To Investigate and Characterise the Wave Energy Resource surrounding Guernsey Island with a particular focus on the Western side

By

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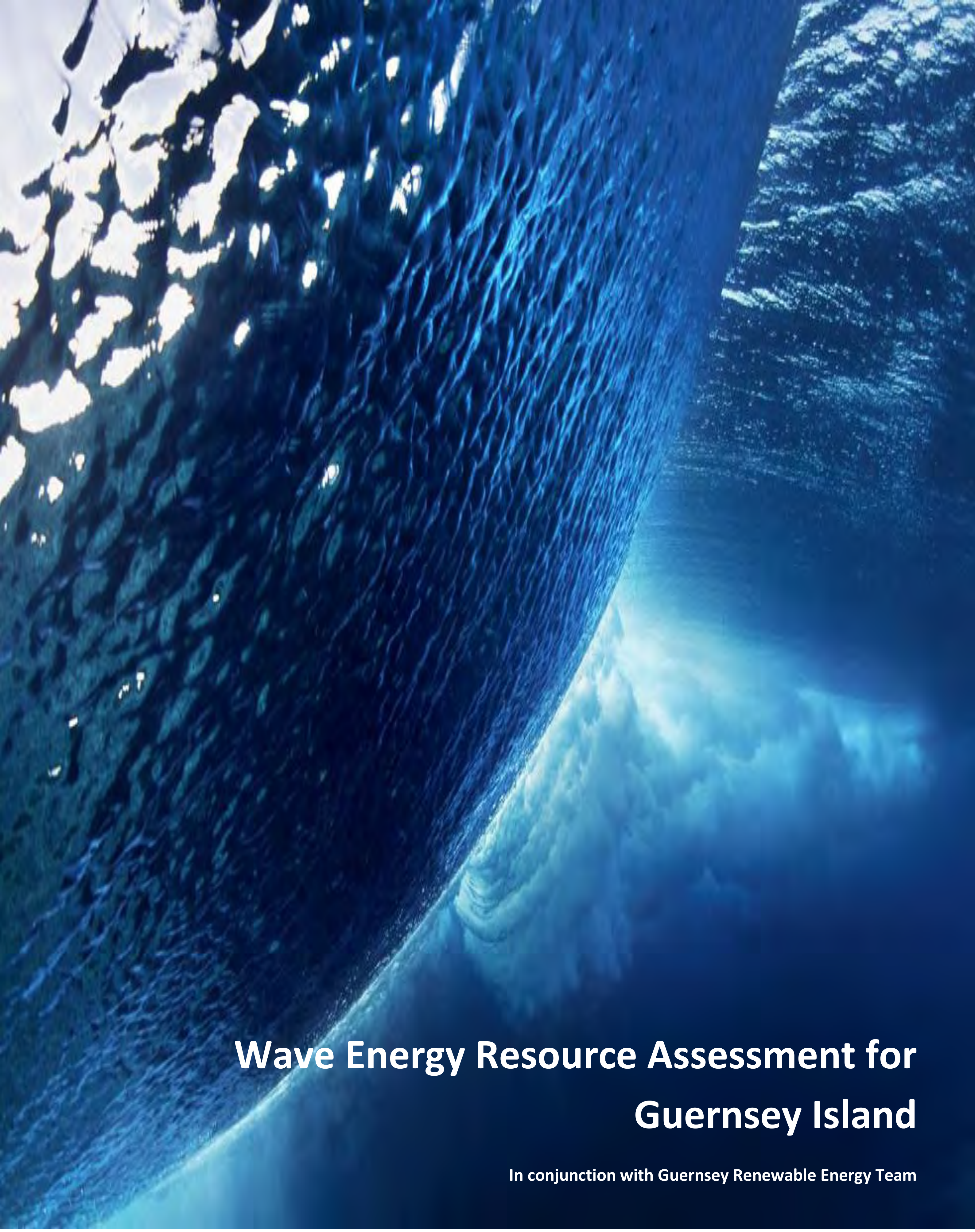

Wave Energy Resource Assessment for Guernsey Island

In conjunction with Guernsey Renewable Energy Team

Marine Institute
UNIVERSITY OF PLYMOUTH

STATES OF GUERNSEY

MARINE RENEWABLE ENERGY WITH PLYMOUTH UNIVERSITY

GUERNSEY WAVE RESOURCE CHARACTERISATION REPORT

September 2012

Report Created for

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List of Abbreviations

Abbreviation	Definition
CIEG	Channel Islands Electricity Grid
EDF	Electricity de France
GEL	Guernsey Electric Limited
GW	Gig watt
kWm	Kilowatts per meter wave crest
MWh	Megawatt hours
OWC	Oscillating Water Column
RET	Guernsey's Renewable Energy Team
ROC	Renewable Energy Certificate
TWh	Terawatt hours
WECs	Wave Energy Convertors

Executive Summary

This report was commissioned by the States of Guernsey, Commerce and Employment, Renewable Energy Team (RET) - in conjunction with Plymouth University - to investigate the electricity generation potential of ocean wave energy resources located within their jurisdictional waters. The intent is to provide the Renewable Energy Team and other policy making bodies with objective and quantitative information upon which to make informed decisions regarding the future development of the state's wave energy resources.

This study focuses on the assessment the wave resource surrounding the island, but with a particular focus on the West coast. Further investigation is carried out at three separate locations to identify the potential contribution to Guernsey Electricity from installed Wave Energy Convertors (WECs).

