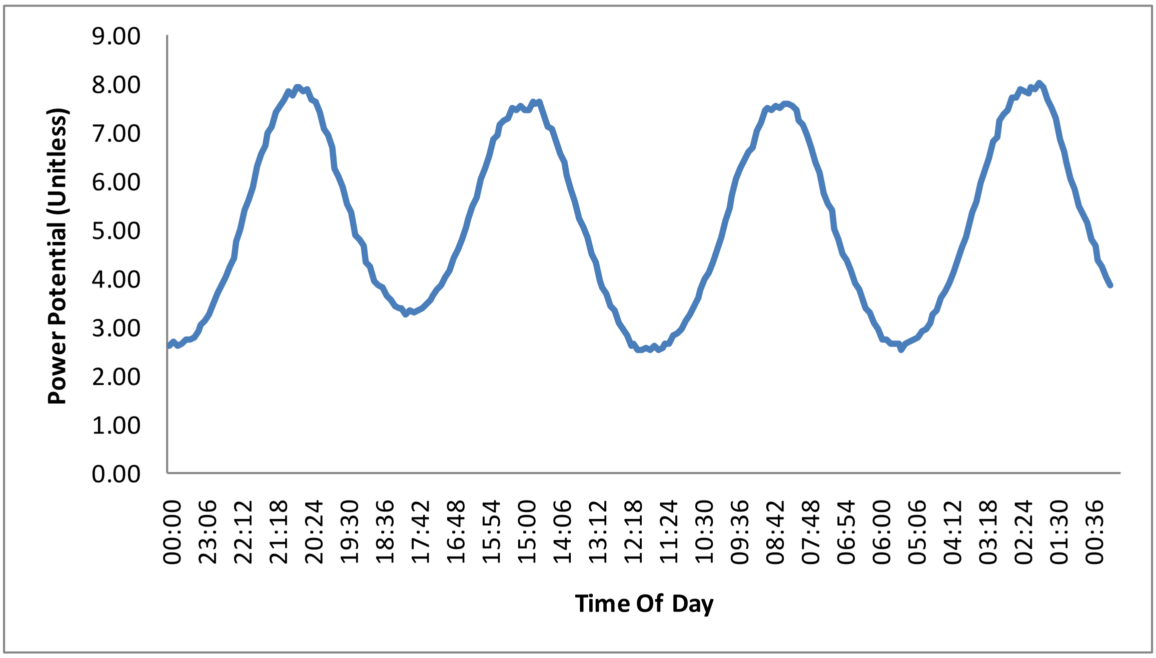

Figure 3.13: Total Power Potential from All Four Sites

The peaks shown at about 02:30, 08:40, 15:00 and 21:00 in this graph could cause this additional plant cycling. If this was the case, the solution presented would have failed in its goal, as the stabilisation of the power supply over the period of one day, although providing a greater base supply, would not be sufficient to prevent the additional cycling. Therefore the gains in base load supply would not justify the implementation of this solution as the main problem would still not be addressed, rendering the inclusion of tidal energy to the grid uneconomical.

3.5.3 Site Locations

The final potential problem resulting from this proposed solution which will be addressed in this paper is related to the location of the chosen sites. The problems related to the site locations could potentially be twofold:

1. The first issue is the relative distances between the sites. As shown previously, the distance between the sites is approximately equal. Figure 3.6 shows that the distance between Malin Head and Sligo is approximately equal to the distance between Sligo and Galway which is again approximately equal to the distance between Galway and Castletownbere.

   These four sites have therefore been spread as far apart as the geography of the island of Ireland will allow. It has also been previously demonstrated that the relative spatial separation of the sites is what causes the difference in their peak power production times (see section 3.4.2) and therefore produces the levelling off of the total power production profile of the four sites.

   This indicates a need for greater separation between the installation sites, thereby providing a greater time lag between the power production profiles and a smoother total power production profile. The geographical restrictions make this a significant drawback to implementing any such solution on the island of Ireland.
2. The second potential problem regarding the location of the chosen sites is one of an economic nature. When power is generated for the purpose of supplying the national grid, it must be taken into account how this supply will be connected to the grid and what the cost of this connection will be. In simple terms, the costs associated to connecting a power supply to the grid will consist of the capital and labour cost of the high voltage cable required to connect to a substation and the cost of commissioning a new substation if there is not already one nearby. Obviously this second cost would be much larger than the first if indeed it applied in this case. Also, the cost of the cabling would be directly proportional to the distance from the site to the nearest substation.

3.6 Mitigating Limitations

In this section the three potential problems detailed in section 3.5 are analysed with a view to ascertaining if the problem is a major limitation and if so what could possibly be done to mitigate the effects of the problem.

3.6.1 Spring – Neap Cycle Fluctuations

The potential problem of the fluctuations in power production over the spring – neap cycle outlined in section 3.5.1 is a problem only in terms of the actual amount of power the device can produce. This is not going to contribute to the problem of additional cycling of conventional power plants as addressed by this paper. This characteristic of the spring – neap power curve will indeed reduce the amount of power produced at certain times (neap) and increase it at other times (spring). However this will only mean that the power supplied to the grid will vary over a large time scale of the order of weeks. This would mean that the conventional power plants would only potentially have to be powered down at the spring section of the cycle and powered up again at the neap section of the cycle. Looking at Figure 3.14 this means that the conventional power plant would be required during the period marked B of the cycle and not during the period marked A.

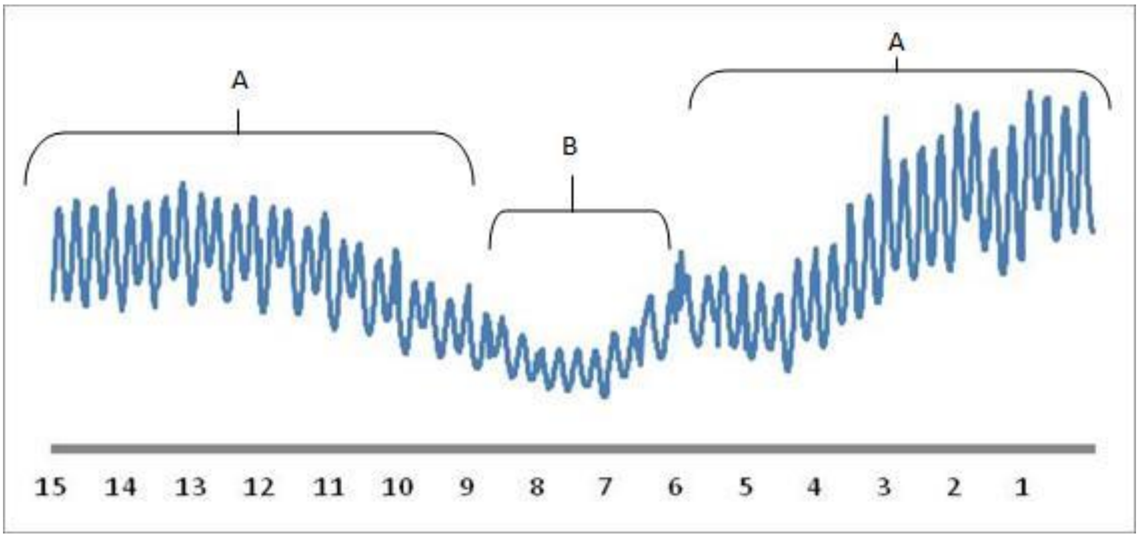

Figure 3.14: Times where conventional plant power required (B) and not required (A)

This would therefore constitute the cycling of the conventional plant twice in the space of a month, which has a negligible effect compared to the worst case scenario of four times a day quoted in the original problem statement (see section 3.2.2).

3.6.2 Supply Peaks

One possible solution to the problem of these remaining supply peaks would be to implement the series of dispersed tidal systems in conjunction with a complementary pumped storage system. The idea being that when the tidal system is producing at or near its peak capacity, some of the electricity is diverted away from the grid to pump water to an elevated storage reservoir. Then when the tidal system is generating at its lower level, the water is released through turbines to generate additional electricity in the traditional hydro-electric manner.

The total power profile of the four sites is shown once again in Figure 3.15. The points on this graph marked Point A show the times of day the electricity supply would be partially diverted from the grid to the pumps supplying water to the pumped storage reservoir. These are the times when the total electricity produced starts to exceed the base supply significantly, producing a supply peak. The points on the graph marked Point B are the times of day when the supply is fully redirected back to the grid. This occurs when the supply generated is returning to the base load generation. At this stage the water which would have been pumped to the reservoir would be released through the turbines to supplement the tidal generation.

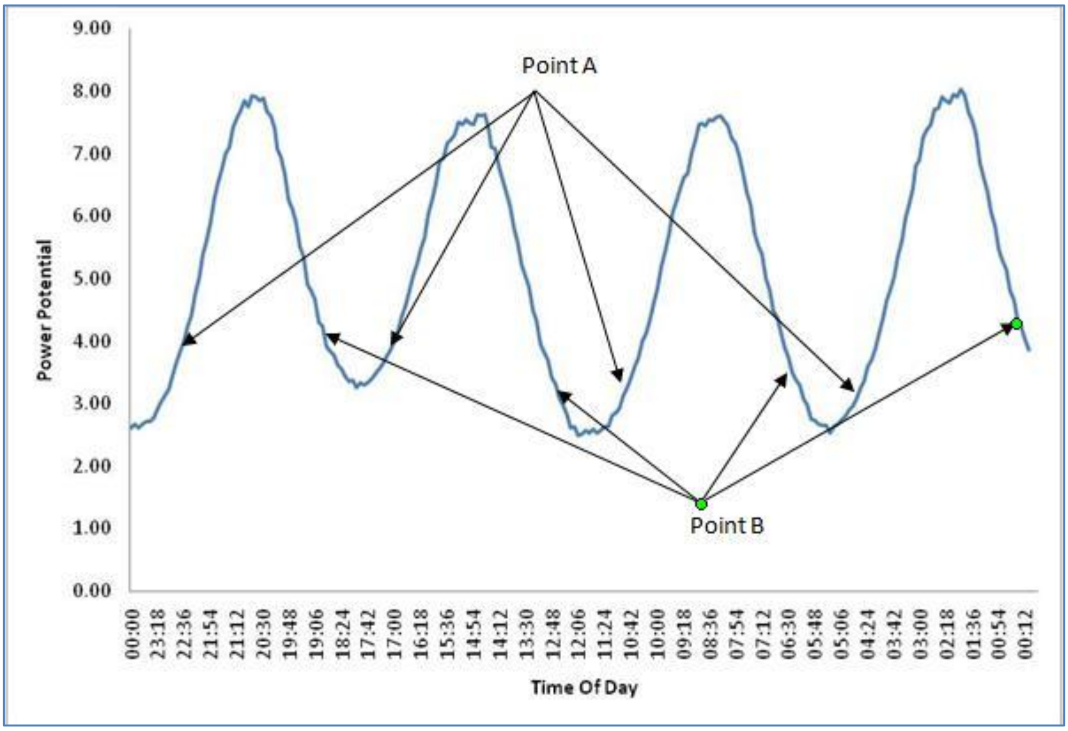

Figure 3.15: Power Profile showing where power is stored (A) and sent to the grid (B)

This would improve the “levelling out” of the power production profile significantly and therefore make the proposed solution even more feasible.

