An Assessment of the tidal resource of Guernsey

An investigation into the tidal resource and potential power extraction of Guernsey using Delft3d software.

MSc Marine Renewable Energy.

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Abstract

The tidal resource in the coastal waters of Guernsey has been well documented since the1990s. Encouraged by the untapped energy resource, the desire for power self - sufficiency and the ratification of the Kyoto protocol on the reduction of CO_2 emissions; Guernsey Department of Commerce and Employment created the Guernsey Renewable Energy Commission that have published a strategy to create a marine renewable energy industry by 2020 on the island.

Delft Dashboard and Delft 3D FLOW software packages were used to model the tidal regime around Guernsey, the model was validated against the Renewable Energy Atlas, Admiralty Easy Tide and Admiralty Tidal Atlas NP 294. The model output revealed that Guernsey has a semi diurnal tide with a tidal range between 5 and 9 meters. The tidal velocity has a quadrant diurnal regime, with maximum velocities at High and Low water, the velocity pattern is a result of the M4 component of the tide.

The model output showed a viable resource within the Big Russel channel, with a total tidal power output of approximately 600 GWh/a. A region to the East of Sark also showed great promise with similar values to the Big Russel. Both areas have 99% generation availability and good bathymetry, favourable for current technology. Assuming the model is correct tidal power generation at these two sites could be incorporated into the base load power generation. Following on from this report it would be advised to further investigate the two regions with higher resolution models and observed and measured data with the view to immediate tidal stream power production. There are also regions to the South of the Big Russel, to the West and North West of Guernsey that may become viable with further investigation and when emerging technology reached maturity.

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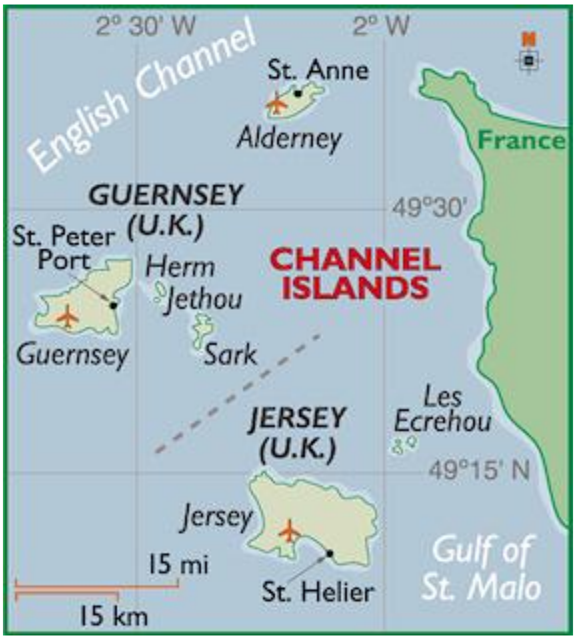
1.0 Introduction

1.1 A Brief Introduction to Guernsey and the Channel Islands.

Situated 30 miles from the northern coast of France in the Gulf of St Malo the Channel Islands consist of a group of 14 islands, eight of which are inhabited. The Channel Islands are two British Crown dependencies, the Bailiwick of Guernsey and the Bailiwick of Jersey; the Bailiwicks are self-governing and independent of UK governance (BBC, 2010). The Bailliwick of Guernsey includes Guernsey, Alderney, Sark, Herm, Jethou, Brecqhou and Lithou.

Figure 1: The Channel Islands. Source: The United Kingdom of Great Britain and Northern Ireland



Under the United Nations Law of the Sea the surrounding coastal waters extend from the low water mark out to the 3 nautical miles (nm) extent are defined as the Territorial water. The coastal state has full sovereign rights over the sea, the seabed and sub soil and the air space immediately above the Territorial water zone. The Crown estate has ownership of the seabed and the waters. Leasing is arranged through Her Majesty's

Receiver General in the States of Guernsey for the Bailliwick. A license would also be required by the FEPA Guernsey Act of 1987 to place any structure in the territorial water. The Bailliwick of Guernsey has extended its fishing rights out to the 12 nm limit (BBC, (a) 2012) and the UK government has agreed in principle to the extension of territorial water limits to 12 nm on the principle that a full agreement of control and legislation of the extended marine territory is reached by all islands within the Channel Islands group (This is Guernsey, 2008).

1.2 Government Energy Policy and Legislation

Guernsey ratified the Kyoto Protocol in 2000, which outlines that all member states should reduce CO_2 emissions by 30% based on 1990 levels. The Energy Policy Group of 2008 produced the Billet d'Etat VIII 2008 report that outlined the aim to reduce the 1990 CO_2 levels by 30% by 2020, and 80% by 2050. These targets have not been formally adopted, but seen as realistic, practical and comparable to UK targets. The 30% reduction target would need to produce 200 GWh/a, which approximate to 100MW of installed capacity (Guernsey Renewable Energy Commission, 2009).

The recognition for the need of the Bailiwick to move to a more carbon neutral economy and the potential resource availability was acknowledged by the Department of Commerce and Employment with the creation of the Guernsey Renewable Energy Commission (GREC) in 2008. GREC has been superseded by the Guernsey Renewable Energy Team (RET). In 2010 the State of Guernsey approved the Renewable Energy Law that enabled legislation to create regulatory statute for the new technology (GREC, 2012).

RET have published their strategy (RET, 2011) which outlines the main renewable energy generation targets. By 2020 it is hoped there will be 10-20 MW of installed locally generated tidal energy, and a similar amount of wind energy. It is estimated there would be a minimum of 16MW of imported power from France through the Channel Islands Electricity Grid. These combined resources should fulfil approximately 39 -53% of the total power demand of the island based on a predicted 2020 demand. The ambition is that during the 2020 decade, there will be further expansion of the wind and tidal industries and that wave energy technology will mature and become part of the renewable energy strategy.

In February 2012, the Channel Islands of Guernsey, Jersey and Sark signed a Joint Statement of Intent on Marine Renewable Energy. The Statement recognises that there may be a degree of competition between the islands but there are also many aspects of the development of the marine renewable industry that would benefit from collaboration and shared knowledge. The three islands have agreed to work towards a common licensing and regulatory regime (State of Guernsey, 2012).

1.3 Guernsey Power Infrastructure

Traditional power infrastructure is vulnerable for peripheral island communities, because outlying islands are situated at the end of a supply chain. Hence island communities are susceptible to poor and intermittent supply (MERiFIC, 2012). Added resilience to the power infrastructure is instigated through imports of raw materials for energy production, or power imports via subsea cables. This situation is exemplified with the current energy and power production in Guernsey.

The current electricity demand peaks at 84 MW during the winter with a 24MW base demand during the summer months. The annual usage is approximately 400,000MWh. Guernsey Electricity are responsible for the domestic power supply which is currently fulfilled by a mixture of domestic power and power imported from France. 75% of all French power is secured from nuclear energy, a source of low carbon power (World Nuclear Association, 2012). Domestic power is provided by the 115 MW Vale Power Station, a mixed diesel and gas turbine generator. Imported power is delivered by two bidirectional subsea cables, connecting France to Jersey and Jersey to Guernsey. Connection from Jersey to France has a capacity of 145 MW. The connection from Jersey to Guernsey is a 60 MW bidirectional subsea cable (Abercromby et al, 2011). The cable connection from the Channel Island to France has the potential for future power exports Jersey and Guernsey to the French mainland. Guernsey Electricity is contracted to provide the cheapest power available, therefore the percentage of imported power and subsequent CO_2 emissions fluctuates with the price of oil. When the price of oil is low the majority of power production will be from the domestic Vale Power station, therefore increasing the CO_2 emissions. In 2009 the total greenhouse gas emissions were the equivalent of 427.4 kt $CO_{2,}$ which was a 10% increase on the previous year. 83% of which were from the combustion of fossil fuels and power generation accounted for a quarter of all greenhouse gas emissions in Guernsey in 2009 (Policy Council, 2011).

The existing power generation of the island is economically and environmentally unsustainable. The low price obligation that governs the power generation on the island creates an untenable situation. If the price of oil increases Guernsey Power will be forced to rely on imported power and despite the reduction in CO_2 emissions the reliance on imported power exposes Guernsey to external market forces. It should be noted that imported power is not totally reliable and a number of power blackouts caused by mechanical failure of the subsea cable have occurred (BBC, (b) 2012). If the price of oil drops the power will be domestically generated, the result of which is increased CO_2 emissions. The need to move to a self-sufficient carbon neutral economy has been recognised and progression towards a renewable energy future has become integrated into government policy (RET, 2011). Technology has emerged over the last decade that allows the natural resources to be investigated, measured and exploited. The move toward renewable energy sources will provide a more diverse power generation underpinned by sustainable energy principles that promote exploitation of local resources.

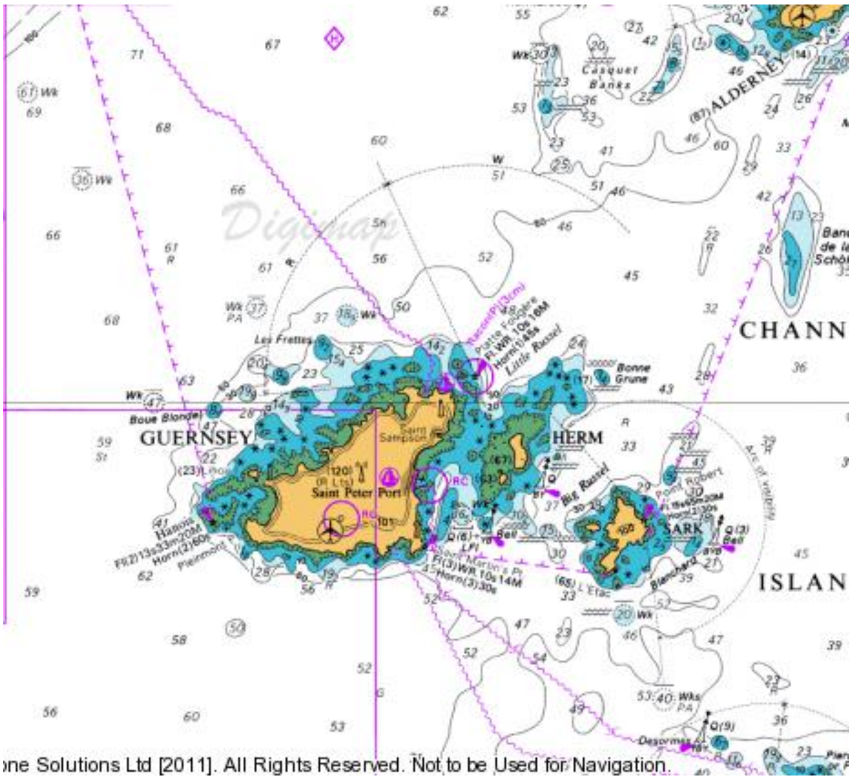
1.4 The Tidal Characteristics of the Channel Islands

The tidal wave travels globally from west to east, traverses the Atlantic and is then forced through a convergence caused by the European land mass into the English Channel. Significant tidal forcing occurs as the tidal wave passes from the deep ocean into shallow continental shelf areas. This forcing creates a tidal velocity generated from the net flux of potential and kinetic energy from the water movement. The energy propagates in the form of a long shallow water wave; the continental shelf can add resonance to the system of the tidal wave and increase the amplitude and thus the tidal velocity (Blunden and Bahaj 2008).

The English Channel is a relatively shallow transitional region between the temperate Atlantic Ocean systems and the boreal North and Baltic Seas. The western extent of the English Channel has a maximum depth of 174 meters in the central trench that lies to the north west of Guernsey. The coastal waters around Guernsey descend to 50+ meters within the three nautical mile limit, the steepest descent located to the south of the island.

Figure 2: Admiralty Chart of Guernsey showing the water depths.

Source: Marine Digimap



The Channel Islands coastal waters are dominated by the influence of Atlantic water and the presence of a seasonal tidal front found offshore from Plymouth in the summer months. The Atlantic waters are characterised as a well homogenised body of water driven by the North Atlantic jet stream. The Plymouth tidal front is the result of current driven Atlantic water meeting the still and stratified coastal waters around the Devon coast (Dauvin, 2012).

Tidal currents around islands are generally characterised by an oscillating rotary current that are clockwise or anticlockwise in direction. The singularities of the currents are caused by the effects of the shape of the island, the topography of the adjacent seabed and the Coriolis force. The shape induced current is known as the Stokes current, the interaction of the seabed friction with the water column in the shallow shoaling regions is known as the residual current. The Coriolis force is the effect of the earths' rotation on a body of water, in the Northern hemisphere the currents are usually deflected in an easterly direction, from the position of looking toward the North Pole from the equator. In the Northern hemisphere the Stokes current and the residual current generally pass around an island in a clockwise direction due to the Coriolis force, however in the Channel Islands current pass in an anticlockwise direction (Dauvin, J.C. 2012).

The anticlockwise nature of the tidal current is explained by Pingree and Mardell (1987) in the report "Tidal flows around the Channel Islands". The anticlockwise residual current is a shallow water phenomenon created by the interaction of the local topography with the M4 component of the tidal cycle (Pingree, 2012 see Appendix 5). A frictional force is created at the boundary layer where the water column is in contact with the seabed. The frictional force increases during the ebb phase of the tidal cycle, as the water depth drops the frictional force has a greater influence over the entire water column, thus slowing the overall water column velocity. At the end of the ebb cycle, the incoming flood tide is met by a residual ebb current which is stronger and thus forces the tide to flow around the island in an anticlockwise direction. The report validates the theory with a number of field observations and measurements that indicated a mean spring residual current of 2m/s anti clockwise around the island.

