Tidal Power Assessment in the Big Russel and the North East of Sark

By

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September 2012

Report Commissioned by:

COMMERCE AND EMPLOYMENT
A STATES OF GUERNSEY GOVERNMENT DEPARTMENT

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List of Abbreviations

Abbreviation	Description
ADCP	Acoustic Doppler Current Profiler
AP	Amphidromic Points
BERR	Department for Business, Enterprise and Regulatory Reform
CAPEX	Capital Expenditure
CIEG	Channel Island Electricity Grid
Cross	Cross channel component of velocity after transformation
DECC	Department of Energy and Climate Change
EMEC	European Marine Energy Centre
EPRI	Electric Power Research Institute
GP&A	General Purposes and Advisory Committee of the Chief Pleas
GREC	Guernsey Renewable Energy Commission
GW	Gigawatt
GWh	Gigawatt Hour
HAT	Highest Astronomical Tide
HS1000	Hammerfest Strom 1 MW Turbine
kW	Kilowatt
kWh	Kilowatt Hour
LAT	Lowest Astronomical Tide
Long	Long channel component of velocity after transformation
m/s	Meters per Second
MATLAB	Matrix Laboratory
MCT	Marine Current Turbines
MH_z	Megahertz
MSV	Maximum Spring Velocity
MW	Megawatt
MWh	Megawatt Hour
NOAA	National Oceanic and Atmospheric Administration
O&M	Operation and Maintenance
QEII	Queen Elizabeth 2 Cruise Ship
RET	Renewable Energy Team Guernsey
RGUS	Robert Gordon University Study
RITE	Roosevelt Island Tidal Energy Project
RYA	Royal Yachting Association
SEA	Strategic Environmental Assessment
U	Cross Channel Component
V	Long Channel Component
V_{mn}	Mean Neap Velocity
V_{ms}	Mean Spring Velocity

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Executive Summary

The following report, commissioned by the States of Guernsey Commerce and Employment's Renewable Energy Team (RET), assesses the potential for the extraction of tidal stream energy from two key locations in the Big Russel, located between the islands of Guernsey and Sark, and one location to the north east of Sark.

The three locations were chosen by Members of Parliament, for the Isle of Sark, to provide information on the potential tidal resource found at each location and to begin a record of baseline flow through these areas before the placement of any technology. Site 1 was positioned in the centre of the Big Russel, Site 2 in the Big Russel closer to Sark and Site 3 on the north east coast of Sark.

The data were collected using an Acoustic Doppler Current Profiler (ADCP) positioned on the seabed looking up through the water column. All three sites had a full month of data on which analysis could be carried out.

Due to the limitations of the data provided analysis is based on a single turbine device. The data has been collected from one specific location for each site therefore analysis can only be conducted for these three specific locations.

Analysis demonstrates that Site 1, located in the centre of the Big Russel, contains the highest resource with a maximum flow velocity of 2.6 m/s and a potential annual power output of 8,378,640 kWh from a single Hammerfest Strom 1 MW turbine. This is equivalent to 2.09% of Guernsey's annual energy requirements which is in the region of 400 GWh per year. Analysis shows there is vertical shear in the horizontal flow and in order to extract the maximum amount of tidal stream energy the turbine needs to be placed as high in the water column as possible, whilst still complying with Royal Yachting Association (RYA) guidelines regarding safe limits for turbine blades. The maximum height of the turbine blades in accordance with RYA guidelines is 32.5 meters for Site 1. The Hammerfest Strom turbine can be positioned with the turbine blades reaching a maximum height of 30 meters in the water column, allowing the recreational shipping industry and commercial shipping industry to traverse the area safely at all states of tide.

Site 2 contains the second highest energy resource with a maximum velocity of 2.45 m/s. The potential annual power output was significantly smaller than Site 1 with an annual power

output of 3,547,320 kWh. This decrease in power potential is due to the larger flow velocity fluctuations at Site 2. The annual power output is equivalent to 0.89% of Guernsey's annual energy requirements. The proposed technology used at Site 2 is a single OpenHydro 2.2 MW turbine. The maximum height of the turbine blades in accordance with RYA guidelines is 28.19 meters for Site 2. This height prevents the use of the Hammerfest Strom turbine. The OpenHydro turbine complies with RYA regulations reaching a height of 21 meters from the seabed.

Site 3 contains the lowest amount of energy. The maximum velocity reached 2.15 m/s and the potential annual power output was 2,781,600 kWh with an OpenHydro turbine. This is equivalent to 0.70% of Guernsey's annual energy requirements. However Site 3 was chosen as a site that could provide energy specifically to Sark's energy grid. The exact amount of energy Sark consumes is unknown but it is known to consume less than 1MW of energy at peak times, and less than 1 GWh in a year. Based on these estimates, one OpenHydro turbine could produce 278.16% of Sark's annual energy requirements. This site has definite potential for micro-generation. Further research is required in order to fully understand the tidal stream energy potential in the surrounding area and to identify the optimum location for a device.

A schematic has been created in this report for a potential array of turbines in the Big Russel. The array has, of necessity, been designed based on assumptions due to insufficient available data. The array has been constructed based on an extrapolation of the data provided for Site 1. Site 1 was chosen as it contained the highest tidal stream energy potential. Based on the assumption that the potential energy output as found at Site 1 is roughly the same throughout the length of the Big Russel, then any array would have to be narrow and positioned down the centre of the channel. Using this assumption and the findings from the Roosevelt Island Tidal Energy (RITE) project, which gives an indication for the spacing for tidal turbines, approximately 40 turbines would fit down the centre of the Big Russel and produce a combined power output of 335.15 GWh per annum, equivalent to 83.79% of Guernsey's annual power consumption.

Much of the economic data surrounding the tidal energy industry is unknown and unpublished. The industry is still in its infancy and only a few devices are commercially ready. There are no commercial scale arrays in place and therefore trying to cost a project such as this is difficult. These results are only indicative at present and based on published industry estimates. As a mere indication the Guernsey Renewable Energy Commission (GREC) have stated that they don't expect a commercial tidal array to be operational anywhere before 2017 and therefore Guernsey's tidal stream energy projects would not be developed until after this date. Overall the cost for one turbine, along with the required infrastructure such as cabling substations, together with the cost of installing the device on the seabed, can be estimated to cost in the region of £8.4 million based on industry estimates of £5 million per MW of installed capacity. Using economies of scale, as suggested by the Electric Power Research Institute (EPRI), the total cost of a 40 turbine array would be £107.1 million.

Allowing time for the tidal energy industry to mature past the installation of the first commercial array would be advisable due to the wealth of knowledge that such an array will provide, including invaluable data on how an array interacts with the surrounding environment, the interaction of the turbines with each other and their resulting efficiency. The first array would also allow greater understanding of the costs involved. Ultimately the economic viability of an array will come down to the cost-benefit analysis of installing such devices. Considering the high economic investment needed for such a scheme Guernsey would be well advised to utilise knowledge gained from other arrays in order to capitalise on cost reducing strategies.

Overall Guernsey has the tidal resources around the island to make tidal energy a reality for the island. However further data needs to be collected from multiple locations along the length and breadth of the Big Russel to highlight exactly how the current velocity varies throughout the channel. A detailed understanding of the current in the channel is necessary before considering the design of any array.

1. Introduction

This study will assess the tidal resource at specific sites in the Bailiwick of Guernsey. The primary goal is to assess how much energy could be converted to electricity for use in Guernsey's electricity grid from the tidal stream through the use of tidal stream turbines (figure 1).

In February 2012 the Government authorities in Guernsey, Jersey and Sark agreed, a joint statement of intent on marine renewable energy, to work together to establish the potential magnitude and costs of the actual energy that could be extracted and exploited in a year. They also wished to determine whether this energy could be harnessed to contribute to meeting local electricity demand in each island as well as for export to markets in other jurisdictions. In this way they hoped to fulfil their commitment to renewable energy whilst providing an economic benefit to the islands (Channel Islands Agreement, 2012). This study will focus on the tidal stream energy potential rather than wind or wave potential in the marine environment.

A CIEG (Channel Island Electricity Grid) cable currently exists between Guernsey, Jersey and France. This cable provides Jersey with up to 200 MW and Guernsey with up to 60 MW of electricity from Europe (Channel Islands Agreement, 2012). The island Governments are now considering plans to increase the capacity brought to the islands which might include, in the longer term, a link via Sark (Channel Islands Agreement, 2012 and Patrick Firth, Personal Communication). At present Guernsey is mainly reliant on the energy imported from France, amounting to 78% of its electricity demand. The remainder (22%) is generated on the island using diesel generators. Most of the energy is imported to supply the islands with a lower unit cost of electricity. Making an investment in marine renewable energy puts the islands in control (Patrick Firth, Personal Communication). The ultimate aim of the islands' Governments is to increase energy security for their respective islands through locally produced marine renewable energy and eventually to be able to export energy to the European grid (Channel Islands Agreement, 2012).

Sark has installed a high capacity cable from the harbour to the power station that could be used to bring renewable energy ashore in the future (Isle of Sark, 2011). Sark currently generates its own energy using diesel generators. However, the cost of the energy it produces is very expensive amounting to 47p per unit (Sark Electricity Ltd, 2012). The energy consumption on Sark is not published but it is known to have a peak demand of less than 1

MW and a yearly consumption of less than 1 GWh (David Gordon-Brown, Personal Communication) and is interested in micro-generation to meet its own needs (Roger Olsen, Personal Communication).

To put Sark's energy demand into perspective, Guernsey had a peak demand of 83 MW in 2010 and a total energy consumption of 400 GWh each year (University of Exeter, 2012). The Super Economy 12 Tariff used in Guernsey costs 17p per normal unit and 7p per cheap rate unit (Guernsey Electricity, 2012). The Super Economy 7 Tariff in the UK costs 14p per normal unit and 6p per cheap rate unit (DECC, 2011).

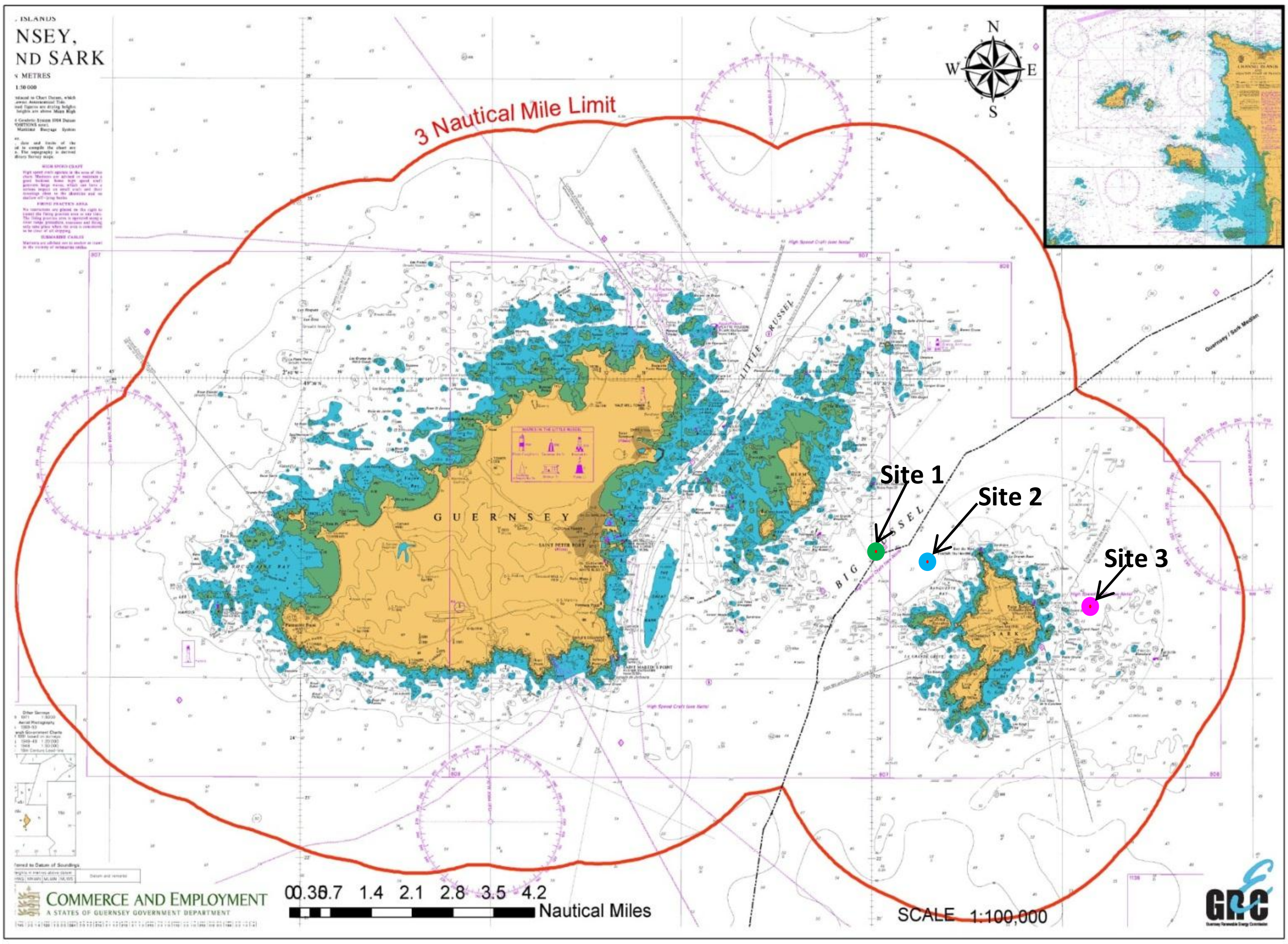


Figure 1: Map showing the islands of Guernsey, Herm and Sark. Highlighted on the map are the 3 sites for which data analysis will be conducted. Note the black line which separates Herm and Sark. This denotes the boundary between Guernsey and Sark waters and also highlights the centre line of the channel between Herm and Sark, known as the Big Russel.
Source: GREC. (2012)

2. Project Scope

Energy security is an increasingly pressing issue for any small scale generators such as the Bailiwick of Guernsey, as fuel prices and the demand for electricity continue to rise. Guernsey has seen an increase in demand of 3.5% for the past ten years (University of Exeter, 2012). The island keeps its electricity costs lower than they would otherwise be thanks to the electricity imported from France via an undersea cable. The French power is mostly generated via nuclear power stations and is therefore not as open to the volatility of wholesale energy prices. In 2011 UK wholesale prices rose by over 200% whereas Npower prices (in France) only rose by 26% (Npower, 2012). The heavy dependence of Guernsey on imported electricity was evident recently when the cable broke in April 2012 (BBC News, 2012). To date the cable has not been repaired and this has increased pressure for on-island generators. Increasing fuel security is a key priority for any government. As a result of the joint statement of intent, RET is working with a selection of English universities to continue and expand the work into researching Guernsey's resource potential to utilise marine renewables (Channel Islands Agreement, 2012).

This report, commissioned by the States of Guernsey looks into the tidal stream energy potential contained at three such sites situated inside Sark waters.

3. The Data

The data to be analysed in this report were obtained at three positions from a bottom mounted ADCP (Acoustic Doppler Current Profiler) (Figure 2). The data were originally commissioned by Sark and the General Purposes and Advisory Committee (GP&A) of the Chief Pleas. The Chief Pleas is Sark's Parliament. The data were collected by a local fisherman, Richard Keen. Sark chose all three of the data sites to accurately assess what resource is available at these sites before any decisions are made regarding deployment of turbines. Site 3 was specifically chosen as a potential site for micro generation for Sark. The site is not positioned in any shipping routes and was chosen after consultations with local fishermen due to their knowledge of the area (Roger Olsen, Personal Communication).

The table below contains some basic information on the various sites and the data collected (Table 1).

Location Name	Coordinates	Start date of Data	Start Time	End date of Data	End Time	Average Depth of Water (Meters)	Chart Datum (Meters)
Site 1	49°27'.128"N 2°24'.519"W	15/11/11	11:54:11	22/12/11	20:15:04	46	40.5
Site 2	49°27'.00"N 2°23'.56"W	07/01/12	15:39:11	07/02/12	07:49:11	42	36.2
Site 3	49°26'.21"N 2°19'.15"W	20/02/12	13:43:16	22/03/12	09:23:16	48	43.0

Table 1: Table highlighting key facts about the data for each site

3.1 Data Acquisition

The data were collected using a Nortek Aquadopp® Current Profiler. This device takes measurements across the whole of the water column from a fixed position either on a mooring looking down, or on the seabed looking up. In this case it was placed on the seabed. It is a multi-function device which can record data about current speed, current direction, depth, temperature, pitch and roll. A schematic of the device is shown in figure 2.

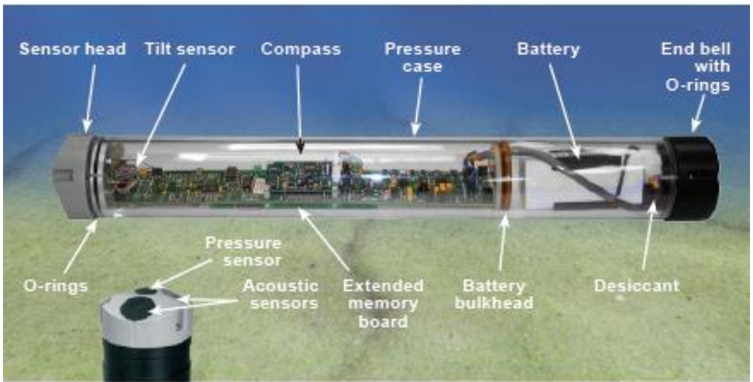


Figure 2: Diagram of ADCP device
Source: Nortek AS. (2008)

The profiler was deployed in fixed positions on the seabed for periods in excess of one month in three different locations. The period of observations thereby spans two complete spring-neap cycles (Table 1). Information about current velocity is collected using acoustic Doppler shift methods. The device sends out an acoustic ping and then listens to the echo of this ping as the sound is reflected off particles in the water column. The device then records changes in the pitch or frequency of the returned sound compared to the original sound.

The equation for the Doppler shift is:

$$F_d = 2F_s(V/C)\cos(A) \quad \textbf{(1)}$$

Where:

F_d = Doppler shift frequency.
F_s = Frequency of the sound when everything is still.
V = Relative velocity between the sound source and the sound receiver
C = The speed of sound (m/s)
A = the angle between the relative velocity vector and the line between the ADCP and particles in the water column.

Figure 3 provides a schematic of how the device monitors the changes in the emitted sound wave.

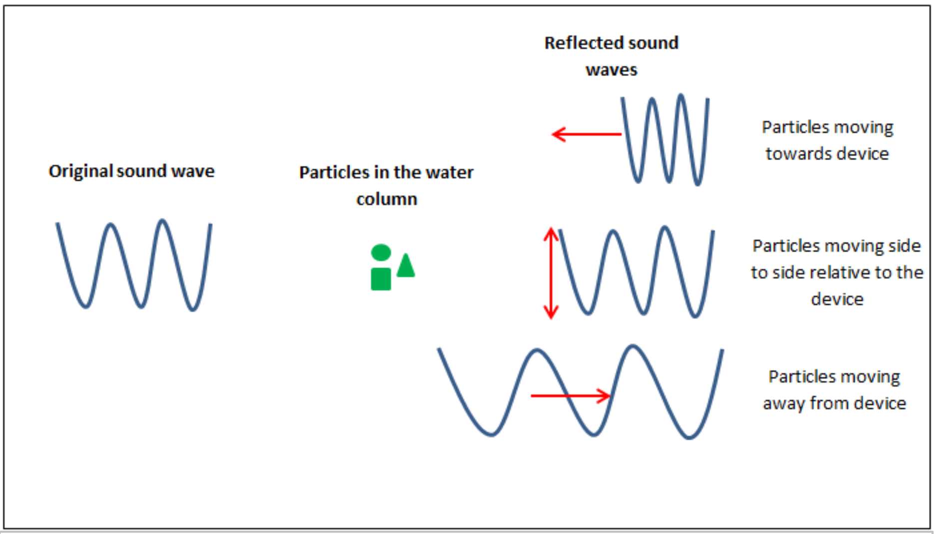


Figure 3: Schematic of how an ADCP uses sound waves to measure the speed of particles in the water column.

In order to measure the current velocity, the Nortek Aquadopp® device emits pulses of sound energy via three beams angled at 25° away from vertical (Nortek AS, 2008). The device collects data about current velocity from each of these beams and then triangulates the results to calculate the water velocity inside the beams. Range-gated vertical 'bins' are used to provide velocity measurements at discrete intervals from the instrument. Each bin covers 2 meters of water for which a value of velocity is estimated (Nortek AS, 2008). For greater accuracy the bins overlap when the data is initially recorded (figure 4). The blanking distance, shown in figure 4, is a time delay set by the ADCP user. The short time delay is needed after transmitting a signal to allow acoustic ringing to decline to the point that a received signal can be interpreted (Gartner *et al.*, 2003). For this device the blanking distance is 0.5 m.

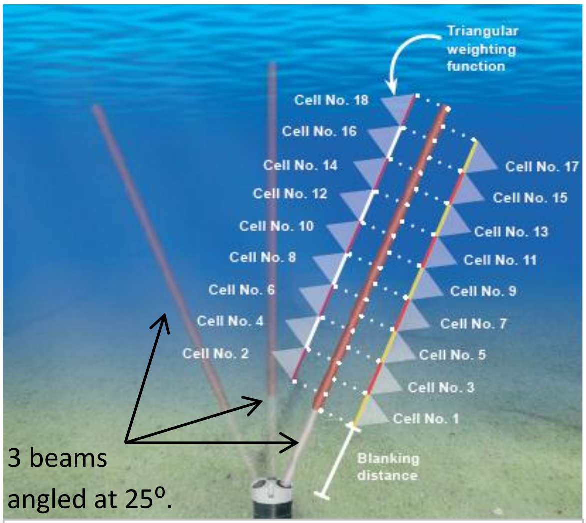


Figure 4: Diagram depicting the emitting of pulses of sound energy from the ADCP that are then range-gated in 2 meter vertical bins to provide velocity measurements at discrete intervals from the instrument.
Source: Nortek AS. (2008)

As the device is looking up from the seabed the data is given in height above the seabed. The height of the device itself is 0.5 meters. Therefore 2.5 meters away from the device is 3 meters off the seabed (Nortek AS, 2008). This means that there will be no data recorded next to the seabed. However due to friction between the seabed and the water, the flow velocity reduces (theoretically) to zero at the bed (Kaczmarska, 2008). Therefore the area of most interest for this study is that portion of the water column outside the bottom boundary layer which is unaffected by flow retardation by the boundary.

3.2 Data Analysis Methodology

The following analysis is based around a tidal resource assessment guide outlined by EMEC (European Marine Energy Centre) which itemises key information needed to appropriately assess a tidal resource (EMEC, 2009). This includes:

- Water Column Profile
- Flow Direction – Tidal Ellipse
- Lowest Astronomical Tide (LAT) – Chart Datum
- Mean Spring Velocity (V_{ms})
- Mean Neap Velocity (V_{mn})

Data are analysed using MATLAB as follows:

3.2.1. Separating U and V Components

The measurement of speed made by the device can be broken down into its U (east – cross channel) and V (north – long channel) components. The direction of the current is important and can be crucial in achieving maximum turbine efficiency. For instance if a turbine is fixed, only that component of the flow that is aligned with the flow will be useful to the turbine. Separating the speed into U and V components also allows analysis of the proportion of time for which there is a cross channel flow and the strength of this flow.

The equations are based on Pythagoras' theorem:

$$U = Data \times \sin(direction\ of\ flow) \tag{2}$$

$$V = Data \times \cos(direction\ of\ flow) \tag{3}$$

Where:

U = East Velocity component

V = North Velocity component

3.2.2. Coordinate Transformation

The dataset has to be adjusted to take account of the orientation of the channel. The ADCP device has a built in compass which tells the device in which direction the flow is travelling. The device measures speed and direction and then decomposes these into the east and north velocity components, i.e. U and V. The orientation of the Big Russel is angled approximately 25.5^{o} away from North. Figure 5 shows a schematic of how this changes the positioning of U and V to align with the channel.

Figure 5: Map showing angle of adjustment needed for velocity data to be correctly aligned with the Big Russel.

The equation used to transform the data by 25.5^{o} is:

$$Cross = U\cos\left(\left(\frac{25.5}{180}\right)\pi\right) - V\sin\left(\left(\frac{25.5}{180}\right)\pi\right) \tag{4}$$

$$Long = V\cos\left(\left(\frac{25.5}{180}\right)\pi\right) + U\sin\left(\left(\frac{25.5}{180}\right)\pi\right) \tag{5}$$

Where:

Cross = Cross channel component of velocity after transformation

Long = Long channel component of velocity after transformation

U = Cross channel component as initially defined in section 3.2.1

V = Long channel component as initially defined in section 3.2.1

3.2.3. Flow Direction Graph

Tidal developers use flow direction graphs to illustrate how tidal currents vary in space, either horizontally or with depth (NOOCTM, 2003). The tighter and narrower the graph the closer the tidal velocity is to a back and forth motion. The looser and wider the graph the more the tidal velocity will travel left to right as well as back and forth. The flow direction graph identifies and isolates that component of the flow that is in the long channel direction and therefore aligned with a fixed rotor.

In this report one complete day has been used to generate the flow direction graph for each site. This graph is representative of the flow direction at that site throughout a tidal cycle.

3.2.4. Water Column Profile

A water column profile illustrates the vertical profile of the current in order to examine the extent to which the horizontal velocity is vertically sheared. The graphs at each site show the vertical profile at maximum spring velocity and the changes in these profiles over the next 4 hours.

The vertical profiles highlight the bottom boundary layer, caused by friction with the seabed where the velocity is gradually reduced to a theoretical zero as it approaches the bed (Kaczmarska, 2008).

The ADCP was set up to record to a height of 40.5 meters above the device at a frequency of 0.6 MHz. Therefore the top of the water column at all three sites has not been recorded. This is not an issue, as there are no turbine technologies available to date that can extract energy from the surface in 40 meters of water or more. At the limit of the ADCP's range (i.e. at 40.5 meters away from the device) there can be larger sources of error caused by side-lobe reflections from the ADCP. This is where reflections from side beams interfere with another beam and cause anomaly data (Plimpton *et al.*, 2004). Side-lobe reflection is inevitable when using an ADCP, as used in this data; It is simply an observational constraint.

3.2.5. Flow Exceedance Probability Curve

A flow exceedance probability curve represents the relationship between the magnitude of the velocity and the frequency with which that magnitude occurs (Vogel *et al.*, 1994). The curve is a cumulative frequency curve that shows the percentage of time that a flow is equal to or greater than a given value (Corvallis Forestry Research Community, 2012). In this report 1 m/s has been highlighted as a value of interest as this is the cut in speed of some turbines. The longer the current is above 1 m/s the more energy that can be produced.

Exceedance probability is based on the following equation:

$$P = \frac{u}{(n+1)} \quad \textbf{(6)}$$

Where:

P =Exceedance probability

u =Rank of the velocity (where the data is put into descending order of magnitude and assigned a number, where the largest number is = 1 and the smallest = 0).

n =Total number of data points

4. Electricity Generation from Tidal Streams

4.1. Theory of Power from Tidal Streams

Continents effectively create basins around which tidal waves travel. In the centre of these basins there is virtually no tidal range. This is called an Amphidromic Point (AP) (Kvale, 2006). AP's occur all around the world. The further away from an AP the larger the tidal range, although this is heavily affected by other factors such as latitude, topography and atmospheric forcings (NOAA, 2008).