Using pumped storage as a method to make the electricity supply from renewable sources more efficient is not a new idea. Iberrola, the largest producer of wind energy in the world, is building an 852 megawatt pumped storage facility in Spain, which they believe will help to improve the availability of their 9.3 gigawatt of installed wind energy (Emerson Process Management, 2009). Due to the greater predictability of tidal energy over wind, pumped storage should provide a viable solution to smoothing out the predictable peaks and troughs in tidal energy supply.

In the next section it is illustrated how the location of the tidal energy sites also contributes to the power peaks discussed in this section. The solution put forward in the next section would also contribute to the levelling off of the power supply profile. These two solutions could potentially be utilised independently, or combined to provide the greatest effect.

3.6.3 Site Locations

The problem of the distance limitations between sites is indeed a serious drawback to implementing this solution in Ireland. There is however a project underway which could nullify the effects of this limitation. This project is the East-West Interconnector project currently being implemented by EirGrid, the operators of the Irish national grid, to connect the grids of Ireland and the UK. As of the end of March 2009, the connection points and converter station site in both countries had been secured, planning was in progress, legislation had been passed and the tendering had been completed (Commission for Energy Regulation, 2009). Since then, the promised grant of €110 million was approved by the European Union and constriction was due to begin in the summer of 2010 (RTE, 2010).

The construction of interconnectors to integrate small electricity grids into larger ones is widely regarded as one of the best ways to increase the efficiency of renewable sources supplying the grid. Taking wind energy as an example, the larger the area covered by the grid the greater the variation in weather conditions is likely to be. Therefore, when the wind is blowing on the west coast of Ireland it may not be on the East coast of England and the surplus wind energy generated by a wind farm located on Ireland’s west coast can be utilised, via the grid interconnection, on England’s east coast.

Tidal energy can also benefit from this new, larger electricity grid by locating the tidal energy sites at greater distances apart and therefore introducing a greater delay between their maximum power production times. This interconnector could therefore help to make the solution proposed in this paper far more effective than indicated in the results depicted in Figure 3.12.

The fact that Britain’s electricity grid is already connected to mainland Europe via the 2 gigawatt interconnector with France makes this even better news for tidal power as the geographical locations where it is possible to install tidal systems could be even more dispersed (UK National Grid, 2010).

This interconnector could therefore solve the first of the location problems. However the second problem regarding location as outlined in section 3.5.3 is more of a logistical problem. The chosen sites need to be located near enough to existing electricity supply substations in order to make the solution economically viable. To ascertain if this was the case the ESB networks website was searched for the locations of substation in the vicinity of the proposed sites (Electricity Supply Board, 2010). The results are displayed in Figure 3.16 to Figure 3.19.

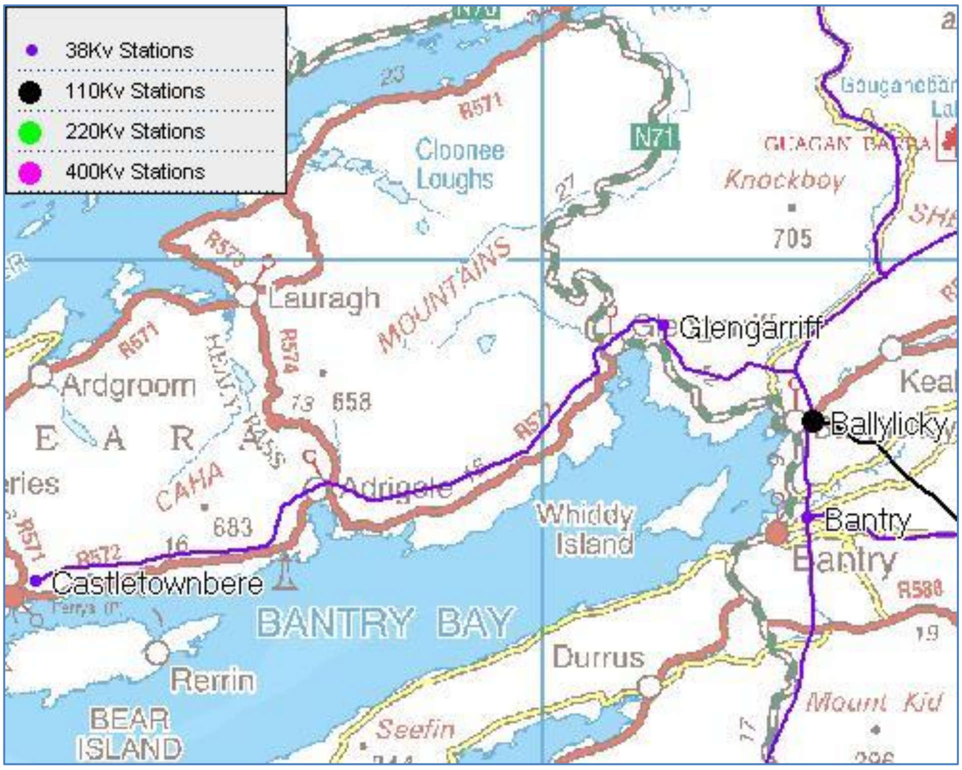

Figure 3.16: Substations in the Vicinity of Castletownbere

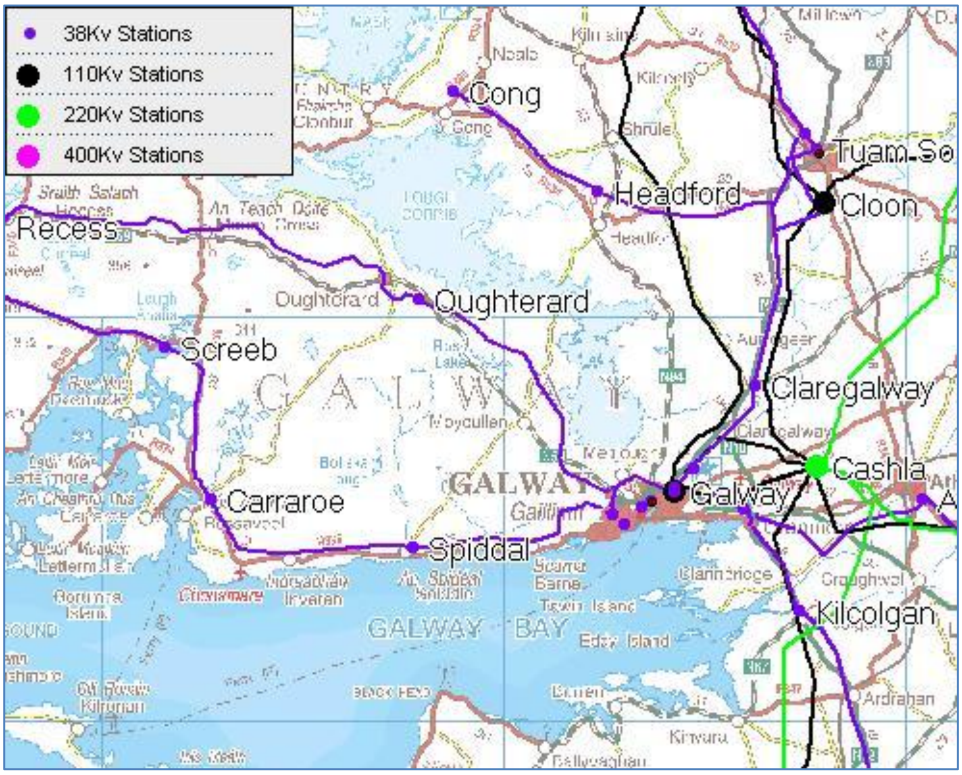

Figure 3.17: Substations in the Vicinity of Galway

Figure 3.18: Substations in the Vicinity of Sligo

Figure 3.19: Substations in the Vicinity of Malin Head

These images show that there are 38 kilovolt stations in close proximity to all of the sites and 110 kilovolt substations relatively close to Castletownbere, Sligo and Galway. Malin Head, being somewhat more remote, is the furthest away from a 38 kilovolt station at around five kilometres according to the measurement tool on the ESB website. There is also no 110 kilovolt station in the area around Malin Head.

These results would suggest that the commissioning of tidal energy systems in these sites would not constitute a major infrastructural undertaking incurring prohibitive capital costs outside of the tidal energy system itself. Adequate electrical grid infrastructure already exists, thereby removing this as an economic consideration of the construction and connection at these sites.

3.7 Discussion of Key Points

The key points raised in this chapter can be summarised as follows,

1. Tidal energy constitutes the most predictable form of energy from renewable sources.
2. Predictability of supply is not the same thing as consistency of supply.
3. Inconsistent supply added to the grid can have negative effects in the shape of increasing the frequency of conventional power plant cycling.
4. This issue is very difficult to mitigate against from the point of view of a single tidal current plant installation, but the effects could be reduced dramatically if a series of installations were commissioned in unison at various specific locations.
5. The solution suggested in the previous point was analysed and shown to be successful in levelling out the supply profile to some degree.
6. The solution could be further improved by,
    i. incorporating it with pumped storage to further level out the supply profile
    ii. using the interconnection of the national grids in Ireland and the UK (and even mainland Europe) to provide a set of locations with a suitable distance between each other. This would provide a greater difference between the maximum production times at each site and therefore level out the overall supply profile of all the sites combined.

Stepping sequentially through the points in this list, it can reasonably be said that the first point is indisputable. Tides are predictable by their nature as outlined in section 2.3.2, and therefore it follows that any conversion device using tidal flow as their energy source will also be capable of producing a predictable supply of electricity.