1.5 Why Tidal Energy?

Dr Alan Owen (2005, 2012) reported an estimated 11.8 TWh/a total tidal resource from three sites surrounding Guernsey, this figure has been calculated without regard to technological, physical or social restraints. The three areas that were sited within the report were; the Big Russel, which is the channel between Guernsey and Sark, a region to the North West of Guernsey and a final area extending south west of Guernsey to France. This report is a significant indicator of the economic potential that the realisation of tidal power will contribute to the future economy of Guernsey. Guernsey can fulfil CO_2 emission obligations, achieve a sustainable energy security future, create a new revenue stream and thus become a pioneer nation and a centre of excellence for marine renewable energy (Guernsey Renewable Energy Commission, 2009).

Tidal energy is completely deterministic and predictable, tidal power can be integrated into the existing power infrastructure and included as part of the base load power supply (Clarke et al, 2004). There are many complex social issues that surround existing renewable energy technologies. The primary concern is the change of use to an area, the associated disruption from the installation phase and the subsequent change of established “ways of life” for those in the locality (Pasqualetti, 2011). However, after installation of a tidal array there is little or no visual or aural pollution. It should be noted that tidal stream technology is incompatible with a number of other marine industries including; shipping, fishing and aquaculture and there is likely to be an exclusion zone applied around the device (Scottish Government, 2012).

Device developers are aware of the vulnerability of the ocean ecosystem and extensive work has been carried out on the impact of these devices, to reduce or mitigate any adverse influence upon the environment.

An environmental impact assessment was commissioned by MCT for the SeaGen turbine in Strangford Lough during the planning phase. The pre installation environmental impact assessment formed the basis of the environmental statement and resulted in the extensive monitoring program for the lifetime of the project. Throughout the project life cycle the benthic community, sea mammals and sea birds have to be frequently surveyed. In the case of the sea mammals a constant daylight watch is kept to observe any cetaceans in the proximity of the turbine, leading to the imminent shut down of the device if the mammal is thought to be too close (Royal Haskoning, 2011). If tidal power generation was realised in the coastal waters of Guernsey an environmental assessment would have to be carried out at each potential site, it would not be unreasonable to assume due to the proximity of the project, that the measures at Strangford Lough would be replicated in the Channel Islands.

1.6 Research Focus

The Guernsey department of Commerce and Employment has acknowledged that the current power infrastructure is incapable of answering the needs of the future and that investment in marine renewable energy will bring significant economic and social benefits to the Guernsey community (Guernsey Renewable Energy Commission, 2009). Technology is at the point of maturing, there have been a number of successful full scale tidal devices deployed around the coast of the UK (see Appendix 1). Past research and reports, discussed in the literature review, have investigated the potential tidal resource around the coastal waters of the Channel Islands. The main focus of the report is to model the tidal flow regime in the coastal water of Guernsey by utilising hydrodynamic software. The results will represent the tidal regime and enable an estimated annual power output to be calculated and form the basis for further desktop and field investigations to be carried out.

Tidal modelling in Europe is dominated by three main companies: Telemac, Mike and Deltares, each company has evolved the modelling software over the last two decades as a solution for different hydrodynamic processes. Telemac and Deltares have issued their software packages to the open market; Deltares software is freely available at http://oss.deltares.nl/web/opendelft3d/source-code . It was decided to use Deltares Delft3d FLOW, It should be noted that tidal modelling results should be validated against observed field measurements as recommended in the EquiMar protocols (EquIMar, Unknown) and the EMEC guidelines (2009).

1.7 Research Aims

The investigation central to the project is the examination of the tidal stream resource in the coastal waters of Guernsey using Delft Dashboard and Delft 3D FLOW software used in a two dimensional depth averaged mode.

A number of objectives would underpin the central aim:

- A study into the nature of the tidal flow of the Channel Islands that would give more scope to the central aim of the report.
- Modelling of the tidal flow of Guernsey coastal waters using Delft3d hydrodynamic software for a month of predicted tidal data.

- The Identification of regions of immediately exploitable tidal resource (≥ 2 m/s mean peak spring tidal velocity), marginal (1 – 2 m/s) and non-viable areas (< 1 m/s).
- To observe the velocity directions so that device placement and optimum alignment will be recommended.
- Formulate, conclude and compare with previous research, making recommendations for a marine renewable action plan that could be initiated in the short term.

2.0 Literature Review

2.1 The Tidal Modelling process.

Initial tidal models were based on field measurements that had been created for navigational purposes. As computational power increased it became possible to include advanced complex fluid mechanic and hydrodynamic equations within bespoke software programs; enabling the user to simulate water movement over a period of time. Initial simple one dimensional flow computations have now advanced to three dimensional flow simulations. Table one summarises the different types of hydrodynamic models, the main features and advantages

Table 1: Tidal Model types, advantages and disadvantages

Tidal flow data	Advantages	Disadvantages
Nearest representative value from Admiralty charts	Simple, data easy to obtain.	Inaccurate large scale model, correction for energy extraction empirically derived
Interpolation between data points	Simple and more accurate than above	Doesn't account for changes in flow with depth, assumes a uniform bathymetry
1d model	Simple, suitable for fences of generators in well- defined channels.	Not suitable for complex topography
2 d model numerical modelling	Well developed	Increasing computational expense, 3d wake not simulated, requires validation
3d numerical modelling	Can simulate wakes of turbines and include a vertical velocity profile.	Complex, suitable for localized models, turbulence data may be lacking

Sustainable Energy Research Group 2008.

Hydrodynamic modelling is the study of fluid behaviour and its constituents which can be solved by fulfilling the equations of the balance of forces and mass balance. Restraints curtail the extent of the model and simplifications have to be introduced to enable practical use.

Tidal modelling enables a better understanding of the flow regime but also enables a degree of prediction through simulated scenarios, it is an immensely powerful tool when resource assessment is needed but also when wider marine plans are being studied (Saloman et al. 1995).

The investigation of a viable and productive tidal stream has a number of fundamental physical limitations in the marine environment that can be examined within the modelling process. The present tidal stream device technology places the constraints for idealised tidal stream flow conditions. Flow velocity is the primary criteria for identifying an area for potential tidal stream exploitation. The secondary concern is the water depth of the area; accurate bathymetric data with a high resolution enables the user to observe the water depth of the study area. An idealised condition for current tidal device deployment would have a mean peak spring tide velocity exceeding 2 m/s and relatively shallow bathymetry ≤ 40 metres water depth. Meeting these criteria would indicate the economic viability of the area and warrant further investigation. An estimation of the power generation over the lifetime of the project is based on the sizing and rating of the device. Environmental assessments and modelling the effect of the energy extraction on the hydrodynamic processes would be needed to complete the tidal modelling process (Sustainable Energy Research Group, 2008).

Previous studies of the Channel Islands have been undertaken using the different modelling techniques and it can be seen that as the tidal modelling process has increased in complexity the estimated tidal energy resource has fallen with the progression of the modelling process. This was identified in the Sustainable Energy Research Group Report; the model outputs for the Channel Islands can be compared in table 2.

Table 2: Predicted tidal power from ETSU, Joule 2 and Black and Veatch reports.

			Black & Veatch (2004)		Joule 2 (1996)		ETSU (1993)	
Tidal Race	Area (km^2)	Max speed (m/s)	Rated Power (MW)	Load Factor %	Rated Power (MW)	Load Factor %	Rated Power (MW)	Load Factor %
NW Guernsey	222	2.1	170	33	422	54	2186	22
Big Russel	190	2.6	101	43	219	47	1001	22
NE Jersey	58	3.1	57	33	196	45	1179	13

Sustainable Energy Research Group 2008

2.2 Previous Tidal Assessments

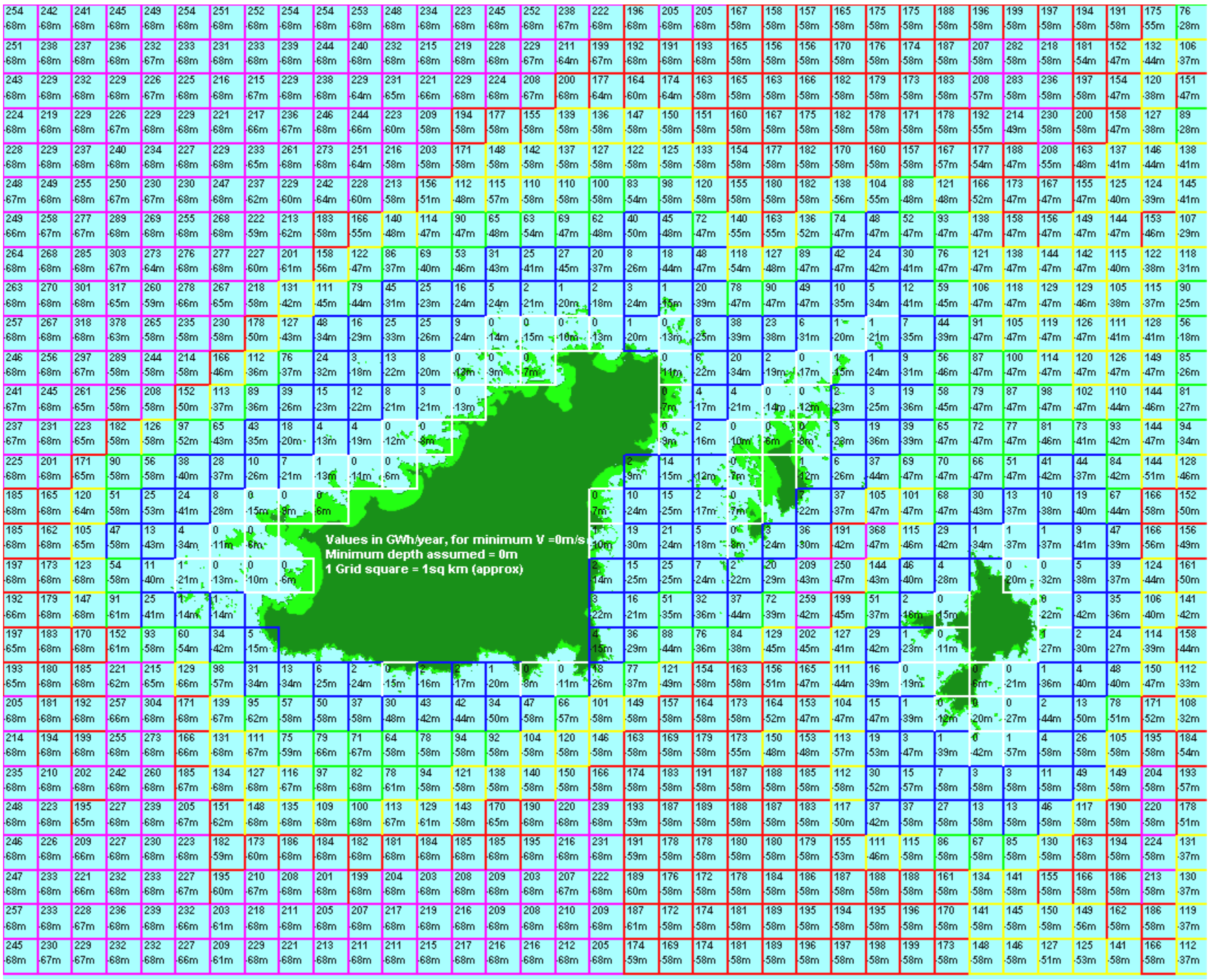
The three models were completed using different methodology which explains the variation in the predicted results.

The ETSU 93 report was based upon the “farm” method of power calculation that assumes the power extraction is equal to installed capacity. The report identified potential tidal resource sites on the basis of the mean spring velocity exceeding 2m/s and a water depth greater than 20 m. Tidal velocity information was extracted from Admiralty chart data, a probability density curve was fitted to the data with 0.26 m/s bins and the annual energy was estimated.

Joule 2 calculated tidal velocities using similar methods to the ETSU report but with a peak speed greater than 1.5 m/s. The main problem with both of these reports is that admiralty data relies upon discrete points with no spatial interpolation. There was no consideration of the change in velocity over the site, for velocity changes with depth, or for a limitation of the extractable resource, therefore the calculated energy was over estimated.

The Black and Veatch tidal stream energy assessment of the Channel Island (2005) was authored by Dr Alan Owen on behalf of the Robert Gordon University (RGU). Dr Owen has continued with the work and an updated report has been subsequently submitted to the Guernsey Renewable Energy Team in 2012. The report was based on a program created by the university; the program is based upon a central finite difference system where two points of known data are taken to create a midpoint of interpolated data. The total data input of the program includes 15% -20% of known information. The information was taken from Admiralty chart 2669 and tidal stream data from Admiralty Tidal Stream Atlas NP264. The 2012 report also included data from the Admiralty digital tide software package "Total Tide". The velocity flow profile was calculated from applying the 1/7th power law to the surface velocities. Bathymetric data was spatially interpolated from depth contour information from the Admiralty chart. The program ran over a 13 hour time series with datasets created every 15 minutes, values were normalised to account for the spring/neap cycle with the neap cycle calculated at 32% of the spring cycle. The output of the program indicated a number of key areas around the Channel Islands with a significant tidal velocity

Fig 3 Raw tidal current resource in Guernsey's waters. Source: Owen 2012



Key

Colour	Power (GWh per annum) per 1km squared
White	No significant resource
Blue	< 50
Green	< 100
Yellow	< 150
Red	< 200
Magenta	>200

The raw tidal current output is defined as the total tidal regime, regardless of whether or not technology would be able to harness the potential energy. From figure 3 it is possible to see that the main areas that offer significant potential tidal power. The Big Russel channel between Herm and Sark, an area approximately 4.5 nm North West of Guernsey and the area approximately 3 nm to the South West of Guernsey. The report estimated the Big Russel to have a total annual power output of 700 GW hours and the area to the north west of Guernsey to have a total annual output of 2300 GW hours.