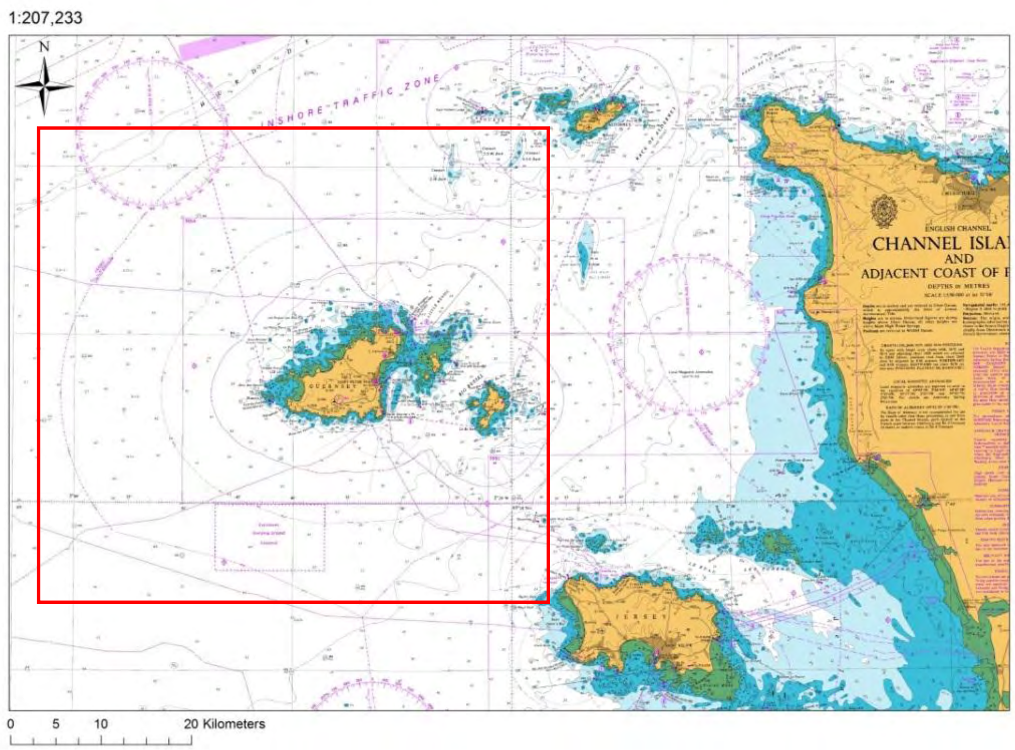


Figure 1 Area of assessment within the scope of the project

Ocean wave energy is one of the most concentrated and widely available forms of renewable energy in coastal areas. The worldwide wave energy resource potential is estimated at 8,000 - 80,000TWh/yr. This compared against current worldwide electric consumption of 132,000 TWh/yr, would see that a significant portion of the planets needs could perhaps be achieved through wave energy. Furthermore it is estimated that 40% of the world's population live within 100km of the coast. This, establishes a strong relationship between resource and demand. As security of supply and population increase becomes more of an issue in future years, this may allow for a widespread adoption of emerging technologies that generate electricity from ocean waves.

Driven by the fact that in isolated island environments, like that of Guernsey, the extraction of renewable energy is becoming an increasing issue as electricity prices intensify. The objective of this report is to gauge the wave energy potential for Guernsey's waters.

Wave power, though relatively predictable in the waters surrounding Guernsey has one main disadvantage - variability. Great variations in power levels between wave to wave, from day to day and even month to month can provide uncertainty to an investor or governing body seeking deployment of wave energy convertors. In this report the principles of wave resource characterisation are addressed, and will set the foundation for future wave development projects in the area. These principles are independent of the scale of the device deployment project.

Guernsey's wave resource is concentrated off the West coast. Small scale installations, such as the OWC Pico power plant, in the Azores, are an exciting prospect for small island communities, which are presently disadvantaged by relatively expensive power supply within the large regions. In order to provide an accurate assessment of the resource but also to study the variability between days, months and even years, longer data sets are required in order to provide these reliable wave climate statistics, thus the aim of this report.

With significant wave heights peaking in winter months of 6.7 meters and summer month's minimal value of 0.25 meters, high level analysis of the available resource is key. The model computations for Guernsey's waters achieved excellent correlation when compared against Met office UK WaveWatch III data.

With no validation data available in shallow waters (less than 40 meters), through wave buoys or freely available sources, the deep water validation location serves as a relatively true representation of the wave climate off Guernsey Island. Here the ratio of water depth to wavelength (h/λ) is greater than 0.5. All power estimates are assumed to have no intermediate or shallow water effects on wave energy.

Finally the model was used to create power density maps and select sites which contained the most energy. These locations where then investigated to identify their extractable energy potential. Using two different devices, 8 Wave dragon energy convertors yielded 3.2% of the islands total energy consumption, over the two years investigated. A total of 12 Pelamis P1 devices yielded 0.88% over the same period. Figures are based on a total Island consumption of 400,000MW/h a year.

Project Benefits for Guernsey's RET

In September 2011 Guernsey's Renewable Energy Team (RET) identified a number of potential research projects in its project plan, and partnered with Plymouth University so that their projects were carried out to a high standard, to enable the RET's objectives of progressing Guernsey's marine energy renewable power. The current project focuses on the wave energy potential of the West coast of the island up to 12 Nautical miles.

Understanding the wave energy resource is of key importance for investors, developers and local government bodies, as without in-depth scientific research, the exact energy potential is unknown and therefore the push to exploit renewable sources ceases. This report aims to provide an insight for Guernsey's (RET) who will greatly benefit from the outcomes of this report, allowing them to make evidence-based decisions on which are the best areas around the Island for wave energy generation and exploitation. The information generated will also assist the RET and wave energy developers to determine which is the preferred technology suited for the available power and specific locations.

This report has been compiled vigorously using the most freely accessible information found within the project window.

1. Introduction

1.1. The need for Renewable Energy

The understanding that there is energy stored in the oscillations of the sea's surface is apparent to those who have experienced an ocean storm. Wave climate statistics, particularly of extremes, have been of significance for many decades to ship, harbour designers, the oil & gas industry and within recent years, the Renewables Industry (Mandal & Pranaharan, 2012). This stored energy travels, which forms a sustainable and constant renewable energy resource, though uncertainty related to variability in wave climate still exists. Improvements in accuracy of data will increase the accuracy of future predictions of Wave Energy Convertors (WEC) yields and aid the industry. The wave industry has only in truth been appreciated over the last decade. The future prospects for such a wealth of energy have plentiful applications.