The second point is of great importance to this whole paper. Predictability of supply is a very desirable characteristic of any electricity generation device, but a further consideration must be the consistency of that supply over a 24 hour period. It is all very well knowing the exact amount of power a device will generate at a particular time of day, but that is not much use if the power produced is at a minimum when the demand is at a maximum.

Point three relates to the problem of inconsistent supply as outlined in section 3.2.2. This would not be a big issue if inconsistent supply was only an inconvenience, such that when the device supplied electricity to its maximum potential the grid would use it and when the device supplied at its minimum, or did not supply at all, the grid did without it. However this is not the case. As demonstrated in section 3.2.2, large peaks of power supplied to the grid at once, such as that which might come from a farm of tidal current devices during maximum tidal flow, could cause cycling of conventional power plants. The associated cost of this could potentially outweigh any gains made from the extra power generation, especially if the peaks occur four times a day as would be the case with tidal current devices.

Point four indicates that solving the problem outlined in point three would only be feasible if the tidal generation system was implemented across a series of sites as opposed to a single-site installation.

The next key point made was that the model demonstration, using the data obtained from the Marine Institute and the conversion mechanisms outlined in section 3.3.2 and section 3.4.4, showed that the proposed solution could be used to smooth out the total power generation profile of the combined generation sites.

The last key point arrived at in this chapter was that while the solution was shown to be effective to a degree; there was also scope for improvement. The power supply profile, though showing significant smoothing compared to the profiles of the individual sites, still displayed supply peaks. These peaks could in practise still cause the cycling of the conventional plants, thus rendering the solution ineffective. The interconnection of the Irish national grid with other international electricity grids could be utilised to smooth out the supply profile further by locating the installation sites further apart. The further the sites are apart, the greater the phase shifts in the supply profiles and the greater the corresponding smoothing of the power generation over all sites. Pumped storage could also be utilised as a separate remedy to this problem or in combination with the more dispersed site location solution.

Chapter Four: Conclusions and Recommendations

4.1 Introduction

In the first section of this concluding chapter a quick recap is given of the aims of the thesis as outline at the beginning of this document in section 1.3. This is followed by a summing up of what was actually achieved during the completion of the thesis and how well the initial aims were met. In order to do this a summary of the findings and results achieved will be provided without going into the level of technical detail supplied in the previous chapter. A synopsis will also be provided on how well the solution proposed in the thesis actually matched the problem, if the solution proposed was beneficial to the advancement of tidal energy conversion for electricity production, and whether or not the solution could be practically implemented.

The second section of this chapter takes a look at some of the problems associated with the proposed solution, and an attempt is made to ascertain if the problematic areas uncovered in this research project could yield subject matter for future research. This section will be primarily centred on the issues outlined in section 3.5 and the mitigation methods suggested in section 3.6 of the previous chapter.

4.2 Conclusions

As a part of the conclusion to this thesis it is necessary to return to the aims which were formulated at the outset of the project. Referring back to the original objectives which were outlined at the beginning of the thesis in section 1.3, an analysis will now be performed on the degree to which these objectives were achieved. In doing this analysis, focus will be given to the results obtained from the research, data collection, data analysis and conclusions drawn, and how these results have contributed to the achievement of the thesis objectives.

The first objective was to understand the reasons behind a move away from conventional fossil energy sources towards renewable sources in the electricity generation market. This objective was considered necessary in order to satisfy the author that the area of research chosen was relevant and worthy of continued study. The specific problem with tidal energy addressed in this thesis could only be considered relevant if the drivers for a transition away from conventional electricity generation were shown to be real and valid. To this end the first part of the literature review was dedicated to these drivers. The three main drivers explored were climate change, the status of the global fossil fuel reserves and energy security for the country. Climate change is undeniably a contentious issue, however, whether or not you believe it is anthropogenic in nature, it is very hard to deny that it is happening. When it comes to deciding if it is man-made and therefore a valid driver for the purposes of this thesis, I would draw the reader’s attention once again to the graph displayed in Figure 2.3 in section 2.2.1 of this paper. If there was only one point to be taken away from this section then it is surely the one portrayed in this graph, and that is the unmistakable correlation between the levels of atmospheric CO_2 and the global average temperatures. As already demonstrated the status of global fossil fuel reserves (the second driver) and can be incorporated into energy security for the country (the third driver) due to the almost non-existent nature of Ireland’s fossil fuel reserves. This is not the case for many countries and so does not apply universally. Some fossil fuel rich nations may view their continued supply of fossil fuels a worry in the long term but they at least have the option to cease export of these fuels in order to shore up their own energy security position. This is not a luxury available to Ireland. Ireland as a nation is at the mercy of external forces beyond our control, such as political stability in oil producing nations and global fuel markets, to ensure our supply.

Once it was decided that the drivers were valid and real, the next objective was to ascertain what part, if any, the oceans had to play in the future energy supply mix for Ireland. This objective was further narrowed to account primarily for tidal sources of marine energy as opposed to wave energy. An attempt to meet this objective was carried out by researching marine energy, understanding the characteristics of wave and tidal energy and indicating the advantages held by tidal energy over other types of renewable sources. The results of this research were formulated into the second and third parts of the literature review. The most important conclusion drawn from this research was that while most forms of renewable energy such as wind and wave are unpredictable, energy generated from tidal sources does not have this problem. The other sources of renewable energy are dependent on the climate but tidal energy is dependent on the relative movement of the sun, moon and earth and is therefore completely predictable. This factor, along with the efficiencies achievable in extracting the energy, shows that tidal energy can have a significant role to play in the future of electricity generation for an island nation such as Ireland.

This is not the whole picture with regard to tidal energy however, as the issue of consistency of supply is also a key consideration. Tidal energy extracted using tidal current devices was shown to be completely predictable but it varies over the course of any 24 hour period, displaying four peaks and four troughs in this timeframe. This characteristic of the tidal current devices power supply profile leads to the specific problem addressed in this thesis. The problem, as originally explained by Denny in her paper ‘The Economics of Tidal Energy’ (Denny, 2009) can be summarised as follows,

1. The national grid can only use what energy is demanded by consumers at any point in time. If the power supplied to the grid outweighs the power used some supply plants may have to be temporarily shut down until they are required again.
2. The characteristic of tidal power mentioned above (four peaks a day) could potentially cause the cycling of conventional power plants up to four times a day.
3. This cycling of power plants has an associated cost, which, if it outstrips the cost savings of the power supplied by the tidal resource, could render the addition of tidal power to the grid uneconomic.

The solution proposed to this issue as part of the third objective, involved installing the tidal systems at a variety of locations around the coast of Ireland instead of installing a farm of devices at a single location. The idea here being if the installation sites are located at a suitable distance apart, the resulting temporal shift in their power profiles will produce an overall profile with a smoother curve.

The fourth objective involved using the tidal data obtained from the Marine Institute to simulate the power production potential of the various sites and how the total power supply profile could be impacted by implementing the solution mentioned above. The results of this simulation first involved using the supplied data to make a choice on the most suitable sites for the installations and then plotting the power potential for each site and the total power potential. A conversion procedure (see section 3.3.2) was implemented to convert the displacement data obtained into a model for the power potential of the specific site over time. Later a new conversion mechanism was employed to take into account the additional complexity introduced by modelling the spring-neap cycle. This mechanism is detailed in section 3.4.4 in chapter three.

The resultant graph shown in Figure 3.7 shows how the temporal shift in the individual profiles produces a greater base load supply and broader peaks. The data for each of the four sites was then processed for the 15 day spring-neap tide cycle to ensure that the one day results extrapolated out to the 15 day period. The graph displayed in Figure 3.12 showed that the results did remain consistent over the 15 day cycle. The fact that the spring-neap tide cycle repeats about every 14 days means that this analysis should cover production over the whole year. This effectively accomplished the fifth objective of analysing the simulation model to ascertain if it could succeed.

The final objective was to suggest how to improve the proposed solution. This was achieved by presenting the following three potential limitations, and suggested solutions, to the method proposed.

1. The fluctuations in supply over the spring-neap cycle. Upon analysis this proved to be a nonissue. The larger timescale fluctuations in power supplied would not affect the grid in the same way as the short timescale fluctuations.
2. Existing supply peaks (see Figure 3.7) in the total power supply profile. The suggested solution here was to incorporate the solution with pumped storage, directing the supply alternatively to the grid and the pumped storage facility to even out the peaks to a greater degree.
3. Site locations are not far enough apart. This contributes to the peaks mentioned in point two, and the solution proposed was to disperse the sites even more using the interconnection of grids with the UK and mainland Europe.

4.3 Recommendations for Future Work

The following are some recommendations for future research which are linked to the subject matter of this thesis. These recommendations come from ideas the author had when completing this thesis but could not follow up due to time restrictions, data availability or subject focus.

1. A quantitative analysis on the actual amount of energy which could be produced at the sites suggested in this thesis. This would be dependent on the availability of tidal current velocity data at these sites. At the time of writing this data was not available.
2. The extension of the solution presented in this thesis to include sites in the UK and Europe. This is the scenario outlined in section 3.6.3 whereby the solution is improved by increasing the spatial distance between the test sites in order to introduce a greater temporal difference in their power supply profiles.
3. An analysis of the SeaGen tidal generation device located at Strangford Lough and currently producing electricity on a commercial scale to ascertain how effective pumped storage would be in levelling out its supply profile.
4. A feasibility study for the positioning of a tidal device at any or all of the locations suggested in this thesis. This could include a geological survey, bathymetry survey and environmental impact assessment.

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APPENDICES

Appendix A: Tide Displacement Data

This appendix contains the daily tide displacement data for the four chosen sites obtained from the Marine Institute. The 15 day data for these sites can be found on the accompanying CDROM in the files indicated in table 3.2 in section 3.4.3.