The RGU report was validated with the BERR tidal atlas and results were found to be ± 5%. The estimated lower power levels than previous reports were due to the consideration of an approximate environmental constraint known as the Significant Impact Factor. The Significant Impact Factor (SIF) is a theoretical limit level of the amount of energy extraction that is possible without adversely affecting the tidal flow regime. The action of energy removal from the water column will cause a net decrease in the remaining energy and therefore velocity. However there will be localised effects of increased and decreased velocities and turbulence around the turbines. These factors can lead to near field changes in seabed topography; such as scouring, removal of the seabed and material deposition leading to loss of benthic communities as well as changes to the wetted perimeter in the far field (Strathclyde University b unknown). The tidal energy assessment assumed a SIF of 20% for all sites, acknowledging that an individual assessment should be carried out for each site as factors affecting the tidal flow regime are unique for each location.

3.0 Methodology

For this tidal modelling study of Guernsey Delft Dashboard and Delft FLOW were used to assess a two dimensional tidal regime and subsequent potential power estimation.

3.1 Delft3d FLOW

Natural phenomena such as tidal and meteorological forcing have inherent spatial characteristics. Variations occur in the vertical and horizontal direction that may be time dependent and inter related. Delft3d is a multi-dimensional hydro dynamic simulation program that has the capability to simulate waves, tides, rivers, winds, and coastal currents through finite difference methods of discretisation of space and time variables. The software solves two dimensional depth averaged or three dimensional shallow water Navier - Stokes equations for incompressible free surface flow over a Cartesian or curvilinear mesh. The Navier-Stokes equations are the equations of conservation of momentum for a fluid and describe the relationship between velocity, pressure, temperature and density of a moving fluid. The equations for conservation of momentum are complemented by an equation of conservation of mass, also called continuity equation, and in some cases an equation for conservation of tracers within the fluid, temperature or salinity, depending on the circumstances. For the case of the Channel Islands, only the equation of continuity and momentum conservation are necessary.

The equation of conservation of momentum is obtained by applying Newton's Law of Motion to a fluid. The resulting equations consist of a set of coupled differential equations that cannot be solved analytically, however can be approximated through mathematical approximations such as the finite difference method. Delft3D flow does not solve the Navier Stokes Equations, it solves the shallow water equations which as are derived from the Navier Stokes Equations through the finite difference method of mathematical approximation.

Figure 4: The Navier Stocks Equations. Source: NASA

Navier–Stokes Equations
3 – dimensional – unsteady

Glenn Research Center

Coordinates: (x,y,z)
Velocity Components: (u,v,w)

Time : t Pressure: p
Density: ρ Stress: τ
Total Energy: Et

Heat Flux: q
Reynolds Number: Re
Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} + \frac{\partial(\rho u w)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho u v)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho v w)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho u w)}{\partial x} + \frac{\partial(\rho v w)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$

$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$

There are mathematical formulations within the program to account for natural physical phenomena such as; free surface gradients caused by the change in atmospheric pressure, the Coriolis effect, changes in water density, the transportation of salt and heat, turbulence-induced mass and momentum fluxes including wave-induced currents, space and time variations due to wind and bottom shear stress as well as an allowance for additional inputs and discharge within a system. Vertical resolution is through the σ grid, where the boundaries are two planes that follow the free surface and the bottom topography, the σ layers are determined by pressure difference within the water column. The number of intermediate layers remains constant, therefore affording greater resolution in the shallow water zones (Delft 2011).

Accuracy and resolution of the model is optimised through the time step function which operates with the grid resolution and dependent on the Courant-(Frederichs-Lewy) (CFL) Number. The CFL Number is defined as;

CFL = $\frac{\Delta t \sqrt{(gH)}}{\{\Delta x, \Delta y\}}$ (Eqn 1)

Where Δt is the time step in seconds, g is acceleration due to gravity, H is water depth and Δx, Δy is the characteristic value of the grid spacing in either direction.

Delft recommend for optimum stability and accuracy that the Courant number should not exceed a value of ten (Delft FLOW manual, 2011)

The model time steps were set for 1.5 minutes, the model outputs were set for 60 minutes, meaning that the data output would record a value every hour.

3.2 Delft Dashboard®

Dashboard is a new piece of Deltares software that is used as a pre-processing tool for use with Delft3D FLOW and WAVE. The program enables the user to set up bathymetry, grid, tidal harmonic and boundary conditions and create input parameters for the Delft FLOW model.

3.3 Delft Dashboard Tidal Model

The TPX 06 and TPX 07 global tidal models utilised by Delft dashboard were created by Gary Egbert and a team of researchers from Oregon State University in 1994. The models are based upon altimetry data received from the Topex Poseidon satellite recorded at a 15 arc minute resolution between ± 66° latitude from 1992 until 2004. The models use a generalised inverse method of coalescing two sets of data; one from observed sea height measurements and the other derived from the Proudman function expansion that constitute a mass conserving orthogonal basis . Harmonic constants from 80 worldwide open ocean tidal gauges were included in the model (Egbert et al 2004). A load tide factor has been included which accounts for the deformation of the earth surface due to the weight of the water. The load tide factor is out of phase with the lunar and solar tide and can change the water depth in the shallow water by a few per cent. As the influence of the load tide is most prevalent in the shallow water it is essential that there is some account in models that use shallow water equations such as Delft. The model tidal software inputs have been deconstructed into the main diurnal and semi diurnal tidal constituents; M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1 MF, MM, M_4, MS_4 and MN_4 (see Appendix 3). These models have been validated against altimetry, coastal and pelagic tide gauge data (AMCG 2011). The progression from version 6.2 to 7.2 was based upon improved bathymetric data, longer and better data assimilations and greater resolution of global and local grids; for this reason it was decided to use TPX 7.2 global tidal model.

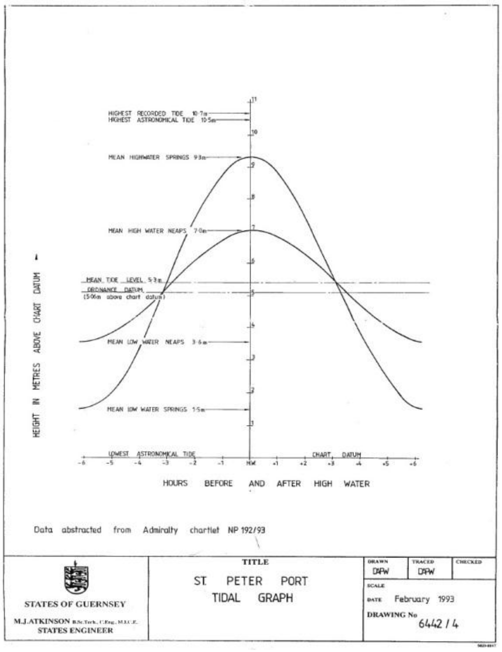
3.4 Delft Dashboard Bathymetry

GEBCO and EMODnet bathymetric data has been embedded into Delft Dashboard. GEBCO is a world wide data set with a resolution of 30 arc second which is approximately one data point every 900 meters, it has a vertical reference datum of mean sea level (MSL) or Ordnance datum (OD) and the horizontal reference co–ordinate system WGS84. EMODnet data has a resolution of15 arc second which is approximately one data point every 450 meters, a vertical reference datum of Chart Datum (CD) and the horizontal reference WGS84. Due to the higher resolution it was decided to use the EMODnet data for this model.

3.5 Guernsey height datum

The UK Mean Sea Level height datum known as Ordnance datum (OD): was established in the early 20th Century (Ordnance Survey, 2012). Each port and trigonometric point on the mainland was measured in relation to mean sea level at Newlyn through a triangulated grid thus establishing a national height datum. However some parts of the United Kingdom were unable to be included within the national datum as visual contact with the neighbouring port or reference point could not be established due to distance. The Channel Islands have a local mean sea level datum. Ordnance Survey surveyed Guernsey in 1890 and referenced the island to a historic tide mean sea level mark in the harbour of St Peters Port, chart datum was taken at a point below this reference mark to eliminate negative height tides.

Figure 5 Guernsey Tidal Heights. Source: Digimap Guernsey (2010)



From this diagram it is possible to see that mean sea level is not the ordnance datum level. The original bathymetric data was presented at chart datum the model should run at mean sea level therefore an adjustment of +5.3 meters was added to the bathymetric data.

3.6 Assumption underpinning Delft 3D-FLOW and Delft Dashboard

- It is assumed that the model depth will be significantly smaller than the horizontal distance therefore validating the shallow water equations.
- From this it is assumed that the vertical acceleration due to buoyancy effects and sudden variations in the bottom contour are small compared to the gravitational acceleration and has been disregarded.
- Vertical momentum has been reduced to the hydrostatic pressure equation.
- The effect of variable density is only accounted for in the pressure term

- The effect of the earth's curvature is not considered in a rectangular grid and a uniform Coriolis parameter has been applied.
- At the base of the model a slip boundary condition is assumed.
- Delft3d Flow resolves the turbulence through Reynolds averaged flow quantities by a turbulence closure model.
- The production of turbulence is based upon the vertical gradients of the horizontal flow.
- The boundary conditions for the turbulent energy and energy dissipation calculations at the free surface and at the bottom assume a logarithmic law of the wall. The logarithmic law of the wall assumes an average velocity that is proportional to the logarithm of the distance from the boundary.
- The horizontal eddy viscosity is assumed to be much larger than the vertical eddy viscosity.

4.0 Results

4.1 The Model

The model was run in accordance with the EMEC tidal assessment guidelines for a category 2a assessment (EMEC, 2009) with a grid resolution of 500 meters; this was appropriate resolution for the category assessment and considered the EMODnet bathymetry data set that was used had a resolution of 480 meters. The grid extended from Lyme Bay (X 485560.58 and Y 5610055.30, UTM 30 coordinates) in the west to the Eastern tip of the Isle of Wight (X 605258.92 and Y 5610055.30, UTM 30 coordinates). The model was run to over a period of 1 month as recommended by the EMEC guidelines (2009) with an observation period from the 20th of August until the

20th of September. This would allow an observation period of two full spring neap cycles during an average month. The EMEC guideline is that the simulated month should be an average month; unfortunately this simulated month was close to the autumn equinox, a period that is typified by bigger tides. The equinox factor may contribute to some of the disparities that were seen in the results when compared to observed data. Time constraints did not allow the rerunning of the model, the influence of the equinox on the model outputs will be discussed.

The initial model outputs were as expected: The tidal range, water levels, tidal velocities were similar to the outputs from previous models and reports. The anticlockwise character of the tidal cycle is clearly visible when the model outputs are run through a tidal cycle.

4.1 Tidal characteristic

The model outputs show the tide in the Channel Islands is, as expected a semi diurnal tidal pattern with a water level range of approximately 5 meters during a Neap tide cycle and a range of 9 meters in a Spring tide cycle. The tidal flows around the island show a number of interesting phenomena that can be seen when the daily tidal patterns that have been graphed in figures 6 and 7.

Figure 6: The daily Neap Tide regime in the Big Russel.