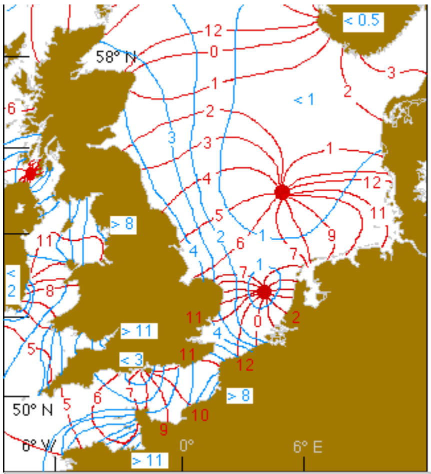


Figure 6: Map showing AP's around the UK. Red lines show path of tidal wave with time shown in hours on the lines. Blue lines show tidal range. **Source:** Eyelotment. (2011)

Around the UK there are several AP's. The closest one to Guernsey and Sark is the one positioned in Southampton (figure 6). Due to the distance from the AP the tidal range is large around the Channel Islands and is amplified due to the shape of the basin within which the Channel Islands are positioned. A tidal range of 10 meters is experienced in Guernsey (Guernsey Harbour Authority, 2011). The large tidal range has the ability to produce strong tidal currents, due to the large volumes of water moved towards and away from the coast during the regular semi-diurnal tidal cycle.

Once a suitable tidal stream has been identified with a dominant long channel component, the amount of energy that can be extracted has to be considered. A turbine will only extract energy from the portion of the water swept by the turbine blades (Fraenkel, 2001).
The equation used to calculate the amount of energy contained in a parcel of water is given by: (Fraenkel, 2001)

$$P_{flux} = \tfrac{1}{2}\,\rho A\overline{U^3}\ \text{Watts} \qquad (7)$$

P_{flux} = Kinetic Energy Flux in $kgm^2\,s^{-1}$ (Watts)

ρ = Density of sea water in kgm^{-3} (around 1025 kgm^{-3} for Guernsey) (Millero *et al.*, 1976)

A = Cross-sectional area of the turbine blades in m^2 (πr^2 where r = length of rotary blade in meters)

U = Flow velocity of the current in ms^{-1} at the rotor hub. The cube rule is used to turn the current speed into power.

Equation 7 quantifies the total amount of power contained in the area swept by the turbine at a given velocity. A turbine will never be able to extract 100% of the energy contained in the system. For wind turbines it is physically impossible to extract more than 59.3% of the energy contained in the system as stated by the Betz Limit, established by Albert Betz, who concluded that due to the very design of wind turbines it was not possible to extract more than this percentage. The turbines need the wind to continue to flow past them in order to turn the rotor. If the turbine was to extract 100% of the energy there would be no flow on the other side of the turbine (REUK, 2007). Assumptions made within the Betz Limit are unrealistic for tidal turbines, as the original Betz Limit assumes the flow is unrestricted. In reality the tidal flow is constrained at the surface and at the sea bed. The variable surface layer is another key component not considered in the Betz Limit. A theoretical upper limit for tidal turbine extraction is under development by manipulating the original Betz Limit (Garrett *et al.*, 2005).

Current calculations do not take into account the feedback between the device and the tidal flow. For example it has not yet been quantified how the placement of a turbine may affect current velocities or change the hydrodynamics of the flow, including an increase in turbulence. This is a key area where our understanding of the environment is still lacking (Bryden *et al.*, 2006).

At present it is the efficiency of the turbine that is limiting the amount of energy that can be extracted from the system. Parameters such as generator efficiencies (95%), drive chain efficiencies (96%) and power conditioning efficiencies (98%) need to be factored in but the overriding efficiency is that of the turbine rotor which is 45% (Hagerman *et al*., 2006). The efficiency of the turbine rotor is linked back to the Betz limit. Present rotor designs limit the extraction to 45% of the total amount of energy contained in the current (REUK, 2007). All of these different efficiencies combine to give a general overall efficiency of approximately 40%. However this will vary slightly depending on the chosen device (Hagerman *et al*., 2006).

Equation 7 represents a simplified equation used to give a reasonable approximation of the amount of power contained in a fluid system. In reality the more accurate equations are much more complex and involve a more accurate estimation of velocity. Due to the dependence of power on the velocity cubed, it is important to ensure that errors in estimates of the velocity are minimized. Within the range of velocities typical for tidal plants, say 1.5m/s to 2.5m/s, an error of just 0.05 m/s in velocity can lead to errors of up to 6% in power (EMEC, 2005). The value of velocity used should be the cube root of the mean, over the swept area, of the speed cubed. The equation for this is shown in equation 8 (Bryden *et al.*, 2006).

$$\left[\overline{(u^3)}\right]^{\left(\frac{1}{3}\right)} = \frac{4}{\pi D^2}\int_{-\left(\frac{D}{2}\right)}^{+\left(\frac{D}{2}\right)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u^3(y+z_0)dy \qquad \textbf{(8)}$$

However, this report is intended as a preliminary assessment of the potential power contained in the system. Therefore the more generalised approximation of velocity at the rotor hub, the centre of the turbine, as used in equation 7, will be utilised in calculating the power from the tidal stream at each site. This approximation is justified by data that demonstrate a lack of significant vertical shear in the horizontal velocity once the bottom boundary layer and near surface region is neglected. Should a significant vertical shear exist then the 1/7th power law would apply and the use of equation 8 would be deemed necessary. The 1/7th power law provides an effective relationship for turbulent mean velocity profiles in moderate flows (De Chant, 2005):

$$\frac{u}{U_e} = \left(\frac{y}{\delta}\right)^{1/7} \qquad \textbf{(9)}$$

The relevant equation(s) (7, 8 & 9) will be used in the analysis for power generation for all three sites as required. An efficiency of 40%, as stated by the EPRI report (Hagerman *et al.*, 2006), will also be applied to the resulting power to give a realistic figure for the amount of attainable energy, rather than the total amount of energy contained in the system.

4.2. Power Data Analysis

The following types of analysis will be conducted in MATLAB after the velocity data has been passed through equation 7.

4.2.1. Power Curve

A power curve shows the relationship between the flow velocity and the amount of power produced. The power curve is created by plotting velocity against the power that can be extracted from the water.

4.2.2. Average Hourly Power Output

Data were collected every ten minutes by the ADCP device. This means there is a value of velocity recorded every 10 minutes. Therefore caution must be exercised as a high velocity may only occur once in a 10 minute window over the course of the dataset. Smoothing techniques are used to average out irregular components (Toporowski, 2011). Therefore a more representative figure for the overall power output would be achieved were the data to be averaged over an hour.

Smoothing was achieved by using equation (10) where the velocity values were added over the course of an hour and then averaged. This was repeated for each hour in the dataset. The resulting values of velocity were then passed through the power equation (equation 7) and plotted.

$$\overline{u} = \frac{\sum_{i=m}^{n} u_i}{n} \tag{10}$$

Where:

$\overline{u}$ = Averaged velocity

n = Upper bound of summation

i = Index of summation (increments of 1)

m = Lower bound of summation

4.2.3. Calculating Total Power Output per Month

Accurately quantifying the amount of power a site is able to produce is crucial to understand how viable a site might be for development. This study covers a full month of data which means it is possible to accurately calculate the total amount of power per month and by extrapolation obtain an estimate for the amount of power a turbine could produce in a year. For many potential developers the annual amount of energy a turbine can produce is the most useful statistic as it can be compared with the local annual power consumption. Using the annual power figures removes variability from the system. The power produced by a turbine will vary depending on the sample time within the neap-spring cycle, in the same way as consumption will vary depending on the time of day and season of the year. A look at a total years consumption and production of energy, removes these short term variables and allows for fair comparison.

To calculate how much power could be generated in a month from a single turbine technology:

$$Mp = \sum_{i=1}^{n} P_{flux} \qquad \textbf{(11)}$$

Where:

Mp = Monthly power output

n = Upper bound of summation i.e. number of time steps

I = Index of summation (increments of 1)

P_{flux} = Kinetic energy flux (as calculated from equation 7)

Calculate the amount of power at each 10 minute time step from the dataset for the whole month, ensuring 40% turbine efficiency is applied. Sum up all of these values to create a cumulative value for the total amount of power produced over a month. This value can be scaled up to the amount of power per year.

4.2.4. Spring-Neap Analysis

It is possible to break down the power output to identify the difference between the power generated by a neap and a spring tide. The average height of a spring tide is 7.8 meters and the average height for a neap tide is 3.4 meters. The maximum tidal range in Guernsey is 10 meters (Guernsey Harbour Authority, 2011). To quantify the power in a spring neap cycle, the boundary between a spring and a neap has to be defined. In this report the boundary from a spring to neap was defined as below:

Highest Tide	10 m		
		2.2	Gap of 2.2 meters between values
Mean Spring	7.8 m		
		2.2	
Boundary tidal height of a neap to a spring tide	5.6 m		
		2.2	
Mean Neap	3.4 m		

This boundary of 5.6 meters between a neap and a spring tide can be applied to the dataset.

Once the dataset is divided into spring and neap sub sets, the amount of power produced in each sub set is calculated by computing the power generated at each 10 minute time step and then integrating the power generated over the time period over which each sub set section of spring or neap tides occur.

5. Practical Resource

A study conducted by the Robert Gordon University in Aberdeen mapped the tidal resource around Guernsey using a software algorithm and Admiralty Tidal Stream Atlas data (Figure 7) (Owen, 2012). The map is colour coded to show which areas are expected to contain the highest energy potential. The approximate positions of the sites used in this report have been added. From the areas highlighted the expected resource is high for Site 1, potentially around 250GWh per year. In comparison Site 2 and Site 3 are expected to contain much lower amounts of energy with 48GWh and 35GWh respectively (Owen, 2012). This can be compared to Guernsey's annual energy consumption of 400 GWh per annum (University of Exeter, 2012).

A number of limitations of the Robert Gordon University Study (RGUS) estimates necessitate the analysis of direct observations of the tidal stream resource. Firstly the map resolution is very coarse. Each grid is one square kilometre. Over an area of this size there can be significant changes in the depth of the water and topography, especially when considered close to the coast. Topography has an important impact on tidal currents and can act to dramatically enhance currents around a topographic feature. Small scale topographic changes that will elicit a response in the tidal streams are therefore not resolved by the map.

Secondly, the calculated value for energy is for the whole of the water column. This contains two large assumptions. The first is that the flow velocity is constant throughout the whole of the water column and the second is that the whole of the energy present in that column can be extracted. A turbine has a finite diameter and can therefore only extract energy over a given portion of the water column. If a large amount of energy is spread over a large water column, then only a small fraction of the energy contained within the entire water column can be extracted by the turbine.

Another resource assessment was carried out by the University of Exeter. Their report suggests that the Big Russel could contain 566 GWh per annum. This figure is for the whole of the Big Russel, but has also taken into account turbine diameters, turbine efficiency and the spacing of turbines in an array, although it has not stated what these individual parameters are (University of Exeter, 2012).

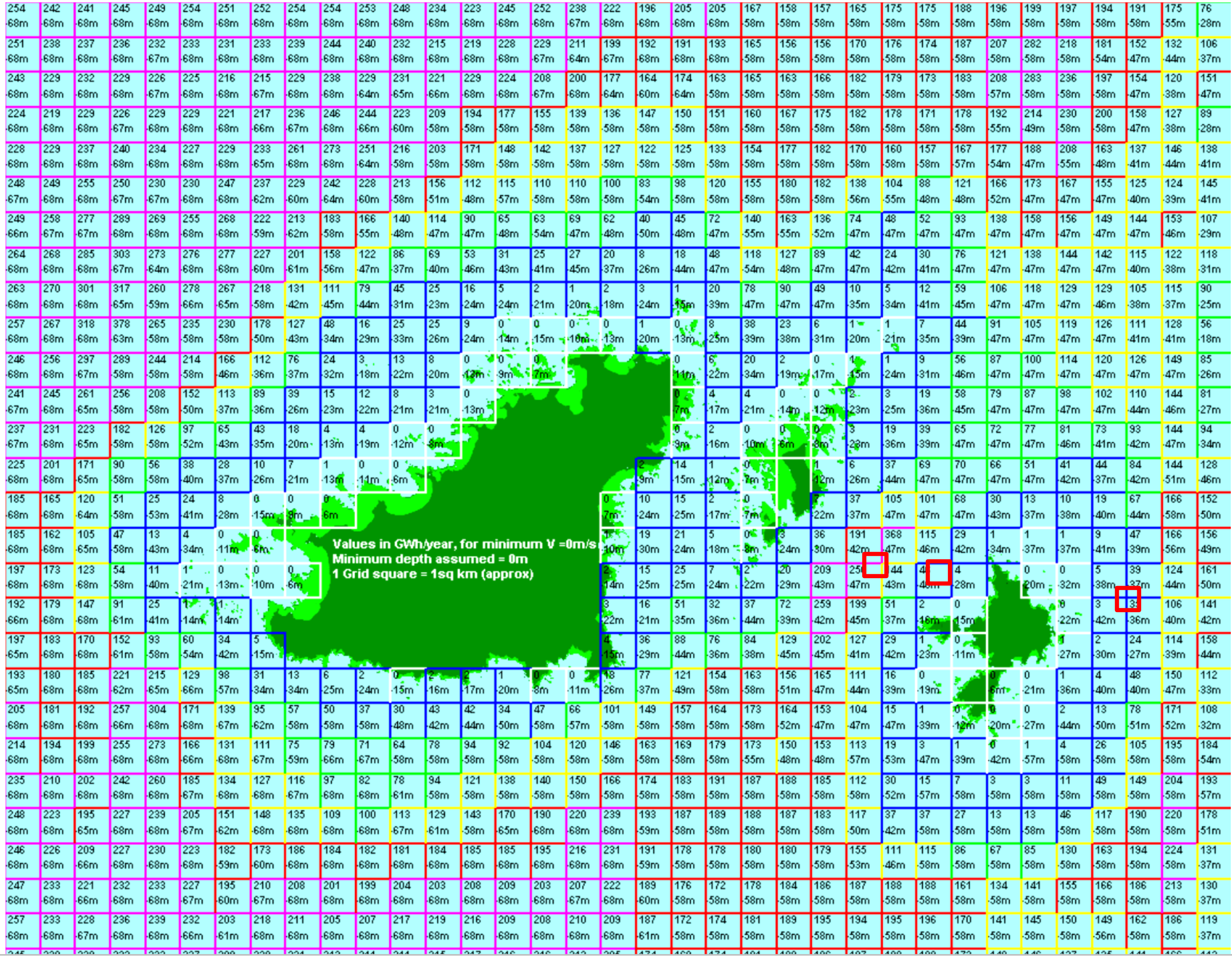


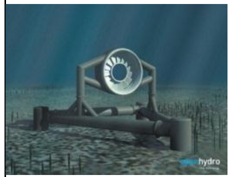
Figure 7: Image taken from the RGUS showing kinetic energy contained in the waters around Guernsey. The additional red boxes in bold highlight the locations of the sites analysed in this study. Everything coloured in whites and blues have a low energy value and boxes in red and pink have the highest energy values. The energy shown is total GWh per annum.

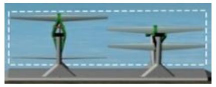
Source: Owen. (2012)

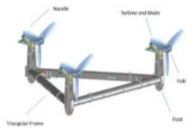
6. Technology Overview

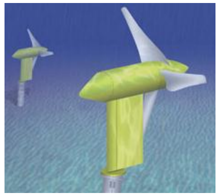
This section reviews the available technology that could be used to extract the energy found in the tidal system. There are a very large number of different devices at various stages of development. This table allows a brief look at some of the proven devices that are the most likely to be considered for any development around Guernsey. Note that this is a small selection of devices and that new devices are being built and developed continually in a rapidly changing market. The characteristics of each device that could be used to extract the energy are important to consider given the specific environment in which the device would be operating in terms of resource, water depth and where in the water column the energy is to be extracted.

Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Marine Current Turbines	Siemens	SeaGen 'S'	Monopile structure, horizontal axis turbine. 16 metre turbine diameter	 Source of information: Marine Turbines. (2012)	1.2 MW with 2.4m/s current	38 meters	Ready for commercial deployment.	Kyle Rhea, west coast of Scotland. Potential for an array of 4 turbines totalling 8MW.	Large amount of operational time since 2008. Proven limited environmental impacts. All equipment to convert energy is inside the device. Monopile structure allows easy maintenance	Limited by depth, Monopile structure has a visible impact, large consideration for a tourist island. Needs to be aligned correctly with current for maximum efficiency.

Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Open-Hydro	Privately owned group, located in Ireland	The Open-Centre Turbine	Horizontal turbine on a gravity weighted triangular base	 Source: OpenHydro. (2012)	1MW and 2.2 MW devices	50 meters	Ready for commercial deployment	Alderney, Channel Islands. Potential for the area to generate 3 GW from an array	Proven turbine design. Submerged design reduces visual impact. Limited overall environmental impacts. Potential 2.2 MW is high. The device is also lubricant free and there is only one moving part.	Turbine position on the seabed means it can only extract energy from the area above the bed. Needs to be aligned correctly for maximum efficiency.
Atlantis Resource Corpora-tion	Privately owned company, with head-quarters in London and Singapore	AR-1000 Series Turbine	Horizontal Axis Turbine, 18 metre turbine diameter	 Source: Atlantis Resource Corporation. (2012)	1.0 MW with 2.65m/s current	Deep Water	Final full scale testing at EMEC since 2011 in preparation for commercial deployment	Pentland Firth. Sole rights to develop a 398 MW site providing power to 40,000 Scottish homes.	Proven turbine with device installed at EMEC. Submerged design has no visual impacts. Limited overall environmental impacts.	Turbine can only extract energy from just above the seabed. Potential seabed impacts. Device has to rotate mechanically into flow at slack water which could increase maintenance costs.

Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Tidal Genera-tion Limited (TGL)	Rolls-Royce PLC	TGL Turbine	Horizontal Axis Turbine, 18 meters turbine diameter	 Source of Information: Tidal Generation Limited. (2012)	1.0 MW at 2.7 m/s	80 meters	In the process of building 1MW device, still being developed based on 500kW prototype.	Install the full scale 1MW device at EMEC in 2013/2014	Proven turbine design. A 500kW installed at EMEC since 2010. Device self-adjusts into flow, helping to maintain maximum efficiency. Easy maintenance. Submerged design means limited environmental impacts	Full commercial scale device still to be built. Only extracts energy from above the seabed. The 1 MW rating is not high compared to competitors. Also 2.7m/s is required to achieve the 1 MW rating. This is high for a naturally occurring current.
Pulse Tidal Ltd	Privately owned company based in Sheffield, UK	Pulse-Stream	Hydrofoil Design	 Source of Information: Pulse Tidal. (2012)	1.2 MW	45 + meters	100kW design proven and generating energy since 2009. Work still continuing on full scale device	Secured a site at Lynmouth, UK for 1.2MW commercial demonstra-tion.	Compact design means it can be deployed in shallow waters where other turbines cannot. Submerged design with limited environmental impacts	Needs the current to conform to a forward and back motion – alignment into the current is crucial.

Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Tidal Energy Ltd	Privately owned company based in Wales.	Delta Stream	Horizontal Axis Turbine. 3 turbines mounted on a triangular frame	 Source of Information: Tidal Energy Ltd. (2012)	1.2 MW for 3 turbines	Deep ocean	Full scale device is still being built and tested	Ramsey project, Wales. Plans to deploy full scale turbine by 2013 which is grid connected for 12 months.	Auto adjusts into current. Quick deployment and relatively simple maintenance. Submerged design with limited environmental impacts. If one turbine breaks power is still produced from 2.	Needs three turbines to produce 1.2 MW. The more turbines used in a tidal farm the more there is to break down. Only extracts energy just above the seabed.
Hammer-fest Strom	Andritz Hydro	HS1000	Horizontal Axis Turbine, 20 meters turbine diameter, stands 30 meters off bed.	 Source: Andritz Hydro Hammerfest. (2012)	1 MW	100 meters	1 MW pre commercial demonstrator installed at EMEC in December 2011	Sound of Islay Tidal Power Project, Scotland. Total of 105 MW potential	Submerged design, limited environmental impacts. Pitch of blades change to account for variations in current direction. Gravity base reduces need for piling operations.	Needs to be aligned into current with accuracy. Changing the pitch of the blades is potentially vulnerable to error. Once again can only extract energy above the seabed.

Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Verdant Power	Privately owned company, based in New York, USA	Free Flow System	Horizontal Axis Turbine, 3 Turbines on 1 platform. 5 meter diameter turbines	 Source of Information: Verdant Power. (2012)	35 kW each. 105 kW total for 3 devices	Depth limit is not stated	Fully developed to commercial scale. Already an array installed at the Roosevelt Island Tidal Energy (RITE) project.	CORE project on the St. Lawrence River, Cornwall, UK. Total project size of 15 MW	Submerged design, well tested with the RITE project. Proven to have minimal environmental impacts. One of the few devices already proven in an array. Auto adjusts into the current	Low amount of energy per device. Only extracts energy just above the seabed.
Voith Hydro	Voith and Siemens company	Voith Hydro Tidal Current Turbine	Horizontal Axis Turbine	 Source: Voith Hydro. (2012) and RWE. (2012)	1 MW	Over 30 meters	110 kW prototype is installed at EMEC for testing. Developments have started on the 1 MW device	Site on the South Korean coast where turbines are being tested.	Fully submerged design. Limited environmental impacts. Uses the seawater as a lubricant reducing risk of oils leaking into marine system.	Energy extracted just above the seabed. Device doesn't adjust into flow. This means the device has to be aligned with tidal current correctly to maintain maximum efficiency

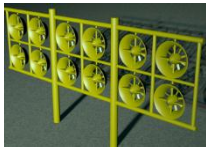
Company	Owned By	Device	Device Design	Picture and Reference	Max Power	Max Depth	Stage of Development	Next Project	Advantages	Disadvantages
Offshore Islands Ltd	Private company based in Texas USA	Current Catcher	Horizontal Axis Turbines inside a frame. Forms a fence.	 Source of Information: Offshore Islands Ltd. (2012)	Each turbine is 0.6 MW	Deep Ocean	Early stages of design, still at prototype stage.	Marine Power Project. A joint venture project where many marine devices can be tested at the same time.	Cone shape helps to funnel water into turbine. Many turbines can be grouped together extracting energy from large area of the water column. Has the potential to extract energy higher up the water column whilst still being submerged. Frame size can be adjusted.	Still in development stage, needs to be proven. Needs to be aligned correctly with the current for maximum efficiency.

Table 2: Table showing tidal turbine technologies

7. Royal Yachting Association (RYA) Regulation

There are regulations determining how close to the surface of the water the turbine blades can reach. The Royal Yachting Association (RYA) states that in order to reduce the risk of collision with a tidal turbine, the blades of the devices should be 8 meters below chart datum, primarily due to the high tidal environments in which the devices will be placed (RYA, 2012). This regulation has to be considered before selecting a tidal turbine device for a development site.

Guernsey is regularly visited by cruise liners. One of the largest is the Queen Elizabeth II (QEII) which has a draught of 10 meters (Ship Technology, 2011). Consideration will need to be given to legislation to protect turbines and large vessels, in order to highlight areas of safe passage.

8. Data Analysis

The three data sites will be analysed using the equations and methods outlined in sections 3 and 4.

8.1. Velocity

Figures 8, 9 & 10 show the collected data in its raw state at a height of 20.5 meters above the ADCP device. This depth was chosen as it represents a point outside the bottom boundary layer and is therefore unaffected by flow retardation by the boundary and is also far enough below the surface boundary layer so as not to be affected by surface friction.

The data at Site 1 were collected from 15th November (year day 318) to 22nd December 2011 (year day 348). Figure 8 shows the highest velocity achieved is just over 2.5 m/s. The fortnightly spring-neap cycles can be clearly seen as well as the differences in the height of the two spring cycles, highlighting the expected variability in the tidal system.

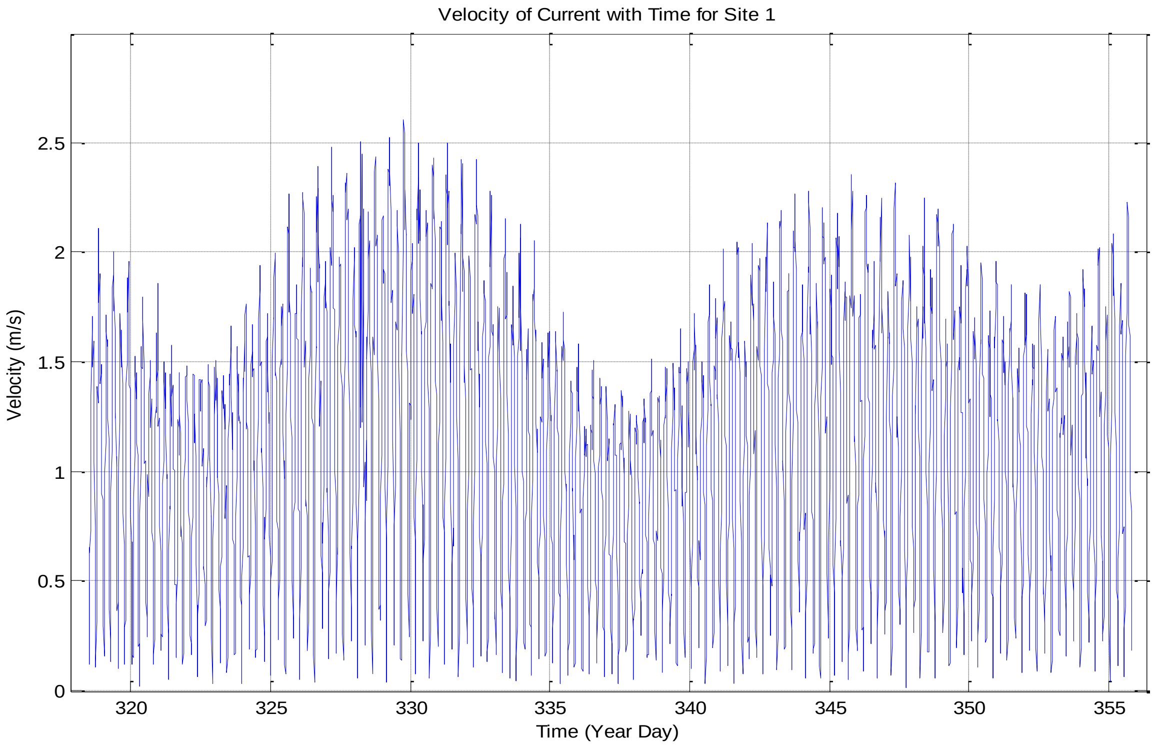


Figure 8: Graph showing velocity at 20.5 meters height above the ADCP device for Site 1

The data at Site 2 were collected from 7th January (year day 6) to 7th February 2012 (year day 37). Figure 9 shows that, as with Site 1, the current speed reaches a peak velocity of over 2.5 m/s on a spring tide. At a first glance the higher velocity of 2.5 m/s is achieved more frequently at Site 2 meaning this site could potentially contain higher energy waters.