Galway Bay

Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.
00:00	-1.98	20:00	-2.02	16:00	-2.05	12:00	-2.08	00:00	-2.09	04:00	-2.11
23:54	-2.11	19:54	-2.10	15:54	-2.09	11:54	-2.09	23:54	-2.07	03:54	-2.01
23:48	-1.98	19:48	-1.95	15:48	-1.88	11:48	-1.81	23:48	-1.76	03:48	-1.68
23:42	-1.58	19:42	-1.49	15:42	-1.41	11:42	-1.29	23:42	-1.18	03:42	-1.08
23:36	-0.96	19:36	-0.84	15:36	-0.73	11:36	-0.62	23:36	-0.52	03:36	-0.40
23:30	-0.30	19:30	-0.20	15:30	-0.10	11:30	0.02	23:30	0.13	03:30	0.23
23:24	0.34	19:24	0.45	15:24	0.55	11:24	0.65	23:24	0.76	03:24	0.86
23:18	0.96	19:18	1.05	15:18	1.15	11:18	1.24	23:18	1.32	03:18	1.44
23:12	1.53	19:12	1.61	15:12	1.72	11:12	1.78	23:12	1.85	03:12	1.94
23:06	2.00	19:06	2.05	15:06	2.13	11:06	2.18	23:06	2.23	03:06	2.30
23:00	2.32	19:00	2.34	15:00	2.37	11:00	2.38	23:00	2.38	03:00	2.36
22:54	2.35	18:54	2.33	14:54	2.30	10:54	2.28	22:54	2.24	02:54	2.19
22:48	2.13	18:48	2.08	14:48	2.02	10:48	1.95	22:48	1.89	02:48	1.82
22:42	1.76	18:42	1.68	14:42	1.61	10:42	1.52	22:42	1.41	02:42	1.35
22:36	1.24	18:36	1.14	14:36	1.05	10:36	0.93	22:36	0.84	02:36	0.73
22:30	0.63	18:30	0.50	14:30	0.38	10:30	0.27	22:30	0.14	02:30	0.04
22:24	-0.07	18:24	-0.20	14:24	-0.28	10:24	-0.36	22:24	-0.46	02:24	-0.52
22:18	-0.60	18:18	-0.68	14:18	-0.76	10:18	-0.86	22:18	-0.97	02:18	-1.06
22:12	-1.17	18:12	-1.29	14:12	-1.37	10:12	-1.46	22:12	-1.58	02:12	-1.66
22:06	-1.71	18:06	-1.79	14:06	-1.88	10:06	-1.93	22:06	-1.95	02:06	-2.01
22:00	-2.04	18:00	-2.05	14:00	-2.08	10:00	-2.13	22:00	-2.14	02:00	-2.14
21:54	-2.19	17:54	-2.21	13:54	-2.19	09:54	-2.19	21:54	-2.19	01:54	-2.18
21:48	-2.14	17:48	-2.13	13:48	-2.11	09:48	-2.08	21:48	-2.02	01:48	-1.99
21:42	-1.94	17:42	-1.86	13:42	-1.79	09:42	-1.72	21:42	-1.63	01:42	-1.53
21:36	-1.44	17:36	-1.33	13:36	-1.20	09:36	-1.08	21:36	-0.97	01:36	-0.84
21:30	-0.69	17:30	-0.58	13:30	-0.48	09:30	-0.35	21:30	-0.22	01:30	-0.12
21:24	-0.01	17:24	0.14	13:24	0.24	09:24	0.32	21:24	0.46	01:24	0.55
21:18	0.63	17:18	0.73	13:18	0.81	09:18	0.91	21:18	1.00	01:18	1.08
21:12	1.19	17:12	1.27	13:12	1.35	09:12	1.47	21:12	1.54	01:12	1.63
21:06	1.72	17:06	1.79	13:06	1.88	09:06	1.98	21:06	2.05	01:06	2.12
21:00	2.21	17:00	2.27	13:00	2.32	09:00	2.38	21:00	2.40	01:00	2.41
20:54	2.46	16:54	2.46	12:54	2.48	08:54	2.48	20:54	2.46	00:54	2.45
20:48	2.45	16:48	2.41	12:48	2.39	08:48	2.36	20:48	2.31	00:48	2.27
20:42	2.22	16:42	2.17	12:42	2.10	08:42	2.05	20:42	2.00	00:42	1.91
20:36	1.86	16:36	1.78	12:36	1.69	08:36	1.62	20:36	1.54	00:36	1.44
20:30	1.34	16:30	1.25	12:30	1.13	08:30	1.03	20:30	0.94	00:30	0.82
20:24	0.72	16:24	0.62	12:24	0.53	08:24	0.45	20:24	0.36	00:24	0.26
20:18	0.17	16:18	0.08	12:18	-0.04	08:18	-0.14	20:18	-0.24	00:18	-0.36
20:12	-0.46	16:12	-0.56	12:12	-0.66	08:12	-0.77	20:12	-0.86	00:12	-0.94
20:06	-1.06	16:06	-1.15	12:06	-1.20	08:06	-1.28	20:06	-1.38	00:06	-1.40

Sligo

Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.
00:00	-1.64	20:00	1.07	16:00	0.64	12:00	-1.75	00:00	0.96	04:00	1.28
23:54	-1.6	19:54	1.14	15:54	0.56	11:54	-1.72	23:54	1.06	03:54	1.22
23:48	-1.56	19:48	1.21	15:48	0.49	11:48	-1.69	23:48	1.12	03:48	1.15
23:42	-1.53	19:42	1.27	15:42	0.4	11:42	-1.66	23:42	1.21	03:42	1.07
23:36	-1.52	19:36	1.33	15:36	0.32	11:36	-1.65	23:36	1.28	03:36	1.01
23:30	-1.5	19:30	1.39	15:30	0.26	11:30	-1.63	23:30	1.35	03:30	0.93
23:24	-1.49	19:24	1.45	15:24	0.16	11:24	-1.62	23:24	1.41	03:24	0.85
23:18	-1.45	19:18	1.5	15:18	0.11	11:18	-1.59	23:18	1.47	03:18	0.77
23:12	-1.42	19:12	1.56	15:12	0.02	11:12	-1.56	23:12	1.54	03:12	0.69
23:06	-1.37	19:06	1.58	15:06	-0.06	11:06	-1.51	23:06	1.59	03:06	0.62
23:00	-1.32	19:00	1.62	15:00	-0.15	11:00	-1.46	23:00	1.64	03:00	0.53
22:54	-1.27	18:54	1.65	14:54	-0.23	10:54	-1.39	22:54	1.68	02:54	0.45
22:48	-1.2	18:48	1.69	14:48	-0.33	10:48	-1.33	22:48	1.72	02:48	0.37
22:42	-1.14	18:42	1.69	14:42	-0.41	10:42	-1.28	22:42	1.77	02:42	0.29
22:36	-1.09	18:36	1.7	14:36	-0.49	10:36	-1.23	22:36	1.79	02:36	0.2
22:30	-1.01	18:30	1.71	14:30	-0.56	10:30	-1.17	22:30	1.82	02:30	0.11
22:24	-0.94	18:24	1.71	14:24	-0.63	10:24	-1.11	22:24	1.85	02:24	0.05
22:18	-0.88	18:18	1.7	14:18	-0.69	10:18	-1.05	22:18	1.87	02:18	-0.03
22:12	-0.81	18:12	1.67	14:12	-0.77	10:12	-0.98	22:12	1.9	02:12	-0.09
22:06	-0.74	18:06	1.66	14:06	-0.84	10:06	-0.91	22:06	1.93	02:06	-0.16
22:00	-0.68	18:00	1.64	14:00	-0.92	10:00	-0.82	22:00	1.95	02:00	-0.22
21:54	-0.58	17:54	1.61	13:54	-0.99	09:54	-0.76	21:54	1.98	01:54	-0.3
21:48	-0.5	17:48	1.59	13:48	-1.06	09:48	-0.68	21:48	1.98	01:48	-0.37
21:42	-0.41	17:42	1.56	13:42	-1.14	09:42	-0.6	21:42	1.98	01:42	-0.46
21:36	-0.32	17:36	1.52	13:36	-1.22	09:36	-0.52	21:36	1.97	01:36	-0.53
21:30	-0.25	17:30	1.49	13:30	-1.28	09:30	-0.42	21:30	1.96	01:30	-0.61
21:24	-0.17	17:24	1.46	13:24	-1.34	09:24	-0.33	21:24	1.95	01:24	-0.67
21:18	-0.06	17:18	1.42	13:18	-1.39	09:18	-0.25	21:18	1.93	01:18	-0.75
21:12	0.05	17:12	1.37	13:12	-1.43	09:12	-0.16	21:12	1.9	01:12	-0.83
21:06	0.14	17:06	1.34	13:06	-1.49	09:06	-0.07	21:06	1.87	01:06	-0.9
21:00	0.22	17:00	1.3	13:00	-1.53	09:00	0.04	21:00	1.85	01:00	-0.94
20:54	0.31	16:54	1.23	12:54	-1.56	08:54	0.13	20:54	1.79	00:54	-1.01
20:48	0.39	16:48	1.18	12:48	-1.59	08:48	0.22	20:48	1.77	00:48	-1.06
20:42	0.47	16:42	1.12	12:42	-1.61	08:42	0.31	20:42	1.73	00:42	-1.13
20:36	0.56	16:36	1.05	12:36	-1.66	08:36	0.4	20:36	1.66	00:36	-1.17
20:30	0.63	16:30	0.98	12:30	-1.72	08:30	0.5	20:30	1.63	00:30	-1.22
20:24	0.72	16:24	0.91	12:24	-1.75	08:24	0.6	20:24	1.56	00:24	-1.25
20:18	0.8	16:18	0.85	12:18	-1.78	08:18	0.7	20:18	1.49	00:18	-1.29
20:12	0.89	16:12	0.79	12:12	-1.77	08:12	0.8	20:12	1.42	00:12	-1.35
20:06	0.99	16:06	0.71	12:06	-1.77	08:06	0.89	20:06	1.36	00:06	-1.41