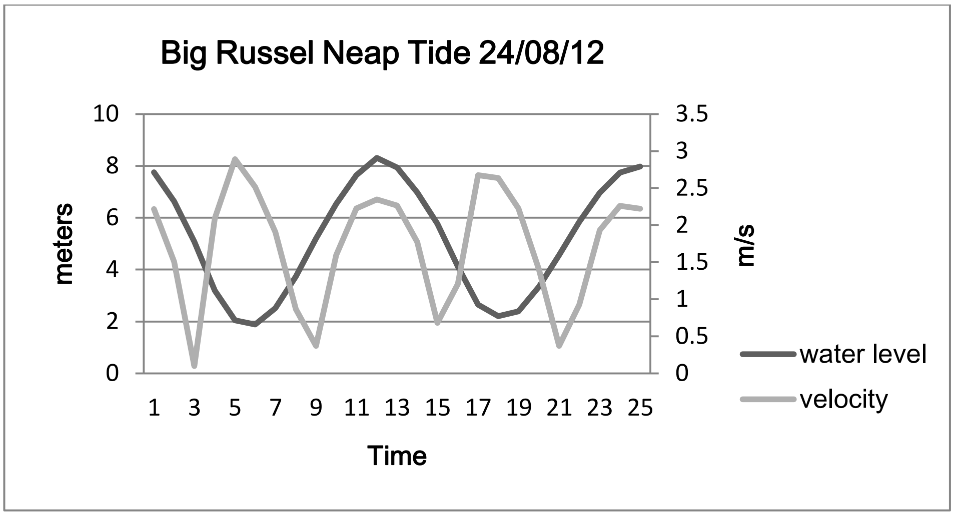
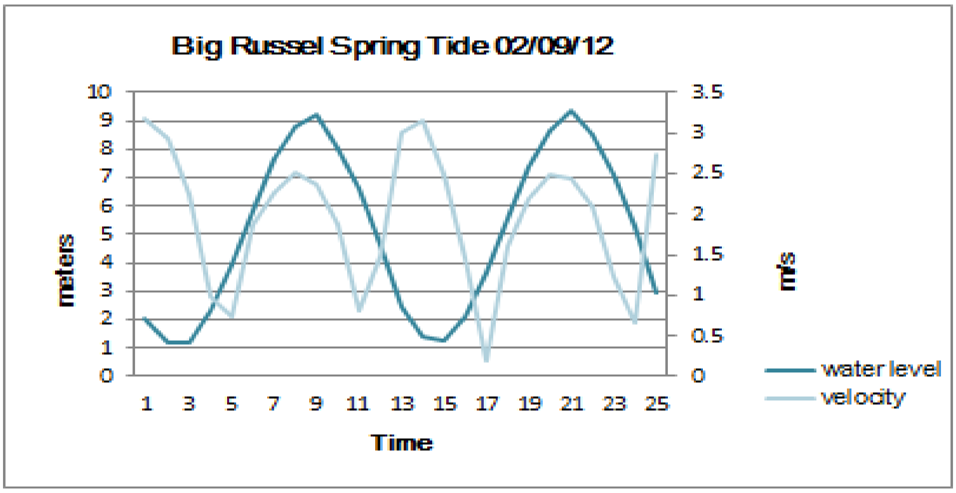


Figure 7: The daily Spring Tide regime in the Big Russel



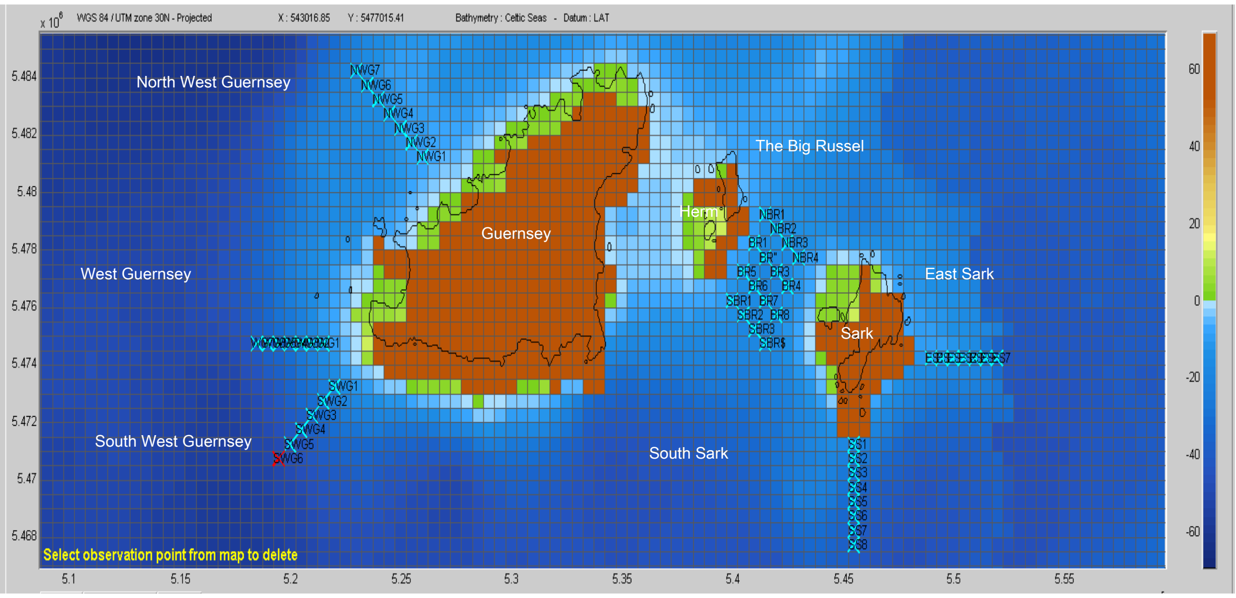
The expected velocity curve for the diurnal tidal pattern would be for the velocity to be 90º out of phase with the water level. This should indicate a maximum velocity occurring through the third and fourth hours preceding and proceeding High Water, with a period of slack around High Water and Low Water. However the velocity and water level relationship through the Big Russel would appear to be in phase, with peaks velocities occurring at each tidal limit and minimum velocity values occurring at the mid tide. This would indicate four periods of peak velocity, throughout a normal day, instead of two, with the greatest velocities occurring at low tide. This tidal pattern is also seen at the observation points around Sark and West Guernsey.

The other tidal occurrence that is expressed in the two figures is the asymmetrical nature of the flood and the ebb tide. The flood tide appears to be longer than the ebb tide with a steeper curve on the ebb tide. The velocity regime also shows an asymmetrical nature, especially during the Low Water period where the period leading up to the maximum velocity exceeds the period leading to the minimum velocity.

4.2 Power Calculations

The power calculations were carried out at a number of points of interest within the model area, see figure 8.

Figure 8: The Observation points in the Model. Source: Delft Dashboard.



The pale blue crosses indicate the position of the observation points in the model area; the observation point is across the entire grid area of 500m x 500m. The observation point were chosen after observing the model outputs and noting the areas where the velocity indicated a resource greater than 2 m/s during the Spring tide

The velocity output enables the power density (Pd) to be calculated using the equation

$Pd = \frac{1}{2} x\ p\ x\ v^3$ (Eqn 2)

Where ρ is water density 1025 kg/m^3 and v is velocity, the output is Watts/m^2.

Velocity changes with time and therefore power density varies over the model month. To calculate the total monthly power, the Power density was integrated over the model month using the Simpsons rule of mathematical approximation.

A ≈ $\frac{s}{3}$ $[(F + L)] + 4E + 2R]$ (Eqn 3)

Where A is the area under the curve, the equivalent of the total monthly power output, s is the number of sections that the area under the curve has been divided into, F is the first section, L is the last section, E is the even numbered sections and R is the odd numbered sections

Annual calculations were estimated by a multiplication of the monthly output by 12, and the total annual resource was calculated by multiplying the annual resource by the area of the observation point. It has been assumed that the year is made up of twelve thirty day months.

4.4 Power Outputs, the total resource.

The total resource is the raw potential power calculated without regard of any consideration to technology restraints or any physical or social constraints.

The Big Russel is the channel that runs between the islands of Herm and Sark, the area is renowned for large tidal currents with water depths between 20 and 40 meters, the area has been cited as the primary region for immediate tidal stream energy capture in previous reports. Typical maximum tidal flows in the region are between 2.5 and 3m/s at Spring tide and 1.5 and 2 m/s during Neap tides. The observation points have been designated into three regions within the area; the south Big Russel has 4 observation points, the mid channel has 8 and the north has 4. Some observation points, close to the land mass were disregarded on first inspection as there appeared insufficient resource to warrant further investigation. Table 3 indicates the monthly and annual power density for four observation points

Table 3: The Big Russel Total Power Output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power density (kWh/m²)	Annual Power Density (kWh/m²)	Total annual resource (GWh)
2	X 541440.59 Y 5477718.66	30	2.82	2.36	2.364	28.372	7.093
3	X 541960.14 Y 5477223.85	30	2.82	2.36	2.364	28.372	7.093
6	X 540970.53 Y 5476679.57	30	2.48	2.08	1.604	19.251	4.812
7	X 541391.11 Y 5476160.03	30	2.54	2.12	1.710	20.516	5.129

The South Big Russel observation points were positioned to indicate the extent of the increased velocity through the channel. Table 4 illustrates the available power density to the south of the Big Russel channel.

Table 4: The South Big Russel total power output.

Obs point	Location UTM30	Approx depth (m)	Mean peak Spring velocity (m/s)	Mean peak Neap velocity (m/s)	Total Monthly Power density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
2	X 540475.75 Y 5475720.69	30	2.24	1.88	1.149	13.791	3.448
3	X 540908.68 Y 5475226.09	30	2.22	1.85	1.159	13.902	3.475

To examine the extent of the elevated flow to the North of the Big Russel, a number of observation points were placed, velocities in the region during Spring tides reached 3 – 3.5 m/s with shallow bathymetry of 40 meters. Table 5 indicates the potential power output of the area north of the Big Russel.

Table 5: The North Big Russel total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
1	X 541428.22 Y 5479196.88	40	1.99	1.66	0.7388	8.866	2.217
2	X 541935.40 Y 5476702.08	40	2.79	2.38	2.376	28.508	7.127
3	X 542417.83 Y 5478194.91	40	3.12	2.60	3.234	38.804	9.701
4	X 542949.74 Y5477687.73	40	3.03	2.55	2.939	35.262	8.816

The region to the North West of Guernsey is characterised by a broad swathe of increased velocity as the tidal wave passes around the island. Velocities of 2.5 m/s are typical during Spring tides. It should be noted that the water to the North West is considerably deeper than the Big Russel and characterised by rough bathymetry. Table 6 indicates the monthly and annual power densities for the North West area.

Table 6: North West Guernsey total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
5	X 523975.62 Y 5483235.95	50	1.24	1.02	0.212	2.549	0.637
6	X 523410.01 Y 5483675.84	60	1.22	1.05	0.225	2.698	0.675
7	X 522938.66 Y 5484178.61	60	1.39	1.21	0.308	3.701	0.925

The tidal flow converges at the western extent of the island and then turns and moves around the southern extent of Guernsey. The model indicates elevated velocities of 2.5 m/s during Spring tides,. The bathymetry in the region is characterised by the close proximity of the 50 meter contour to the island. Table 7 estimates the monthly and annual power output for the West of Guernsey.

Table 7: West Guernsey total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s0	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
3	X 520456.26 Y 5474751.76	50	1.19	1.02	0.607	7.285	1.821
4	X 519922.07 Y 5474751.76	50	1.67	1.40	0.758	9.091	2.273
5	X 519419.31# Y 5474751.76	60	1.99	1.82	0.892	10.705	2.676
6	X 518916.54 Y 5474751.76	60	1.97	1.87	0.946	11.352	2.838
7	X 518445.20 Y 5474751.76	60	1.90	1.88	0.9518	11.422	2.855

The model indicates a reduced flow to the south west as the velocity disperses after rounding the western extent of Guernsey. The bathymetry is very similar to the Western region with the 50 meter drop off positioned very close to the island, therefore all observation points are in deeper water. Table 8 estimates the monthly and annual power output for the South West region

Table 8: South West Guernsey total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
1	X 521398.94 Y 5473243.46	50	1.90	1.88	0.513	6.160	1.540
2	X 521938.94 Y 5472740.70	60	1.16	1.10	0.448	5.285	1.346
3	X 520927.60 Y 5472237.93	60	1.05	1.00	0.319	3.829	0.957

During the tidal cycle the water passes around the island of Sark and subsequently heads north or south, to or from the Alderney race depending on the state of tide. The region to the South of Sark is characterised by shallow bathymetry and a mean peak Spring tidal flow of 2.3 m/s. Table 9 indicates the potential power output for the region to the South of Sark

Table 9: South Sark total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual Resource (GWh)
2	X 545437041 Y 5473243.46	30	1.47	1.15	0.462	5.542	1.385
3	X 545437041 Y 5472740.70	40	2.31	1.64	1.122	13.463	3.365
4	X 545437041 Y 5472237.93	40	2.37	1.60	1.104	13.251	3.313

5	X 545437041 Y 5469221.34	50	2.32	1.54	1.002	12.021	3.005
6	X 545437041 Y 5468721.34	60	2.31	1.55	0.976	11.717	2.929
7	X 545437041 Y 5468221.34	60	2.28	1.55	0.965	11.584	2.896
8	X 545437041 Y 5467721.47	60	2.28	1.55	0.930	11.162	2.790

The waters to the East of Sark are characterised by elevated tidal velocities around the island, the mean peak Spring tides velocities of 2.3– 2.5 m/s, the mean peak velocity is only marginally slower with values around 2.4 m/s. The bathymetry close to the island is shallow with a gentle drop to 40 + meters. Table 10 indicates the potential power output of the East of Sark.

Table 10: East Sark total power output

Obs point	Location UTM30	Approx depth (m)	Mean Peak Spring velocity (m/s)	Mean Peak Neap velocity (m/s)	Total Monthly Power Density (kWh/m^2)	Annual Power Density (kWh/m^2)	Total Annual resource (GWh)
2	X 549459.53 Y 5474217.57	30	2.38	2.27	1.758	21.102	5.275
3	X 549930.87 Y 5474217.57	30	2.66	2.45	2.354	28.242	7.061
4	X 550496.48 Y 5474217.57	40	2.66	2.44	2.562	30.744	7.686
5	X 550904.98 Y 5474217.57	40	2.79	2.48	2.397	28.764	7.191
6	X 551407.74 Y 5474217.57	40	2.57	2.08	1.714	20.574	5.144
7	X 551910.51 Y 5474217.57	40	2.27	1.77	1.108	13.291	3.323

4.2 Power outputs, the technical resource.

The technical annual resource calculation is based upon taking an approximate cut-in speed of 1 m/s, assuming no generation below that velocity, and calculating the power density over the year. The device annual resource is calculated by multiplying the technical resource by 100π which has been taken as the assumed rotor area with a 20 meter diameter rotor. An assumed limitation of 20% has been added to the annual device resource, this is an extremely approximate figure to account for device capacity factors and environmental site constraints. The maximum cut out speed has not been included in the calculation. A percentage of the total resource has been calculated to indicate the estimated power generation period throughout the entire year. The tables below are the annual technical power calculations for the observation points used in the total power resource calculations.