With such an immature and fast advancing industry, precise figures on available power are hard to quantify. Surrounding the UK the Carbon Trust reports a "practical" wave resource of 50 TWh/yr which could yield, if incorporated with a tidal resource 20% of the UK's national energy requirements by 2020.

According to Renewable UK (2012) the UK and adjoining waters have the best wave and tidal resource in Europe. This is attributed to the wide distribution and long fetch of the annual wind resource over the North Atlantic, with the highest wind belts occurring between the latitudes of 40^0 and 60^0 (Hardisty, 1990).

Currently the wind industry is the most mature offshore renewable technology, with wave and tidal still in their infancy. The progression amongst developers and the recently revised Government incentive of 5 Renewable Obligation Certificates (ROC's), in the UK, this year is driving the industry forward.

In the UK, the South West of England, together with the North West of Scotland are prime locations for the advancing industry, Scotland's Pentland Firth is awaiting the first array deployment and this in turn is eagerly awaited by industry experts. If successful, the scope for supplying energy converted from these abundant waves is unquantifiable. The heart of the industry in the UK is situated at EMEC (European Marine Energy Centre) in Orkney, Scotland and the Wave Hub in Hayle, Cornwall where the testing facility is expecting first deployments this year.

Guernsey Island, located in the English Channel, West of Cherbourg, would be most suited for this clean energy source. The small island community is presently heavily involved in assessing their own resources through collaborations with Plymouth, Exeter and Cranfield Universities with the aim to potentially obtain a significant portion of their energy supply from renewable sources. Currently the Island is assessing the majority of renewable options; wind, tidal and wave - with this report focusing on the latter.

The Channel Islands consist of 14 islands, 8 of which are inhabited. Within these islands there are two British Crown dependencies, Bailiwick of Guernsey and Bailiwick of Jersey. Both are self-governing assets of the British crown, neither UK nor EU. The Island of Guernsey has an elected parliament, called ‘The States of Deliberation’, located in St Peters Port, which legislate the islands of Guernsey, Herm, Jethou, Lihou and some characteristics of Alderney. Currently Guernsey has a population of circa 65,573 while covering a land mass of 78 square kilometres.

The need for Renewable energy on the island draws on 3 main foundations: firstly energy security as the Island community relies on imports from France, through Jersey; secondly, to diversify the economy and create jobs; and thirdly, to reduce the effects of climate change by sourcing clean energy. Wave energy converters (WEC’s) also can provide a return on investment by bringing money into the economy through the sale or export of energy. In addition it can shelter against swiftly intensifying energy costs, largely attributed by rising fuel prices, reduced oil/coal supplies which will eventually run dry.

Currently the island depends on electricity from France through two unidirectional 90,000v cables but also has an oil fired generator to ensure a constant power supply. The first cable of which was installed in 1984 and has a capacity of 55mw, the second cable of 90 mw was installed in 2000. Both cables come ashore in Jersey at Archirondel from La Haye du Puits in France, (Cranfield report, 2011). The Channel Islands Electricity Grid (CIEG) is a joint venture between Jersey electricity and Guernsey electricity; between them they cover 80% of their electricity needs by importing from EDF (Electricity de France), (ABB, 2006). In 2006, as stated by ABB, CEIG supplied 75% of the Channel Island’s annual power demand and met the full islands load for 9 months of the year.

From Jersey the electricity is transferred via another 60mw bidirectional cable, Guernsey’s requirements have maximum consumption values of 84MW and a minimum of 24MW, leading to a total annual requirement of 400,000 MWh.

Outlined in Guernsey's Policy Council 2008; they put forward a proposal to "switch progressively to clean renewable energy sources to achieve a long-term reduction of carbon dioxide emissions of 80% from 1990 levels by 2050" (Cranfield report, 2011). This switch to renewable sources would require the termination of a present policy where Guernsey Electricity is obliged to supply at lowest possible cost, (Guernsey electric Ltd, 2011). This is a key issue as currently marine renewable electricity, especially wave generation, is at a higher premium thus garners more incentives and government funding. This can be in two forms, Renewable Obligation Certificates (ROC's) from the UK and the other subsidy through the French Feed-in Tariff, which is through the state owned energy utility - EDF.

The wave features in the English Channel are well known for having continuous winds blowing with significant velocities and is thus a suitable location to carry out an assessment on the wave resource. Surrounding the Channel Islands, especially Guernsey's West Coast, wave action is relatively constant and therefore predictable to a degree of accuracy due to exposed coastlines fed directly west from the Atlantic Ocean, thus the appealing nature of the project.

According the BERR technical report (2008), the annual significant wave height surrounding Guernsey is between 1.51 – 1.75 meters. The same report also presents seasonal mean significant wave heights, where winter wave heights of 1.76 - 2.51 meters and summer wave heights of 1.01 – 1.25 meters can be found. Through the deployment of ANEMOC buoys (Atlas Numérique d'Etats de mer Océanique et Côtier) in and around the Channel islands, buoy 7 as stated in the Cranfield report (2011) shows a directional trend that the orientation of the waves is 270^0 +/- 15^0.

This trend allows for accurate prediction and precise knowledge for firstly characterising the climate using numerical modelling and future positioning of wave energy converters ,thus allowing for best possible energy extraction.

1.2. Aims and Objectives

This unique project, together with the model results will provide key information to The States of Guernsey, Commerce and Employment, Renewable Energy Team (RET) which will aid in the decision to exploit their wave climate. This project was carried out in conjunction with Guernsey's Renewable Energy Team (RET), with additional contribution to the project through the University of Plymouths, Marine Institute. An assessment of the wave resource climate around Guernsey Island was conducted as per the RET request, the modelling was conducted using Deltares's Delft 3D-WAVE version 3.04.01.000000 (Open source).