Malin Head

Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.
00:00	-1.49	20:00	1.23	16:00	0.25	12:00	-1.49	00:00	1.19	04:00	0.83
23:54	-1.43	19:54	1.31	15:54	0.16	11:54	-1.46	23:54	1.27	03:54	0.73
23:48	-1.43	19:48	1.37	15:48	0.09	11:48	-1.41	23:48	1.33	03:48	0.66
23:42	-1.38	19:42	1.37	15:42	0	11:42	-1.34	23:42	1.41	03:42	0.63
23:36	-1.33	19:36	1.43	15:36	-0.1	11:36	-1.31	23:36	1.44	03:36	0.53
23:30	-1.28	19:30	1.45	15:30	-0.2	11:30	-1.29	23:30	1.47	03:30	0.47
23:24	-1.23	19:24	1.47	15:24	-0.31	11:24	-1.19	23:24	1.53	03:24	0.35
23:18	-1.16	19:18	1.57	15:18	-0.4	11:18	-1.17	23:18	1.59	03:18	0.27
23:12	-1.09	19:12	1.51	15:12	-0.45	11:12	-1.05	23:12	1.56	03:12	0.17
23:06	-1.04	19:06	1.55	15:06	-0.57	11:06	-1.03	23:06	1.63	03:06	0.15
23:00	-0.98	19:00	1.55	15:00	-0.64	11:00	-1.01	23:00	1.69	03:00	-0.02
22:54	-0.87	18:54	1.53	14:54	-0.71	10:54	-0.89	22:54	1.7	02:54	-0.06
22:48	-0.82	18:48	1.55	14:48	-0.79	10:48	-0.87	22:48	1.69	02:48	-0.14
22:42	-0.73	18:42	1.54	14:42	-0.84	10:42	-0.77	22:42	1.78	02:42	-0.23
22:36	-0.68	18:36	1.52	14:36	-0.94	10:36	-0.69	22:36	1.71	02:36	-0.31
22:30	-0.62	18:30	1.52	14:30	-1	10:30	-0.62	22:30	1.76	02:30	-0.42
22:24	-0.56	18:24	1.5	14:24	-1.11	10:24	-0.53	22:24	1.74	02:24	-0.49
22:18	-0.44	18:18	1.44	14:18	-1.13	10:18	-0.49	22:18	1.74	02:18	-0.57
22:12	-0.37	18:12	1.49	14:12	-1.24	10:12	-0.4	22:12	1.73	02:12	-0.64
22:06	-0.26	18:06	1.42	14:06	-1.28	10:06	-0.34	22:06	1.74	02:06	-0.72
22:00	-0.18	18:00	1.42	14:00	-1.3	10:00	-0.25	22:00	1.73	02:00	-0.8
21:54	-0.12	17:54	1.35	13:54	-1.4	09:54	-0.15	21:54	1.72	01:54	-0.86
21:48	-0.01	17:48	1.34	13:48	-1.4	09:48	-0.08	21:48	1.69	01:48	-0.94
21:42	0.06	17:42	1.31	13:42	-1.47	09:42	0.01	21:42	1.69	01:42	-1.01
21:36	0.17	17:36	1.29	13:36	-1.49	09:36	0.12	21:36	1.62	01:36	-1.06
21:30	0.25	17:30	1.22	13:30	-1.52	09:30	0.14	21:30	1.61	01:30	-1.09
21:24	0.33	17:24	1.17	13:24	-1.54	09:24	0.29	21:24	1.61	01:24	-1.17
21:18	0.39	17:18	1.13	13:18	-1.55	09:18	0.32	21:18	1.53	01:18	-1.22
21:12	0.47	17:12	1.08	13:12	-1.58	09:12	0.46	21:12	1.5	01:12	-1.26
21:06	0.55	17:06	1.02	13:06	-1.6	09:06	0.5	21:06	1.43	01:06	-1.28
21:00	0.59	17:00	0.96	13:00	-1.61	09:00	0.57	21:00	1.42	01:00	-1.34
20:54	0.7	16:54	0.92	12:54	-1.62	08:54	0.68	20:54	1.35	00:54	-1.39
20:48	0.74	16:48	0.83	12:48	-1.6	08:48	0.7	20:48	1.32	00:48	-1.43
20:42	0.8	16:42	0.77	12:42	-1.6	08:42	0.78	20:42	1.27	00:42	-1.42
20:36	0.88	16:36	0.71	12:36	-1.59	08:36	0.88	20:36	1.22	00:36	-1.44
20:30	0.99	16:30	0.61	12:30	-1.57	08:30	0.9	20:30	1.16	00:30	-1.44
20:24	1.01	16:24	0.55	12:24	-1.58	08:24	1.03	20:24	1.07	00:24	-1.5
20:18	1.07	16:18	0.49	12:18	-1.57	08:18	1.07	20:18	1.07	00:18	-1.5
20:12	1.09	16:12	0.43	12:12	-1.53	08:12	1.05	20:12	1.01	00:12	-1.54
20:06	1.22	16:06	0.33	12:06	-1.52	08:06	1.18	20:06	0.93	00:06	-1.53

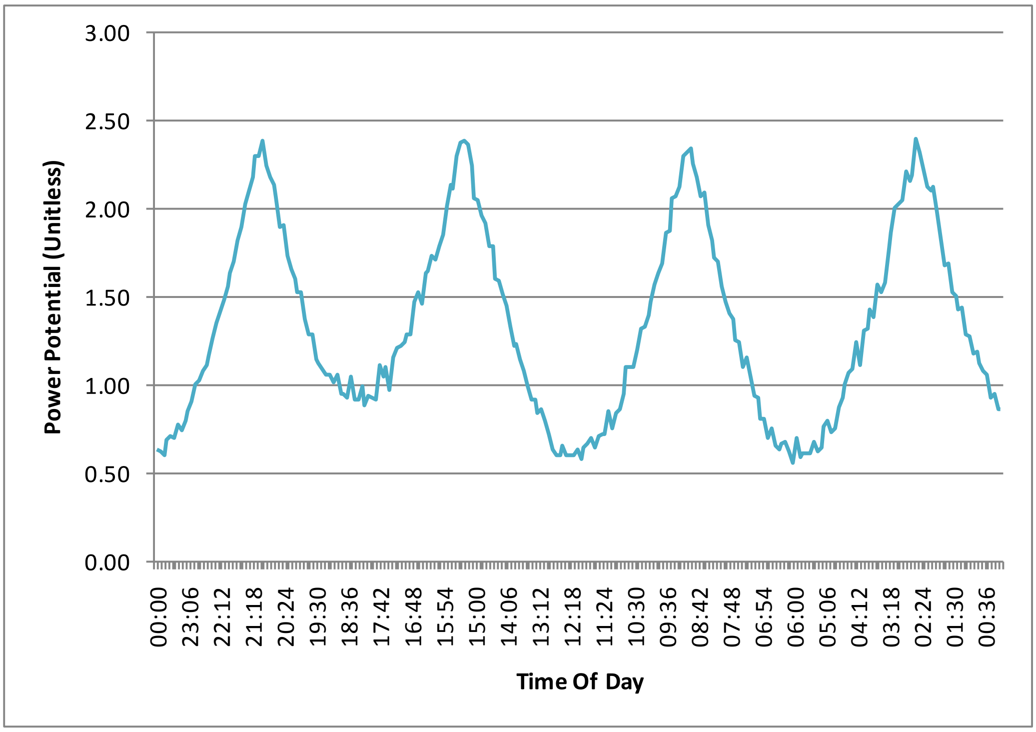
Castletownbere

Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.	Time	Disp.
00:00	-1.45	19:45	0.29	15:30	1.05	11:15	-1.57	07:00	0.59	02:45	0.86
23:45	-1.52	19:30	0.49	15:15	0.87	11:00	-1.59	06:45	0.76	02:30	0.73
23:30	-1.57	19:15	0.68	15:00	0.7	10:45	-1.59	06:30	0.97	02:15	0.53
23:15	-1.55	19:00	0.89	14:45	0.47	10:30	-1.56	06:15	1.12	02:00	0.31
23:00	-1.57	18:45	1.08	14:30	0.29	10:15	-1.52	06:00	1.23	01:45	0.14
22:45	-1.52	18:30	1.19	14:15	0.1	10:00	-1.47	05:45	1.37	01:30	-0.03
22:30	-1.49	18:15	1.34	14:00	-0.12	09:45	-1.36	05:30	1.45	01:15	-0.23
22:15	-1.41	18:00	1.46	13:45	-0.31	09:30	-1.25	05:15	1.53	01:00	-0.39
22:00	-1.3	17:45	1.5	13:30	-0.47	09:15	-1.12	05:00	1.57	00:45	-0.53
21:45	-1.2	17:30	1.55	13:15	-0.67	09:00	-0.96	04:45	1.6	00:30	-0.71
21:30	-1.04	17:15	1.58	13:00	-0.84	08:45	-0.78	04:30	1.59	00:15	-0.88
21:15	-0.88	17:00	1.58	12:45	-0.99	08:30	-0.63	04:15	1.55	00:00	-0.98
21:00	-0.71	16:45	1.55	12:30	-1.13	08:15	-0.44	04:00	1.51		
20:45	-0.5	16:30	1.5	12:15	-1.29	08:00	-0.22	03:45	1.45		
20:30	-0.32	16:15	1.45	12:00	-1.38	07:45	-0.03	03:30	1.32		
20:15	-0.13	16:00	1.33	11:45	-1.46	07:30	0.18	03:15	1.23		
20:00	0.09	15:45	1.2	11:30	-1.54	07:15	0.41	03:00	1.08		

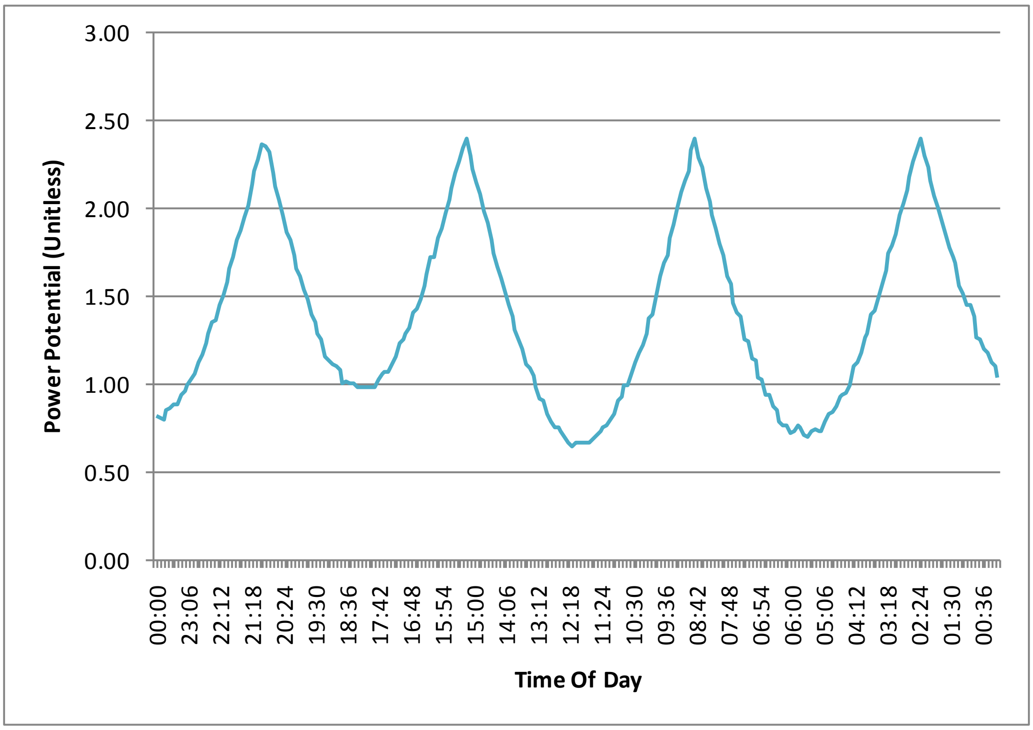
Appendix B: Daily Power Graphs

This appendix contains daily power potential graphs of all the sites for which daily displacement data was collected and analysed but not deemed suitable for further analysis (15 day analysis).