Table 11: The Big Russel Technical power output.

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m^2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
2	X 541440.59 Y 5477718.66	30	28.212	8.86	1.77	99.5
3	X 541960.14 Y 5477223.85	30	28.212	8.86	1.77	99.5
6	X 540970.53 Y 5476679.57	30	19.030	5.98	1.2	98.8
7	X 541391.11 Y 5476160.03	30	20.327	6.39	1.3	99.1

Table 12: The South Big Russel Technical power output.

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m^2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
2	X 540475.75 Y 5475720.69	30	13.533	4.25	0.85	98.1
3	X 540908.68 Y 5475226.09	30	13.625	4.28	0.85	98.0

Table 13: The North Big Russel Technical power output.

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m^2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
1	X 541428.22 Y 5479196.88	40	8.421	2.64	0.53	94.9
2	X 541935.40 Y 5476702.08	40	28.304	8.89	1.78	99.3
3	X 542417.83 Y 5478194.91	40	38.640	12.14	2.43	99.5
4	X 542949.74 Y5477687.73	40	35.101	11.06	2.21	99.5

It was decided that the North West Guernsey and South West Guernsey resource would need further investigation and these have been excluded from the device resource assessment.

Table 14: The West Guernsey Technical power output

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m^2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
3	X 520456.26 Y 5474751.76	50	7.090	2.23	0.45	97.3
4	X 519922.07 Y 5474751.76	50	8.667	2.72	0.54	95.3
5	X 519419.31# Y 5474751.76	60	10.351	3.25	0.65	96.6
6	X 518916.54 Y 5474751.76	60	11.043	3.47	0.69	97.3
7	X 518445.20 Y 5474751.76	60	11.090	3.48	0.69	97.1

Table 15: South Sark Technical power output.

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m^2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
2	X 545437041 Y 5473243.46	30	4.981	1.56	0.32	89.9
3	X 545437041 Y 5472740.70	40	13.115	4.12	0.82	97.5
4	X 545437041 Y 5472237.93	40	12.934	4.06	0.81	95.1
5	X 545437041 Y 5469221.34	50	11.695	3.67	0.73	97.3
6	X 545437041 Y 5468721.34	60	11.388	3.57	0.71	97.2
7	X 545437041 Y 5468221.34	60	11.261	3.57	0.71	97.2
8	X 545437041 Y 5467721.47	60	10.810	3.4	0.68	96.8

Table 16: East Sark Technical power output.

Obs point	Location UTM30	Approx depth (m)	Technical Annual resource kWh/m2	Device Annual resource (MWh)	20% limit of Device resource (MWh)	% of Total Annual resource
2	X 549459.53 Y 5474217.57	30	20.889	6.56	1.31	99.0
3	X 549930.87 Y 5474217.57	30	28.022	8.80	1.76	99.2
4	X 550496.48 Y 5474217.57	40	30.535	9.59	1.92	99.3
5	X 550904.98 Y 5474217.57	40	28.525	8.96	1.79	99.2
6	X 551407.74 Y 5474217.57	40	20.315	6.38	1.28	98.7
7	X 551910.51 Y 5474217.57	40	12.984	4.08	0.82	97.5

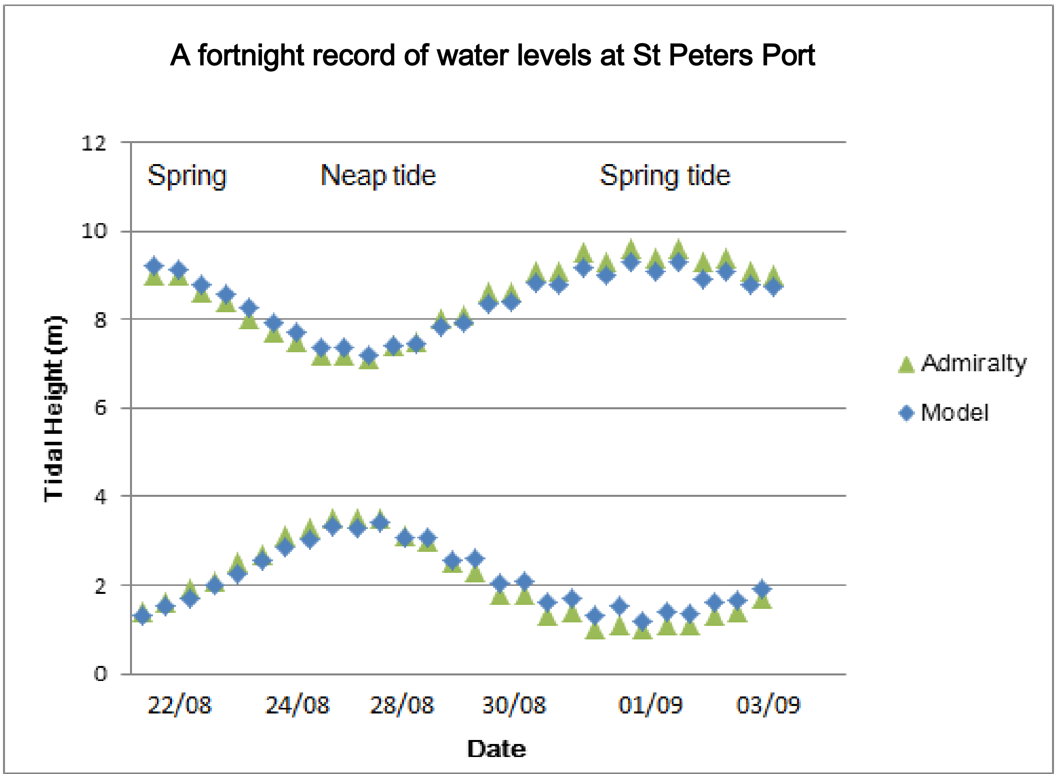
4.3 Validation

Under the EquiMar protocols (unknown) and EMEC guidelines (2009) the model should be validated against measured and observed data. The water levels have been compared with Admiralty tidal predicted water levels at St Peters Port. The tidal velocities and directions have been validated against the Renewable Energy Atlas, another model and the Admiralty Tidal Stream Atlas NP 264 which is measured data.

Initial validation of water levels at St Peters Port was carried out using the model water level outputs compared to predicted tidal information from Admiralty Easy Tide (See Appendix 4). The Admiralty Easy Tide information is based around the lowest astronomical tide (LAT) datum, the data from the model is based around the local chart datum. Therefore an adjustment of 5.3 meters was made to allow for direct comparison

Data from a fortnight period was used, the height of each low and high tide was recorded and the information then graphed to observe the correlation. The water levels were consistently within ± 0.2 meters at the apex of the tide.

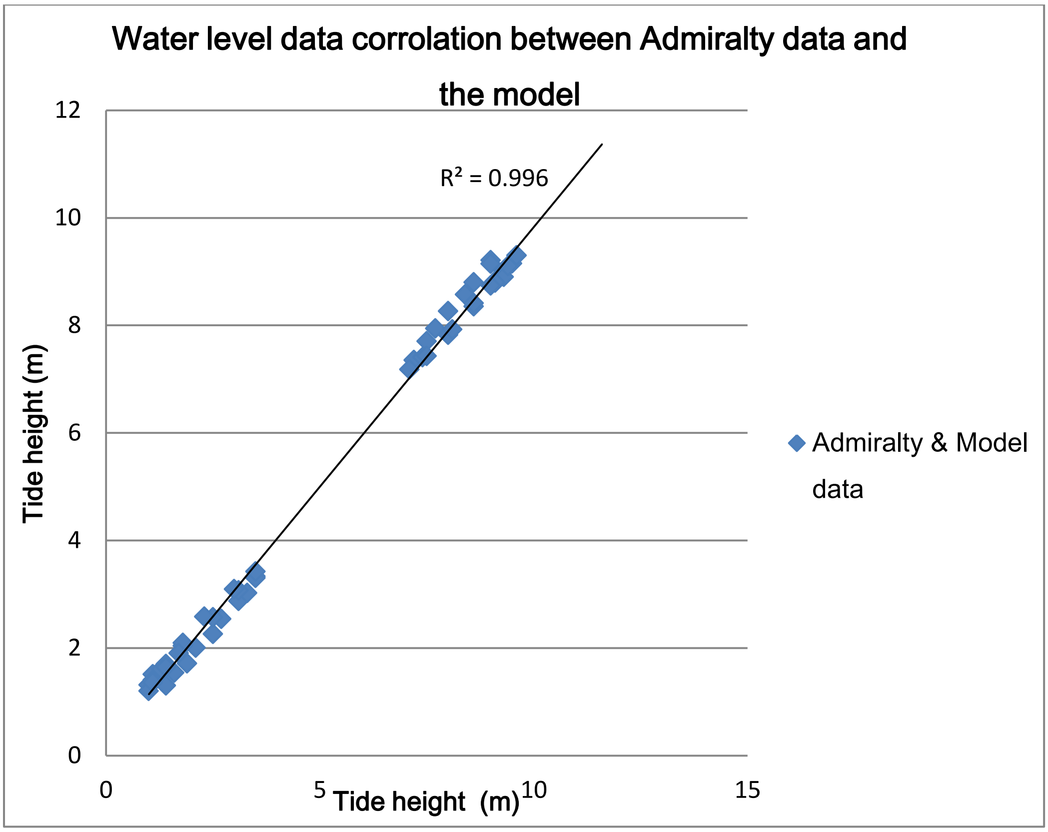
Figure 9: A graph of the water levels at St Peters Port from the Easy Tide data set and the Delft 3D FLOW model, mapped over a two week period.



It should be noted that the model data shows the greatest deviation from the Admiralty chart data during the peak of the second spring a phenomena that could be explained by the presence of the autumn equinox being modelled more prominently in the admiralty chart data.

When all the data is compared the two data sets show a good correlation as can be seen in figure 8.

Figure 10: A graph showing the correlation between the Admiralty and model data sets.

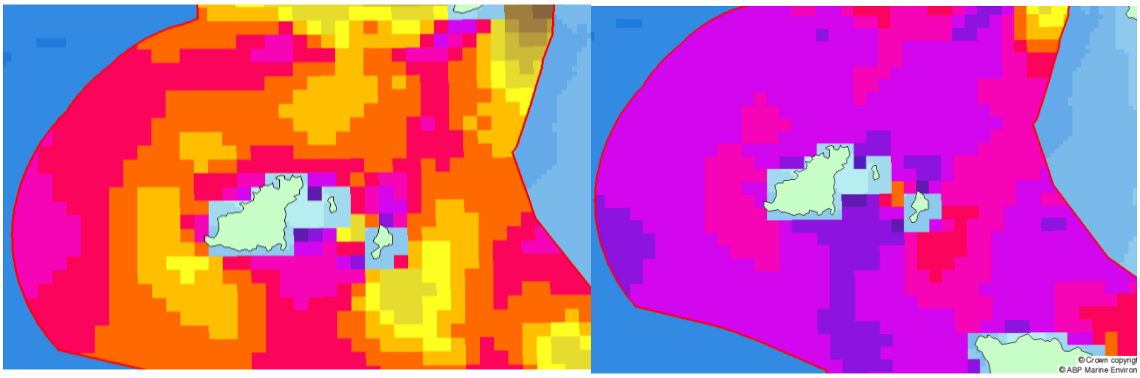


From the graph it is possible to see that the two data sets have a close correlation and a linear line of best fit was placed in the data with an R^2 value of 0.996.

Tidal velocity validation was carried out by comparison to the ABPMer Renewable Energy Atlas. The Renewable Energy Atlas is a model based upon the Navier Stokes shallow water equations, the bathymetry used within the model is the GEBCO data set embellished with Proudman Oceanic Laboratory Data sets. The model is an annual time record forced with 14 tidal harmonics including the M4 constituent. The basis of the computation is a finite central difference method with a grid resolution of 1.8 km. The illustrated outputs are the mean peak spring and neap tides; the data that underpins the figure is a compilation of peak spring and neap velocities over a year (ABPMer, 2008).

Figure 11: Renewable Energy Atlas, Guernsey Spring and Neap tidal velocity.