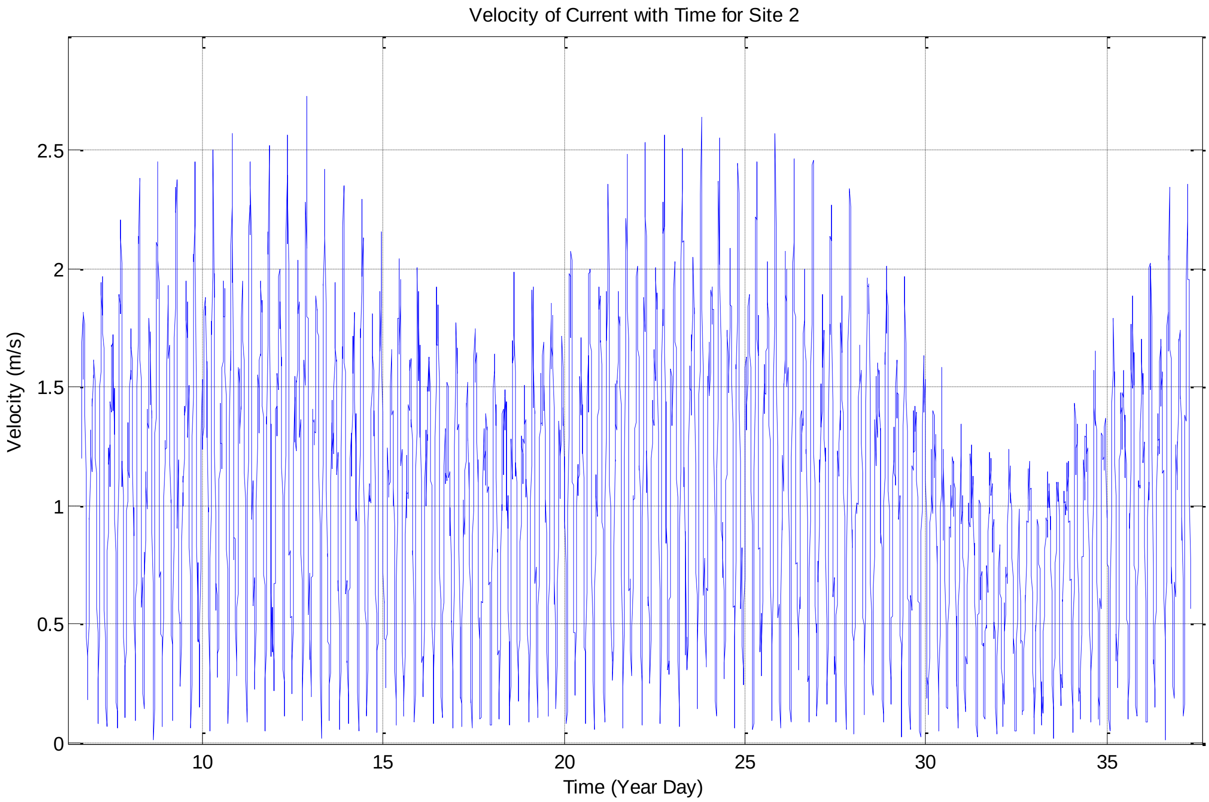


Figure 9: Graph showing velocity at 20.5 meters height above the ADCP device for Site 2

The data at Site 3 were collected from 20th February (year day 50) to 22nd March 2012 (year day 81). Figure 10 shows the current reaching a velocity of 2.1 m/s on a spring tide. This is lower than the 2.5 m/s reached at both Sites 1 and 2.

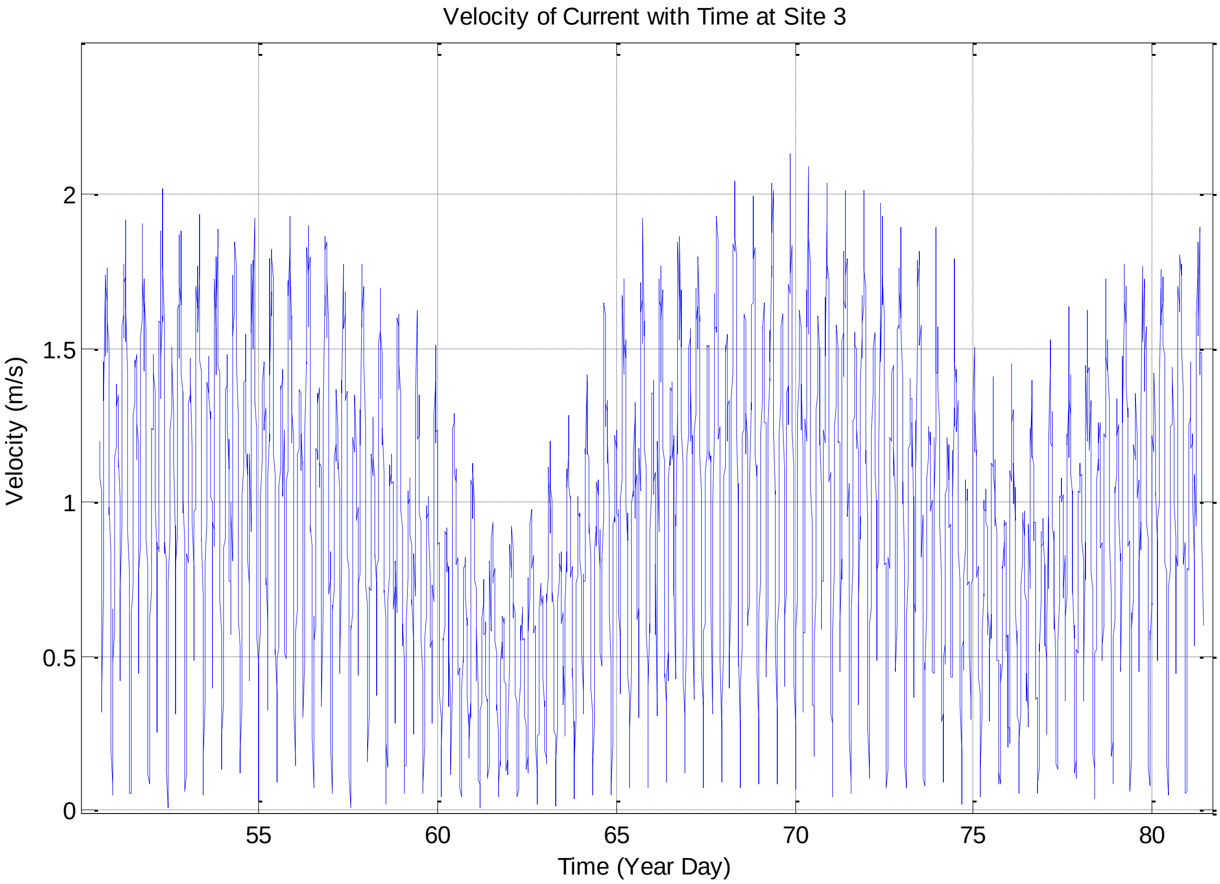


Figure 10: Graph showing velocity at 20.5 meters height above the ADCP device for Site 3

8.2. Separating U and V Components

Separating the U and V components at Site 1 produced a graph that showed the V component of flow is stronger than the U component by a ratio between 9:5 and 3:2 on the flood and a ratio between 3:2 and 6:5 on the ebb. This highlights the differences between flood and ebb currents (Figure 11). On a large spring tide the flood current reaches 2.2 m/s in the long channel direction, but only reaches 1.7 m/s on the ebb. The separation of the U and V components of the tide also highlighted an error in the data that could not be seen in figure 8. At year day 328, there is a blip in the data caused by instrumental error. This will be completely ignored in further analysis.

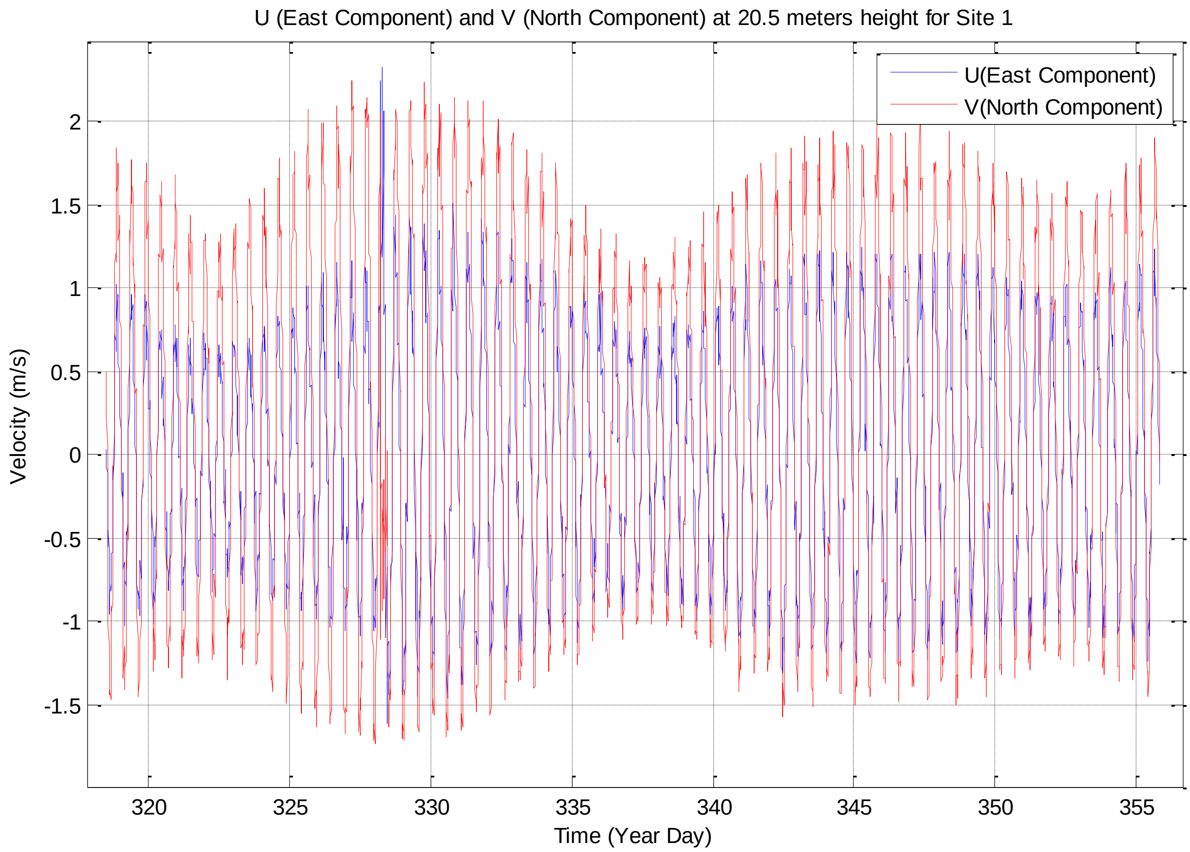


Figure 11: Graph showing the U and V component of flow at 20.5 meters height for Site 1

At Site 2 (figure 12) on the flood tide the V component is stronger than the U component by approximately 0.3 m/s. On the ebb tide the U component is also stronger by approximately 0.3 m/s. Both the V component on the flood and the U component on the ebb are stronger by a ratio of between 6:5 and 11:10. On a large spring tide the flood current reaches 2.16 m/s in the long channel direction, but only reaches 1.6 m/s on the ebb. This could imply that Site 2 is unsuitable for a turbine device due to equally large currents in the V and U directions.

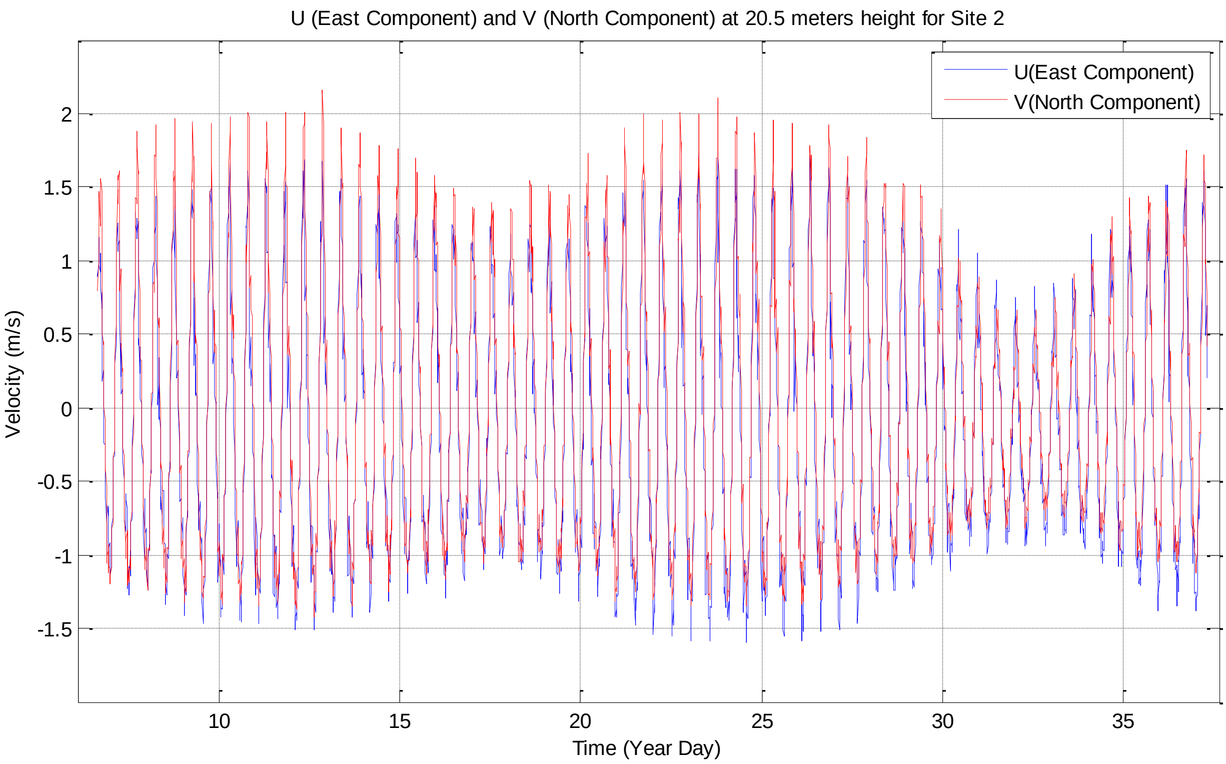


Figure 12: Graph showing the U and V component of flow at 20.5 meters height for Site 2

When Site 3 (figure 13) is split into its U and V components a graph similar to Site 1 is produced. At Site 3 the V component is stronger than the U component by a ratio of between 2:1 and 7:5 on the flood tide and a ratio of between 2:1 and 9:5 on the ebb tide. On a large spring tide the flood current reaches 1.83 m/s in the long channel direction, but only reaches 1.53 m/s on the ebb.

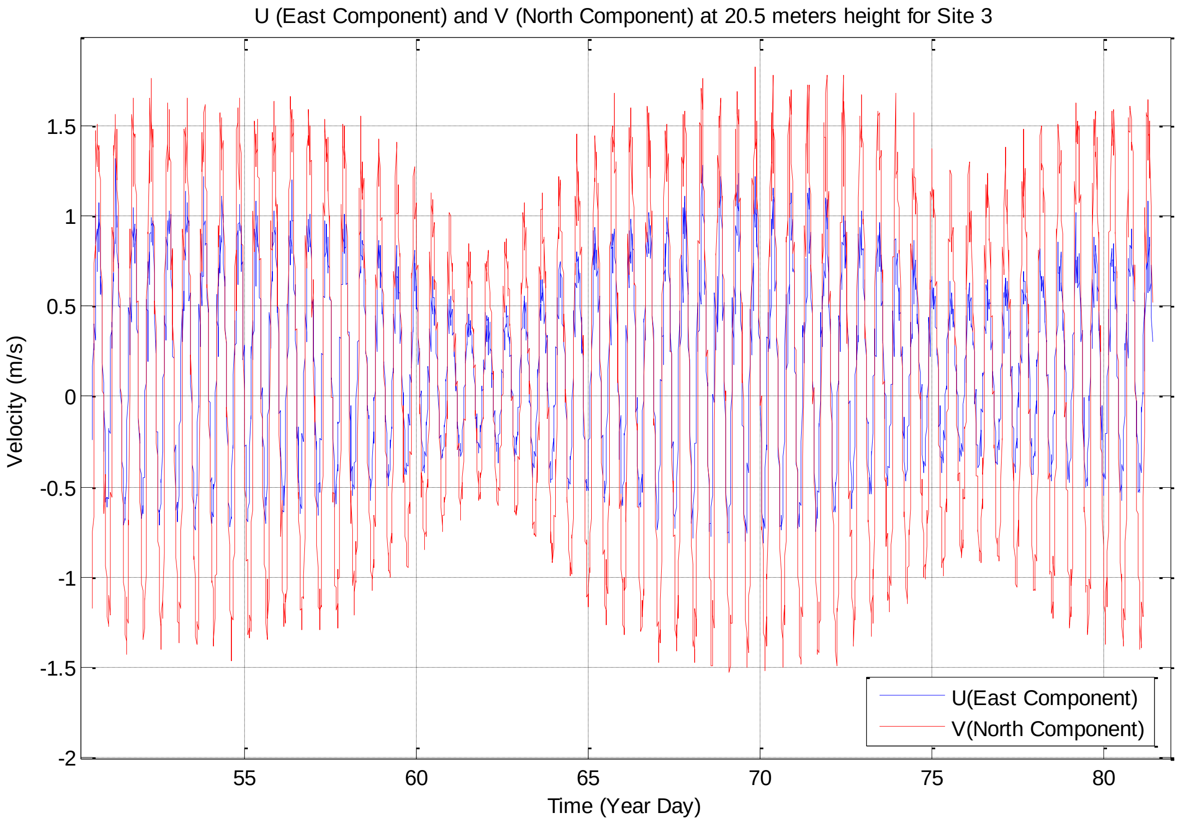


Figure 13: Graph showing the U and V component of flow at 20.5 meters height for Site 3

8.3. Coordinate Transformation

Once Site 1 and 2 are adjusted for the heading of the Big Russel, at 25.5° to the north east, the graphs change significantly (figure 14). At Site 1 the long channel flow is stronger than the cross channel flow by a ratio between 7:1 and 5:1 on the flood and a ratio between 4:1 and 3:1 on the ebb. When compared with figure 11, the alignment with the channel has magnified the difference between the cross channel and long channel currents. The long channel maximum velocities have increased by 0.4 m/s in both the flood and the ebb flows and these are now 2.6 m/s and 2.1 m/s respectively.

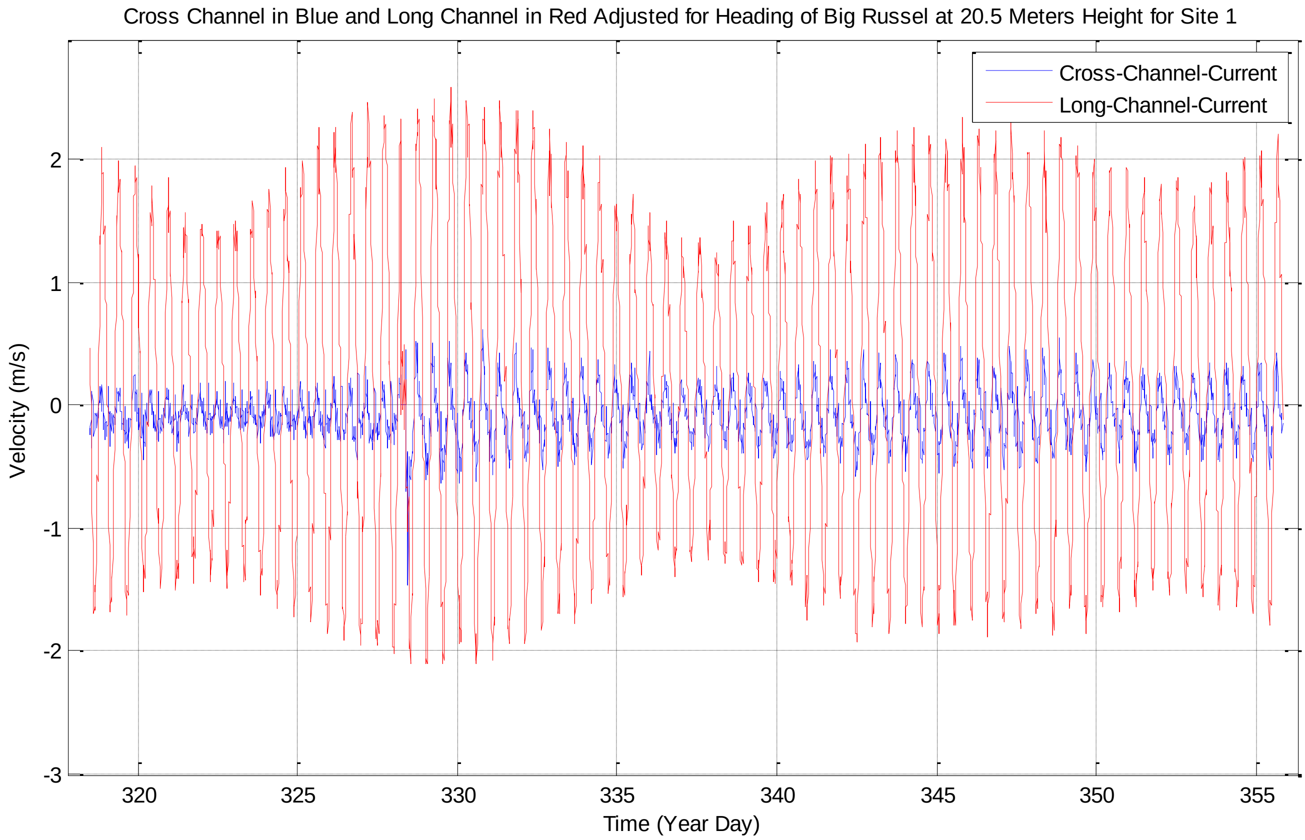


Figure 14: Graph showing cross channel and long channel velocities for Site 1

In Site 2 the long channel flow is now dominant. However the cross channel flow is slightly stronger than at Site 1 reflecting marginally more cross channel flow. Site 1 had a maximum cross channel flow of 0.5m/s on the largest spring tide whereas Site 2 has a cross channel flow that is consistently larger than 0.5 m/s reaching a maximum of 0.9 m/s. This difference is important for a fixed turbine, which is positioned in the direction of the dominant flow and therefore cannot utilise the cross channel flow. A significant cross channel flow causes stress on the turbine thereby increasing mechanical wear. The ratio between long channel and cross channel flow on the flood tide is between 17:5 and 13:5 and the ratio on the ebb tide is between 11:5 and 12:5. The alignment with the channel has magnified the long channel maximum flow velocities. The highest current velocity on a spring tide is now 2.55 m/s for the flood tide and 1.9 m/s for the ebb tide.

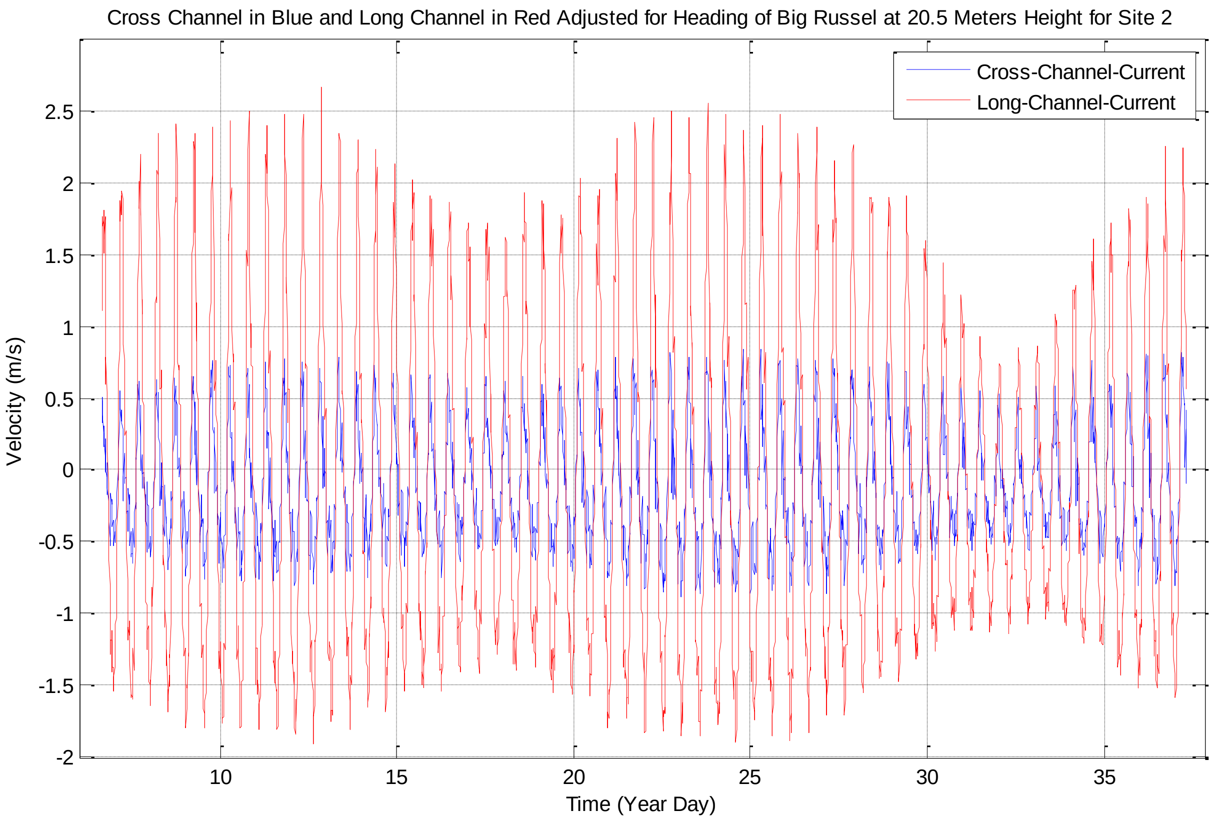


Figure 15: Graph showing cross channel and long channel velocities for Site 2

As Site 3 is not situated in the Big Russel the adjustment of 25.5^{o}, as used for Sites 1 and 2, will not be applied. When the data was collected by the ADCP device a measurement of direction was also taken. The directional data for Site 3 was averaged with respect to the tidal state, to find the primary axis of tidal flow. The analysis showed a turbine should be positioned approximately 16.2^{o} away from north to the north-east. On analysis the long current velocity was stronger than the cross current velocity on a flood tide by a ratio between 3:1 and 13:5. The long current was also stronger on the ebb tide by a ratio between 4:1 and 17:5. The long channel current reaches a maximum flood velocity of 2 m/s and a maximum ebb velocity of 1.6 m/s.

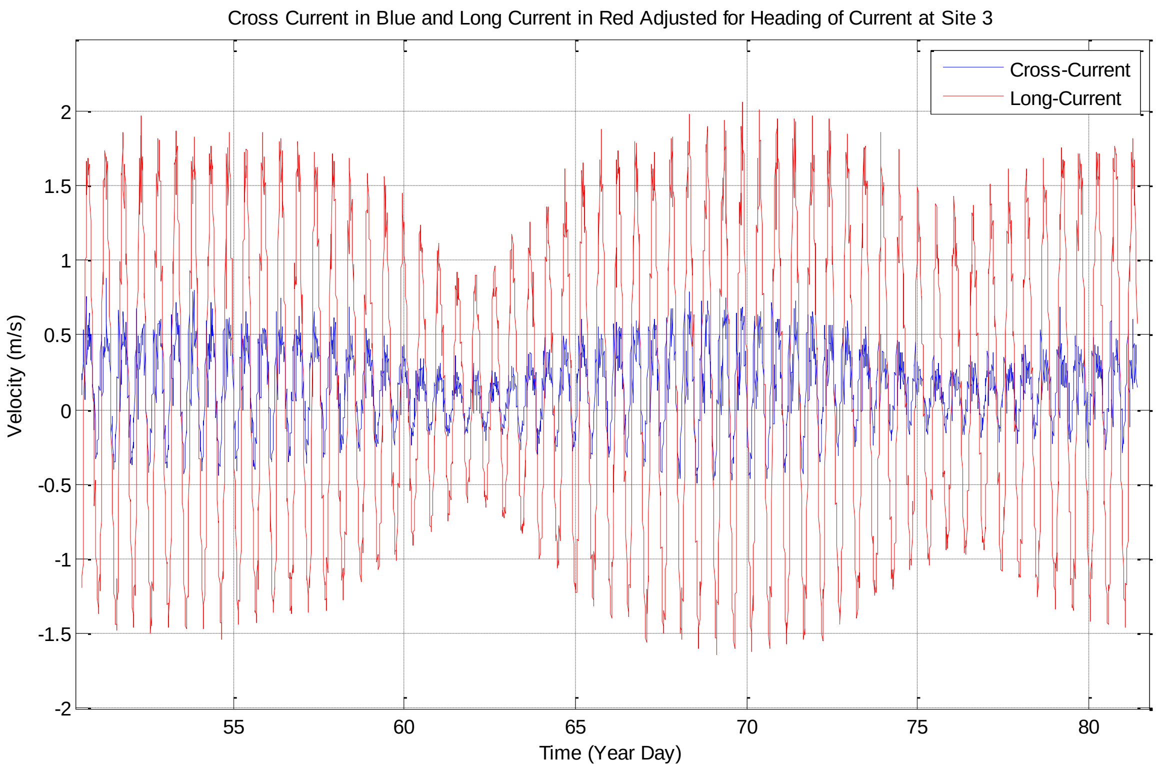


Figure 16: Graph showing cross channel and long channel velocities for Site 3

8.4. Flow Direction Graph

The direction graph for Site 1 validates the findings shown in figure 14. The graph is very narrow highlighting a predominantly rectilinear flow.