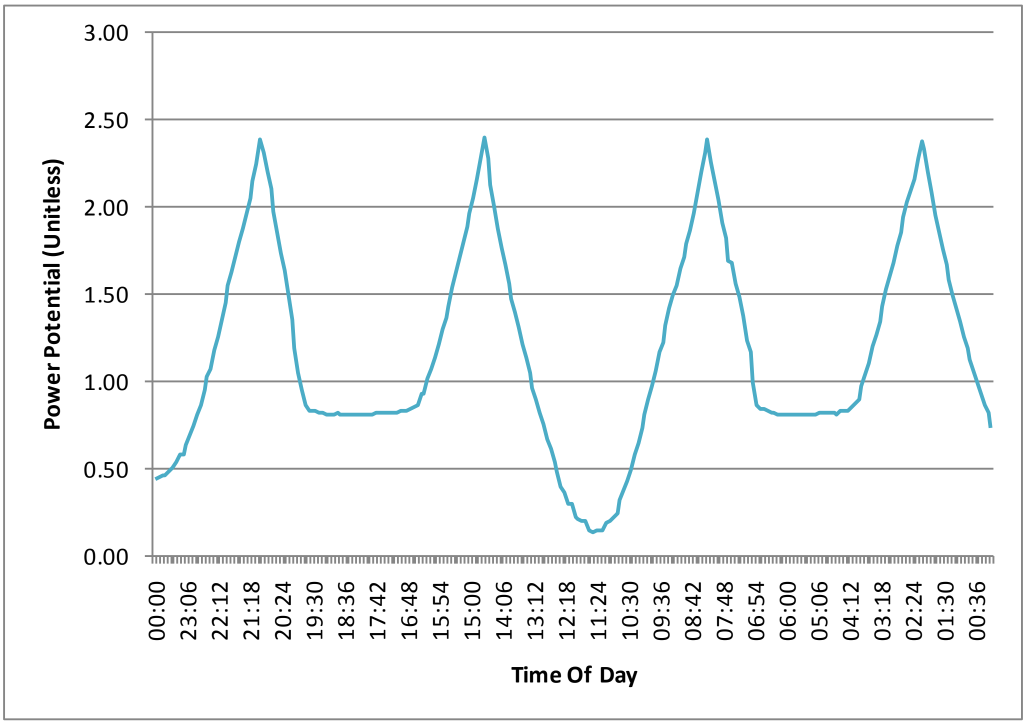
Arunmore



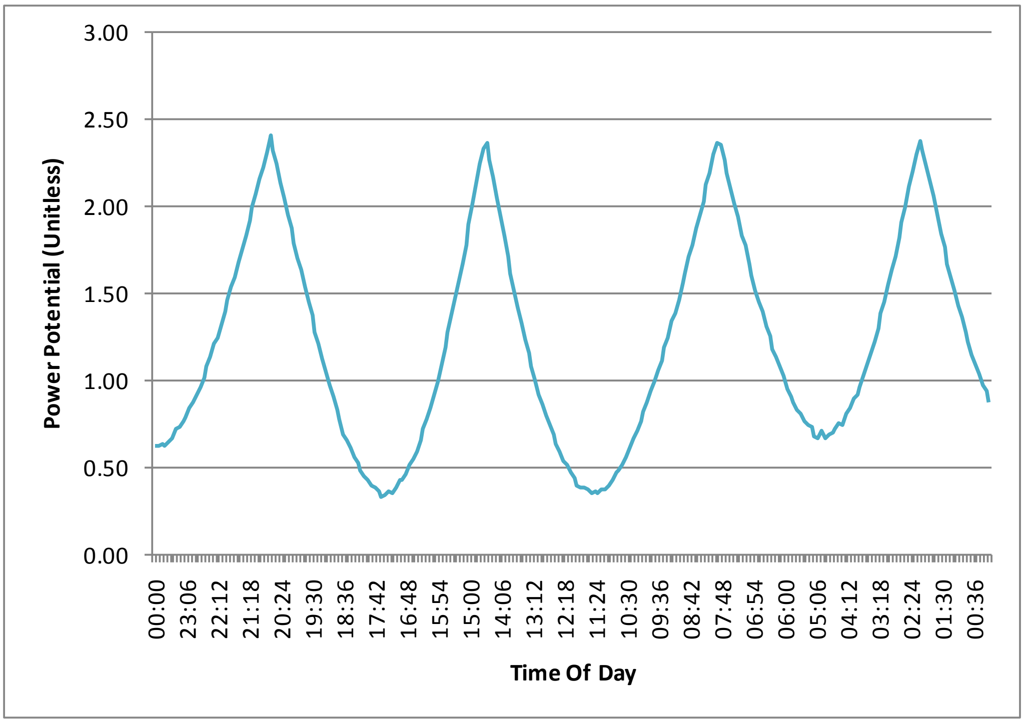
Ballyglass



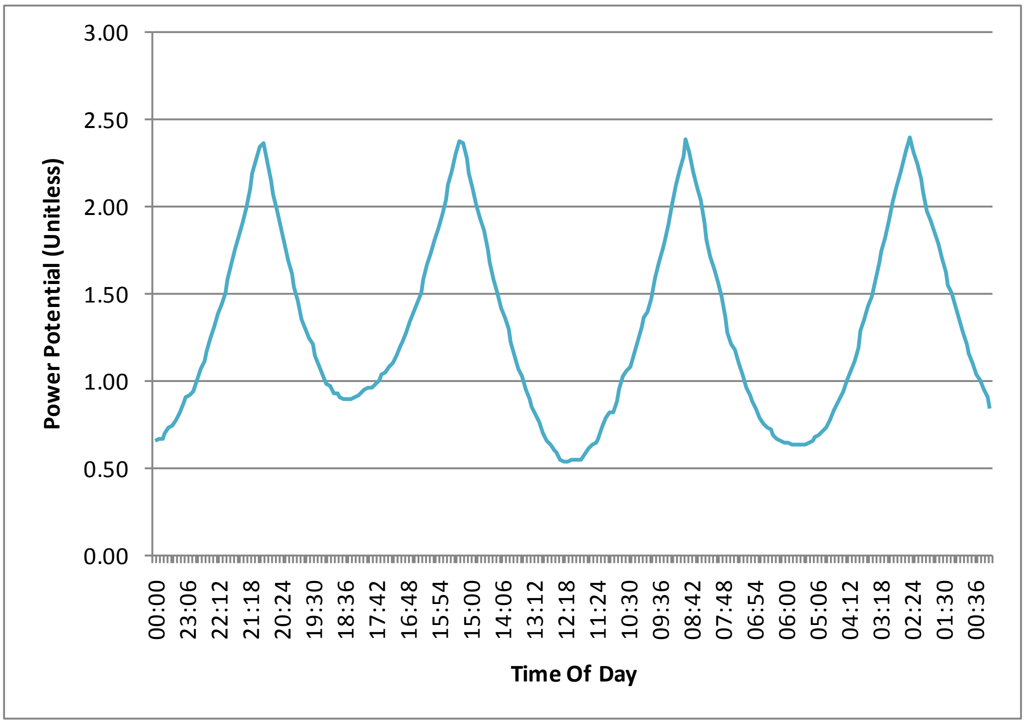
Dundalk



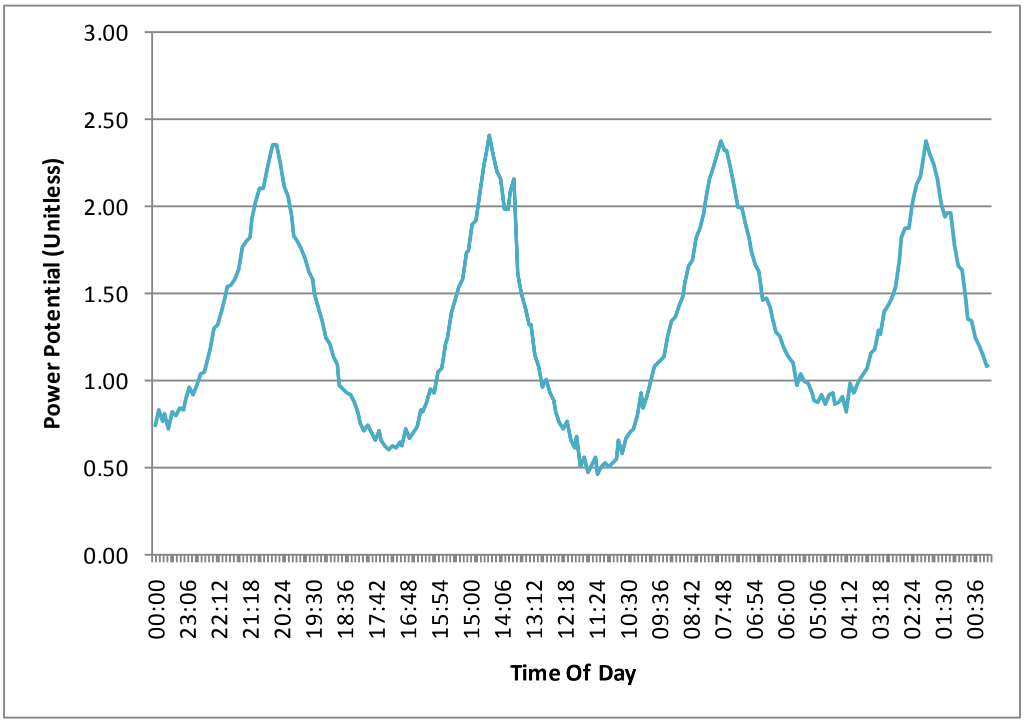
Howth



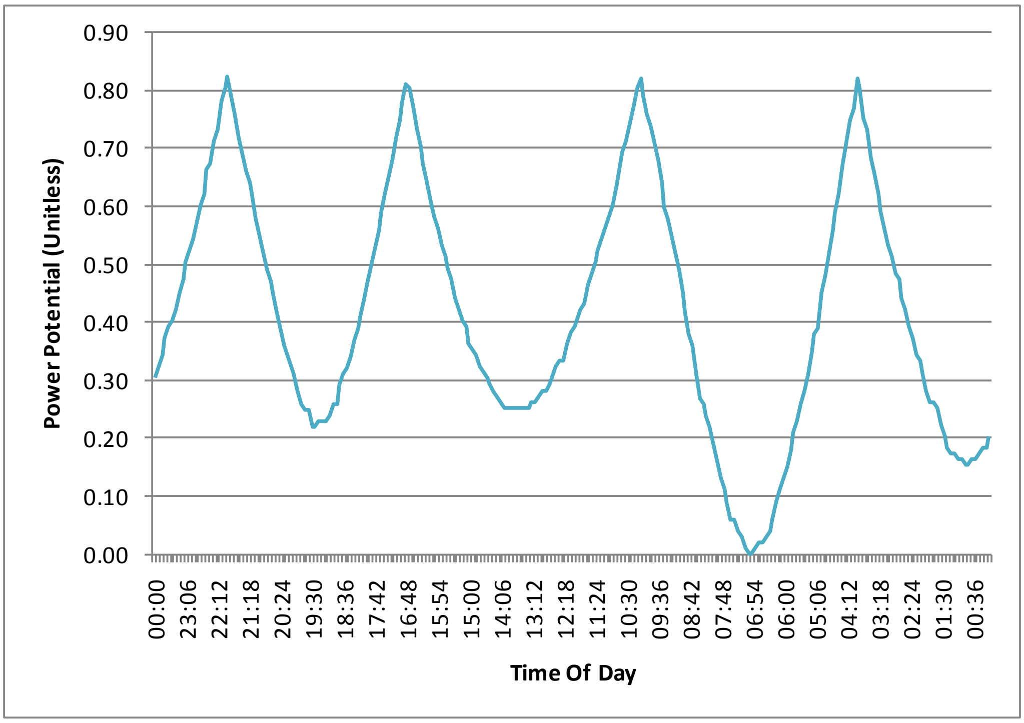
Killybegs



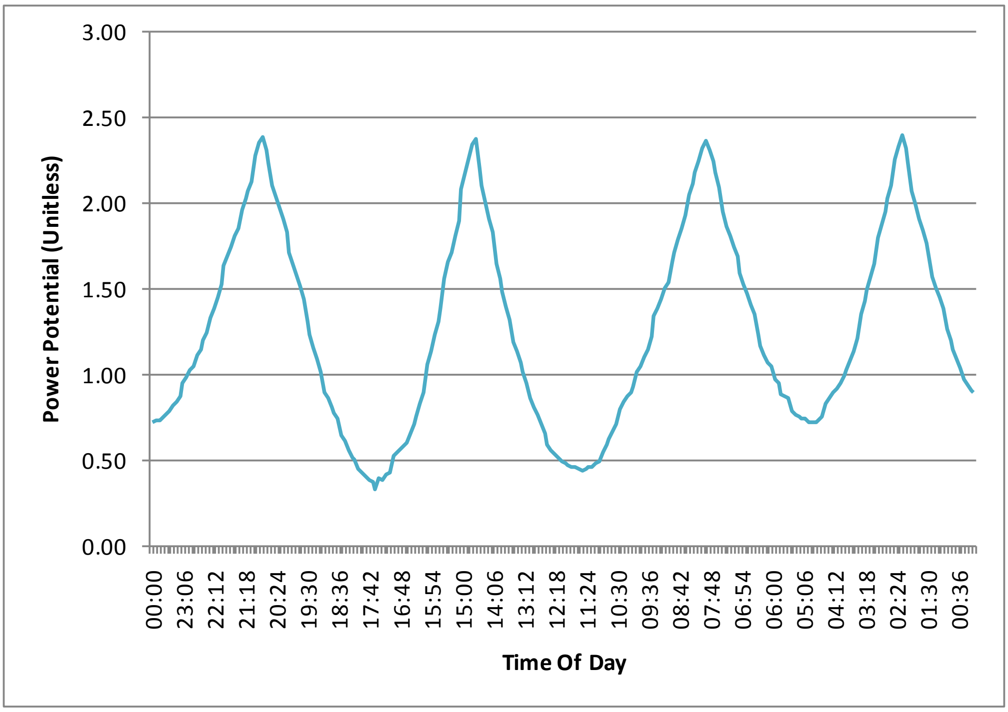