The primary aim of the project is to investigate and characterise wave energy resources on the Western side of Guernsey. The specific objectives include: a) simulation of wave conditions over 2 years (1st January 2009 – 31st December 2010; b) generate annual wave energy plots. A further objective was added towards the end of the project, this involved the selection of three sites and the integration with two freely available device power matrixes.

This report is intended to enlighten the reader with knowledge in the field of wave resource assessment using numerical modeling. It examines the application, validation and scope of how Delft3D was used to assess the waters surrounding Guernsey Island. The accuracy of these outputs are discussed, together with the constraints surrounding selection of specific site.

2. Literature review

2.1. Basic wave physics

The fundamentals form around Airy wave theory also known as small-amplitude or linear wave theory. This theory presents a linear description of the propagation of gravity waves on the surface of a potential flow and above a horizontal bottom and is strictly only applicable to conditions in which the wave height is small compared to the wave length and water depth, (Reeve et al, 2012). This section merely serves to provide the reader with the basic principles surrounding waves in deep water.

The theory carries a number of assumptions where:

- a uniform mean depth is present
- fluid is in viscid, incompressible and irrotational
- density ρ is a constant
- friction and turbulence are ignored
- surface tension can be neglected
- Coriolis effect from the earth's rotation is neglected
- Pressure at the free surface is uniform and constant
- Waves do not interact with any other motions
- Waves are long crested (i.e. two-dimensional)

Some of the above assumptions can be relaxed, depending on the engineering difficultly. The applications of such a theory are adopted in numerous disciplines, where ocean and coastal engineering use the submissions for the modelling of random sea states in order to plan for the design of harbours, ports and shoreline defences.

Oceanographers equally apply the theory for assessing tsunami waves in the deep open ocean waters. Furthermore, Airy wave theory provides a good approximation to the distribution of individual wave heights which are defined by the zero – up crossing and zero – down crossing methods (Goda, 2000).

Airy wave theory is derived from two-dimensional ideal fluid flow, of which are typical of ocean waves, though not greatly affected by viscosity, surface tension or turbulence (Reeve et al, 2012), as previously stated. Figure 2 shows a typical sine wave of where the two-dimensional flow is characterised by the parameters of wave length L, height H, depth d and celerity c. Celerity, as expressed by c = L/T which is the speed at which the waves move along the x axis.

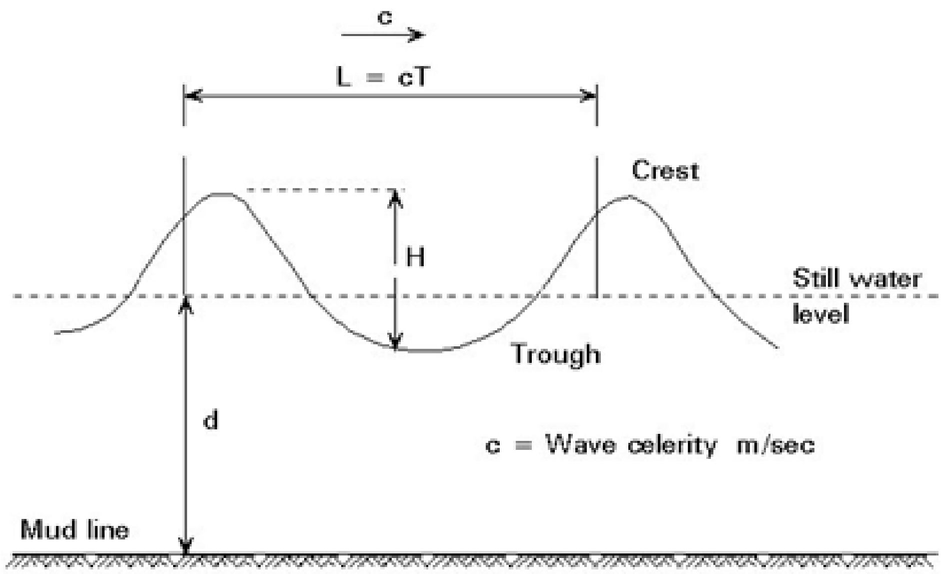


Figure 2 Basic description of a sinusoidal wave and its simplified properties (ESDEP, n.d.)

Pressure variation stimulated by wave motion

In deep water, waves can travel across ocean thousands of miles away and with minimal power loss, until their energy dissipates on distance shores. Ocean waves can be seen as an oscillatory system, in which water particles travel in orbits. As the water depth decreases, the oscillations become smaller. Close to shore, in shallow water, the ocean waves are influenced by the ocean floor, which results in a loss of energy due to friction of the water particles on the ocean floor, (Navarro, et al., 2007). This oscillation merely moves the energy within, Figure 3; this project has a focus in deep water.

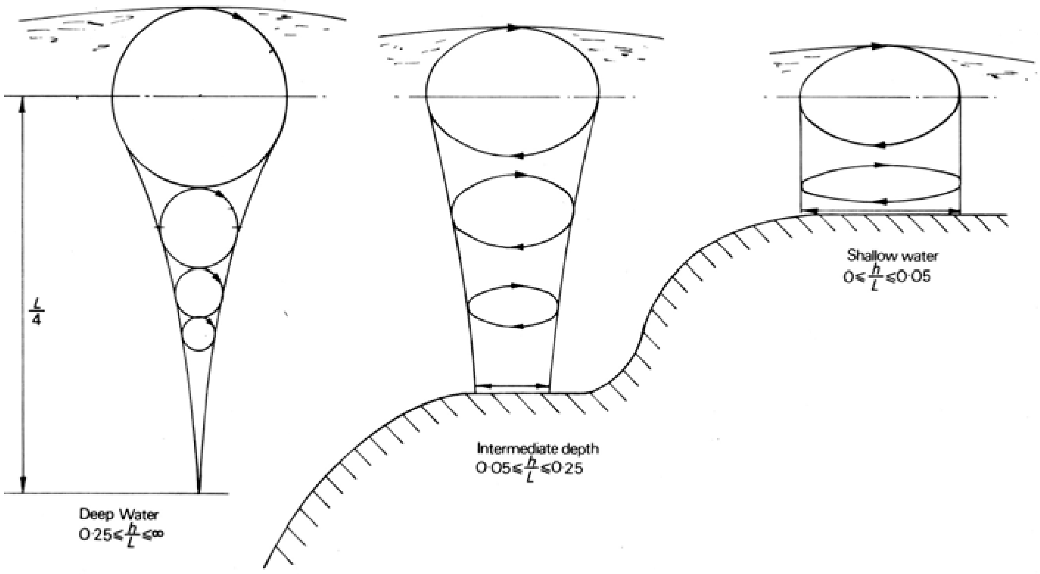


Figure 3 Particle displacements for deep and transitional waves (Navarro et al, 2007)