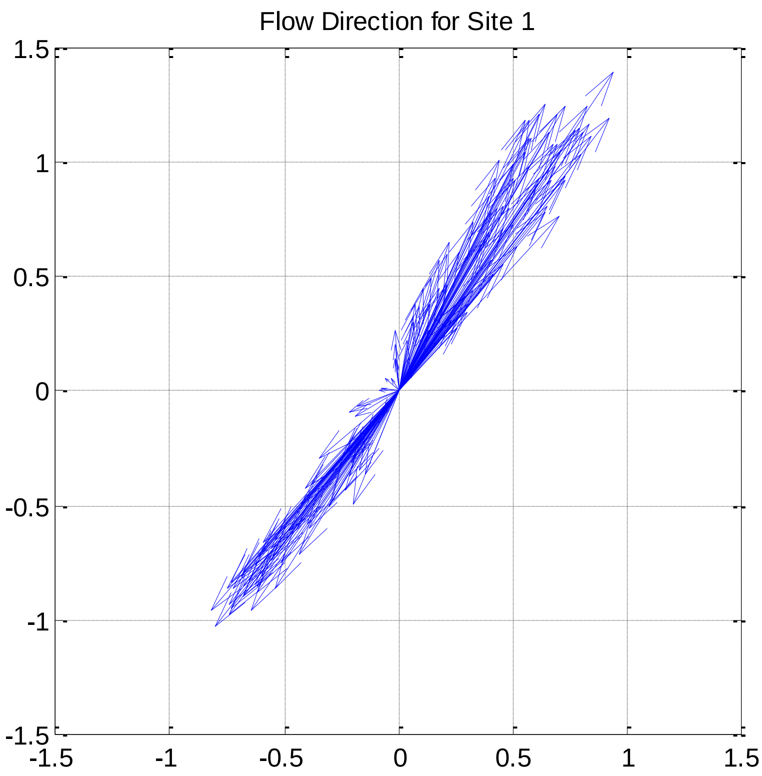


Figure 17: Velocity vectors throughout a tidal cycle at Site 1

Site 2 highlights that the flow is not as narrow as at Site 1. The top half of the flow direction graph shows much more variation. This validates the findings in figure 15, that a more prominent cross channel flow exists at this site. The cross channel component could be larger at Site 2 due to its proximity to Sark. Site 2 is positioned almost in line with a small island off Sark called Brecqhou. Brecqhou could be disturbing the flow of water past the island, causing eddies and increased turbulence. This in turn could cause increased flow in the cross channel component. A further more detailed analysis of the effect of Brecqhou on the tidal flows in the Big Russel would have to be undertaken.

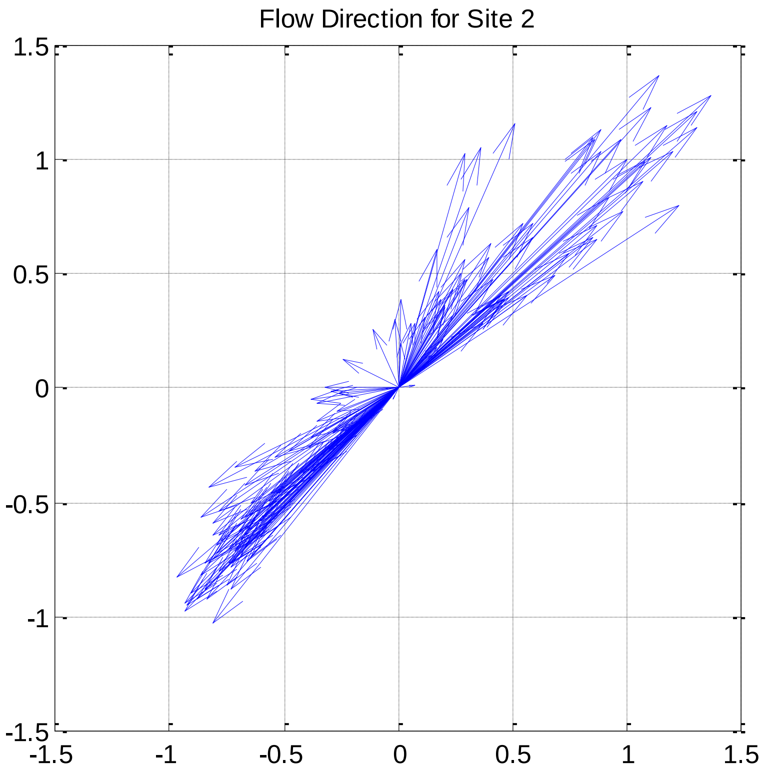


Figure 18: Velocity vectors throughout a tidal cycle at Site 2

Site 3 shows that the flow is relatively narrow at the top half of the graph. However the lower half of the ellipse shows a much more erratic current. The current appears to change direction much more when the tide is on the ebb compared to when the tide is on the flood and is uniform. This change between the flood and the ebb is brought about by the topography of the area. Although there are not any high resolution bathymetry maps of the area, it can be assumed that on a flood tide the tidal current is not affected by topography. Conversely the ebb tide has a more turbulent path which is not ideal for a tidal turbine.

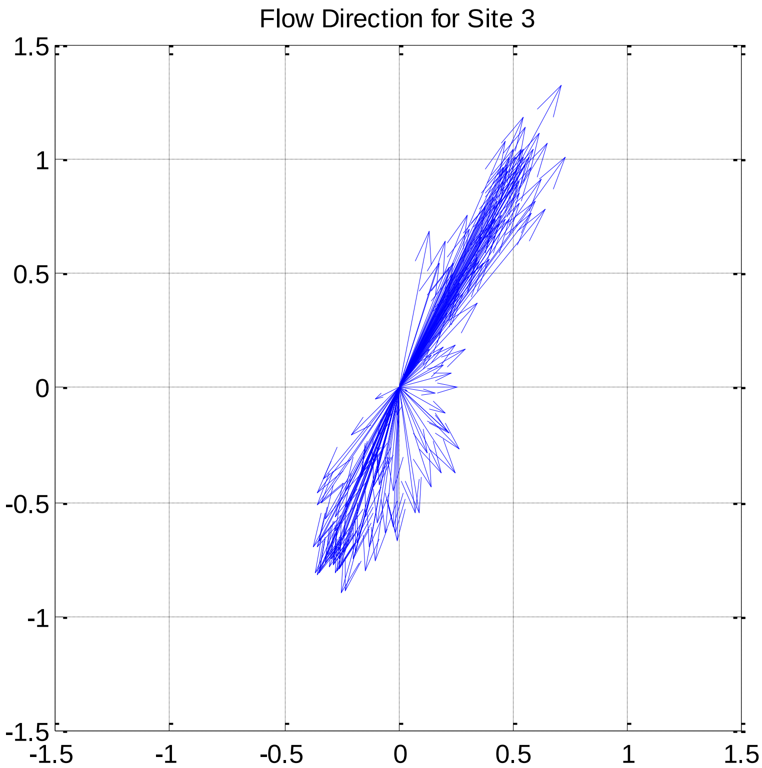


Figure 19: Velocity vectors throughout a tidal cycle at Site 3

8.5. Water Column Profile

Water column profiles of the current at each site are used to examine the extent to which the horizontal velocity is vertically sheared. Site 1 shows that the bottom boundary layer extends to approximately 15 meters above the seabed during Maximum Spring Velocity (MSV). After MSV there is a steady decrease in the velocity profile as the tide begins to change state. Two hours after MSV the current has changed from 2.6 m/s to 2 m/s at a height of 20.5 meters.

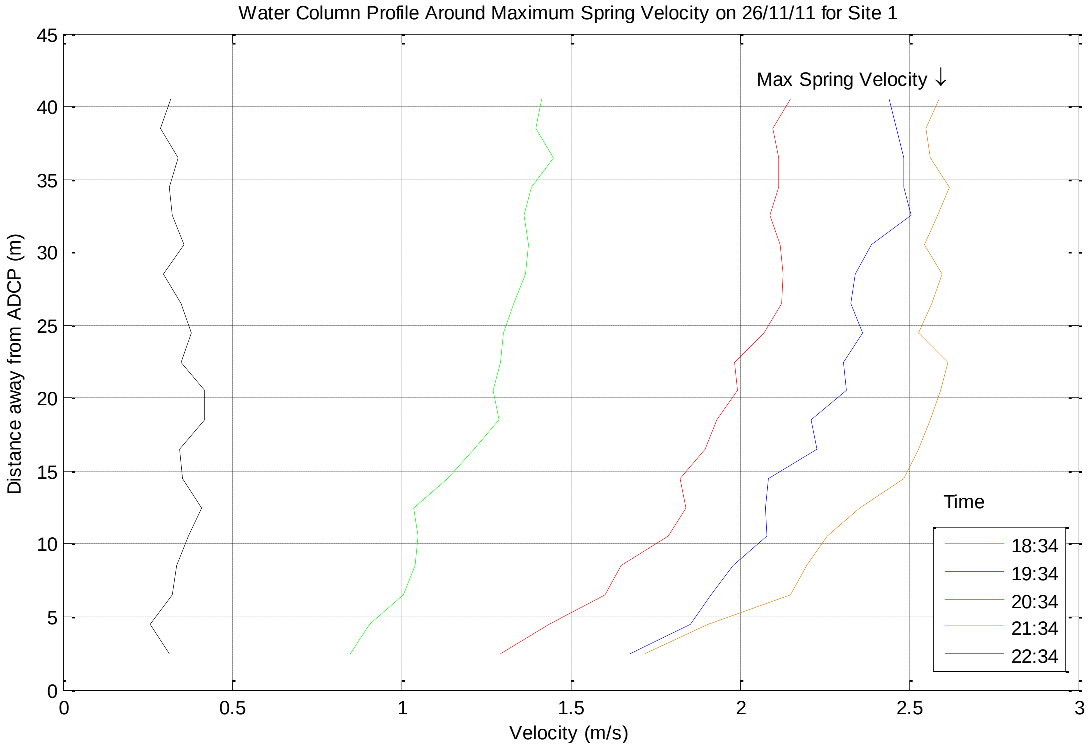


Figure 20: Graph showing water column profiles for Site 1. Reading the graph from right to left, the orange line shows the maximum spring velocity experienced in the water column. Each subsequent line shows an hour change in tidal state. Data is collected in 2 meter bins up the water column by the ADCP device

Site 2 has a different profile to that seen at Site 1. Although the maximum current velocity obtained is the same at 2.6 m/s, the rate at which the current velocity changes is much greater at Site 2; this is important when considering energy extraction. Two hours after MSV the current has changed from 2.6 m/s to 0.4 m/s at 20.5 meters height. The current offers less energy for a turbine to extract over a tidal cycle.

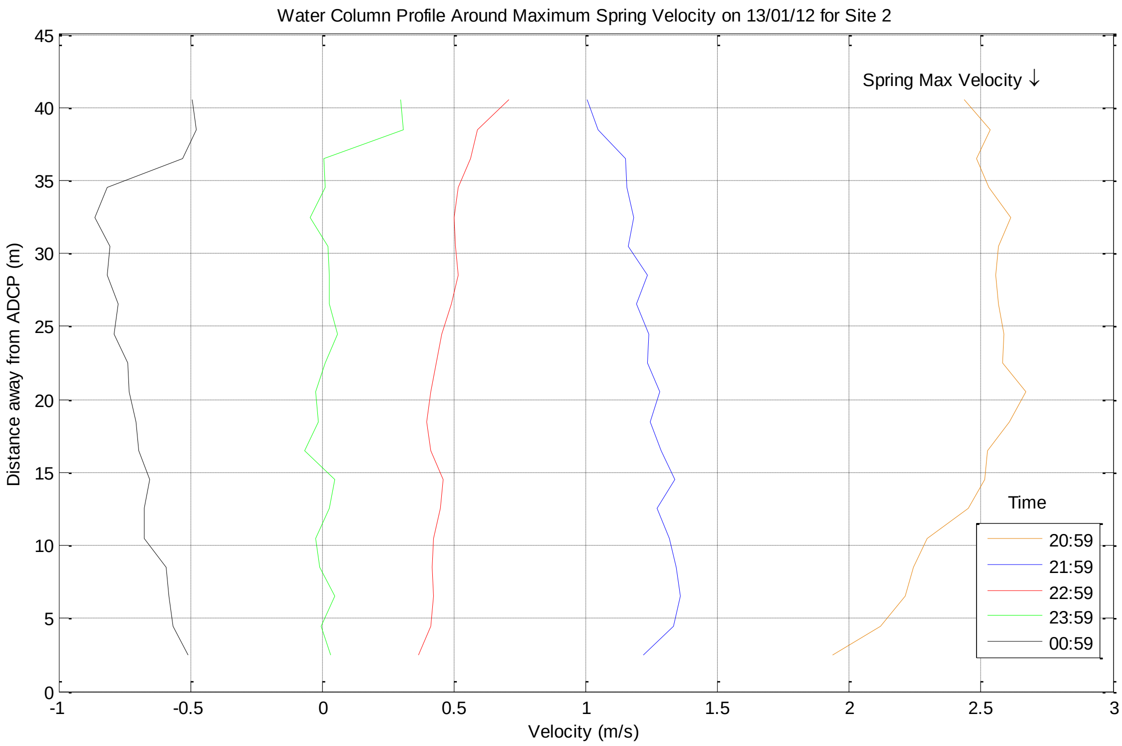


Figure 21: Graph showing water column profiles for Site 2. Reading the graph from right to left, the orange line shows the maximum spring velocity experienced in the water column. Each subsequent line shows an hour change in tidal state. Data is collected in 2 meter bins up the water column by the ADCP device.

At Site 3 there is a bulge at MSV from a height of 6 to 25 meters. It is unusual for the peak in velocity to occur close to the seabed due to friction from boundary affects. This bulge could point to the topography of the area highlighted in the discussion of flow direction at this site. The MSV is 2.15 m/s at a height of 15 meters. Two hours after MSV the current has changed from 2 m/s to 0.9 m/s at 20.5 meters height from the seabed. The drop off in velocity is not as severe as at Site 2 and Site 3 does not maintain a high velocity for as long as occurs at Site 1.

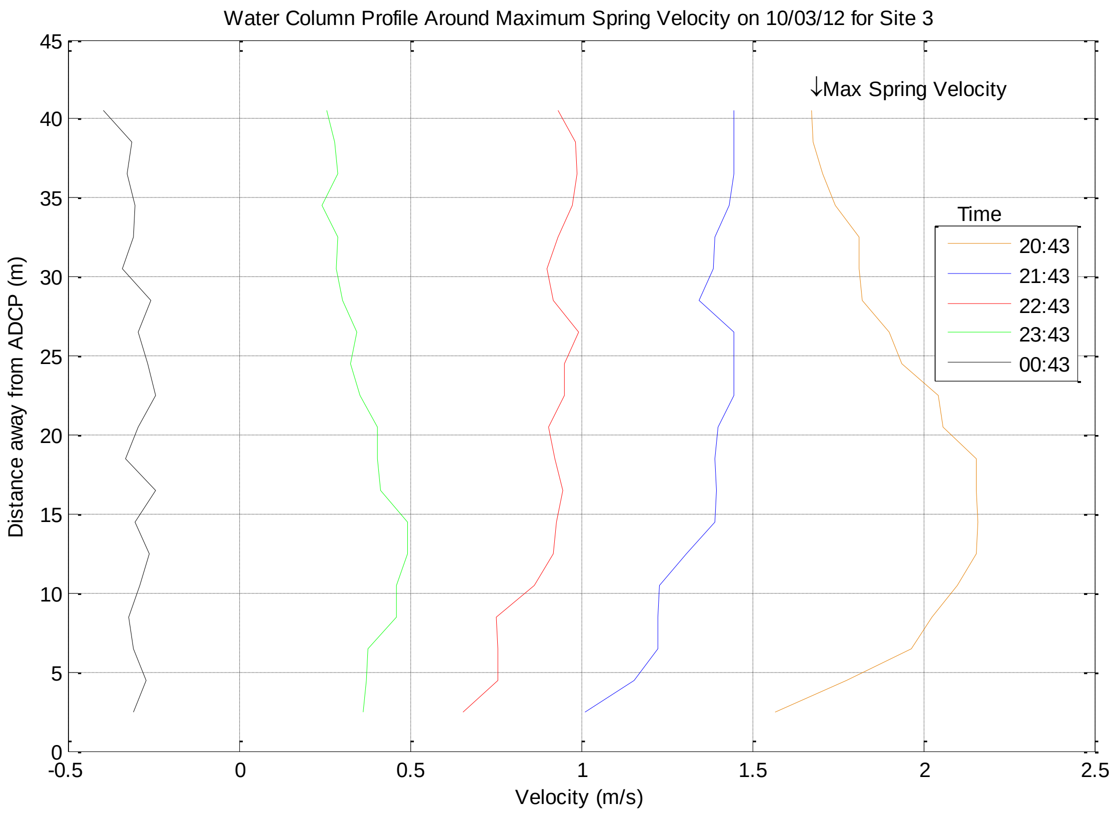


Figure 22: Graph showing water column profiles for Site 3. Reading the graph from right to left, the orange line shows the maximum spring velocity experienced in the water column. Each subsequent line shows an hour change in tidal state. Data is collected in 2 meter bins up the water column by the ADCP device.

8.6. Flow Exceedance Probability Curve

Figure 23 shows the flow exceedance curve for Site 1 at 20.5 meters above the ADCP device. The curve shows the highest velocity obtained during the data collection. Therefore the chance for this velocity to be exceeded is very low. Only during a rare event such as a large storm surge or the event of the Highest Astronomical Tide (HAT) could cause the velocity to increase further. A key factor with Site 1 is that at 1 m/s there is still approximately a 75% chance of the flow velocity exceeding 1 m/s. This is advantageous in terms of energy production as some devices may have a cut in speed of 1 m/s as marked on the curve.

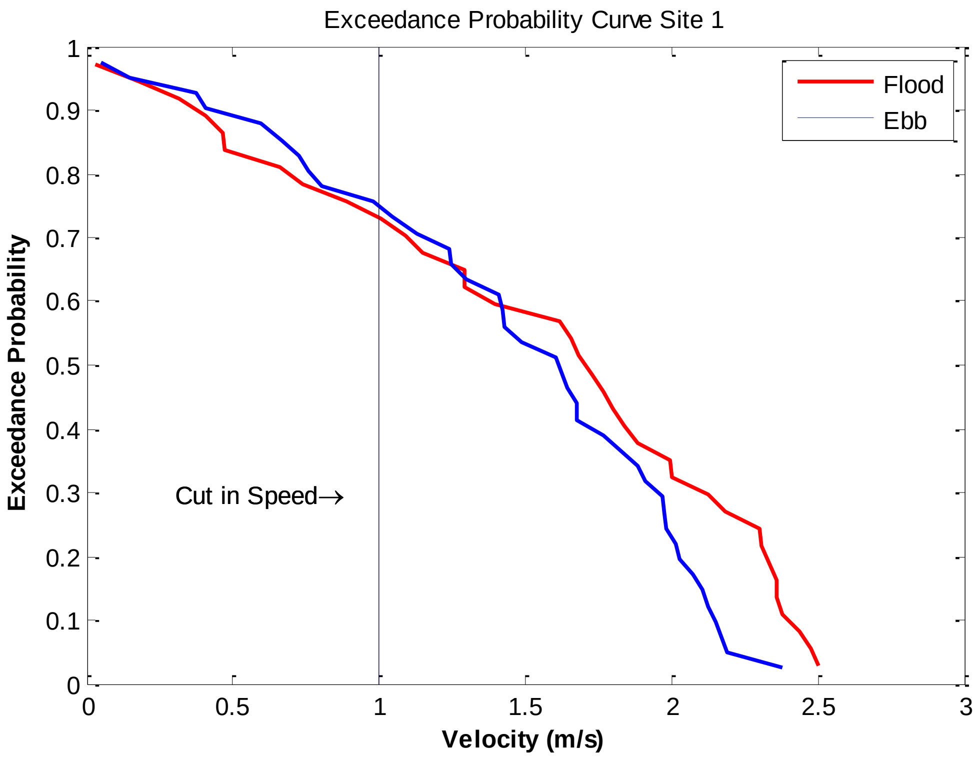


Figure 23: Flow exceedance curve for Site 1. The red line shows the exceedance probability on a flooding tide and the blue line for an ebbing tide.

Figure 24 shows that Site 2 has a slightly concave shape compared to Site 1 which has a marginally convex shape. A concave shape means that the chance of exceedence remains low as current speed increases. The current does not maintain higher current velocites for extended periods of time. At 1 m/s there is an exceedance probability of 0.55, i.e. there is a 55% chance of 1 m/s being exceeded. This is much lower than the 75% seen for Site 1.

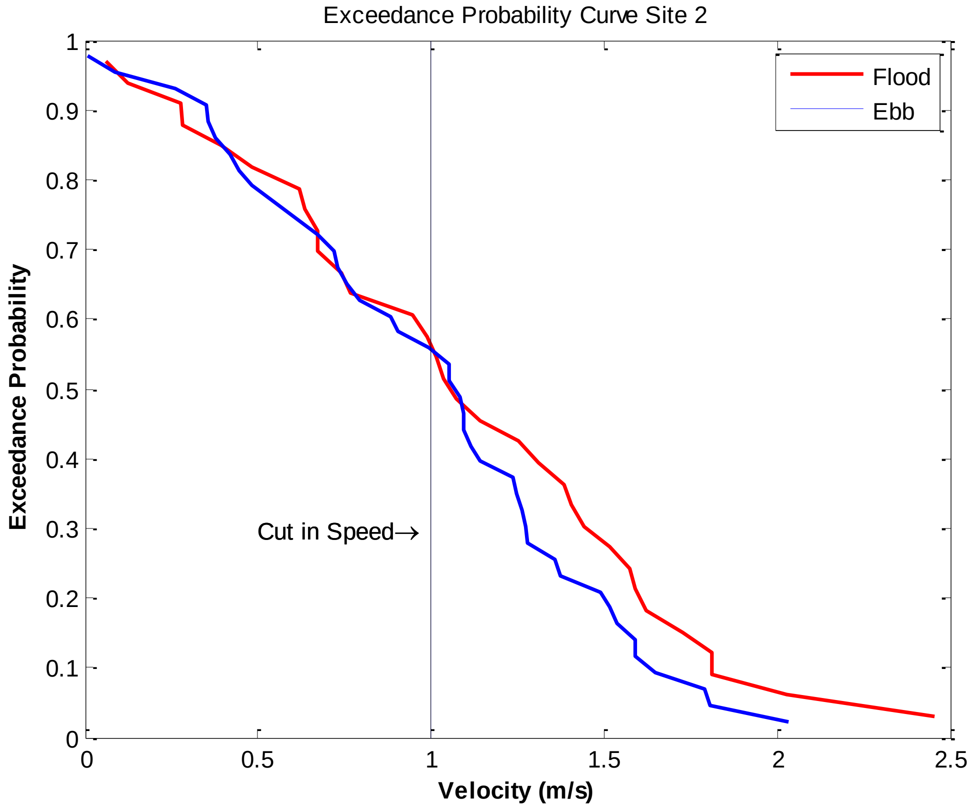


Figure 24: Flow exceedance curve for Site 2. The red line shows the exceedance probability on a flooding tide and the blue line for an ebbing tide.

Site 3 shows that at 1 m/s there is still a 48% chance of exceedance of 1 m/s on the ebbing tide and a 63% chance of exceedance 1 m/s on a flood tide. These figures are similar to those seen at Site 2. However after 1 m/s the curves at Site 2 become much steeper. The chance of exceedance drops rapidly as the current velocity increases.

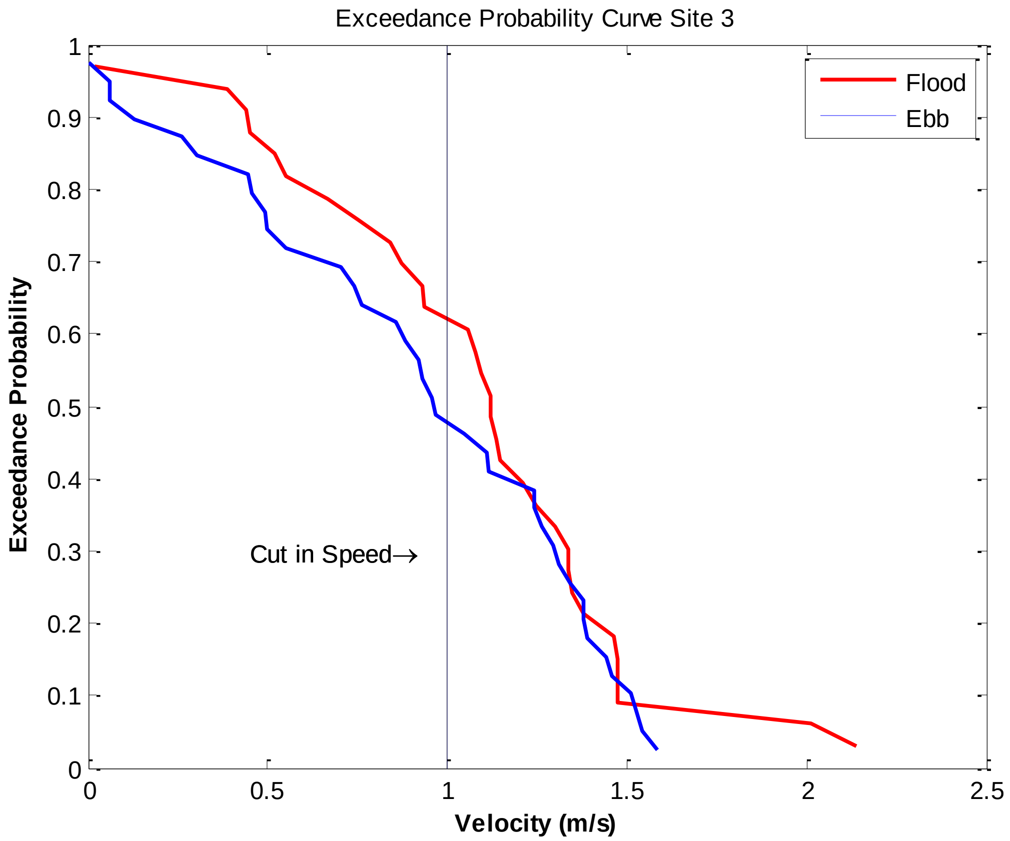


Figure 25: Flow exceedance curve for Site 3. The red line shows the exceedance probability on a flooding tide and the blue line for an ebbing tide.