Kish Bank



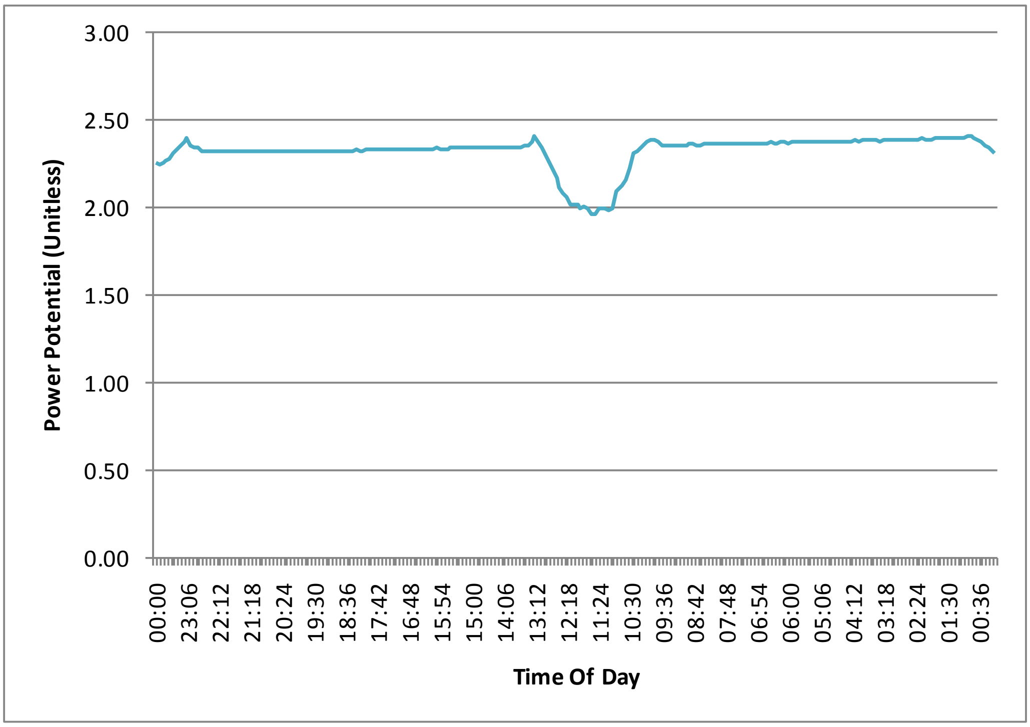
Wexford



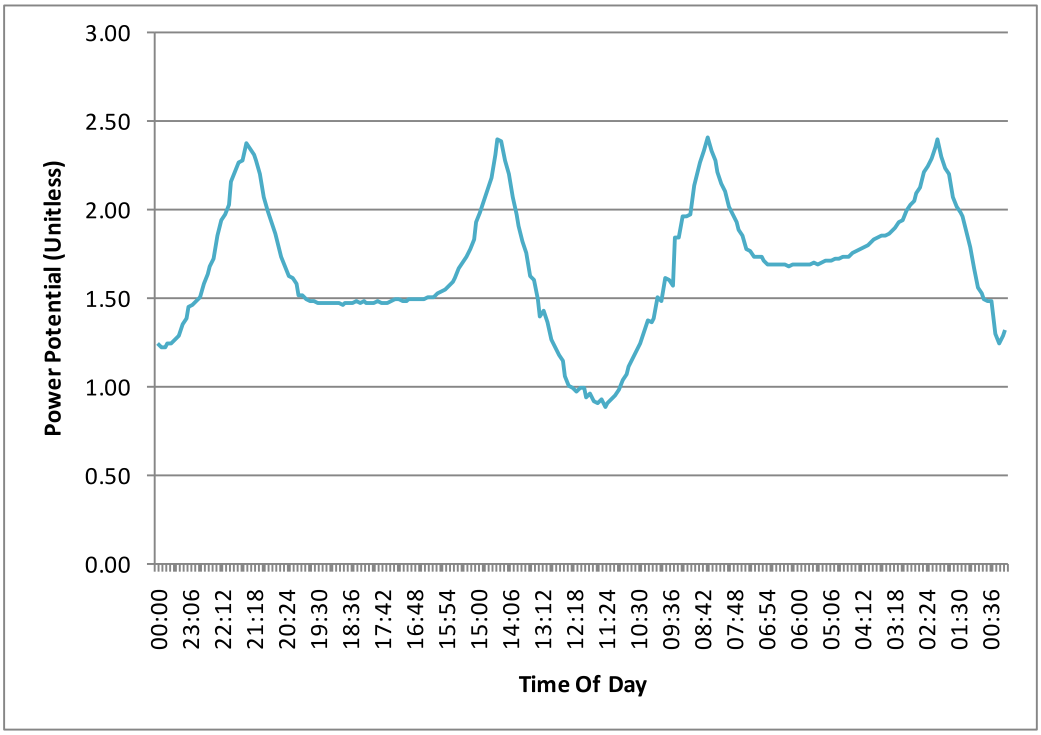
Dublin



Dodder



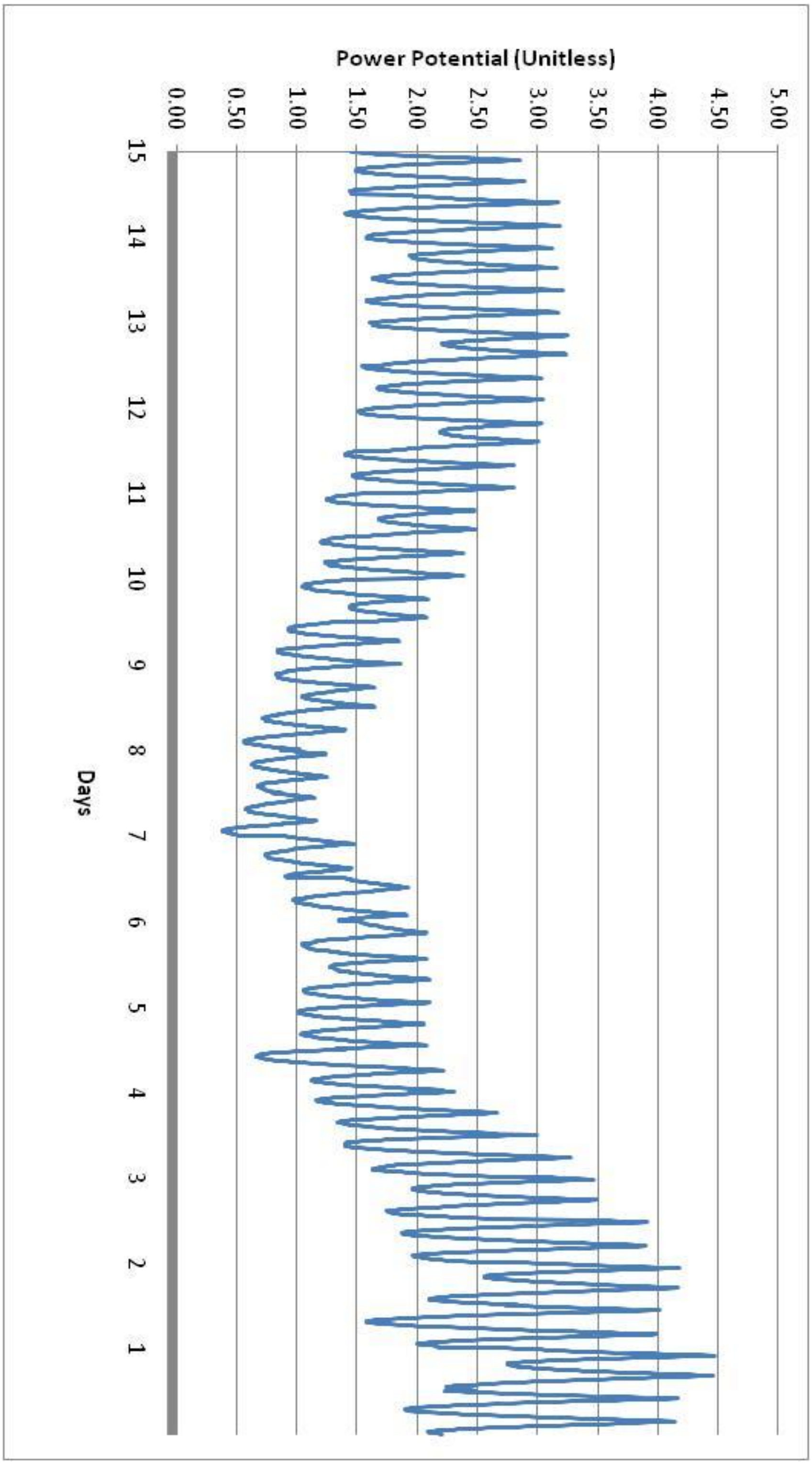
Liffey



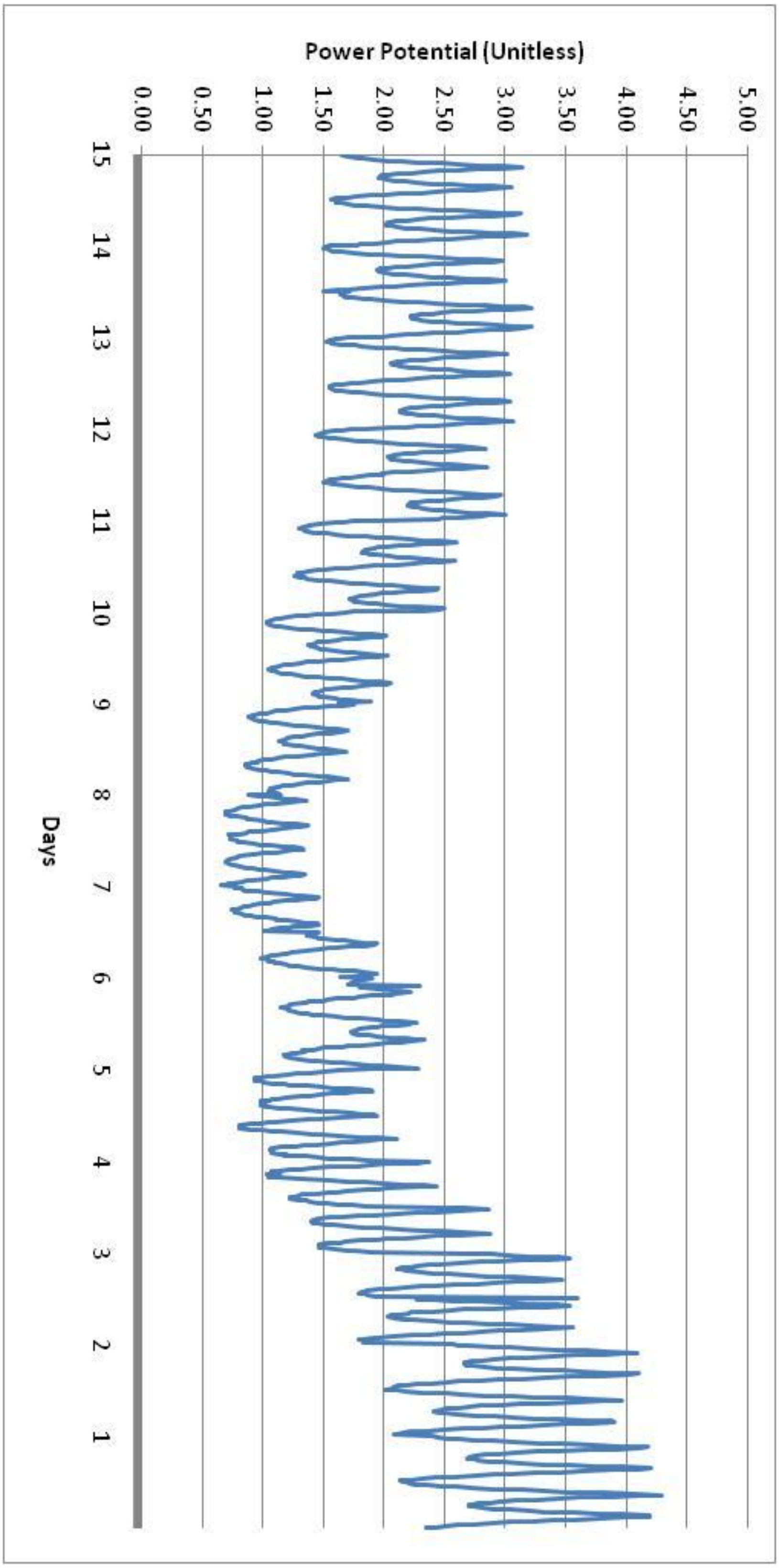
Appendix C: 15-Day Power Potential Graphs