Influence of depth on wave characteristics

Deep water waves are found to be unaffected by depth and have little or no influence/ interaction on or with the seabed. These deep waves are expressed as:

For $\frac{h}{L} \geq 0.5, \tanh(kh \cong 1)$ this equates to $c_0 = \frac{gT}{2\pi}$

Thus deep water wave celerity and wave length are determined solely by the wave period T:

Shallow water waves are affected by depth and defined by the equation $h/L \leq 0.04, tanh\,(kh) \cong kh$

this equates to $c = gTh/L$ and further to on to $c = \sqrt{gh}$, where g is representative of gravity

Therefore for shallow water, wave celerity is determined by depth and not by wave period

Finally *Transitional waters,* where deep water waves begin to shallow and the effects of refraction and shoaling take effect, in other words the region between shallow and deep waters.

This intermediate area is expressed by $0.5 > \frac{h}{L} > 0.04$ where $\tanh(kh) < 1$ and therefore equates to:

$$c = \frac{gT}{2\pi}\tanh(kh) = c_0 \tanh(kh) < c_0$$

The latter two are neglected throughout this project. This application of wave theory allows the prediction the potential energy, which is applied to the power estimations within this project. An estimation of this energy across the world in presented in Figure 4.

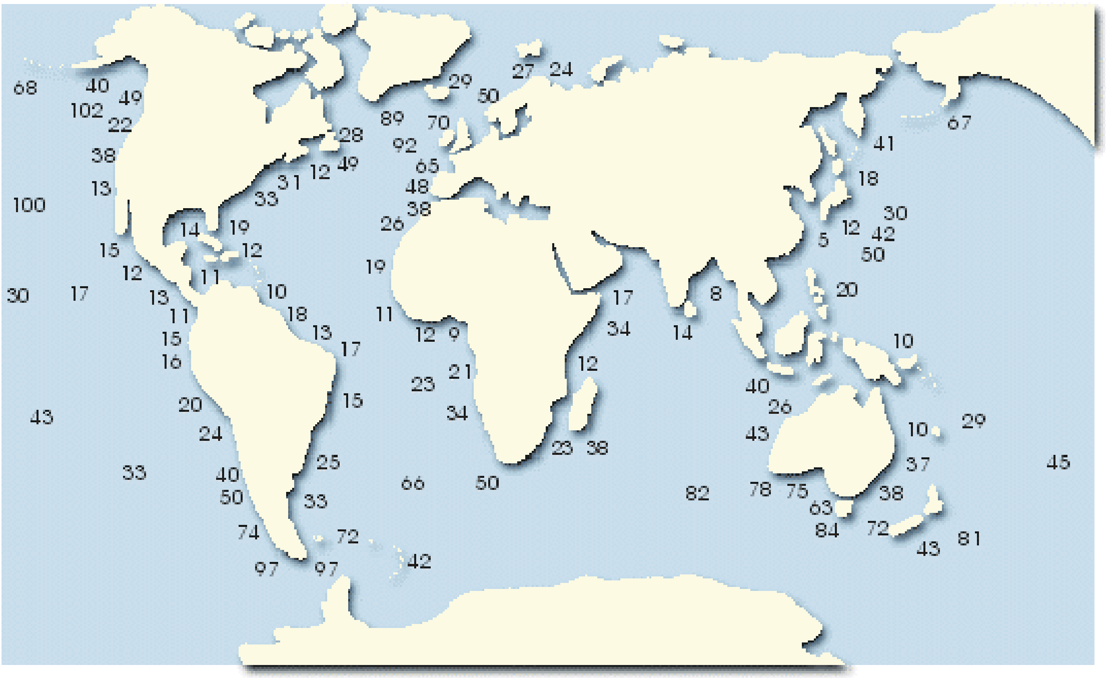


Figure 4 Annual average wave power densities worldwide in kW/m (AEEA)

As Atlantic Ocean waves propagate easterly over waters of decreasing depth, these waves are modified by a number of spectacles such as refraction and diffraction. This would provide a wave energy resource that can vary significantly over distances of 1km or much less, depending on local bathymetry, (Navarro, et al., 2007). Thus the energy is usually lower close to shore. However bathymetric conditions can also have a focusing effect on the waves, resulting in “hot-spots” close to shore.

Resource assessments are conducted to inform governing bodies through accurate and evidence based decisions how best to manage conserve and / or exploit their resource. Assessments can be conducted in numerous ways, each of which have their own pro’s and con’s, a number of assessment methods are discussed but a focus is pressed on numerical and wave modeling for resource assessments.

Resource assessments, but more specifically, wave resource assessments are conducted in order to gain an understanding of the regional and local wave climates with a view to extract available energy from the ocean waves. Analyses of wave extremes are important to allow accurate siting of wave farms. Survivability is also important in order to engineer these Wave Energy Convertors (WEC) to with stand extreme wave events.

Understanding the regional and local wave climates is of high importance to the modeling process, though long term changes in the wave climates cannot be accounted for – how will the resource change with climate change? – and will our wave devices / farms be in the wrong place in 20 years’ time?

The BERR Renewable Energy Atlas has quantified the resources for wind, tidal and wave, with annual and seasonal figures presented through a publically available and user friendly interface. Comparisons between BERR are discussed in Results and Discussion.