8.7. Power Equation

The dataset for each site was cropped so that it only contained one month's worth of data. This enables accurate extrapolation for a year's energy production. A month of data covers a full 29.5 day lunar cycle and therefore covers all the major components of the tidal cycle (FIG, 2005).

As the variation in velocity across the front of the turbine rotor is less than 0.4 m/s at all sites as seen in the water column profiles (figure 20, 21 & 22) and considering this is a preliminary report, equations 8 and 9 do not need to be used in calculating potential power. Therefore equation 7 will be used.

In equation 7 the area, A, will vary depending on the turbine device chosen due to differences in rotor diameters. Therefore it is important to determine which turbine technology will be used at each site taking into account RYA guideline restrictions.

Equation 7 uses the velocity at the rotor hub. All the turbine devices covered in table 2 have the ability to generate power on both the flood and the ebb tide. Therefore the velocity data values used to calculate power for each site are made positive.

Based on the comparisons made in the technology table (table 2), the tidal turbine device that has been chosen for Site 1 is the Hammerfest Strom 1MW device (HS1000) for several reasons:

- The device is a proven design currently being tested at EMEC.
- 1MW power output is in line with many other devices.
- The device is tall compared to other devices. The HS1000 turbine stands 30 meters tall at its highest point. It is comfortably below the 32.5 meter RYA regulation height.
- The device can extract energy from the higher energy flows.
- The 20 meter turbine diameter is large, enabling the device to extract energy from as large an area as possible.

The data at Site 1 was cropped down to cover the month from 15 November 2011 at 11:54:11 to 15 December 2011 at 11:54:11.

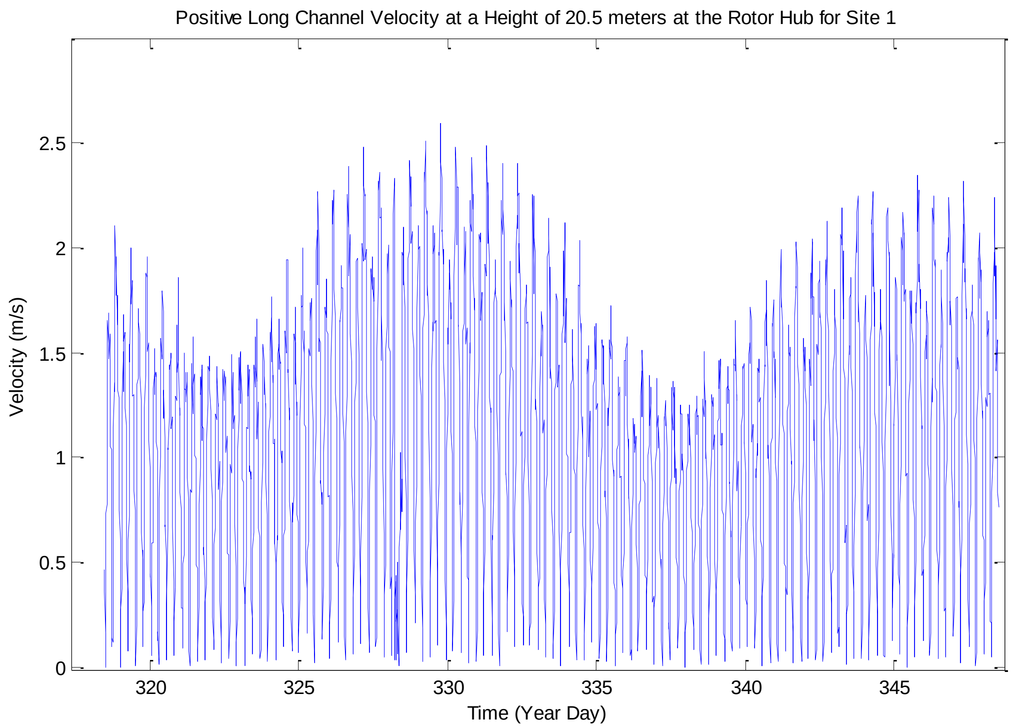


Figure 26: Graph showing positive flow velocity at a height of 20.5 meters from the ADCP for Site 1

All data points from figure 26 are now passed through equation 7. An efficiency of 40% will also be applied to the results (section 4).

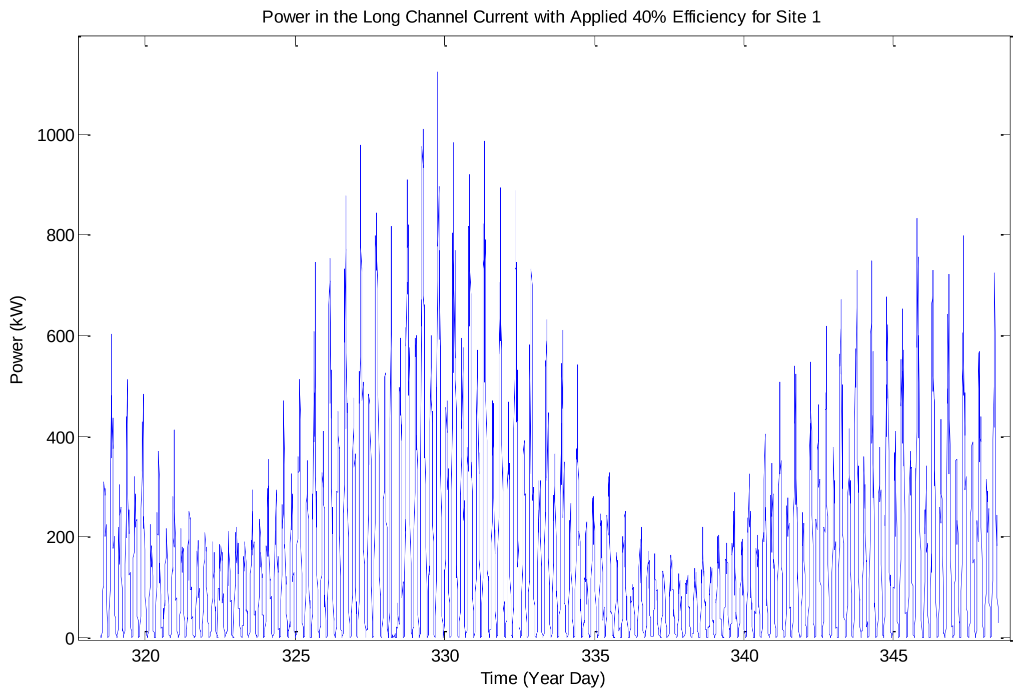


Figure 27: Power in the long channel current at Site 1 with 40% efficiency applied

When figures 26 and 27 are compared, the effect of cubing the velocity in the power equation has a clear impact on the graphs. Figure 27 has a far more 'peaked' distribution due to the fact that the cube rule exaggerates any small change in velocity. The current at Site 1 can produce a maximum of 1123 kW from a single HS1000 turbine, although the turbine would limit the maximum output to 1000kW.

At Site 2 an OpenHydro 2.2 MW turbine was chosen as a suitable device for the following reasons:

- The turbine is well tested. This turbine has been chosen for the Alderney site and will give vital information about arrays and device performance. (ARE, 2012)
- The potential output of 2.2 MW for a single turbine is very large compared to other available technologies.
- The turbine is 21 meters tall at its highest point which is well below the maximum height of 28.19 meters as per the RYA regulations due to a chart datum depth of 36.19 meters.
- The turbine is fully submerged and is designed to be environmentally friendly.

The turbine has a diameter of 16 meters and the centre of the turbine is at a height of 12.5 meters from the bed.

This time the data presented shows one full month of data from 7th Jan 2012 at 15:39:11 to 7th Feb 2012 at 07:49:11.

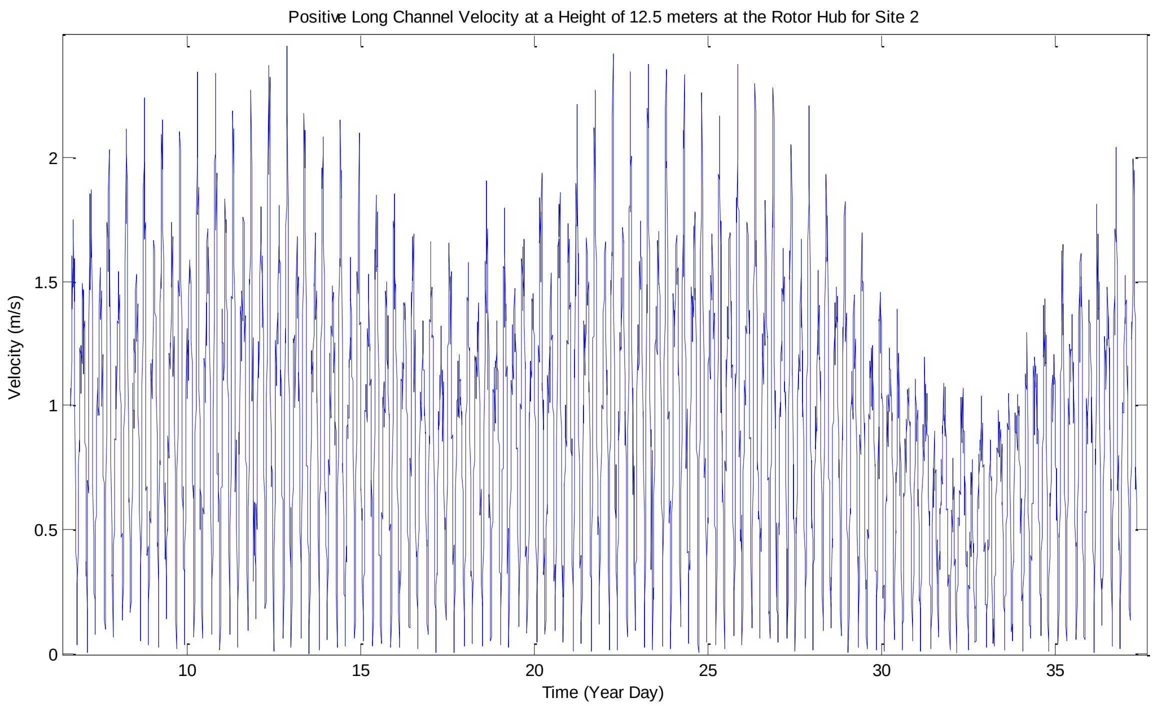


Figure 28: Graph showing positive flow velocity at a height of 20.5 meters from the ADCP for Site 2

All data points from figure 28 are now passed through equation 7.

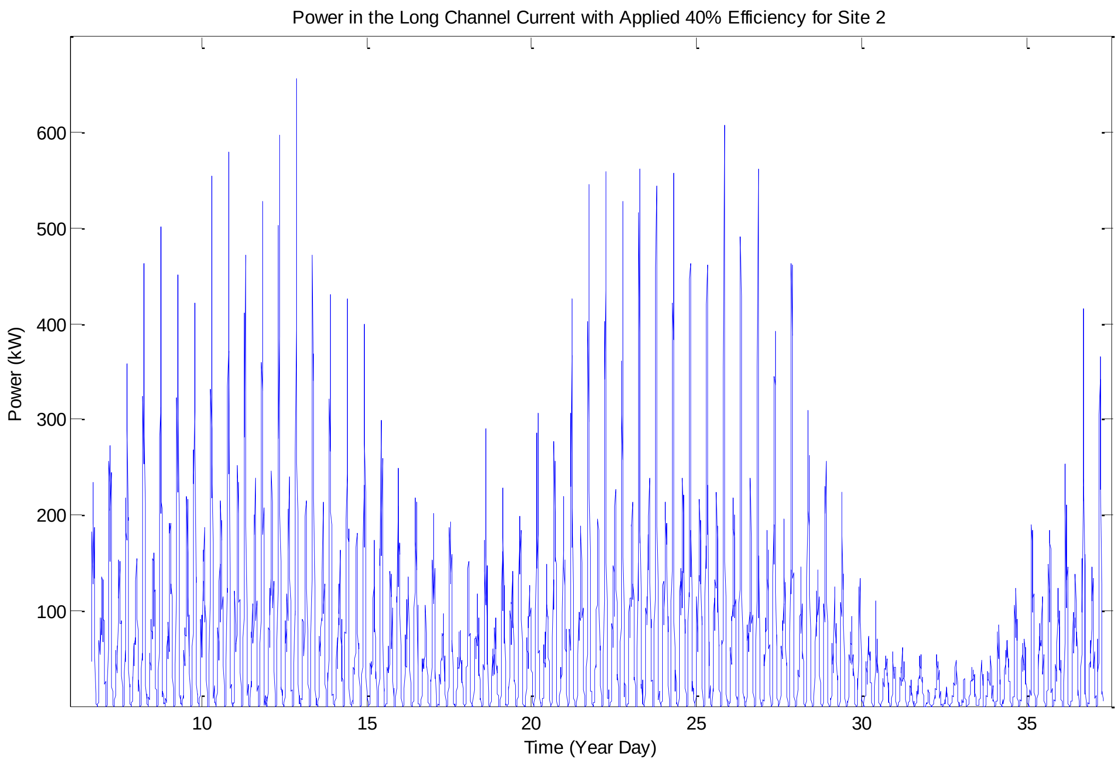


Figure 29: Power in the long channel current at Site 2 with 40% efficiency applied

Figure 29 shows that Site 2 can produce a maximum of 656 kW from one OpenHydro turbine.

At Site 3 the OpenHydro 2.2 MW turbine will once again be used for the same reasons as stated for Site 2. Additionally figure 22 showed that there is a bulge in the water column profile which occurs between a height of 6 to 25 meters. This coincides with the area covered by the OpenHydro turbine blades.

The data covers one full month from 20th February 2012 at 13:43:16 to 22nd March 2012 at 09:23:16. Due to February being a short month an extra two days have been added at the end of the dataset which means the data run for a complete 31 day month to enable direct comparisons to be made.

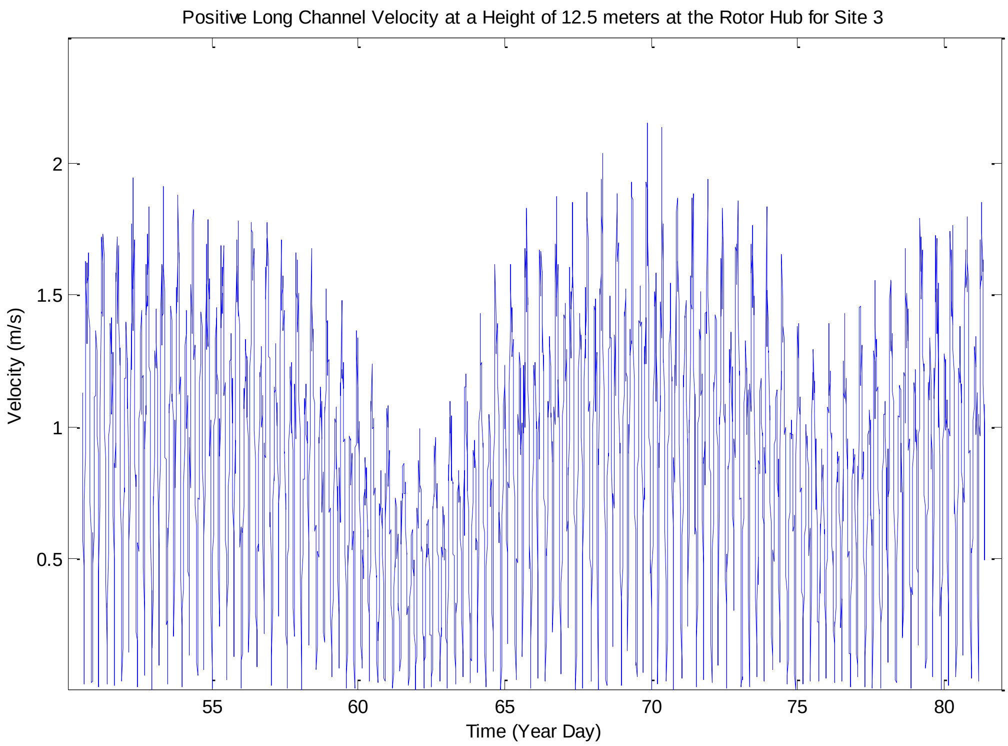


Figure 30: Graph showing positive flow velocity at a height of 20.5 meters from the ADCP for Site 3

All data points from figure 30 are now passed through equation 7.

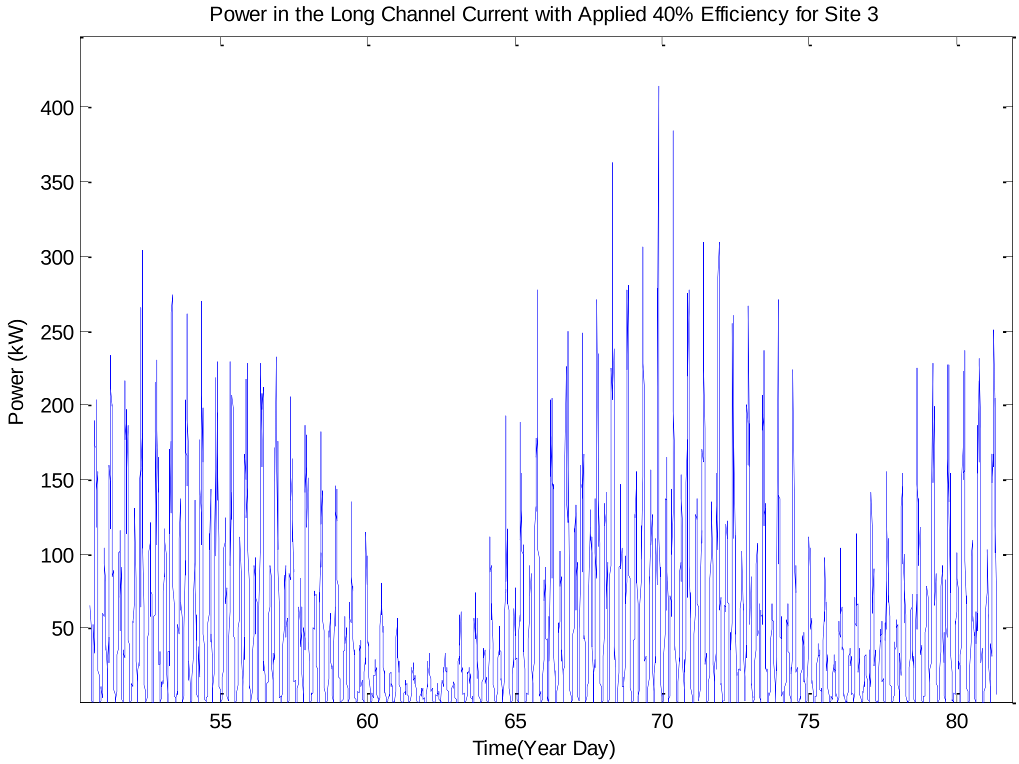


Figure 31: Power in the long channel current at Site 3 with 40% efficiency applied

Figure 31 shows that Site 3 can produce a maximum of 414 kW from one OpenHydro turbine.

8.8. Power Curve

The data from figures 26 and 27 can be used to generate a power curve for Site 1. Figure 32 shows that the power output peaks at around 1100kW when the current velocity is approximately 2.6 m/s. However the HS1000 is rated at 1000kW therefore the power curve would plateau past this point.

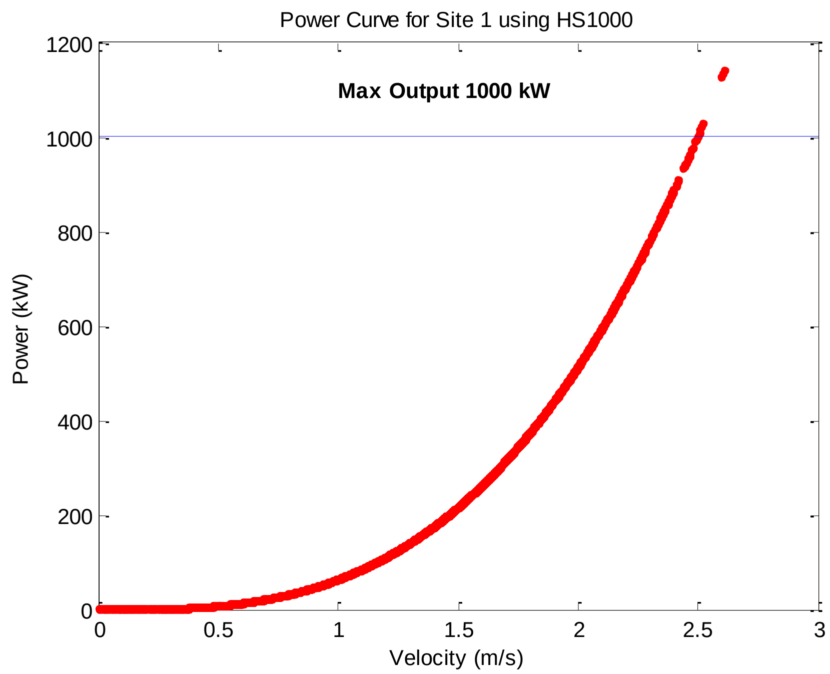


Figure 32: Graph showing the power curve for Site 1

Data from figures 28 and 29 are used to generate the power curve for Site 2. The power curve for Site 2 is not as steep as at Site 1, and shows that power output here is well short of the cut-off point of 2200 kW for the OpenHydro turbine.

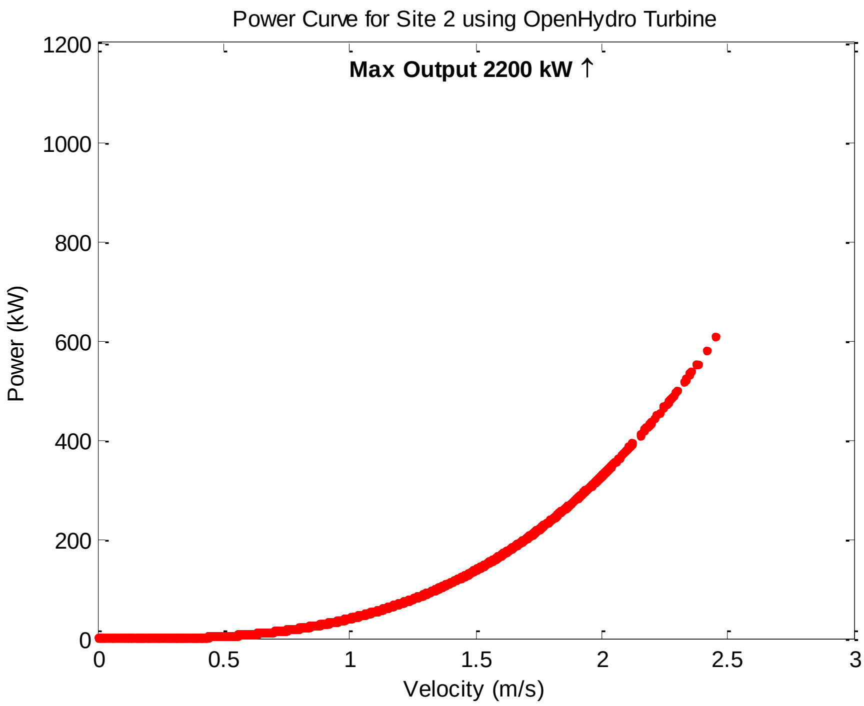


Figure 33: Graph showing the power curve for Site 2

As before figures 30 and 31 can be combined to show the power curve at Site 3 (figure 34). As with Site 2, Site 3 does not produce enough energy to reach the maximum output potential of the OpenHydro device. The power curve shows a shallow gradient with the power not exceeding 100 kW until a velocity of 1.4m/s is reached. From figure 25 it is clear that the probability of 1.4 m/s being exceeded and therefore more energy being produced is 0.15, a low probability.

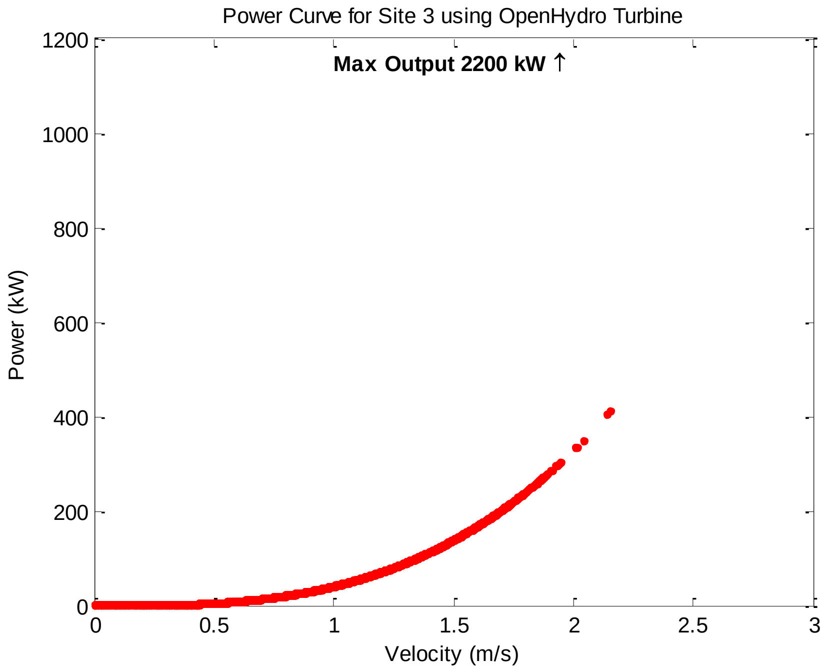


Figure 34: Graph showing the power curve for Site 3

8.9. Average Hourly Power Output

The data can be smoothed at each site to give a more representative view of the amount of power produced each hour.

At Site 1 the highest power output achieved after smoothing is 910kW at 2.4 m/s, lower than the 1123kW at 2.6 m/s originally calculated (figure 27). The value averaged over an hour is lower as many of the short term fluctuations have been smoothed.