This appendix contains the 15-day power potential graphs of the three sites chosen in addition to Galway Bay (chapter 3 of main text).

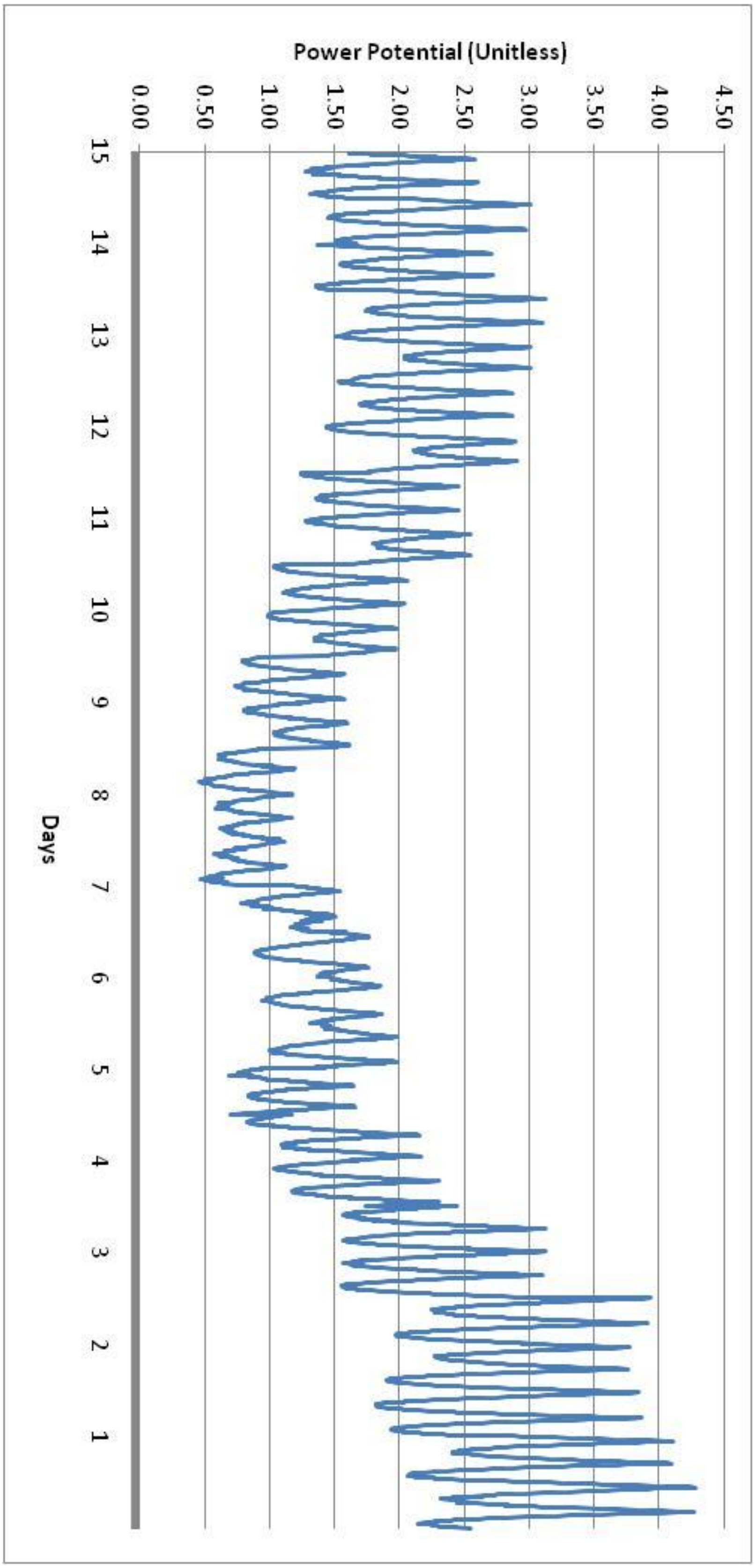
Sligo



Castletownbere



Malin Head


Power Potential (Unitless)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Days