Source: The Marine Renewable Energy Atlas



Key

- > 4.00 (m/s)
- 3.51 - 4.00
- 3.01 - 3.50
- 2.51 - 3.00
- 2.01 - 2.50
- 1.76 - 2.00
- 1.51 - 1.75
- 1.26 - 1.50
- 1.01 - 1.25
- 0.76 - 1.00
- 0.51 - 0.75
- 0.26 - 0.50
- 0.11 - 0.25
- < 0.11 (m/s)

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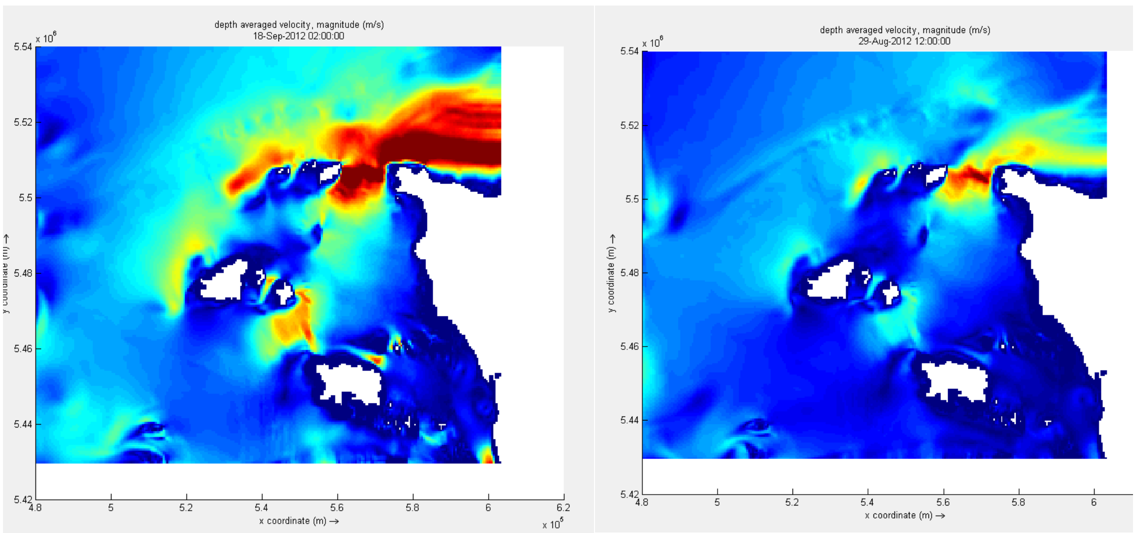
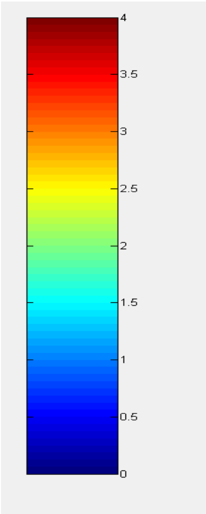
Figure 12: Delft3D FLOW Model Output, A Typical Guernsey Spring and Neap tide velocity.



Key in m/s



The model illustrated output is a single point of time that represents a typical peak spring velocity flow. There is a good correlation of tidal velocities and positions for both the spring and neap tidal cycles of the model output and the Renewable Energy Atlas.

The Spring tide velocity through the Big Russel for both the Renewable Energy Atlas and the model is 2.5m/s, with the model output showing a small area of velocity of 3m/s. The Renewable Energy Atlas shows a tidal velocity to the South and East of Sark of 2.25 – 2.5 m/s, the model output shows a slightly higher velocity of 2.5 – 3.0 m/s. For both sites the model shows a larger tidal velocity. This could be explained by the short model month influenced by the equinox compared to the annual average of the Renewable Energy Atlas.

The region to the south and west of Guernsey show the greatest difference in position and velocity. The difference in position can be explained by the age of the tide in the model output, as the tide progresses it travels from the North West to the South of the Island, the model indicates an earlier point of the tidal cycle. The velocity difference for this region is between 20 and 25%, with the Renewable Atlas estimating a velocity between 1.5 and 2 m/s, the model output indicates a tidal velocity of 2 – 2.5 m/s.

The Neap cycle shows a very similar pattern, the model estimates a higher velocity of 1.5 m/s in the Big Russel, the South and East of Sark and the West of Guernsey. The Renewable Energy Atlas indicates a slightly smaller resource of 0.75 – 1 m/s in these regions.

The velocity and water direction were also compared to the Admiralty Tidal Stream Atlas NP 264, the results were summarised in Table 17.

Table 17: Tidal Direction and velocity validation with the Admiralty Tidal Atlas NP294

Tide Time	Velocity (m/s)	B R Adm	B R Model	W G Adm	W G Model	E S Adm	E S Model
LW	Neap	1.08	1.66	0.26	0.56	0.62	1.36
	Spring	2.52	2.30	0.67	1.63	1.39	2.3
	Direction (degrees)	210	225	225	210	225	180
3 hours before HW	Neap	0.46	0.73	0.26	1.52	0.21	1.39
	Spring	1.1	1.68	0.57	1.03	0.46	0.93
	Direction (degrees)	90	60	135	180	90	60
HW	Neap	1.29	2.45	0.10	0.54	0.51	2.38
	Spring	2.67	2.24	0.21	1.36	1.18	2.57
	Direction (degrees)	45	45	30	0	45	45
3 hours after HW	Neap	0.26	0.6	0.56	1.54	0.21	1.11
	Spring	0.62	1.52	1.44	0.93	0.51	0.5
	Direction (degrees)	30	225	315	340	30	20

Key

LW = low water. HW = high water. MN= mean Neap. MS = mean Spring.

BR = Big Russel. WG = West Guernsey. ES = East Sark. Adm = Admiralty data

The direction is the flow direction that the water is moving toward.

The Admiralty data for the tidal stream atlas is collected via direct measurement over the surface layer of the water column, usually at a depth of 5 – 10 meters. The data is collected in calm waters at Spring tides over a period of 25 – 50 hours, the data is then analysed using a non-harmonic method of analysis and an adjusted mean is calculated for Spring and Neap cycles (see Appendix 6). It should be noted that this data is produced for the purposes of navigation and therefore scrutiny of the surface conditions is the paramount aim of the publication.

The Admiralty data does validate the tidal characteristics of the model output. The increased number of daily tidal velocity cycles is indicated in the tidal atlas; also the occurrence of peak velocities at Low and High Water is also seen in the Tidal Stream Atlas. The Tidal Stream Atlas velocities are generally lower than the model outputs. The closest correlation of data is for the region of the Big Russel, where Spring velocities are between 90% and 60% lower than the model. The velocity directions are within 30^{o}, except for the measurement 3 hours after High Water. The two data sets for the East Sark and West Guernsey show the greatest deviation with the greatest velocity differences being seen during the Neap cycle.

Without a period of measurement and observation it would be difficult to definitely say if the model is accurate, the model does validate well to the Renewable Energy Atlas and with water level data from the Admiralty Easy Tide. It should be noted that these are both numerical models. The comparison with the Tidal Atlas data reveals a good correlation with the Big Russel data and a poor correlation with the sites to the West of Guernsey and to the East of Sark. However the Tidal Atlas is a measurement of the surface layer and not depth average or harmonically analysed.

5.0 Discussion

5.1 The Total and Technological Power Resource

The model output indicates that the Big Russel has the most significant Spring and Neap tidal velocities in the region. The optimum velocity is in the mid channel during the Low and High water periods, the minimum velocity is at mid tide, this is also the time when the flow changes direction. The flow moves towards the south west at low tide and towards north east at high tide. It should be noted that there is approximately 6% more available resource on the southern half of the channel.

The significant Neap velocity is the primary reason that underpins the prominence of this area in terms of potential tidal stream investment. The main observation points within the Big Russel channel indicate that 99% of the tidal flow is above 1 m/s and therefore power generation would be possible for 99% of the year. The model outputs combined with the favourable bathymetry would indicate that further investigation and measurement of the actual flow should be carried out in the region.

The South Big Russel observation points indicate that the increased velocity drops off as the channel opens into the basin between the Channel Islands and Brittany. The technical power calculations indicate that just 2% of the total resource is below 1 m/s.

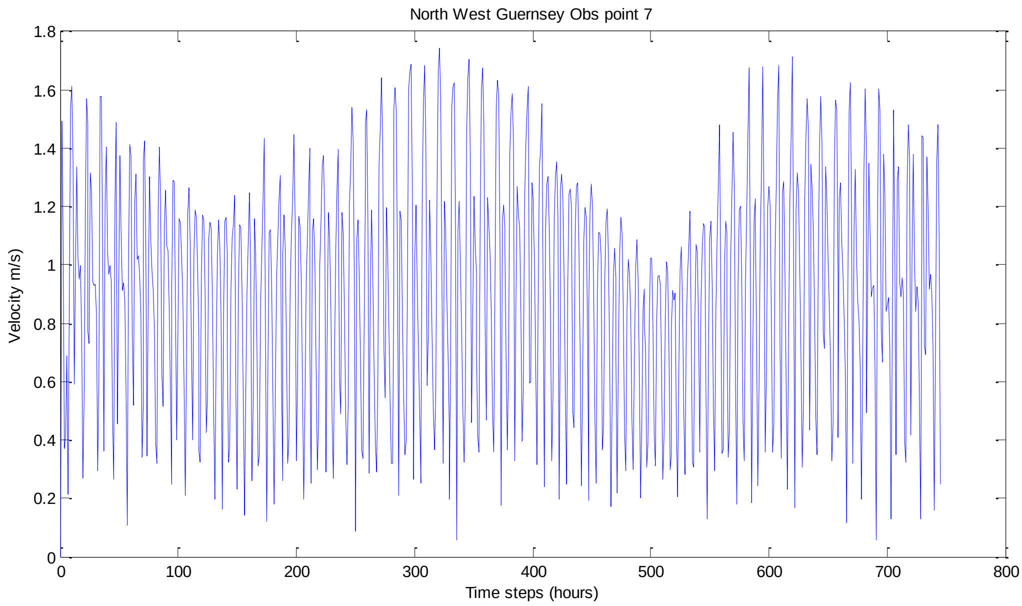
Despite the reduced peak velocity this region could have economic potential if a device has a cut in speed of 1 m/s and a lower optimum generating speed in the region of 1.5 – 1.8 m/s, such as the Minesto kite and the Flumill Archimedes screw (see Appendix 1). From the model output the region to the south of the Big Russel would be considered a marginal region that could be realised once emerging technology is fully mature.

The increased tidal velocity through the Big Russel channel extends to the north of the channel. If the project were to be extended it would be recommended to extend the observation points to the North of the Big Russel channel. The flow travels in the same direction as the flow in the main channel. It should be noted that the flow in the southern half of the channel is 25% greater than the north of the channel. The technical power calculations reveal that the 99% of the flow is above 1 m/s, signifying another substantial period of generation throughout the year. It would be advised that this region presents an immediately exploitable resource and further investigation and measurement of the tidal flow would be needed to validate the resource.

The Dr Owen (2012) reported there was 700 GWh of power within the entire Big Russel region, it is hard to directly compare the two modelled outputs as this report has chosen a number of areas within the channel and not investigated the entire region. As a quick comparison if the total resource outputs from this model were averaged over the Big Russel area the annual total resource output would be approximately 600 GWh.

The region to the North West model output indicates a disappointing mean peak Spring velocity of 1.3 m/s and a neap velocity of 1.1 m/s. The flow direction is primarily toward the North East at High Water and toward the South West at Low Water. The Neap tide is generally 75% of the Spring tide and in this region this is not the case. The Neap tide is 85% of the Spring tide. This phenomenon is also observed in the model outputs from the west and south west of the Guernsey. When the velocity is graphed over the month it is apparent that there is a residual current on the ebb generation, see figure 13. The usual ebb/flood tidal pattern is a mirror image; in the North West there is a significant flattening of the ebb tide that indicates a residual current.

Figure 13: North West Guernsey, observation point 7, monthly tidal velocity.



It should also be noted that there is a difference in the bathymetry detail between the Admiralty chart and the model output. Further investigation into the sensitivity of the model outputs to bathymetry should be carried out to truly investigate the nature of the tidal velocity in this region and within the entire model.

The observation points placed at the Western extent indicate a Neap peak flow at mid tide and a Spring peak tide at Low and High water. The flow direction is generally towards the North at High water and 3 hours after, South Westerly at Low water and

South Easterly three hours after Low water. This complicated flow regime may have an impact upon the commercialisation of the area, as some tidal devices need to be placed in the primary flow direction and would be misaligned for a portion of the tidal flow. The Western observations have the greatest velocity being situated further away from the island. This would imply that the friction from the seabed and shoaling has greater influence in the shallow water, managing to reduce the tidal flow. The furthest observation point has a mean Spring tide velocity of 1.98 and a mean tide velocity of 1.88m/s, the Neap tide velocity is 95% of the Spring tide velocity, this can be illustrated by the velocity output over the month, see figure 14.