2.2. Methods of resource assessment

A brief discussion into the available methods used for resource assessments are presented. Numerical models are preferable and used widely. Primarily due to the low costs compared to other methods, such as:

Wave buoys (point measurement devices)

- Representative of only a small area
- Difficult to gain spatial information
- Limited deployment life
- Licenses are required for deployment
- Vulnerable to extreme conditions
- Expensive
- Require multiple deployments in order to achieve a representative data set

Lidar

- Global
- High resolution
- Mutli-decadal record
- Limited in its operating depth
- Expensive

Satellite altimeters (remote measurement devices)

- High resolution
- Expensive
- Generally only commercially available
- Detailed spatial information
- Temporal coverage can be sporadic

Numerical models

- Versatile, widely used tool for wave resource assessments
- Most existing assessments based on model data
- Different models, resolution, forcing, configurations
- Data is often expensive and commercial in confidence

2.3. Wave resource assessment

According to European marine energy centre report, (2009) there are two closely related but separate aspects of wave energy resource assessment;

1. Wave power which is available at a particular location at a particular time, including Information about its variability on short timescales (from hours to days). This can be assessed by making wave measurements at the position of interest.

2. Wave power climate at a particular location. The wave power climate includes the monthly, seasonal and annual statistics of wave power as well as a consideration of the variability of wave power on monthly, seasonal, annual and inter-annual timescales.

Research revealed the most current guidelines available, which provide up to date information on resource characterisation, numerical modelling, and statistical analysis for wave energy are Equimar protocols and guidelines. These are compiled by Commission of the European communities.

Equimar Deliverable 2.6; Extremes and Long term extrapolation outlines the process for assessing wave climates; this states that resource assessment can be divided into three stages:

- *Early stage* resource assessment where the resource characterisation process identifies specific regions suitable for a more detailed site assessment, taking into account seasonal and inter-annual variability.
- *Project development* where an assessment is conducted to outline detailed site characteristics for assessing the exploitable potential of the site.
- *Operation phase* which involves the assessment of the operating conditions facing in water devices.

A flow diagram presenting the stages of a marine project is presented in Figure 5.

The stage at which a resource assessment achieves is dependent on project time constraints, contractual agreements or sponsor requirements. Initial assessments simply outline zones of high energy concentration; further to this a more detail site specific assessment can be instigated to draw in on the project.

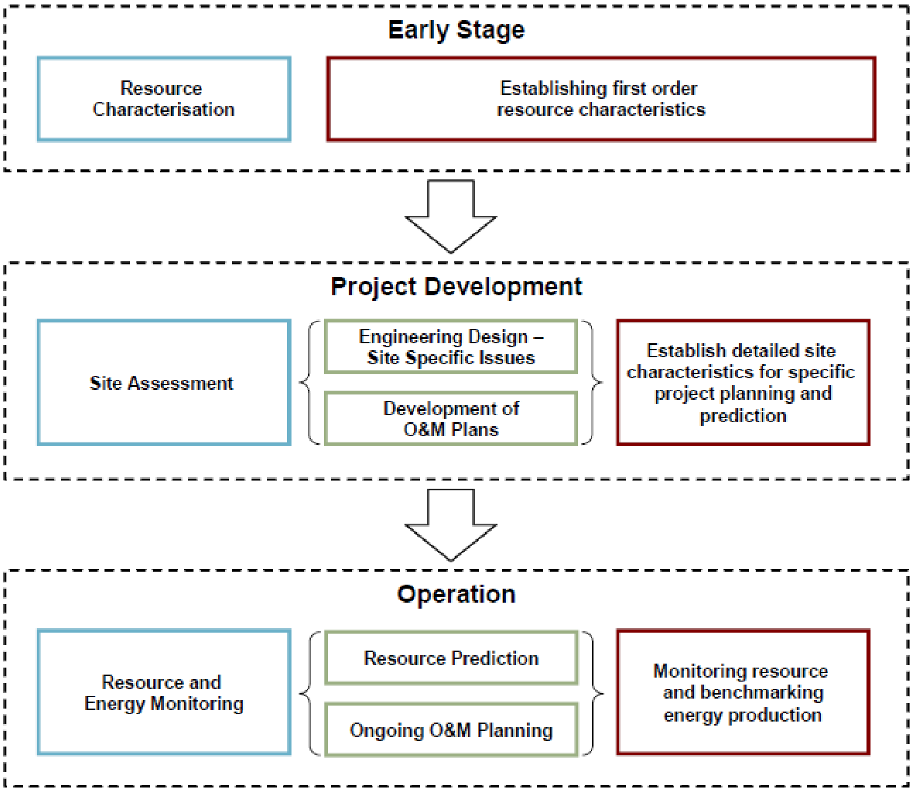


Figure 5 outlines the stages of a marine energy project and how the resource assessment will be incorporated during each stage

Outlined in the Equimar deliverable 2.7; Protocols for wave and tidal resource assessment**,** the three main drivers pushing wave resource assessments are:

1. Firstly Energy resource – to in steer confidence in project development.
2. Secondly engineering design – assessments on wave loading for design of moorings, site specific for various devices.
3. Finally Marine operations – wave / wind and tidal characteristics are required to predict installations and maintenance strategies and to provide information for designers, marine contractors, insurers, constructors.

The longer the modelled period, the better representation of local conditions will be present together both with annual and seasonal variability. Wave models are essential for wave resource assessment, but not on their own as confidence is required of in-situ measuring devices/products together with accurate data analysis. According to Mandal & Prabaharan, (2010), numerical models carry many assumptions, boundary conditions and simplifications of non-linear wave-wave interaction. Some aspects of wave climates are scarce in knowledge, like that of extremes, wave power continuity and long term changes, (Davey, et al., 2010). Therefore a more cost-effective and spatially extensive data source is required.