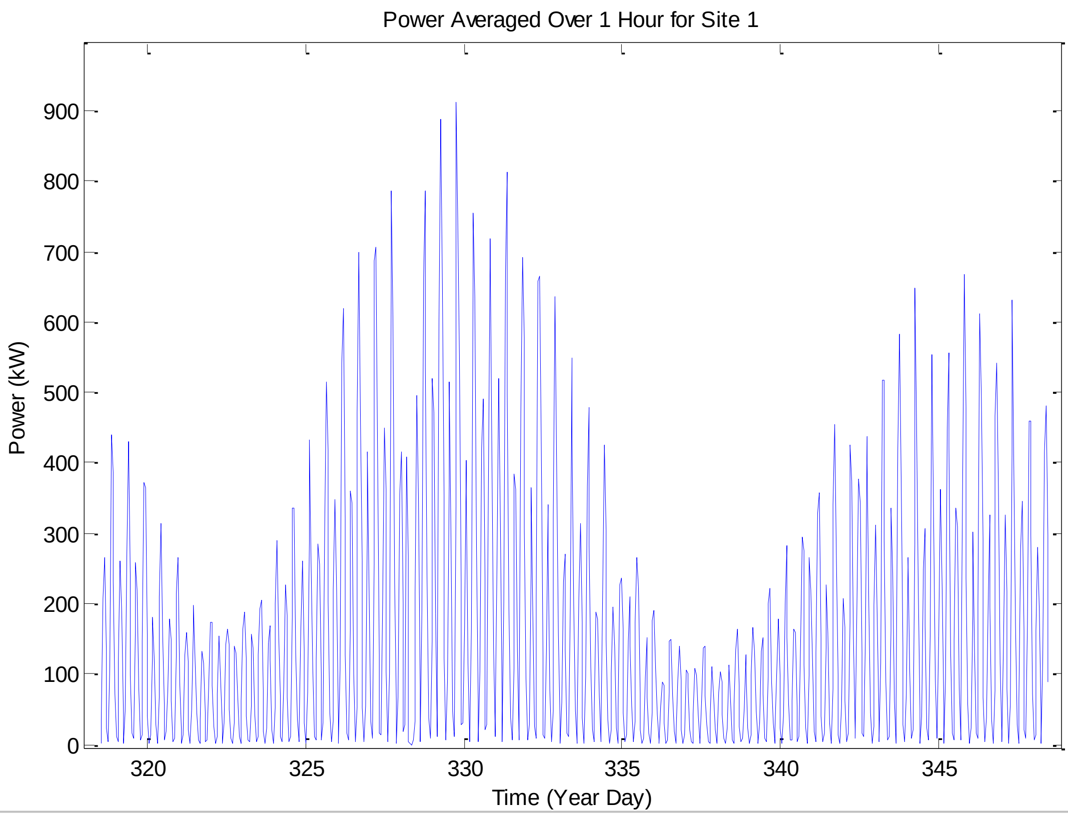


Figure 35: Graph showing power average over 1 hour for Site 1

At Site 2 figure 36 shows the maximum power produced after smoothing is now 430 kW at 2.18m/s. This is less than the original 656 kW produced at 2.45m/s (figure 29). The time for the highest power produced has also changed. In figure 29 the highest power is found around year day 14, however after the power has been smoothed the highest power is found around year day 23. This shows that the second spring tide contains more power but does not contain the same short term peaks in velocity of the first spring tide.

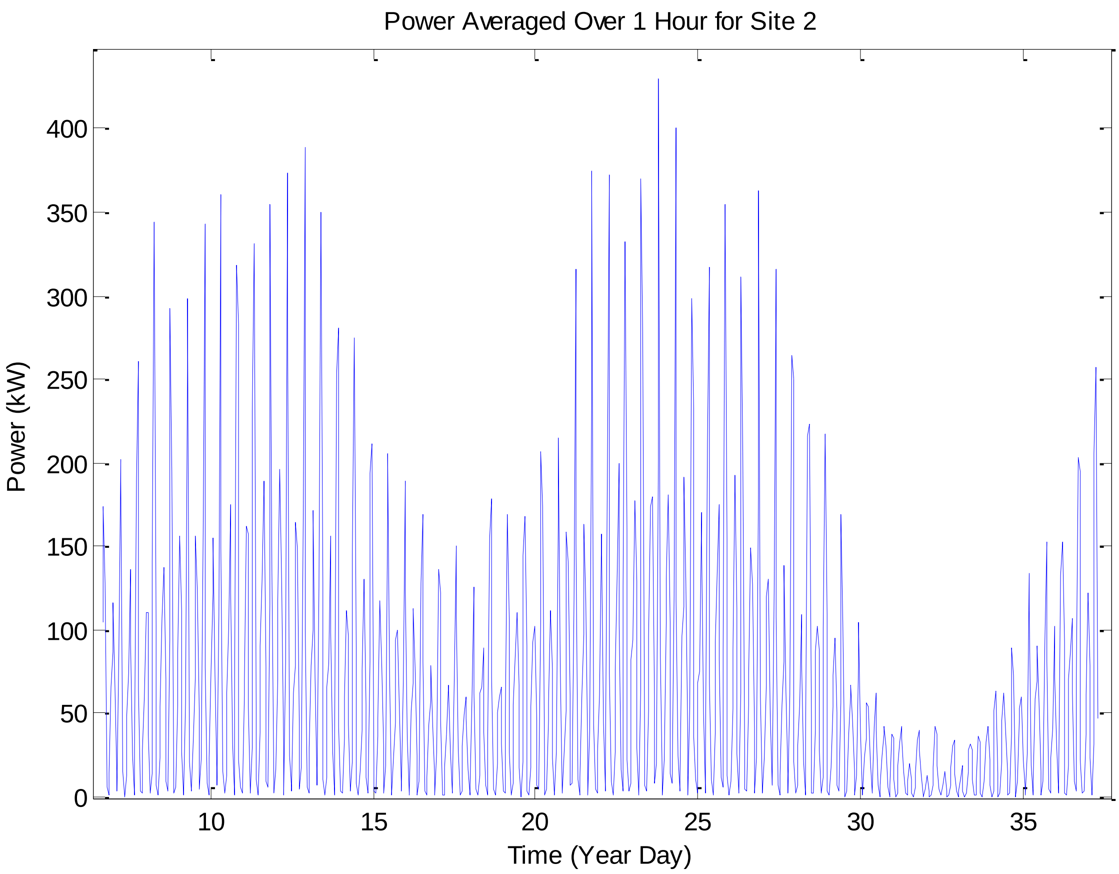


Figure 36: Graph showing power average over 1 hour for Site 2

At Site 3 figure 37 shows that the highest average power after smoothing is 258 kW at 1.8m/s. This can be compared to 414 kW at 2.15 m/s in figure 31.

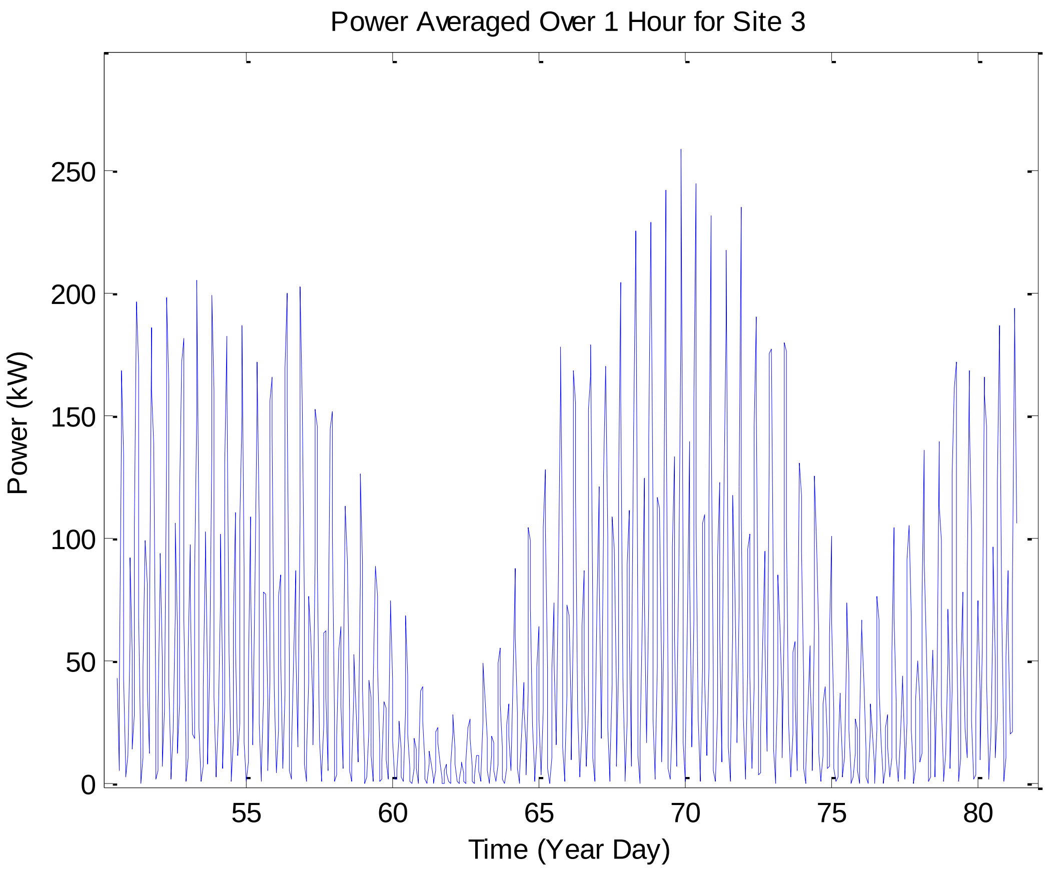


Figure 37: Graph showing power average over 1 hour for Site 3

8.10. Calculating Total Power Output per Month

To calculate the total amount of power produced over a month, the amount of power generated at each 10 minute time step is integrated over the entire time series (a month). When calculated for Site 1 a single HS1000 turbine can produce 698,220 kWh in a month.

This power calculation can also be scaled up:

- Amount of energy per year: 698,220 kWh X 12 months = 8,378,640 kWh
  Equivalent to 8,378.64 MWh
- In comparison Guernsey consumed 400 GWh (400,000,000 KWh) in 2011 (University of Exeter, 2012). This means that a single HS1000 turbine at Site 1 could produce 2.09% of Guernsey's annual energy requirements.

The same calculation for Site 2 gives a power output of 295,610 kWh in a month for a single OpenHydro turbine. This can be scaled up to:

- Amount of energy per year: 295,610 kWh X 12 months = 3,547,320 kWh
  Equivalent to 3,547.32 MWh
- A single OpenHydro turbine at Site 2 could produce 0.89% of Guernsey's annual energy requirements.

Site 3 gives a power output of 231,800 kWh in a month for a single OpenHydro turbine. Scaled up this approximates to:

- Amount of energy per year: 231,800 kWh X 12 months = 2,781,600 kWh
  Equivalent to 2,781.60 MWh
- A single OpenHydro turbine at Site 3 could produce 0.70% of Guernsey's annual energy requirements.
- However Site 3 was initially chosen specifically by Sark for micro-generation. The exact amount of energy Sark consumes is unknown but it is known to consume less than 1000 kW of energy at peak times and less than 1,000,000 kWh in a year (David Gordon-Brown, Personal Communication). Based on these estimates a single OpenHydro turbine could produce 278.16% of Sark's yearly energy consumption.

8.11. Spring-Neap Analysis

In order to apply the boundary tidal height of 5.6 meters to the graph, the 5.6 was halved to give an upper and lower boundary, based around the mean sea level.

Thus for Site 1 the upper limit can be set at 48.9 meters and the lower limit at 43.3 meters as shown by the horizontal lines in figure 38. The resulting separation from neap to spring tide can seen using the vertical lines (figure 38).

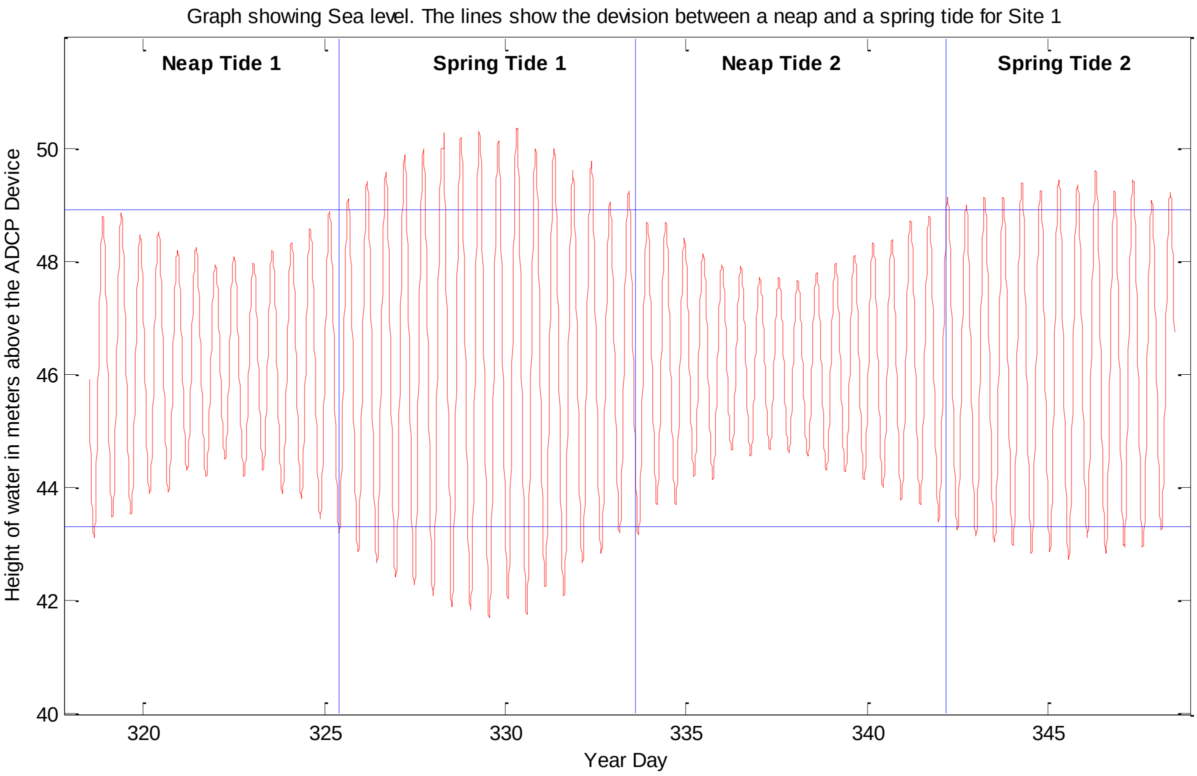


Figure 38: Graph showing how the data have been divided for analysis into neap and spring tides for Site 1

When the data at Site 1 were analysed there was a mean spring velocity (V_{ms}) of 1.25 m/s. When converted to power Spring 1 produced a total of 299,480 kWh and Spring 2 produced a total of 177,190 kWh. This gives a combined total of 476,660 kWh of energy produced from the spring tides over a month. This can be scaled up to achieve an annual amount of energy from spring tides of 5,719,920 kWh.

There was a mean neap velocity (V_{mn}) of 0.96 m/s. When converted to power Neap 1 produced a total of 107,040 kWh and Neap 2 produced 114,520 kWh giving a combined total of 221,560 kWh over a month. The amount of energy neap tides produce over a year can be extrapolated to 2,658,720 kWh.

Thus spring tides make up 68.27% of the total amount of energy extracted from the tidal stream over a year at Site 1.

At Site 2 the boundaries will be at slightly different heights. This time the upper boundary is 44.8 meters and the lower boundary is 39.2 meters (figure 39).

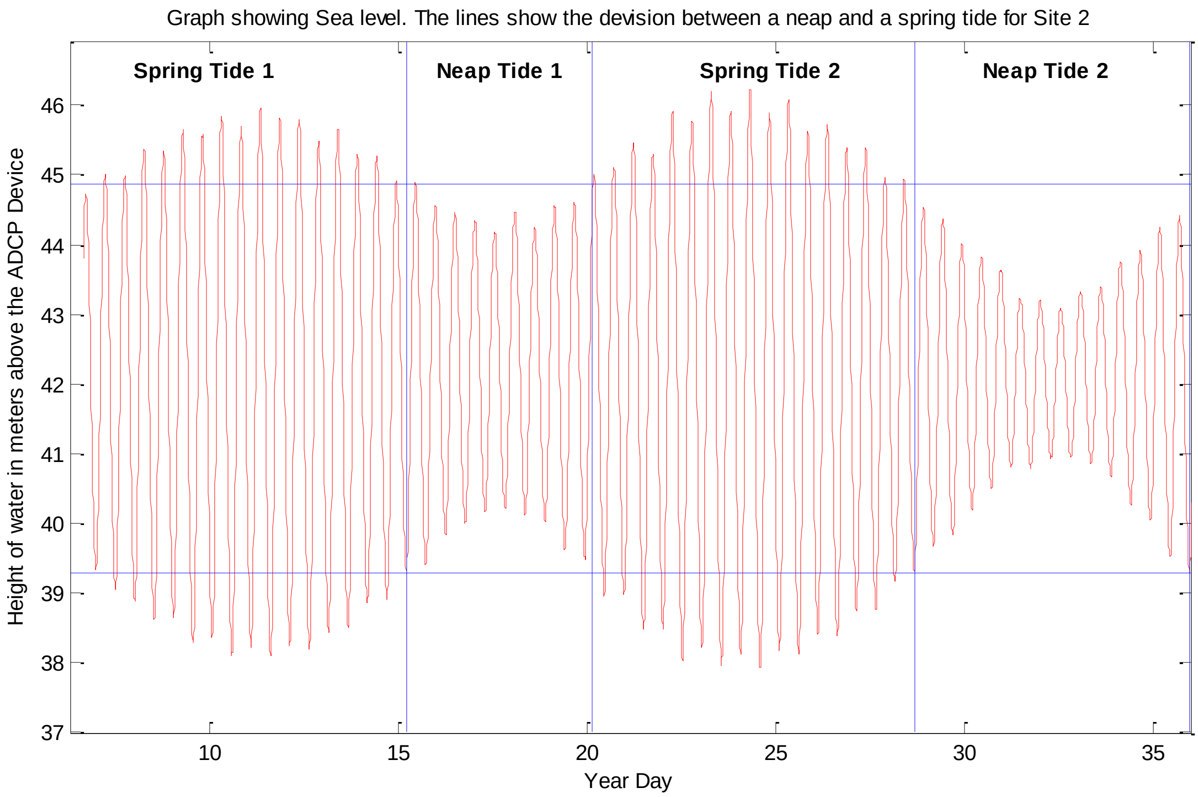


Figure 39: Graph showing how the data has been divided for analysis into neap and spring tides for Site 2

When the data at Site 2 were analysed there was a V_{ms} of 1.04m/s. When converted to power, Spring 1 produced a total of 108,044 kWh and Spring 2 a total of 112,484 kWh. This gives a combined total of 220,528 kWh of energy produced from spring tides over a month. This can be scaled up to show that the amount of energy from spring tides over a year is 2,646,336 kWh

There was V_{mn} of 0.80m/s. When converted to power Neap 1 produced a total of 41,160 kWh and Neap 2 produced 33,921 kWh, resulting in a combined total of 75,081 kWh over a month. The amount of energy neap tides produce over a year is 900,972 kWh.

Thus spring tides make up 74.60% of the total amount of energy extracted from the tidal stream over a year at Site 2.

At Site 3 the upper boundary is 51.08 meters and the lower boundary is 45.4 meters.

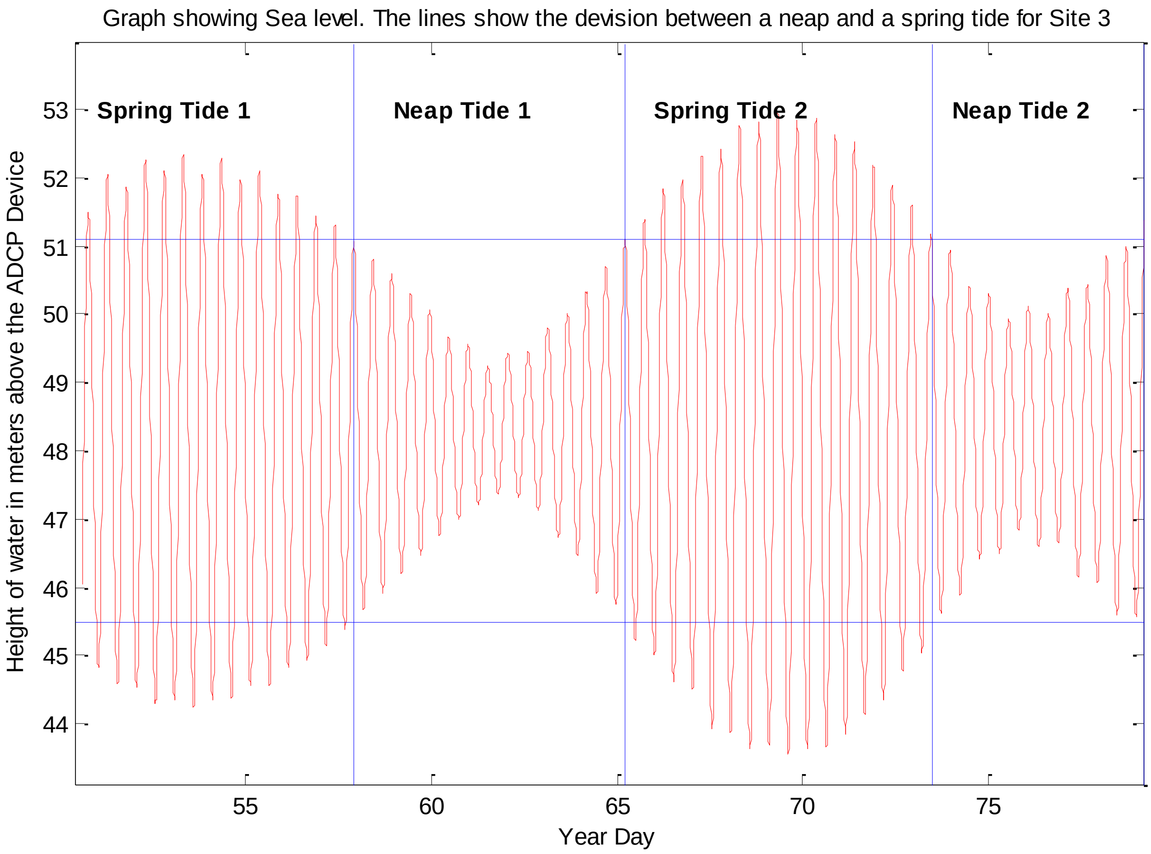


Figure 40: Graph showing how the data have been divided for analysis into neap and spring tides for Site 3

When the data at Site 3 were analysed there was a V_{ms} of 1.01m/s. When converted to power, Spring 1 produced a total of 76,077 kWh and Spring 2 a total of 90,512 kWh. Therefore a combined total of 166,589 kWh, of energy is produced from spring tides over a month. This can be scaled up to show that the amount of energy from spring tides over a year is 1,999,068 kWh.

There was V_{mn} of 0.72m/s. When converted to power Neap 1 produced a total of 31,013 kWh and Neap 2 produced 34,198 kWh giving a combined total of 65,215 kWh over a month. The amount of energy neap tides produce over a year is 782,532 kWh.

Thus spring tides make up 71.87% of the total amount of energy extracted from the tidal stream over the year at Site 3.

9. Summary of the 3 Sample Sites

It is useful to bring all the key information from each site together for easy comparison.

	Site 1	Site 2	Site 3
Device Used	Hammerfest Strom	OpenHydro	OpenHydro
Mean Water Depth	46 Meters	42 Meters	48 Meters
Max Spring Velocity	2.6 m/s	2.45 m/s	2.15 m/s
Mean Velocity at Turbine Height	1.15 m/s	0.92 m/s	0.88 m/s
Peak Power from Current	1,123 kW	656 kW	414 kW
Peak Power after Smoothing	910 kW	430 kW	258 kW
Total Power for Spring Tides in a Month	476,660 kWh	220,528 kWh	166,589 kWh
Total Power for Spring Tides in a Year	5,719,920 kWh	2,646,336 kWh	1,999,068 kWh
Total Power for Neap Tides in a Month	221,560 kWh	75,081 kWh	65,215 kWh
Total Power for Neap Tides in a Year	2,658,720 kWh	900,972 kWh	782,532 kWh
% of Power Spring Tides Generate per Yr	68.27%	74.60%	71.87%
Total Power per Month	698,220 kWh	295,610 kWh	231,800 kWh
Total Power per Year	8,378,640 kWh	3,547,320 kWh	2,781,600 kWh

Table 3: Table showing key data from all 3 data sites

Based on the above table Site 1 appears to be the best site, having the highest velocity and most linear flow, ideal for turbine devices. However further factors still need to be taken into consideration for determining how ideal a site might be.

10. Extreme Events

Strong onshore winds can cause set-up conditions whereby the wind forces more water to the shoreline leading to a piling of water (NOAA, 2012). Should the event coincide with a high tide, the tide will exceed the height of the predicted astronomical tide. Similarly a low pressure system causes the surface of the water to be 'sucked-up'. Weather events such as these occur daily, however the effects are not particularly noticeable. These events are usually referred to as residuals (Hess *et al.*, 2004) and not only affect sea level, but also change the volume of water transferred with the tide. A larger volume of water leads to higher current velocities, which in turn can cause additional mechanical stress on tidal turbines.

Tidal gauge stations measure the real time sea level and this can be compared with the expected astronomical tide leaving the atmospheric residual level.

Ten years (2002 – 2011) of tidal data from the Jersey tide gauge station were analysed to assess the larger storm surges over this period. The highest residual surge from the data was 1.25 meters which occurred only once. Therefore this surge is a 1 in 10 year event.

The highest spring tidal velocity obtained in this data measured 2.6 m/s. All surges have varying effects on velocity depending on their size and the topographical features of the area. One paper suggests that a 1 in 50 year event could produce a maximum current surge velocity of 1m/s (EMEC, 2009). Thus there is the potential for a current velocity of 3.6 m/s on a spring tide. For unusually high velocities some devices, such as the Atlantis AR1000, will enter a 'safe' mode where the turbine effectively shuts down and locks the rotor blades in place to protect the device from additional mechanical stress (Atlantis Resource Corporation, 2012).

11. Other Considerations

Bathymetry, wave climate and turbulence are important characteristics for turbine placement (EMEC, 2009).

The map of bathymetry for the Bailiwick of Guernsey is relatively coarse in its resolution but it does however provide an overall view of the channel. Figure 41 shows that the seabed does not contain any significant topographical features, an important consideration for the placement of turbine devices.

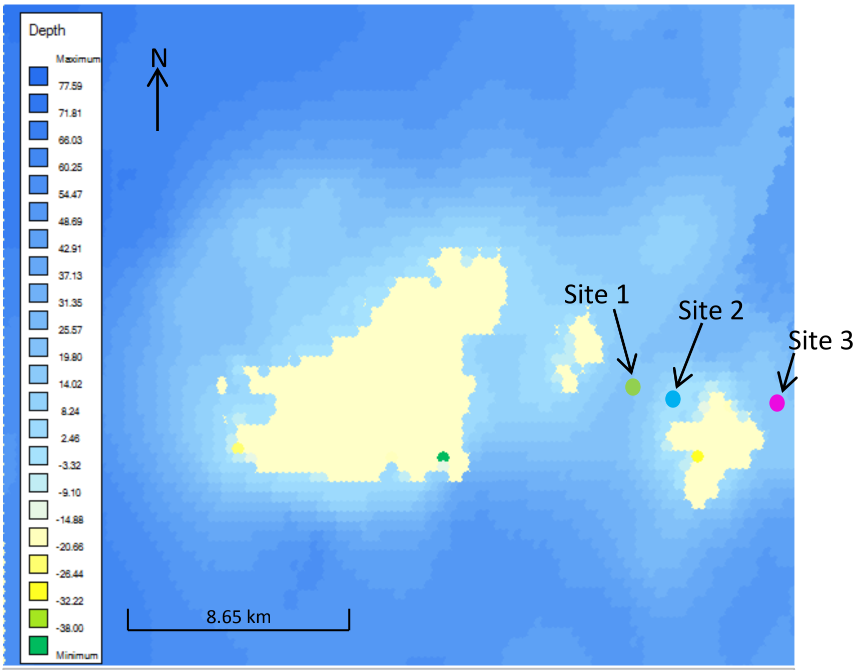


Figure 41: Bathymetry map of the waters around Guernsey. Although the map has a low resolution the general bathymetry of the area can be seen.

The wave climate in shallow coastal waters is often heavily influenced by the bathymetry. The BERR (Department for Business, Enterprise and Regulatory Reform) Atlas states that in winter there is a significant wave height of 2 meters and an annual average of 1.55 meters for the Big Russel (BERR, 2012). The small wave climate should not create enough turbulence to impact upon the turbines due to the water depth. However the BERR map has a resolution of 12 km squares (BERR, 2012) and finer resolution data would be needed in order to appropriately analyse the wave climate.