Figure 14: Western Guernsey The tidal velocity of Observation point West 7

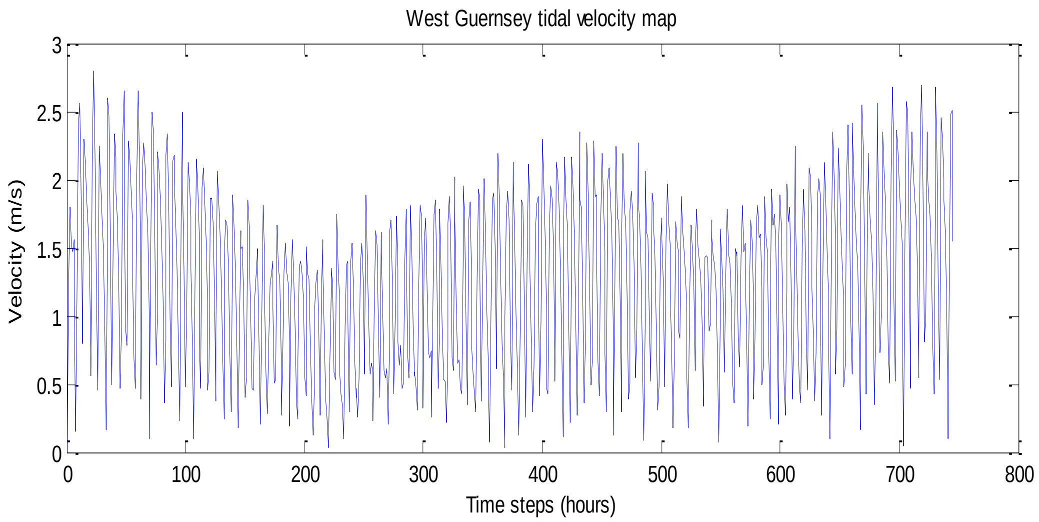


Figure 14 reveals that the ebb tide is never fully realised and there is a flattening of the tidal pattern that indicates the presence of a residual tidal current. The theory was explored by Pingree and Mardell (1987) that reported a residual tidal current at 50 meters water depth positioned to the west of the Guernsey to be in the region of 2 m/s. Further discussion with Dr Pingree (see Appendix 5) has revealed that the significant friction that reduces the ebb tide velocity is underpinned by the effects of the M4 component of the tide. The M4 component of the tide is known as one of the shallow water constituent, and its' influence on the tidal regime is identified by an asymmetric flood/ebb tidal period (Gomez–Valdes et al, 2003). This can be seen in the tide timetable for St Peters Port (see Appendix 5). The period between low and high water is approximately 6½ hours, the period from high water and low water is approximately 6 hours. The M4 component of the tide has a period of 6.2 hours which is the same period of the tidal velocity regime around the Channel Islands.

The residual current is also indicated in the technical power calculations, where 97% of the total resource is above 1 m/s. The amount of potential resource is similar to the resource in the South of the Big Russel with the same caveat; as the new technology matures the resource potential may be realised.

The model indicates a significant tidal resource around the islands of Sark. The flow around the south of Sark is generally polarised with the flow at Low water heading toward the South West and the reverse at High Water. The region's maximum flows are position in observation point 3 and 4 after which the resource drops off with distance from the island. The south of Sark also has the least technical availability of all the resources investigated in this model; between 95 and 97% of the resource is above 1m/s. The South of Sark would be considered a marginal region that will reach its' full potential once technology has matured.

The region of East of Sark has a promising tidal resource, indicating a mean peak spring tide of 2.6 m/s and a mean peak neap tidal velocity of 2.3 m/s. The primary flow direction is towards the South West at Low Water and towards the North East at High water. As with the Big Russel resource this neap tide velocity is a significant factor for potential investment in tidal stream technology. The technical power calculation indicates 1% of the total annual velocity falls below 1 m/s. The total power resource in the region is significant and warrants further measurement and investigation.

It should be noted that any tidal stream energy extraction around the island of Sark will have an effect on the tidal front that exists to the south west of the island. The front has proliferated from the existence of the anticlockwise gyre of Guernsey and Jersey (Pingree and Mardell, 1987). A tidal front can often be biologically significant and the decrease in local velocity and the increased mixing of the water column by tidal energy devices would have to be modelled to indicate any changes to the tidal front.

5.3 Wind driven currents

Throughout the model process there has been little consideration to the meteorological conditions that may prevail. The coastal waters surrounding the Channel Islands are subject to storm and bad weather events accompanied by periods of strong wind. The wind stress can increase the tidal currents, a model set up by Pingree and Griffiths (1980) found that a prolonged simulated south westerly wind blown over a period of 5 tidal cycles; could increase the tidal current in the same direction by up to 0.5 m/s. It should be noted that wind driven currents will increase the overall current especially during the winter months.

6.0 Further Work

With further time the author would have hoped to carry out the further work to the model.

- Incorporation of SeaZone with a resolution of 6 arc seconds, an approximate data point every 180 meters, to the EMODnet bathymetric date.

- Investigate the model in 3D mode and compare to the 2 D model
- Place additional investigation points around the North Big Russel, South West Sark and North West Guernsey
- Rerun the model over an average month and over a year with an increased data output interval of 15 minutes.

7.0 Conclusion

The model has been validated against the Renewable Energy Atlas and Admiralty Easy Tide data for tidal velocities and water levels, comparisons were also carried out with Admiralty Tidal Atlas NP 264. It has been shown that the greatest correlation of all three data sets within the Big Russel channel. The estimated total power output for the channel was 600GWh p.a. It was also found that 99% of the resource was above 1 m/s throughout all states of tide. The significance of this almost continual power generation is that the outputs from tidal devices placed in the Big Russel channel could be considered as part of the base load for the islands' power generation. Taking into consideration a very approximate limitation of 20% there are five sites within the Big Russel that would yield over 1.7 MWh/a for each device. Along with very favourable bathymetry and close proximity to land this site should be the main focus of the further investigations and measurement s.

The resource to the South and East of Sark also shows a very promising resource, with three sites directly to the East showing an annual power output above 1.7 MWh/a. The bathymetry is favourable, being slightly deeper than the Big Russel it may be a site for the slightly braver device developer. It would be the authors' recommendation to rerun the model with far more observation points in this region as there is some uncertainty as to where the optimum observation points were chosen. On an optimistic note the tidal velocities that were recorded were typical of the tidal flow for the region. Assuming a small array of 5 devices of the current technology were deployed at each favourable site within the Big Russel and East Sark there should be a yield of over 80 MWh/a

The North West was possibly the least successfully modelled region, with lower estimated tidal velocities than other reports. The bathymetry in the area within the model showed deviation to the Admiralty data. It would be interesting to re-access this region once the SeaZone higher resolution data was incorporated into the model. It should be noted that this region is deeper and has rougher bathymetry than the other areas around the island making it less attractive to a device developer.

Other areas such as the areas to the South of Sark and the West of Guernsey should be considered a marginal resource. With the maturing of the emerging technology that is able to operate in deeper waters and a lower optimum generating speed these site should once again be investigated for the potential tidal power resource.

References

Abercromby, G. Dufour, E. Franc, P. Garcia Sanabria, I. Mayal Ortiz, J. Mbuk, O. Mirval, L. (2011). *A feasibility Study of the Marine Renewable Energy in the Channel Islands.* Available at: http://www.guernseyrenewableenergy.com/documents/managed/REA%20Final/DOC344.1%20REA%20Consultation%20Report.pdf (Accessed on 5 May 2012)

ABPMer (2008) *Atlas of UK Marine Energy Resource, Technical Report.* Available at:

http://www.renewables-atlas.info/downloads/documents/R1432_Final_15May08.pdf. (Accessed on 20 August 2012)

AMCG (2011) *Local: Global Tide Models.* Available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990089548_1999150788.pdf (accessed on 9 July 2012)

(2010), *BBC News - Regions and territories: The Channel Islands*, available at: http://news.bbc.co.uk/1/hi/world/europe/country_profiles/7515502.stm (accessed 20 May 2012).

BBC (a) (2012) *BBC News _ Guernsey States to debate fishing limit plans.* Available at: http://www.bbc.co.uk/news/world-europe-guernsey-16790694 (accessed on 16 August, 2012)

BBC (b) (2012) *BBC News- Guernsey power cut caused by cable failure.* Available at: http://www.bbc.co.uk/news/world-europe-guernsey-17893640 (Accessed on 30 August 2012)

Black and Veatch (2005). *Phase II, UK tidal stream energy resource assessment.*

Blunden, L. S. Bahaj, A. S. (2008). *Tidal energy resource assessment for tidal stream generators*. Available at: http://www.see.ed.ac.uk/~shs/Tidal%20Stream/April%2007%20I%20MechE%20papers/Blunden%20and%20Bahaj.pdf. (Accessed on: 02 July 2012)

Clarke, J.A, Grant, A.D and Johnson, C. (2004) *Output characteristics of tidal current power stations.* Proceedings of the 14th International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers (ISOPE). pp. 113-119

Dauvin. J.C (2012). *Are the Eastern and Western basins of the English Channel two separate ecosystems?* Marine Pollution Bulletin. (64) pp. 463-471.

Delft (2011). *Delft 3D-FLOW user manual.* Available at: http://www.rsmas.miami.edu/users/prynne/Tidal_Inlet_files/Delft%203D%20Flow%20Manuel.pdf. (Accessed on 10 November 2011)

Digimap Guernsey (2010). *Height Datum for the Guernsey Grid.* Available at: http://www.digimap.gg/height_datum_for_the_guernsey_grid (Accessed on 10 July 2012)

Egbert, G. Bennett, A. Foreman, M. (1994) *Topex/Poseidon tides estimated using a global inverse model.* Available at: http://www.agu.org/pubs/crossref/1994/94JC01894.shtml (Accessed on, 10 July 2012)

EMEC (2009) *Assessment of Tidal Energy Resource*. Available at: http://www.emec.org.uk/download/4%20Assessment%20of%20Tidal%20Energy%20Resource.pdf. (Accessed on 2 September 2012)

EquiMar (Unknown) *I.A Resource Assessment.* Available at: http://www.chrissmithonline.co.uk/files/ia_finaldraft_hs.pdf. (Accessed on 30 August 2012)

Gomez-Valdes, J. Delgado, J.A. and Dworak J.A. (2003) *Overtides, compound tides, and the tidal residual current in Ensenada de la Paz lagoon , Baja California Sur, Mexico.* Available at: http://www.geofisica.unam.mx/unid_apoyo/editorial/publicaciones/investigacion/geofisica_internacional/anteriores/2003/04/gomez.pdf (Accessed on 2 September 2012)

Guernsey Renewable Energy Commission (2009) *Regional Environmental Assessment Scoping report.* Available at: http://oreg.ca/web_documents/guernsey_rea.pdf. (Accessed on 5 June 2012)

Guernsey Renewable Energy Team (RET). (2011). *Renewable Energy Team (RET) Strategy 2012 and Beyond.* Available at http://www.guernseyrenewableenergy.com/documents/managed/DOC453%201%20RET%20Strategy%202012%20and%20Beyond%20-%20Final.pdf. (Accessed on 31 July 2012)

Guernsey Renewable Energy Commission. (2012). *About RET.* Available at http://www.guernseyrenewableenergy.com/about/About-RET.aspx. (Accessed on 31 July 2012)

Jersey Electricity Company (Unknown), *Channel Islands Electricity Grid (CIEG)*. Available at: http://www.jec.co.uk/aboutus/groupbusinesses/channelislandselectricitygridcieg/ (Accessed 21 May 2012).

MERiFIC (2012) *MERiFIC brochure.* Available at: http://www.merific.eu/files/2011/08/MERiFIC_brochure.pdf . (Accessed on 17 August 2012)

NASA (2012) *Navier Stokes Equations.* Available at: http://www.grc.nasa.gov/WWW/k-12/airplane/nseqs.html. (Accessed on 15th August 2012)

Olver. P.J (2012) *Numerical Methods: Finite differences*. Available at: http://www.math.umn.edu/~olver/pd_/nfd.pdf . (Accessed on 13 August 2012)

Ordnance Survey (2012) *Ordnance Survey Coordinate system*. Available at: http://www.ordnancesurvey.co.uk/oswebsite/gps/information/coordinatesystemsinfo/guidecontents/guide5.html (Accessed on 5 September 2012)

Owen. A. (2012) *Tidal Resource Mapping for the Territorial Water of Guernsey.* Available at:

http://www.guernseyrenewableenergy.com/documents/managed/Consultation%20Report.pdf (Accessed on 28 August 2012)

OXP (2003), *Tidal Prediction*. Available at: http://luk.staff.ugm.ac.id/etc/sw/lecture5.pdf. (Accessed on 30 August 2012).

Pasqualetti. M (2011) *Social Barriers to Renewable energy Landscapes.* Geographical Review. Volume 101, Issue 2, pp. 201-223.

Pingree R. D and Griffiths, D. K. (1980) *Currents driven by a steady uniform wind stress on the shelf sea around the British Isles.* Oceanol Acta, Vol 3. Issue 2 pp. 227-236

Pingree.R.D and Mardell, G.T (1987) *Tidal Flows around the Channel Islands.* Journal of the Marine Biological Association of the United Kingdom. Vol 67. Issue 4. pp. 691-707

Policy Council. (2011). *Guernsey Facts and Figures.* Available at: http://www.guernseyfinance.com/files/Facts%20&%20Figures%202011.pdf. (Accessed on 31 July 2012)

Royal Haskoning (2011) *SeaGen Environmental Monitoring Program.* Available at: http://www.marineturbines.com/sites/default/files/SeaGen-Environmental-Monitoring-Programme-Final-Report.pdf. (Accessed on 30 August 2012)

Saloman. J. C, Lazure. P, Breton. M. (1994) *Numerical hydrodynamic modelling, as a management tool for our marine environment.* Ocean Engineering for today's technology and tomorrow's preservation. Vol 1, pp. I/48- I/58.

States of Guernsey (Unknown), *Information about the Bailiwick of Guernsey*, available at: http://www.gov.gg/ccm/navigation/about-guernsey/about-the-bailiwick-of-guernsey/ (accessed 20 May 2012).

State of Guernsey (2012) *Joint Statement of Intent on Marine Renewable Energy.* Available at: http://www.gov.gg/article/7089/Joint-Statement-of-Intent-on-Marine-Renewable-Energy. Accessed on 16 August 2012.