2.4 Numerical Models

Numerical models have a number of appealing qualities, for example - models can provide data across large geographical areas, but equally can cover locally refined areas over a significant period of time. The combination of wide spatial and long temporal coverage is generally not feasible by direct measurement (Davey, et al., 2010). Models appropriately validated against buoy or altimeter data, can provide highly resolved, and accurate wave data. If no buoy or altimeter data is available within the area of interest, then wave model data would be the most reliable form of resource assessment.

The amount of data available is dependent on cost and the time frame available. Only two years of data was obtained for this project. It is however, recommended that duration of ten years be used to provide the most accurate assessment of a region. A five-year period is thought to be considered satisfactory, however assessments based on a shorter period (two or three years) still provide a valuable estimate. (Navarro, et al., 2007).

Third generation wave models are considered nowadays the most appropriate for such a task, these are full spectral models based on the integration on the wave energy, or wave action balance equation, (Deltares, 2011). Furthermore these models solve the spectral action balance equation without any prior restrictions on the spectrum for the evolution of wave growth. See model set up, within Methodology Chapter.

Other examples of spectral phase averaging wave models are: Wavewatch III, Watershed assessment model (WAM), simulating waves nearshore, (SWAN) and Delft 3D.

Outputs estimate potential available energy to a degree, but encompass uncertainty while drawing on the numerous assumptions and constraints originally applied to the model. (See modelled limitations and assumptions in chapter 4.)

With presently available technology, sites of specific interest to marine energy convertors are generally focused in depths between 35 – 70 meters. Presently only the ‘Oyster’ device can operate in less than 35 meters. However, the device is not recommended to Guernsey RET as it operates in depths of approximately 10 meters, and given the ‘beauty spot’ that is Guernsey would be most visible from the shoreline.

Many sites of interest to the wave energy community are in relatively shallow water, near coastal communities. Models can be used to focus on specific sites and also to transform data from a well described deep water region to shallower regions. The deep water data may be based on physical measurements, like that of the National Oceanic and Atmospheric Administration (NOAA), or a validated global model like the UK Met office. The transformation process is intended to take into account factors such as, local bathymetry, wind and current.

2.5 Site Assessment

Site assessments are generally carried out prior to deployment of WECs, with a tenacity to obtain a detailed understanding of the local environment that a particular marine energy development will encounter. Once more, Equimar guides lines serve as a note to outline such assessments; they are, as stated by (Venugopal, et al., 2011).

- To assess the energy production throughout the life cycle of the project;
- To characterise the bathymetry of the site to an clearly specified and appropriate resolution;
- To determine the spatial and temporal variation of the resource with an explicitly stated degree of uncertainty;
- To describe met ocean conditions;
- To establish extreme (survivability) conditions with a defined return period;
- To identify potential interference between multiple devices at the site.

The reports from both Exeter University and Cranfield University outline extensively the constraints across Guernsey's jurisdictional waters. However, as knowledge of the wave energy resource gathers sites assessments must be carried out in depth. A full Environmental impact assessment is recommended prior to deployment.

2.6 Wave resource modelling

According to (Venugopal, et al., 2010), in order to accurately model any environment high quality information is required. Extensive research is the key; there are numerous freely available sources of bathymetry, wave data (directional and non-directional) and open source modelling software. However, selecting the most suitable and accurate data sets can be challenging and time consuming.

Further to this initial valuation, models can be directed to focus on particular areas, such as; device selection. The modelled area can be easily used to aid wave energy designers. This knowledge would allow an assessment of extreme events experienced at a specific site.

However simplistic the model maybe, they are also complex and contain numerous draw backs;

- Point measured local data can be scarce, limited deployments, as well accessibility can hinder investigations.
- Point measurement programmes are costly and time consuming.
- Most local point measurement programmes (directional wave buoys and ADCPs) provide only point measurements, thus not spatial.

Wave modelling has the main advantage of providing this spatially available data, to a degree of accuracy. Providing calibration and validation is conducted. This project uses the UK Met office WaveWatch III model for calibration and validation.

3. Study Area

Guernsey is a small island in the English Channel, located approximately 58 nautical miles south of the English coast and 26 nautical miles South West of Cherbourg Peninsula. The area of interest in this study is the Western Coast of the Island, where the highest wave action takes place. Resource characterisation is conducted within Guernsey's 3 & 12 nautical mile waters; Figure 6 outlines the potential jurisdiction that the island may govern out to that 12 nautical miles.