Turbulence is the motion of water, where local velocities fluctuate and the direction of flow changes abruptly and frequently at any particular location (King County, 2011). Large amounts of turbulence can put stress on the turbines mechanical structure, increasing wear and maintenance costs (NREL, 2012). Turbulence is caused by topographic features on the seabed and by waves. It can reduce the efficiency of a turbine especially when considering an array of tidal turbines. If a turbine is placed too close behind another turbine, then the efficiency of the second turbine will be impacted. The Roosevelt Island Tidal Energy (RITE) project investigated the optimum spacing for turbines in a large array. They found that minimum interference occurred when the turbines were spaced 12 turbine diameters apart, based on a 5 meter diameter turbine (Colby et al., 2010). Turbines with different diameters will need to be modelled further. Using the results of this study as a reasonable approximation, a turbine with a diameter of 20 meters, such as the HS1000, would need to be 240 meters away from the next turbine.

11.1. Potential Array for Site 1

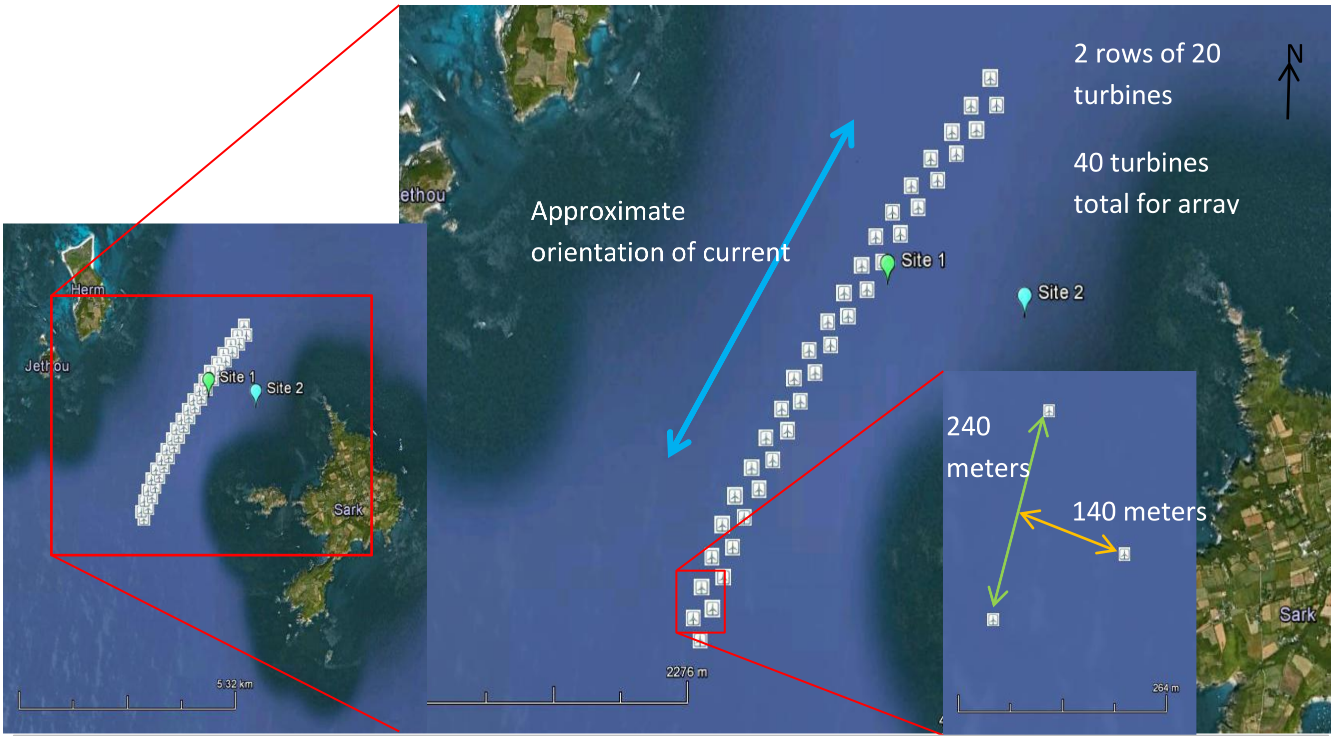


Figure 42: Map showing a theoretical array which could be used to extract power from the Big Russel, assuming the current velocity down the centre of the Big Russel is the same as at Site 1.

Based on the findings of the data analysis, Site 1 has the most potential for an array development. Therefore a schematic for an array has been generated (figure 42) deploying a total of 40 turbines in two rows down the centre of the Big Russel. Assuming the velocity of the current at Site 1 is replicated along the length of Big Russell, then the potential power from the array can be calculated. The total amount of power a single HS1000 turbine can produce in a month at Site 1 is 698,220 kWh. Therefore:

698,220 kWh X 40 turbines = 27,928,800 kWh (27,928.8 MWh or 27.93 GWh)

Further power calculations for an array of 40 turbines based on Site 1 show:

- Peak Power: 1,000 kW X 40 = 40,000 kW (40.00 MW)
- Annual Power: 27,928,800 kWh X 12 months = 335,145,600 kWh (335,145.6 MWh or 335.15 GWh)
- Guernsey consumed 400 GWh (400,000,000 kWh) in 2011 (University of Exeter, 2012). An array of 40 turbines has the potential to produce 83.79% of Guernsey's annual electricity consumption.

Caution must be used when viewing the array and the proposed energy generation. The energy statistics predicted for the array make the assumption that the current remains constant for the full length of the Big Russel. The analysis has already highlighted the large difference in energy generation potential between Site 1 and Site 2. Before an array can be considered, a large scale detailed analysis along the length of the Big Russel must be undertaken to understand how the current changes along the length and breadth of the channel.

12. Environmental Considerations

Both of the turbines used in this report, the HS1000 and OpenHydro 2.2 MW turbine, have been designed to keep environmental impacts low. Often the greatest impact from these devices is on the benthic environment. Both of the devices chosen use gravity foundations which have a smaller impact than those requiring piling operations. A detailed characterisation of the benthic environment in the Big Russel has been carried out by Plymouth University (Sheehan *et al.*, 2011).

The local populous often has concerns regarding the blades of a turbine and the danger they pose to marine life. SeaGen, who have installed the Marine Current Turbine (MCT) in Strangford Lough, have employed close environmental monitoring techniques which have proven that the blades of this turbine do not pose any danger for marine life as they revolve slowly, at 14 rpm (SeaGeneration, 2012). Other companies have developed different innovations which mitigate their environmental impact. OpenHydro developed its turbine with its blades enclosed inside an external housing. The device also has a central hole which allows marine life to pass through.

An environmental scoping report has already been completed by Guernsey's Renewable Energy Team. The scoping report assesses the water quality, benthic ecology, geology, birds and marine mammals contained in the waters around Guernsey with a view to future marine renewable energy projects (Guernsey Renewable Energy Team, 2011).

13. Economics of a Tidal Energy Project

The tidal energy industry is immature, as much of the technology is still being fully developed. Due to its immaturity the cost of building turbines is very high which means the CAPEX (Capital Expenditure) of a project to install a turbine and its surrounding infrastructure is also high. By contrast the wind industry is more mature and as the designs of the turbines have converged, the overall costs decreased due to more efficient manufacture processes linked with economies of scale (Blanco, 2008).

Guernsey Renewable Energy Commission (GREC) have stated that they don't expect a commercial tidal array to be operational anywhere before 2017 and therefore Guernsey's tidal stream energy projects would not be developed until after this date (Lord, 2010). Much of the costs for devices, including installation and cabling, will have changed dramatically by the time Guernsey is ready to invest. For example the price of copper plays a large part in the price of cabling. For the costings in table 4, the price of the cable has been taken from a paper by Murray in 2004, as this is the latest known published figure. However the price of copper itself over the last 8 years has increased by 318% from £1,529.78 per metric ton in July 2004 to £4805.17 per metric ton in July 2012 (Index Mundi, 2012). As a result the cost of cabling will be significantly more than stated. However it is important to have an estimate of the significant level of investment needed for a renewable energy project. An attempt to cost a project has been made here, although caution must be urged with these figures. Many of these costs have been put together from a variety of sources. The only way to get an accurate cost of a project is to speak directly with device manufacturers. Therefore the numbers shown should only be viewed as a very basic guideline for the potential costs involved (table 4).

Capital Expenditure		
Object/Piece of Equipment	**Information**	**Cost (£)**
Turbine Device	Cost of 1 complete turbine device based on a recent Strategic Environmental Assessment (SEA) which estimated a price of £5 million per MW (DETI, 2012).	5,000,000.00
Turbine Installation	Cost of boat hire and transport etc. in order to install turbine on seabed (Polagye, 2006).	919,130.80
Subsea Cable and Cable Installation	Cost of cable is dependent on price of copper on commodities market. Price of cable is approx. £250 per meter (Murray, 2004). Guernsey harbour to Site 1 = 9 km	2,250,000.00
Onshore Electric Grid Interconnection	Substation needed in Guernsey harbour to smooth energy generated by turbines and connect to grid (Polagye, 2006).	216,716.00
Total Cost	For 1 installed and grid connected turbine	**8,385,846.80**

Additional Array Costs		
Turbine costs	Example array considers 40 turbines (figure 42). Economies of scale could prove an important factor in reducing costs. An EPRI (Electric Power Research Institute) report suggests economies of scale could reduce costs by 47% to around £2,350,000 per MW (Polagye, 2006).	94,000,000.00
Turbine Installation	EPRI report suggests installation costs decrease to £205,501.58 per turbine (Polagye, 2006).	8,220,063.20
Subsea Cable and submerged Interconnector	Additional cable is required to connect each device. The cables then link to an interconnector to send the power back to shore via one cable. Distance between devices = 240 meters (Murray, 2004).	2,400,000.00
Total Array Cost	**Includes cost of substation (£216,716.00) and original length of cable (£2,250,000.00).**	**107,086,779.20**

Operation and Maintenance (O&M) Costs		
O&M	Regular O&M schedule is required. Many devices state regular O&M at 2 year intervals (Tidal Generation Limited, 2011). However O&M on a yearly basis is advised due to high wear situation. EPRI state £22,512.04 per turbine (Polagye, 2006).	900,481.60 per annum
Insurance Costs	Cost of insuring each device in case of failure £15,456.31 (Polagye, 2006)	618,252.40 per annum
Total Costs Per Annum		**1,518,734.00**
Annual income required to break even	Based on project lifespan of 30 years (Tidal Generation Limited, 2011)	**5,088,293.31**

Table 4: Table highlighting potential costs for a turbine array

Based on the costings in table 4 the array would need to return over £5 million income each year over the life time of the project in order to be viable. Most turbine companies state their devices have a lifespan of 25-30 years with regular maintenance (Tidal Generation Limited, 2011). This does not account for any significant outlays such as replacing broken turbines or for decommissioning costs at the end of the project's lifespan. There can be heavy costs associated with removing the turbine from the seabed and returning the area back to its previous, undisturbed state. It is impractical to put a cost on decommissioning devices due to the long range forecast required. It is however necessary before the start of the project to draft guidelines for the decommissioning of renewable energy systems in order to comply with laws and licences. These need to outline who will be responsible for these costs at the end of the project lifespan (Alderney Commission for Renewable Energy, 2012).

A marine renewable energy development needs to be seen as an infrastructure project and it therefore needs to generate a regular return to the provider (Patrick Firth, Personal Communication). Whether a project such as this can become viable depends on many factors including how the renewable energy is priced, the cost of importing energy from France and the cost of diesel fuel. At present, Guernsey is mainly reliant on the energy imported from France, amounting to 78% of its electricity demand. The remaining 22% is generated on island using diesel generators. The cable used to import energy from France is currently under repair and as a result the on island generators are working at maximum capacity to provide energy to the island's population, however this has already resulted in short term power cuts (BBC News Guernsey, 2012).

Not all of the costs associated with a project such as this have to be negative. The project would generate jobs with regard to the regular operation and maintenance required on the devices. The repair of the cable that runs from Guernsey to Jersey has already highlighted a skills base in the Island (Jeremy Thompson, Personal Communication). Having this skills base could mean that the island can export its expertise to other companies in the future.

14. Conclusion

This project set out to analyse the resource found at three sites within the Bailiwick of Guernsey. Site 1 has the potential to generate the most energy out of the three sites amounting to 8,378,640 kWh in a year from a single turbine. Site 3 has the potential for micro-generation for the island of Sark producing more than the islands annual consumption of 1 GWh.

The Robert Gordon University Study (RGUS) focussed on the kinetic energy contained in the waters around Guernsey. In that study the 1 km^2 area around Site 1 contained a kinetic energy flux of approximately 250GWh per year (figure 7) (Owen, 2012). If the theoretical array from this report is considered (figure 42), approximately 10 turbines could be placed in an area of 1 km^2. Using the average power per year for Site 1 the total energy for the 1 km^2 area over a year would be 83,786,400 kWh equivalent to 83.79 GWh per year. This is only 33.52% of the RGUS figure. Similarly sites 2 and 3 were predicted by the RGUS to contain 48GWh and 35GWh respectively (Owen, 2012). In this report, assuming 10 turbines are used at each site, Site 2 has the potential to generate 35.47 GWh per year (73.9% of RGUS figure) and Site 3 has the potential for 27.82 GWh per year (79.49% of RGUS figure). The RGUS model consistently over estimates the energy potential when compared to this report. The difference between the two reports highlights the need for caution when viewing the output from a model or from an array constructed based on an extrapolation of data from a single point.

The University of Exeter study stated an extractable resource of 566 GWh per year for the Big Russel (University of Exeter, 2012). In comparison the proposed array in this report is estimated to have an extractable resource of 335.15 GWh per year, which is 40.79% smaller (figure 42). However the Exeter report gave no details on the array size or number of devices involved and the estimate they produced is largely based on the RGUS.

The calculations carried out in the primary analysis are based around a single turbine, however an array is likely to be more economically viable. The theoretical array designed in this report (figure 42) has the potential to generate an annual power output of 335.15 GWh which accounts for 83.79% of Guernsey's annual energy demand. However caution must be urged, as the array is based on the large assumption that the velocity at Site 1 is replicated along the length of the Big Russell. Even with this assumption an array of turbines still falls short of Guernsey's full energy requirements. In general, no one source of renewable energy will provide all of a country's energy needs. A combination of renewable energy sources including wind, wave, tidal and solar need to operate in conjunction with each other to ensure a consistent supply of energy to the grid.

GREC have stated that they don't expect a commercial tidal array to be operational anywhere before 2017 and therefore Guernsey's tidal stream energy projects would not be developed until after this date (Lord, 2010). Until a time when investment is likely, it is important to focus on the preparation needed for renewable energy projects. It is crucial to ensure that the relevant legislation is in place, the appropriate environmental impact assessments are carried out, and all appropriate planning procedures are followed (such as the Marine and Coastal Access Act, 2009 (HM Government Legislation, 2009)) (Jeremy Thompson, Personal Communication). With only a single cable link to France, through Jersey, additional cables from Guernsey direct to France may be required to develop a 'no single point of failure' system (Jeremy Thompson, Personal Communication). This means that should one cable be damaged there is always another source of energy, thus increasing energy security. It is here where 'Guernsey needs to be innovative to survive' *Jeremy Thompson, Personal Communication.*

Site 3 has shown that it has the potential to generate 278.16% of Sark's yearly demand. It is therefore ideal for micro-generation and creates the possibility of Sark being able to export energy to Guernsey via a new undersea cable connecting the islands. However before energy generation can be considered, the area around Site 3 needs to be analysed in detail to establish the optimum location for turbine deployment. A detailed cost benefit analysis also needs to be completed to assess whether a project such as this is viable for the island. Finally, should Sark wish to export energy to Guernsey's grid then appropriate legislation would have to be drafted.

Guernsey does have a viable tidal stream energy source in the Big Russel. An array with a significant level of investment could return a large proportion of Guernsey's annual energy demand. However, further research has to be carried out. As highlighted previously, research is required to accurately assess the wave climate in the Big Russel and establish the effect of Brecqhou on tidal flows. Legislation also needs to be drafted to protect turbines and large vessels and to highlight areas of safe passage. Finally, all of the Big Russel needs to be assessed in detail in order to fully understand the tidal energy potential contained in the channel. Once the channel is fully understood Guernsey can then start to look at the best way to utilise the energy potential.

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Appendix A

Site 1 MATLAB Script for Data Analysis

```
clc
clear
load sark0101_DATA

%need to crop the data to row 132 to remove where it started
collecting
%data out of the water

time=sark0101_header(132:end,1); %The time has been placed in the text
data as the first column, rather than the data array

TIME_START=datenum(2011,11,15,11,54,11)-datenum(2011,1,1,0,0,0);%
covert time into a format that MATLAB can read
interval=1/24/6;
time_increment=ones(size(time)).*interval;
tt=cumsum(time_increment);
final_time=TIME_START-interval+tt;

height=[2.5:2:40.5];% height above the device.

sark_data=sark0101_data(131:end,:);

U=sark_data(:,9:2:end).*sin(sark_data(:,10:2:end).*pi/180);%East
velocity
V=sark_data(:,9:2:end).*cos(sark_data(:,10:2:end).*pi/180);%North
velocity

speed=sark_data(:,9:2:end);

figure
plot(final_time,speed(:,10));%speed shows little info other than the
current speed
%no info about direction etc. which is why it has to be split into U &
V
title('Velocity of Current with Time for Site 1');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
grid on

%Graph shows the U and V without channel adjustment
figure
plot(final_time,U(:,10))%Plot U (east) velocity component at 20.5 m
height
hold on
plot(final_time,V(:,10),'r')
grid on
title('U (East Component) and V (North Component) at 20.5 meters
height for Site 1');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend U(East Component) V(North Component)

%Convert U and V to along channel and across channel velocities
%Big Russell is orientated at ~25.5 degrees to the NE;
long=V.*cos((25.5/180)*pi)+U.*sin((25.5/180)*pi);
cross=U.*cos((25.5/180)*pi)-V.*sin((25.5/180)*pi);
```

```
%Graph shows the U and V with channel adjustment (25 degress)
figure
plot(final_time,cross(:,10))%Plot cross (east) velocity component at
20.5 m height
hold on
plot(final_time,long(:,10),'r')
grid on
title('Cross Channel in Blue and Long Channel in Red Adjusted for
Heading of Big Russel at 20.5 Meters Height for Site 1');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend Cross-Channel-Current Long-Channel-Current

%Plot showing the Tidal ellipse
figure
plot(U(:,10),V(:,10))
u=U(1975:1975+6*24,1);%Plot one day of data, so 144 data points
v=V(1975:1975+6*24,1);
quiver(zeros(size(u)),zeros(size(u)),u,v);
axis equal
grid on
set(gca,'xlim',[-1.5,1.5])
set(gca,'ylim',[-1.5,1.5])
title ('Flow Direction for Site 1')

%vertical profile of water column over 5 hours of spring tide.
 figure
 h = plot(long(1625,:),height);
 set(h,'Color',[0.9,0.5,0])
 hold on
 plot(long(1631,:),height);
 hold on
 plot(long(1637,:),height, 'r');
 hold on
 plot(long(1643,:),height, 'g');
 hold on
 plot(long(1649,:),height, 'k');
 title('Water Column Profile Around Maximum Spring Velocity on
26/11/11 for Site 1');
ylabel('Distance away from ADCP (m)');
xlabel('Velocity (m/s)');
legend 18:34 19:34 20:34 21:34 22:34
text(2.05,42,'Max Spring Velocity \downarrow')
text(2.6,13,'Time')
grid on

%calculate the section of water that will be analysed in the power
equation

sealevel=sark_data(:,5);

figure
plot(sealevel)
title('Sealevel Height')
xlabel('time')
ylabel('Depth of Water')

%lowest sealevel is 41.68 at 1594 at yearday 329.5585
%gives 26/11/11 at 13:24.11, tide = 1.02 meters at low tide. so still
1
%meter above chart datum (LAT)
```

```
%this means Chart datum Depth is approx 40.5 meters of water at lowest
%point.
%according to RYCA turbines need to be a futher 8 meters below this
level
%to reduce risk of collision.
%Turbine cannot be higher than 32.5 meters from the bottom.

%Largest turbine diameter is 20 meters. (Hammerfest Strom)
%Based on Large turbine diameter and reaching 30meters height the
turbine
%blades will sweep from 10.5 meters tall to 30.5 meters.

%Crop the data from 10.5 to 30.5 meters
croplong=long(:,5:15);
%crop the data further so it only contains a full month of data
croplong2=croplong(1:4321,:);
finaltime2=final_time(1:4321,:);
%Change all the  values of velocity to positive values
poslong=((long.^2).^0.5);
%need to crop dataset down to one months worth of data (15/11/11 -
11:54.11
%to 15/12/11 - 15:54.11)
poslong2=poslong(1:4321,:);

%Plot of velocity at 20.5 meters depth
depth20=poslong2(:,10);
figure
plot (finaltime2,depth20)
title('Positive Long Channel Velocity at a Height of 20.5 meters at
the Rotor Hub for Site 1')
xlabel('Time (Year Day)')
ylabel('Velocity (m/s)')

%Flow Exceedence Curve
%Cumumlative probability distribution

% Use Eprob function to calculate Flow exceedence curve
springflood = depth20(1520:1555,:);
eX=eprob(springflood);
springebb = depth20(1555:1594,:);
hold on
eX=eprob(springebb);

%use power equation of 0.5*p*u^3 per unit area
power=((croplong2.^2).^0.5);%make values all positive first
 for p=1:4321
     for o=1:11
         power(p,o)=(0.5*1025*(pi*(10^2))*((power(p,o)).^3));%Radius
of turbine=10
     end
 end

power1=power.*0.40; %Apply 40% efficiency
powerkw=power1./1000; %Change from watts to kilowatts

%Plot the output for 20.5 meters depth in kW
figure
plot(finaltime2,powerkw(:,6));
title('Power in the Long Channel Current with Applied 40% Efficiency
for Site 1')
xlabel('Time (Year Day)')
ylabel('Power (kW)')
```

```
%add up all the individual power values for each 10 minute timestep to
%quantify the total amount of power produced in a month. this can then
be
%scaled up accurately for the year

totalpowerkw=sum(powerkw(:,6));

%need to average the velocity over the hour.
%add up all the power values in an hour and then average them.

%gives average power per hour. each row is per hour.
for m=1:11,
    for n=1:6:(floor(length(power)/6)*6),
        hourpower(floor(n/6)+1,m)=mean(power(n:n+5,m));
    end
end

%Work out the average hour in year day for plotting purposes
for g=1:6:(floor(length(finaltime2)/6)*6),
        hourtime(floor(g/6)+1)=mean(finaltime2(g:g+5));
end

hourpower40=((hourpower.*0.4)./1000);% apply 40% efficieny to hour
power values

%Plot the power averaged over an hour at 20.5 meters depth.
figure
plot(hourtime,hourpower40(:,6));
title('Power Averaged Over 1 Hour for Site 1')
xlabel('Time (Year Day)')
ylabel('Power (kW)')


%how much electricity on a spring tide? how much electricty on a Neap
tide?

%Mean Spring = 7.8 meters
%Mean Neap = 3.4 meters

%add 2.2 meters to the averages for upper ranges.
%know the heighest tide is 10 meters.
%know the mean spring tide is 7.8 meters. Gap is 2.2 meters

%Approximate Spring tides to have a range from 5.6 meters +.
%Approx Neap tides have a range from 5.59 meters -.

avsealevel=mean(sealevel(1:4321,:));%Average Depth of water in Sample
= 46.1378


%Plot of spring and neap cycles showing how they have been divided
figure
plot(finaltime2,sealevel(1:4321,:),'r')%sealevel cropped to a month
title('Graph showing Sea level. The lines show the devision between a
neap and a spring tide for Site 1');
xlabel('Year Day')
ylabel('Height of water in meters above the ADCP Device')
h= text(320.5,51.5,'Neap Tide 1');
set(h, 'FontWeight', 'bold')
```

```
h= text(328,51.5,'Spring Tide 1');
set(h, 'FontWeight', 'bold')
h= text(336,51.5,'Neap Tide 2');
set(h, 'FontWeight', 'bold')
h= text(343.6,51.5,'Spring Tide 2');
set(h, 'FontWeight', 'bold')
line([325.4 325.4], [52 40]);% coordinates
line([333.6 333.6], [52 40])
line([342.2 342.2], [52 40])
line([315 350], [48.9 48.9])
line([315 350], [43.3 43.3])

%Separting data into sections of Springs and Neaps for analysis.
spring1=power(997:2187,:); %Using power which is the calculation of
power, not in hours without 40% efficency applied
spring2=power(3418:4321,:);
neap1=power(1:996,:);
neap2=power(2188:3417,:);

spring40= spring1.*0.4;% 40% Effciency applied
springkw=spring40./1000; % Calculate kW
avspringkw=mean(springkw); %Calculate average kW
totalspringkw=sum(springkw(:,6));% Calculate total energy for Spring 1

spring402= spring2.*0.4;% 40% Effciency applied
springkw2=spring402./1000;% Calculate kW
avspringkw2=mean(springkw2);%Calculate average kW
totalspring2kw=sum(springkw2(:,6));% Calculate total energy for Spring
2

neap40= neap1.*0.4;% 40% Effciency applied
neapkw=neap40./1000;% Calculate kW
avneapkw=mean(neapkw);%Calculate average kW
totalneapkw=sum(neapkw(:,6));% Calculate total energy for Neap 1

neap402= neap2.*0.4;% 40% Effciency applied
neapkw2=neap402./1000;% Calculate kW
avneapkw2=mean(neapkw2);%Calculate average kW
totalneap2kw=sum(neapkw2(:,6));% Calculate total energy for Neap 2

%Total combined power in a Spring and a Neap
overallspringkw = totalspringkw + totalspring2kw;
overallneapkw = totalneapkw + totalneap2kw;


%Calculate Mean Spring Velocities in Neaps and Springs.
poscroplong2=((croplong2.^2).^0.5);
springv1=poscroplong2(997:2187,:);
springv2=poscroplong2(3418:4321,:);
neapv1=poscroplong2(1:996,:);
neapv2=poscroplong2(2188:3417,:);

avspringv1=mean(springv1);
avspringv2=mean(springv2);

avneapv1=mean(neapv1);
avneapv2=mean(neapv2);

overallavspringv=((avspringv1+avspringv2)./2);%1.25 m/s
overallavneapv=((avneapv1+avneapv2)./2);%0.96 m/s
```

```
%Calculate a Power Curve

vel=croplong2(:,10);
vel2=((vel.^2).^0.5);

pow=powerkw(:,10);

%Plot the Power Curve
figure
plot(vel2,pow,'r.');
title('Power Curve for Site 1 using HS1000')
xlabel('Velocity (m/s)')
ylabel('Power (kW)')
h= text(1,1100,'Max Output 1000 kW');
set(h, 'FontWeight', 'bold')
line([0 3], [1000 1000]);% coordinates

%Data is for the whole month. Realistically device cannot produce
above 1
%MW so would flatten out there.

avevel = mean(vel2);
```