Scottish Government. (2012) *Scoping study for tidal stream energy development in Scottish waters.* Available at: http://www.scotland.gov.uk/Publications/2012/04/2639/4 . (Accessed on 7 September 2012)

Strathclyde University b (unknown) *Environment: Significant Impact Factor.* Available at: http://www.esru.strath.ac.uk/EandE/Web_sites/05-06/marine_renewables/envimpact/sif.htm (accessed on 10 July 2012)

Sustainable Energy Research Group, (2008) *Importance in Design of Tidal Stream Farms.* Available at: http://www.energy.soton.ac.uk/marine/resource.html (accessed on 9 July 2012)

This is Guernsey (2008) *Guernsey set to get back its 12- mile limit.* Available at: http://www.thisisguernsey.com/latest/2008/02/05/guernsey-set-to-get-back-its-12-mile-limit/. Accessed on 21 May 2012

World Nuclear Association (2012). *Nuclear Power in France.* Available at http://www.world-nuclear.org/info/inf40.html . Accessed on 21 May 2012

Appendix

Appendix1 Tidal Technology, a brief overview

Marine renewable energy technology is currently dominated by the horizontal axis turbine, other technologies such as vertical axis turbines and hydrofoils have reached full scale deployment; however these technologies are unsuitable for this project and therefore have not been included in this review. The Neptune Proteus is a shallow water estuary base device that does not work well in a wave environment, and the Pulse Tidal hydrofoil has idealised deployment in less than 20 meters of water. The dominance of the horizontal turbine is apparent as all of the devices below are from that design; however each device is unique. The question of suitability will be dictated by a number of factors such as cost and availability. In terms of power output the machines are well matched, however the cut in and cut out speed will dictate the amount of time power production is available. All of the devices are generating at EMEC tidal test site or independently connected to the grid.

Established Technology

	MCT SeaGen	Open Hydro	Hammerfest Strom	Atlantis
Cut in speed (m/s)	1	1	1.1	1
Optimum generation speed (m/s)	2.4	2.8	3	2.65 m/s
Turbine Diameter (m)	20	18	18	18
Rated Power (W)	1.2MW	1MW	1 MW	1 MW
Max operating depth (m)	?	?	100	?
Grid Connected	Yes	yes	yes	yes
Foundation type	Monopile	Tri piled	Piled	Piled

Emerging Technology

	Flumill 2	Minesto
Technology	Twin Archimedes Screw	Tidal Kite
Full scale	No	No
Rated power	120 kW	120 kW
Cut in Speed (m/s)	1	0.5
Optimum generating Speed (m/s)	1.5	1.2 – 1.8
Water depth (m)	Up to 66m	50 -65
Foundation type	Gravity base	Tethered
Stationed	EMEC	Strangford Loch
Highlights	Excellent test results, larger models in production, no water cavitation, will allow a greater packing density	Light and small, extremely low cut in speed, low material costs
website	http://www.flumill.co.uk	http://www.minesto.com/

Appendix 2 Eularian and Legrangian and Stokes

Lagrangian and Eularian fluid mechanic theories are two different ways of measuring fluid flow with reference to time. Lagrangian Measurements describe the velocity of a material in a direction with reference to a point of time, if there is a continuous fluid then there would be an infinite number of measurements. For practicalities a chosen point and reference time becomes the origin. Flow velocities are indicated in vectors that reference to the original reference point as a function of time. When Lagrangian measurements are used the measurements are taken within the material through time, which for large bodies of water can be difficult to establish. Making measurements at fixed points as the material passes is known as an Eularian measurement, the velocity at this point does not refer to the entire material, just the material that passes that point at that instant.

Stokes drift. It is assumed that there is an absence of viscosity and rotation within the water column and that the waves induce a current along the wave direction, the current is proportional to the square of the wave amplitude. The Stokes drift is a mass transport velocity measured in Lagrangian terms.

Appendix 3 Tidal Harmonics

Tides are predominantly caused by the gravitational action of the sun, moon and the earth; tidal prediction has historically been used for marine navigational purposes, with an increasing modern use in marine recreation and traditional hydro carbon energy industry and emerging renewable industries. Tidal prediction can be disseminated into over 400 harmonic components each individual sinusoidal component demonstrates amplitude (m) and frequency (degrees) that is unique to the location.

Tidal Harmonic	Description and speed (degrees per solar hour)
M2	Principle Lunar semi diurnal constituent. 28.984°
S2	Principle Solar semi diurnal constituent.30.000°
N2	Larger Lunar elliptical semi diurnal constituent. 28.440°
K2	Lunar Solar semi diurnal. 30.082°
K1	Lunar- Solar declination diurnal constituent. 15.041°
O1	Lunar declination diurnal constituent. 13.943°
P1	Solar declination diurnal constituent. 14.958°
Q1	Larger lunar elliptical constituent. 13.398°
MF	Lunar fortnightly 1.098°
MM	Lunar monthly 0.544°
MS4	Lunar solar constituent 6.104°
M4	Lunar quarter diurnal large, primary shallow water constituent. 6.210°
MN4	Sallow water quarter diurnal 6.270°

Source New South Wales Glossary @ http://www.mhl.nsw.gov.au/www/tide_glossary.htmlx#P1

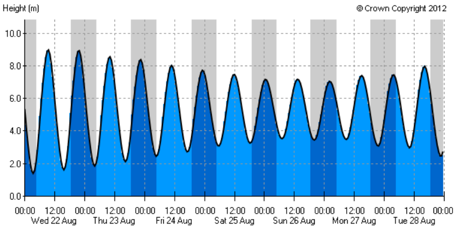
Appendix 4 Water levels for St Peters Port (CD) add 5.3 meters to compare with LAT data)

Appendix 4

Tide times and heights at St Peters Port Guernsey (LAT)

Please not these tide times are at Greenwich Mean time and were obtained from the Easy Tide website.

http://easytide.ukho.gov.uk/EasyTide/EasyTide/ShowPrediction.aspx?PortID=1604&PredictionStart=22/08/2012&PredictionLength=14&PaymentMethod=OneOff



Your EasyTide Prediction (enhanced)

View printer friendly prediction

ST. PETER PORT, Channel Islands
Port predictions (Standard Local Time) are equal to UTC

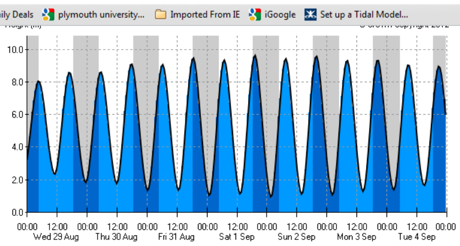
Start Date: Wednesday 22nd August 2012 (Standard Local Time)
Duration: 14 days

Daylight saving: 0 hours
see daylight saving warning
Select units: Metres / Feet
Max graph size: 7 days
Apply

Height (m) © Crown Copyright 2012

Wed 22 Aug				Thu 23 Aug				Fri 24 Aug				Sat 25 Aug			Sun 26 Aug				Mon 27 Aug				Tue 28 Aug			
LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW
03:21	09:22	15:39	21:38	03:58	10:02	16:19	22:21	04:41	10:48	17:07	23:13	05:36	11:49	18:15	00:26	06:59	13:17	19:54	02:10	08:45	14:54	21:30	03:37	10:05	16:05	22:37
1.4 m	9.0 m	1.6 m	9.0 m	1.9 m	8.6 m	2.1 m	8.4 m	2.5 m	8.0 m	2.7 m	7.7 m	3.1 m	7.5 m	3.3 m	7.2 m	3.5 m	7.2 m	3.5 m	7.1 m	3.5 m	7.4 m	3.1 m	7.5 m	3.0 m	8.0 m	2.5 m

Height (m) © Crown Copyright 2012



Wed 29 Aug				Thu 30 Aug			Fri 31 Aug				Sat 1 Sep				Sun 2 Sep				Mon 3 Sep				Tue 4 Sep			
HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW	HW
04:39	11:03	16:59	23:29	05:28	11:52	17:46	00:14	06:12	12:35	18:29	00:57	06:53	13:16	19:09	01:35	07:30	13:52	19:45	02:10	08:03	14:25	20:18	02:41	08:33	14:54	20:47
8.1 m	2.3 m	8.6 m	1.8 m	8.6 m	1.8 m	9.1 m	1.3 m	9.1 m	1.4 m	9.5 m	1.0 m	9.3 m	1.1 m	9.6 m	1.0 m	9.4 m	1.1 m	9.6 m	1.1 m	9.3 m	1.3 m	9.4 m	1.4 m	9.1 m	1.7 m	9.0 m

Predicted heights are in metres above Chart Datum

Springs and Neaps

Wednesday 22nd August 2012 9 days before full moon
3 days after spring tide

Moon Phases

First Quarter Friday 24th August 2012
Full Moon Friday 31st August 2012
Last Quarter Saturday 8th September 2012
New Moon Sunday 16th September 2012

Times of Sunrise

Wed 22 Aug	Thu 23 Aug	Fri 24 Aug	Sat 25 Aug	Sun 26 Aug	Mon 27 Aug	Tue 28 Aug	Wed 29 Aug	Thu 30 Aug	Fri 31 Aug	Sat 1 Sep	Sun 2 Sep	Mon 3 Sep	Tue 4 Sep
05:11	05:13	05:14	05:16	05:17	05:19	05:20	05:22	05:23	05:24	05:26	05:27	05:29	05:30

Appendix 5: Personal e mail correspondence with Dr R Pingree

Sarah

You are doing very well; it is not possible to know all about tides in the CI region, even after 46 years (that's me).

You are right, and that contributes to the Eulerian tidal residual flow, and if considered in terms of bed stress shows the way the sediments / sand waves etc. move and why St Malo has some nice beaches and why tidal power stations might silt up. I have a book on the Admiralty tidal steams (measured for you if you want, but they are similar to those given in the paper you/I copied).

Anyway it is due to the M4 tidal the first harmonic for the M2. If you want to do it exactly right you need to put M4 on your boundaries as well as M2. I have these values if you want. But I think you have already done enough to satisfy the requirements of UoP, shouldn't you be thinking about breakfast at this time (someone just interrupted me it was 9 am when I started this note).

Robin

From: (pg) Sarah Bedingham [mailto:sarah.bedingham@postgrad.plymouth.ac.uk]
Sent: 24 August 2012 08:40
To: Robin Pingree
Subject: Just checking

I hope this e mail gets to you. I do have a quick question for you, in the model there is an uneven velocity flow in the flood and ebb tides , basically the ebb tide is slower than the flood tide at all my observation points around Guernsey and Sark , would this be a cause/resultant of the friction force that you reported . Or is that friction due to something else? The more I find out about the tide the less I seem to know !!! Thanks again for your help, regards Sarah

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Appendix 6: Personal e mail from Christopher Jones , head of tides at UKHO

Dear Sarah

Thank you for your e-mail.

The below information regarding the traditional tidal stream (diamond) data on Admiralty Charts and Tidal Stream Atlases will hopefully help with the information you require:-

Collection & Analysis of Tidal Stream Data

Observations

- Tidal Stream data is preferably obtained over a period of 25 or 50 hours in calm weather, during Spring tides, when the range of the tide is greatest.

- The majority of UKHO data-based tidal stream information came from pole log-ship observations. Basically this is a spar or tube, of uniform thickness throughout its length, weighted so that it floats vertically with its upper end just showing above the water line. The length of pole is usually either 15 or 30 feet (approx. 5 to 10 metres). More recently acquired data now comes from current meters or ADCP's (Acoustic Doppler Current Profilers). Crucially, the pole log-ship technique captured 'depth averaged' surface stream movement (down to the depth of the length of the pole), where the pole *always* represented the 'surface' layer, as it moved up and down with the tide height.

- The pole was tracked from an anchored vessel at regular intervals (usually half-hourly) and its rate of movement calculated. Thus the tidal-stream data plotted on Admiralty Charts and in Tidal Stream Atlases is representative of the mean tidal stream 5-10 metres below the surface. We now take the relevant 'bin' of data which best represents this surface depth but are wary of the problems concerning the corruption of the data in ADCP 'surface bins'.

Analysis

- The primary method of analysis is Non-Harmonic (semi-graphic) – employed in UK waters, and for areas where the tidal regime is semi-diurnal.

- This method was / is also used owing to the limited time period over which the tidal stream observations have been collected (i.e. 25 – 50 hours). Of course a minimum of 30 days' observation are preferred for harmonic analysis. This was simply not possible using the pole log-ship method. ADCP's can of course be left in-situ for this time period, but, as much of our stream data is collected during the course of a hydro graphic survey (often MCA-contracted work), this is largely controlled by the cost of acquiring this data and the duration of the survey itself.

- The semi-graphic method requires the resultant rates and directions to be plotted on a 360° plotting sheet, in order to eliminate the residual motion (i.e. the effect of any current which may have influenced the readings). This method also allows weather effects to be eliminated, and also mitigates any diurnal inequality which may exist.
- The stream observations are always referred to the time of High Water at a suitable Standard Port, and may be re-referenced to other Standard Ports as necessary.
- The rates derived directly from the analysis are then adjusted to make them representative of the values expected at Mean Spring and Mean Neap tidal states.
- The results are then published in the tidal stream tables on Admiralty Charts, and the individual figures accompanying the arrows in the Tidal Stream Atlases.

Best regards

Christopher Jones
Head of Tides
United Kingdom Hydrographic Office

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