Appendix B

Site 2 MATLAB Script for Data Analysis

```
clc
clear
load sark0201_DATA

%need to crop the data around row 10 to remove where it started
collecting
%data out of the water

time=sark0201_header(10:4427,1); %The time has been placed in the text
data as the first column, rather than the data array

TIME_START=datenum(2012,01,07,15,39,11)-datenum(2012,1,1,0,0,0);%
covert time into a format that MATLAB can read
interval=1/24/6;
time_increment=ones(size(time)).*interval;
tt=cumsum(time_increment);
final_time=TIME_START-interval+tt;

height=[2.5:2:40.5];% height above the device.

sark_data=sark0201_data(10:4427,:);

U=sark_data(:,9:2:end).*sin(sark_data(:,10:2:end).*pi/180);%East
velocity
V=sark_data(:,9:2:end).*cos(sark_data(:,10:2:end).*pi/180);%North
velocity

speed=sark_data(:,9:2:end);

figure
plot(final_time,speed(:,10));%speed shows little info other than the
current speed
%no info about direction etc. which is why it has to be split into U &
V
title('Velocity of Current with Time for Site 2');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
grid on

%Graph shows the U and V without channel adjustment
figure
plot(final_time,U(:,10))%Plot U (east) velocity component at 20.5 m
height
hold on
plot(final_time,V(:,10),'r')
grid on
title('U (East Component) and V (North Component) at 20.5 meters
height for Site 2');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend U(East Component) V(North Component)

%Convert U and V to along channel and across channel velocities
%Big Russell is orientated at ~25.5 degrees to the NE;
long=V.*cos((25.5/180)*pi)+U.*sin((25.5/180)*pi);
cross=U.*cos((25.5/180)*pi)-V.*sin((25.5/180)*pi);
```

```
%Graph shows the U and V with channel adjustment (25 degress)
figure
plot(final_time,cross(:,10))%Plot cross (east) velocity component at
12.5 m height
hold on
plot(final_time,long(:,10),'r')
grid on
title('Cross Channel in Blue and Long Channel in Red Adjusted for
Heading of Big Russel at 20.5 Meters Height for Site 2');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend Cross-Channel-Current Long-Channel-Current

%Plot showing the Tidal ellipse
figure
plot(U(:,6),V(:,6))
u=U(2311:2311+6*24,1);%Plot one day of data, so 144 data points
v=V(2311:2311+6*24,1);
quiver(zeros(size(u)),zeros(size(u)),u,v);
axis equal
grid on
set(gca,'xlim',[-1.5,1.5])
set(gca,'ylim',[-1.5,1.5])
title ('Flow Direction for Site 2')

%vertical profile of water column over 5 hours of spring tide.
 figure
 h=plot(long(897,:),height);%Gap of 6
 set(h,'Color',[0.9,0.5,0])
 hold on
 plot(long(903,:),height);
 hold on
 plot(long(909,:),height, 'r');
 hold on
 plot(long(915,:),height, 'g');
 hold on
 plot(long(921,:),height, 'k');
 title('Water Column Profile Around Maximum Spring Velocity on
13/01/12 for Site 2');
ylabel('Distance away from ADCP (m)');
xlabel('Velocity (m/s)');
legend 20:59 21:59 22:59 23:59 00:59
text(2.05,42,'Spring Max Velocity \downarrow')
text(2.6,13,'Time')
grid on

%calculate the section of water that will be analysed in the power
equation

sealevel=sark_data(:,5);

figure
plot(sealevel)
title('Sealevel Height')
xlabel('time')
ylabel('Depth of Water')

%lowest sealevel is 37.19 at 2584 at yearday 24.59
%gives 25/1/12 at 14:09:11, tide = 1.06 meters at low tide. so still 1
%meter above chart datum (LAT)
```

```
%this means Chart datum Depth is approx 36.19 meters of water at
lowest
%point.
%according to RYCA turbines need to be a futher 8 meters below this
level
%to reduce risk of collision.
%Turbine cannot be higher than 28.19 meters from the bottom.

%Suitable turbine is Open Hydro with a diameter of 16 meters.
%Based on turbine diameter and reaching 21 meters height the turbine
%blades will sweep from 5 meters tall to 21 meters.

%Crop the data from 5 to 21 meters

croplong=long(:,2:10);
%crop the data further so it only contains a full month of data,
already
%does!
croplong2=croplong;
finaltime2=final_time;
%Change all the  values of velocity to positive values
poslong=((long.^2).^0.5);
%need to crop dataset down to one months' worth of data (07/01/12 -
15:39.11
%to 07/02/12 - 07:49:11)
poslong2=poslong;

%Plot of velocity at 12.5 meters depth
depth20=poslong2(:,6);
figure
plot (finaltime2,depth20)
title('Positive Long Channel Velocity at a Height of 12.5 meters at
the Rotor Hub for Site 2')
xlabel('Time (Year Day)')
ylabel('Velocity (m/s)')

%Flow Exceedence Curve
%Cumumlative probability distribution

% Use Eprob function to calculate Flow exceedence curve
springflood = depth20(866:897,:);
eX=eprob(springflood);
springebb = depth20(825:866,:);
hold on
eX=eprob(springebb);

%use power equation of 0.5*p*u^3 per unit area
power=((croplong2.^2).^0.5);%make values all positive first
 for p=1:4418
     for o=1:9
         power(p,o)=(0.5*1025*(pi*(8^2))*((power(p,o)).^3));%Radius of
turbine=8
     end
 end

power1=power.*0.40; %Apply 40% efficiency
powerkw=power1./1000; %Change from watts to kilowatts

%Plot the output for 12.5 meters depth in kW
figure
plot(finaltime2,powerkw(:,6));
```

```
title('Power in the Long Channel Current with Applied 40% Efficiency
for Site 2')
xlabel('Time (Year Day)')
ylabel('Power (kW)')

%add up all the individual power values for each 10 minute timestep to
%quantify the total amount of power produced in a month.
totalpowerkw=sum(powerkw(:,6));

%need to average the velocity over the hour.
%add up all the power values in an hour and then average them.

%gives average power per hour. each row is per hour.
for m=1:9,
    for n=1:6:(floor(length(power)/6)*6),
        hourpower(floor(n/6)+1,m)=mean(power(n:n+5,m));
    end
end

 %Work out the average hour in year day for plotting purposes
for g=1:6:(floor(length(finaltime2)/6)*6),
        hourtime(floor(g/6)+1)=mean(finaltime2(g:g+5));
end

hourpower40= ((hourpower.*0.4)./1000);% apply 40% efficieny to hour
power values

%Plot the power averaged over an hour at 20.5 meters depth.
figure
plot(hourtime,hourpower40(:,6));
title('Power Averaged Over 1 Hour for Site 2')
xlabel('Time (Year Day)')
ylabel('Power (kW)')

%how much electricity on a spring tide? how much electricty on a Neap
tide?

%Approximate Spring tides to have a range from 5.6 meters +.
%Approx Neap tides have a range from 5.59 meters -.

avsealevel=mean(sealevel(1:4418,:));%Average Depth of water in Sample
= 42.0759

%Plot of spring and neap cycles showing how they have been divided
figure
plot(finaltime2,sealevel(1:4418,:),'r')%sealevel cropped to a month
title('Graph showing Sea level. The lines show the devision between a
neap and a spring tide for Site 2');
xlabel('Year Day')
ylabel('Height of water in meters above the ADCP Device')
h= text(16,46.5,'Neap Tide 1');
set(h, 'FontWeight', 'bold')
h= text(8,46.5,'Spring Tide 1');
set(h, 'FontWeight', 'bold')
h= text(30.5,46.5,'Neap Tide 2');
set(h, 'FontWeight', 'bold')
h= text(23,46.5,'Spring Tide 2');
set(h, 'FontWeight', 'bold')
line([15.21 15.21], [47 37]);% coordinates
line([20.16 20.16], [47 37])
line([28.69 28.69], [47 37])
```

```
line([35.99 35.99], [47 37])
line([5 38], [44.8759 44.8759])
line([5 38], [39.2759 39.2759])

%Separting data into sections of Springs and Neaps for analysis.
spring1=power(1:1234,:); %Using power which is the calculation of
power, not in hours without 40% efficency applied
spring2=power(1947:3175,:);
neap1=power(1235:1946,:);
neap2=power(3176:4226,:);

spring40= spring1.*0.4;% 40% Effciency applied
springkw=spring40./1000; % Calculate kW
avspringkw=mean(springkw); %Calculate average kW
totalspringkw=sum(springkw(:,6));% Calculate total energy for Spring 1

spring402= spring2.*0.4;% 40% Effciency applied
springkw2=spring402./1000;% Calculate kW
avspringkw2=mean(springkw2);%Calculate average kW
totalspring2kw=sum(springkw2(:,6));% Calculate total energy for Spring
2

neap40= neap1.*0.4;% 40% Effciency applied
neapkw=neap40./1000;% Calculate kW
avneapkw=mean(neapkw);%Calculate average kW
totalneapkw=sum(neapkw(:,6));% Calculate total energy for Neap 1

neap402= neap2.*0.4;% 40% Effciency applied
neapkw2=neap402./1000;% Calculate kW
avneapkw2=mean(neapkw2);%Calculate average kW
totalneap2kw=sum(neapkw2(:,6));% Calculate total energy for Neap 2

%Total combined power in a Spring and a Neap
overallspringkw = totalspringkw + totalspring2kw;
overallneapkw = totalneapkw + totalneap2kw;

%Calculate Mean Spring Velocities in Neaps and Springs.
poscroplong2=((croplong2.^2).^0.5);
springv1=poscroplong2(1:1234,:);
springv2=poscroplong2(1947:3175,:);
neapv1=poscroplong2(1235:1946,:);
neapv2=poscroplong2(3176:4226,:);

avspringv1=mean(springv1);
avspringv2=mean(springv2);

avneapv1=mean(neapv1);
avneapv2=mean(neapv2);

overallavspringv=((avspringv1+avspringv2)./2);
overallavneapv=((avneapv1+avneapv2)./2);

%Calculate a Power Curve

vel=croplong2(:,5);
vel2=((vel.^2).^0.5);

pow=powerkw(:,5);

figure
```

```
plot(vel2,pow,'r.');
title('Power Curve for Site 2 using OpenHydro Turbine')
xlabel('Velocity (m/s)')
ylabel('Power (kW)')
h= text(1,1150,'Max Output 2200 kW \uparrow');
set(h, 'FontWeight', 'bold')
line([0 3], [1200 1200]);

avevel = mean(vel2);
```

Appendix C

Site 3 MATLAB Script for Data Analysis

```
clc
clear
load sark0301_DATA

%need to crop the data around row 10 to remove where it started
collecting
%data out of the water

time=sark0301_header(10:4448,1); %The time has been placed in the text
data as the first column, rather than the data array

TIME_START=datenum(2012,02,20,13,53,16)-datenum(2012,1,1,0,0,0);%
covert time into a format that MATLAB can read
interval=1/24/6;
time_increment=ones(size(time)).*interval;
tt=cumsum(time_increment);
final_time=TIME_START-interval+tt;

height=[2.5:2:40.5];% height above the device.

sark_data=sark0301_data(10:4448,:);

U=sark_data(:,9:2:end).*sin(sark_data(:,10:2:end).*pi/180);%East
velocity
V=sark_data(:,9:2:end).*cos(sark_data(:,10:2:end).*pi/180);%North
velocity

speed=sark_data(:,9:2:end);

figure
plot(final_time,speed(:,10));%speed shows little info other than the
current speed
%no info about direction etc. which is why it has to be split into U &
V
title('Velocity of Current with Time at Site 3');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
grid on

%Graph shows the U and V without channel adjustment
figure
plot(final_time,U(:,10))%Plot U (east) velocity component at 20.5 m
height
hold on
plot(final_time,V(:,10),'r')
grid on
title('U (East Component) and V (North Component) at 20.5 meters
height for Site 3');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend U(East Component) V(North Component)

%Convert U and V to along channel and across channel velocities
angle=sark_data(:,20);

angle2=angle;
```

```
for i = 1:4439
        if angle2(i) > 80
        angle2(i) = 0;
        end
end
aveangle=mean(angle2); %16.2 degress average angle

long=V.*cos((16.2/180)*pi)+U.*sin((16.2/180)*pi);
cross=U.*cos((16.2/180)*pi)-V.*sin((16.2/180)*pi);

%Graph shows the U and V with channel adjustment
figure
plot(final_time,cross(:,10))%Plot cross (east) velocity component at
20.5 m height
hold on
plot(final_time,long(:,10),'r')
grid on
title('Cross Current in Blue and Long Current in Red Adjusted for
Heading of Current at Site 3');
ylabel('Velocity (m/s)');
xlabel('Time (Year Day)');
legend Cross-Current Long-Current

%Plot showing the Tidal ellipse
figure
plot(U(:,6),V(:,6))
u=U(1000:1000+6*24,1);%Plot one day of data, so 144 data points
v=V(1000:1000+6*24,1);
quiver(zeros(size(u)),zeros(size(u)),u,v);
axis equal
grid on
set(gca,'xlim',[-1.5,1.5])
set(gca,'ylim',[-1.5,1.5])
title ('Flow Direction for Site 3')

%vertical profile of water column over 5 hours of spring tide
 figure
 h=plot(long(2779,:),height, 'y');%Gap of 6
 set(h,'Color',[0.9,0.5,0])
 hold on
 plot(long(2785,:),height);
 hold on
 plot(long(2791,:),height, 'r');
 hold on
 plot(long(2797,:),height, 'g');
 hold on
 plot(long(2803,:),height, 'k');
 title('Water Column Profile Around Maximum Spring Velocity on
10/03/12 for Site 3');
ylabel('Distance away from ADCP (m)');
xlabel('Velocity (m/s)');
legend 20:43 21:43 22:43 23:43 00:43
text(1.67,42,'\downarrowMax Spring Velocity')
text(2.1,34,'Time')
grid on

%calculate the section of water that will be analysed in the power
equation

sealevel=sark_data(:,5);

figure
```

```
plot(sealevel)
title('Sealevel Height')
xlabel('time')
ylabel('Depth of Water')

%lowest sealevel is 43.57 at 2742
%gives 10/3/12 at 14:33:16, tide = 0.48 meters at low tide. so still
0.5
%meter above chart datum (LAT)
%this means Chart datum Depth is approx 43.00 meters of water at
lowest
%point.
%according to RYCA turbines need to be a futher 8 meters below this
level
%to reduce risk of collision.
%Turbine cannot be higher than 35.00 meters from the bottom.

%Suitable turbine is OpenHydro with a diameter of 16 meters.
%Based on turbine diameter and reaching 21 meters height the turbine
%blades will sweep from 5 meters tall to 21 meters.

%Crop the data from 5 to 21 meters

croplong=long(:,2:10);
%crop the data further so it only contains a full month of data,
already
%does!
croplong2=croplong;
finaltime2=final_time;
%Change all the  values of velocity to positive values
poslong=((long.^2).^0.5);
%need to crop dataset down to one months' worth of data (07/01/12 -
15:39.11
%to 07/02/12 - 07:49:11)
poslong2=poslong;

%Plot of velocity at 12.5 meters depth
depth20=poslong2(:,6);
figure
plot (finaltime2,depth20)
title('Positive Long Channel Velocity at a Height of 12.5 meters at
the Rotor Hub for Site 3')
xlabel('Time (Year Day)')
ylabel('Velocity (m/s)')

%Flow Exceedence Curve
%Cumumlative probability distribution
% Use Eprob function to calculate Flow exceedence curve
springflood = depth20(2821:2852,:);
eX=eprob(springflood);
springebb = depth20(2784:2821,:);
hold on
eX=eprob(springebb);

%use power equation of 0.5*p*u^3 per unit area
power=((croplong2.^2).^0.5);%make values all positive first
 for p=1:4439
     for o=1:9
         power(p,o)=(0.5*1025*(pi*(8^2))*((power(p,o)).^3));%Radius of
turbine=8
     end
 end
```

```
power1=power.*0.40; %Apply 40% efficiency
powerkw=power1./1000; %Change from watts to kilowatts

%Plot the output for 12.5 meters depth in kW
figure
plot(finaltime2,powerkw(:,6));
title('Power in the Long Channel Current with Applied 40% Efficiency
for Site 3')
xlabel('Time(Year Day)')
ylabel('Power (kW)')

%add up all the individual power values for each 10 minute timestep to
%quantify the total amount of power produced in a month.
totalpowerkw=sum(powerkw(:,6));

%need to average the velocity over the hour.
%add up all the power values in an hour and then average them.

%gives average power per hour. each row is per hour.
for m=1:9,
    for n=1:6:(floor(length(power)/6)*6),
        hourpower(floor(n/6)+1,m)=mean(power(n:n+5,m));
    end
end

 %Work out the average hour in year day for plotting purposes
for g=1:6:(floor(length(finaltime2)/6)*6),
        hourtime(floor(g/6)+1)=mean(finaltime2(g:g+5));
end

hourpower40= ((hourpower.*0.4)./1000);% apply 40% efficieny to hour
power values

%Plot the power averaged over an hour at 20.5 meters depth.
figure
plot(hourtime,hourpower40(:,6));
title('Power Averaged Over 1 Hour for Site 3')
xlabel('Time (Year Day)')
ylabel('Power (kW)')

%how much electricity on a spring tide? how much electricty on a Neap
tide?

%Approximate Spring tides to have a range from 5.6 meters +.
%Approx Neap tides have a range from 5.59 meters -.

avsealevel=mean(sealevel(1:4439,:));%Average Depth of water in Sample
= 48.2864

%Plot of spring and neap cycles showing how they have been divided
figure
plot(finaltime2,sealevel(1:4439,:),'r')%sealevel cropped to a month
title('Graph showing Sea level. The lines show the devision between a
neap and a spring tide for Site 3');
xlabel('Year Day')
ylabel('Height of water in meters above the ADCP Device')
h= text(59,53,'Neap Tide 1');
set(h, 'FontWeight', 'bold')
h= text(51,53,'Spring Tide 1');
set(h, 'FontWeight', 'bold')
```

```
h= text(74,53,'Neap Tide 2');
set(h, 'FontWeight', 'bold')
h= text(66,53,'Spring Tide 2');
set(h, 'FontWeight', 'bold')
line([57.91 57.91], [43 54]);% coordinates
line([65.22 65.22], [43 54])
line([73.47 73.47], [43 54])
line([79.18 79.18], [43 54])
line([50 82], [51.0864 51.0864])
line([50 82], [45.4864 45.4864])

%Separting data into sections of Springs and Neaps for analysis.
spring1=power(1:1057,:); %Using power which is the calculation of
power, not in hours without 40% efficency applied
spring2=power(2110:3298,:);
neap1=power(1058:2109,:);
neap2=power(3299:4120,:);

spring40= spring1.*0.4;% 40% Effciency applied
springkw=spring40./1000; % Calculate kW
avspringkw=mean(springkw); %Calculate average kW
totalspringkw=sum(springkw(:,6));% Calculate total energy for Spring 1

spring402= spring2.*0.4;% 40% Effciency applied
springkw2=spring402./1000;% Calculate kW
avspringkw2=mean(springkw2);%Calculate average kW
totalspring2kw=sum(springkw2(:,6));% Calculate total energy for Spring
2

neap40= neap1.*0.4;% 40% Effciency applied
neapkw=neap40./1000;% Calculate kW
avneapkw=mean(neapkw);%Calculate average kW
totalneapkw=sum(neapkw(:,6));% Calculate total energy for Neap 1

neap402= neap2.*0.4;% 40% Effciency applied
neapkw2=neap402./1000;% Calculate kW
avneapkw2=mean(neapkw2);%Calculate average kW
totalneap2kw=sum(neapkw2(:,6));% Calculate total energy for Neap 2

%Total combined power in a Spring and a Neap
overallspringkw = totalspringkw + totalspring2kw;
overallneapkw = totalneapkw + totalneap2kw;

%Calculate Mean Spring Velocities in Neaps and Springs.
poscroplong2=((croplong2.^2).^0.5);
springv1=poscroplong2(1:1057,:);
springv2=poscroplong2(2110:3298,:);
neapv1=poscroplong2(1058:2109,:);
neapv2=poscroplong2(3299:4120,:);

avspringv1=mean(springv1);
avspringv2=mean(springv2);

avneapv1=mean(neapv1);
avneapv2=mean(neapv2);

overallavspringv=((avspringv1+avspringv2)./2);
overallavneapv=((avneapv1+avneapv2)./2);

%Calculate a Power Curve
```

```
vel=croplong2(:,5);
vel2=((vel.^2).^0.5);

pow=powerkw(:,5);

figure
plot(vel2,pow,'r.');
title('Power Curve for Site 3 using OpenHydro Turbine')
xlabel('Velocity (m/s)')
ylabel('Power (kW)')
h= text(1,1150,'Max Output 2200 kW \uparrow');
set(h, 'FontWeight', 'bold')
line([0 3], [1200 1200]);

avevel = mean(vel2);
```

Appendix D

MATLAB Script for the Probability Function

```
function [eX] = eprob(X)
% eprob: calculates the exceedance probability for n column vectors in
the
%        array [m n] X, where m are the observations. The probability
is
%        output in percent. eX is output as a structure (see Output
Arguments).
%
% Input Arguments:
%
%   X - [m n] vector where m are the observations and n are the number
of
%   datasets for which the exceedance probability is to be calculated.
%   The size of m must be the same for all datasets.
%
% Output Arguments:
%
%   eX - structure array containing all output data
%   ex.data - input data X [m n]
%   ex.r - the number of rows, m
%   ex.c - the number of datasets (columns), n
%   ex.sort - X input data sorted in descending order
%   ex.rank - single column matrix of the sorted data rank
%   ex.eprob - calculated exceedance probability (rank/m+1)

Scap = 10; % active operational energy storage capacity
% Scap = StorCapPercent eX average annual generation
eX = struct;

eX.data = X;
eX.r = size(eX.data,1); % no. rows
eX.c = size(eX.data,2); % no. cols

eX.sort = sort(eX.data,'descend'); % sorts data in descending order
eX.rank = (1:eX.r)';
eX.eprob = zeros(eX.r,1);
eX.eprob = eX.rank./(eX.r+1);

% plotting exceedance probability curve (in %)
plot(eX.sort, eX.eprob,'LineWidth',2);%'r-',
xlabel('Velocity (m/s)','FontWeight','Bold');
line([1 1], [0 1])
text(0.3,0.3,'Cut in Speed\rightarrow')
title('Exceedance Probability Curve Site 1')
legend Flood Ebb
ylabel('Exceedance Probability','FontWeight','Bold');
```

Appendix E

Extreme Events MATLAB Script for Data Analysis

```
clc
clear

%Load the data for each year
load('2002JER.dat')
date_2002=X2002JER(:,2:7);
surge_2002=X2002JER(:,9);

load('2003JER.dat')
date_2003=X2003JER(:,2:7);
surge_2003=X2003JER(:,9);

load('2004JER.dat')
date_2004=X2004JER(:,2:7);
surge_2004=X2004JER(:,9);

load('2005JER.dat')
date_2005=X2005JER(:,2:7);
surge_2005=X2005JER(:,9);

load('2006JER.dat')
date_2006=X2006JER(:,2:7);
surge_2006=X2006JER(:,9);

load('2007JER.dat')
date_2007=X2007JER(:,2:7);
surge_2007=X2007JER(:,9);

load('2008JER.dat')
date_2008=X2008JER(:,2:7);
surge_2008=X2008JER(:,9);

load('2009JER.dat')
date_2009=X2009JER(:,2:7);
surge_2009=X2009JER(:,9);

load('2010JER.dat')
date_2010=X2010JER(:,2:7);
surge_2010=X2010JER(:,9);

load('2011JER.dat')
date_2011=X2011JER(:,2:7);
surge_2011=X2011JER(:,9);

%organise the data into a large matrix, one corresponding to Surge
data,
%one to the time variable
surge=[surge_2002;surge_2003;surge_2004;surge_2005;surge_2006;surge_20
07;surge_2008;surge_2009;surge_2010;surge_2011];
date=[date_2002;date_2003;date_2004;date_2005;date_2006;date_2007;date
_2008;date_2009;date_2010;date_2011];

%convert date into a format MATLAB can read
datem=datenum(date);
surge2 = max(0,surge);
```

```
%find the largest surges that occur in a week interval
[pks locs] = findpeaks(surge,'minpeakdistance',672);

%Exclude values smaller than 0 from dataset
B=pks;
for i = 1:400
    if B(i) <= 0;
        B(i) = NaN;
    end
end

%plot data
figure(1)
plot(datem,surge2);
hold all
plot(datem(locs),B,'.k')
datetick('x')

%unusally high surge occurred on 27/09/10 - nothing major in weather
record
%therefore this measurement is an error.

%Exclude erroneous data from dataset
H=surge2;
for i = 1:350592
    if H(i) >= (2);
        H(i) = NaN;
    end
end

figure(2)
plot(datem,H);
hold all
plot(datem(locs),B,'.k')
datetick('x')

%plot tidal data with residual data separate to show small scale
%frequencies.
tide_2002=X2002JER(:,8);
tide_2003=X2003JER(:,8);
tide_2004=X2004JER(:,8);
tide_2005=X2005JER(:,8);
tide_2006=X2006JER(:,8);
tide_2007=X2007JER(:,8);
tide_2008=X2008JER(:,8);
tide_2009=X2009JER(:,8);
tide_2010=X2010JER(:,8);
tide_2011=X2011JER(:,8);

tide=[tide_2002;tide_2003;tide_2004;tide_2005;tide_2006;tide_2007;tide
_2008;tide_2009;tide_2010;tide_2011];

T=tide;
for i = 1:350592
    if T(i) <= 0;
        T(i) = NaN;
    end
end

R=surge;
```

```
for i = 1:350592
    if R(i) <= (-1);
        R(i) = NaN;
    end
end

T2=T-((R.^2).^0.5);

figure (9)
plot (datem,T2)
hold on
plot (datem,R,'r')
datetick('x')
title('Regular tide and residual component')
ylabel('Tidal Height (m)')
xlabel('Time')
legend Tide Residual


%put data into bins to qantify how many times each surge occurs
bin=0.05:0.05:4.8;
binmin=bin-0.05;
binmax=bin+0.05;

%load a file of the data seperated into bins
load ('hist.dat')
binsize=hist(1,:);
occ=hist(2,:);

%plot a histogram of the bins
figure (3)
bar(binsize,occ);
xlabel('Surge Size (m)');
ylabel('Occurence');
title('Histogram showing number of times a surge height is reached');
% plot a log log plot of the data
figure (4)
p=semilogy(binsize,occ,'-O');
xlabel('Surge Size (m)');
ylabel('Occurence');
title('A semi logarithmic plot showing number of times a surge height
is reached');
set(p,'Color','red')

%Locate heighest surge from data
[row]=find (surge2 > 1.24);

surgeplot=surge2(216954:217219,:);
surgetime=datem(216954:217219,:);
surgetime2=surgetime(1:92,:);

%Plot heighest surge
figure (5)
plot(surgetime,surgeplot);
datetick('x')
title('1.2482');

surgeplot2=surgeplot(1:92,:);
%crop the data to highlight the surge of interest
figure(6)
plot(surgetime2,surgeplot2);
```

```
datetick('x')
ylabel('Surge Height (m)');
xlabel('Time');
title('Largest Storm Surge Event on 10/03/2008 of 1.248 meters');
%Save the surge event separately after the data has been forced to
zero
load ('surgeevent.dat')
%Plot the surge event
figure(7)
plot(surgetime2,surgeevent);
datetick('x')
ylabel('Surge Height (m)');
xlabel('Time');
title('Largest Storm Surge Event on 10/03/2008 of 1.248 meters');

crop1=X2008JER(:,8);
crop1=crop1(6587:6657,:);
crop2=X2008JER(:,8);
crop2=crop2(6657:6680,:);

%There is a sudden dip in pressure around the date, proving the surge.
%Load normal tide data
load ('normaltide.dat')
load ('surgetide.dat')


timesurge=datem(6588:6679);
%Plot a regular tide and also the tide with a surge added to it.
figure (8)
plot (timesurge,normaltide)
hold on
plot (timesurge,surgetide,'r')
datetick('x')
title('Effect of tidal surge if it co-insides with spring high tide')
ylabel('Tidal Height (m)')
xlabel('Time')
legend Regular-tide Surge-tide
```