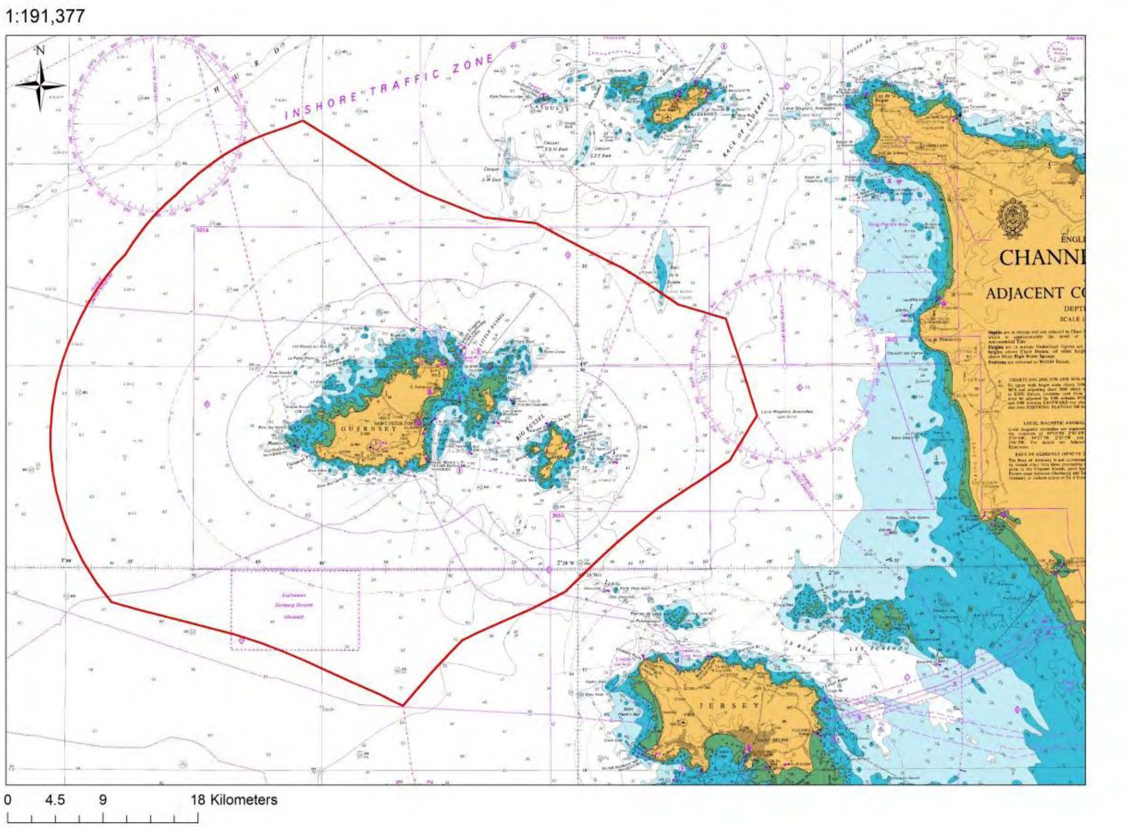


Figure 6: Potential jurisdictional waters of Guernsey out to 12 nautical miles.

The study area has numerous constraints that would hinder the deployment location of wave energy convertors. Like any other island nation goods and services are carried on the seas, together with the islander's use of local resources, numerous constraints exist. These are but not limited to;

- leisure activities and recreational users
- protections of the natural environment
- sub surface cabling
- shipping lanes
- scallop dredging

- explosive's ordnance disposal
- depth of surrounding waters
- physical environmental conditions (e.g. wave & tidal components)
- geological compositions

These constraints are also a hinder to tidal and wind turbine sites. A more in depth study regarding constraints and mapping surrounding the island would direct the reader to an associates report; James Sutton, University of Plymouth, called 'Identification of Minimum Impact for Offshore Wind Energy Sites in Guernsey's Territorial waters' sites but also Guernsey Renewable Energy commission; Pre-feasibilty Technical Report, (Halcrow, 2009).

Within the study area, data can be extractable anywhere within the jurisdictional limits of Guernsey's waters. See Chapter 4 for data calibration and accuracy limitations of the model and their outputs. The complexity of the issues associated within the study areas are vast and out of scope with in this report. However they are addressed briefly when identifying three suitable locations for further analysis. Cranfield University report, (2011) and the Exeter University report, (2012) address the issue of limitations surrounding the island in more detail.

Further to this a report by Guernsey's Renewable Energy Team (2011) compiled a report, 'The Environmental assessment of marine energy', and outlined all the (Sutton, 2012)potential environmental issues that would be associated with the exploitation of marine renewables.

Surrounding the island, water depths exceed 100 meters, 18 nautical miles to the North West coast, 60 – 75 meters within 12 nautical miles to the west. The waters within 2km of Guernsey's coastline are considerably shallower in comparison, with a range of less than 15 meters. The bathymetry of the region is very important, current devices are limited in location by their foundations and mooring design. The bed rock and superficial layers also influence the choice of devices, in addition anchoring systems carry a significant cost with them, and thus an accurate geological assessment is of importance and should be considered when investigating and assessing the viability of high energy zones.

4. Methodology & Resource Assessment

4.1 Software Used: Delft 3D module

With available expertise within the University of Plymouth, time frame for learning and competently modelling the selected environment and assessing various other numerical modules, Delft 3D was selected.

To simulate the evolution of wind-generated waves in coastal waters, which can include estuaries and tidal inlets, the Delft3D-WAVE module was used. The wave module of Delft3D computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation, over a given bottom topography, water level and current field. This can be for waters of deep, intermediate and restricted depth, (Deltares, 2011).

At the time of writing Delft3D (as stated in Delft3D-WAVE_User_Manual) incorporates two wave models (both of the phase-averaged type). They are the second-generation HISWA wave model and its successor the third-generation SWAN (Simulating WAves Nearshore) wave model. SWAN has a number of advantages compared to HISWA and according to their creators, also overcomes the limitations of the HISWA model, these include:

- Fully spectral in frequencies and directions (0^o – 360^o)
- Wave computations are unconditionally stable due to fully implicit schemes
- The computational grid in SWAN does not require to be oriented in the mean wave direction, therefore handling all wave directions
- Varying resolution can be achieved by nesting grids within the main computational grid
- Outputs can be generated in terms of one - and two-dimensional wave spectra in SWAN

The SWAN wave model was used and is currently the standard option within Delft 3D.

Furthermore, as Delft can use Cartesian or spherical co-ordinates within its models, the spectral action balance equation for small scale applications may be expressed below, (SWAN, 2012). This equation was used to resolve the computations within the model.

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}$$

4.2 Setting up the model

In order to drive the model, extensive research was conducted to gain an understanding of the local and regional climate. Dominate wave and swell directions where evaluated. A focus on the physical processes surrounding the Channel Islands was also explored in order to establish the optimal location for the model boundarys.

4.2.1 Boundary limits

Obtaining wave data suitable for the project was of primary concern, data available from various deployed wave buoys and governing bodies were investigated. Data was found to be available from two presently deployed observation sites. Firstly the metrological monitoring buoy “Channel Ship light vessel” (Station ID: 62103) was investigated, this vessel is geographically situated approximately 29 nautical miles North - Northwest of Guernsey. Data was extracted for 10 years but was found not to contain any ‘directional’ wave parameters and was thus unsatisfactory for this project. The directional aspects of each wave are key; like wind, where the waves come from is of importance. This allows the accurate positioning of the model boundaries and device alignment. Furthermore the light ship vessel was in an unsatisfactory position for accurately assessing Guernsey’s wave climate, as it was located too far north.

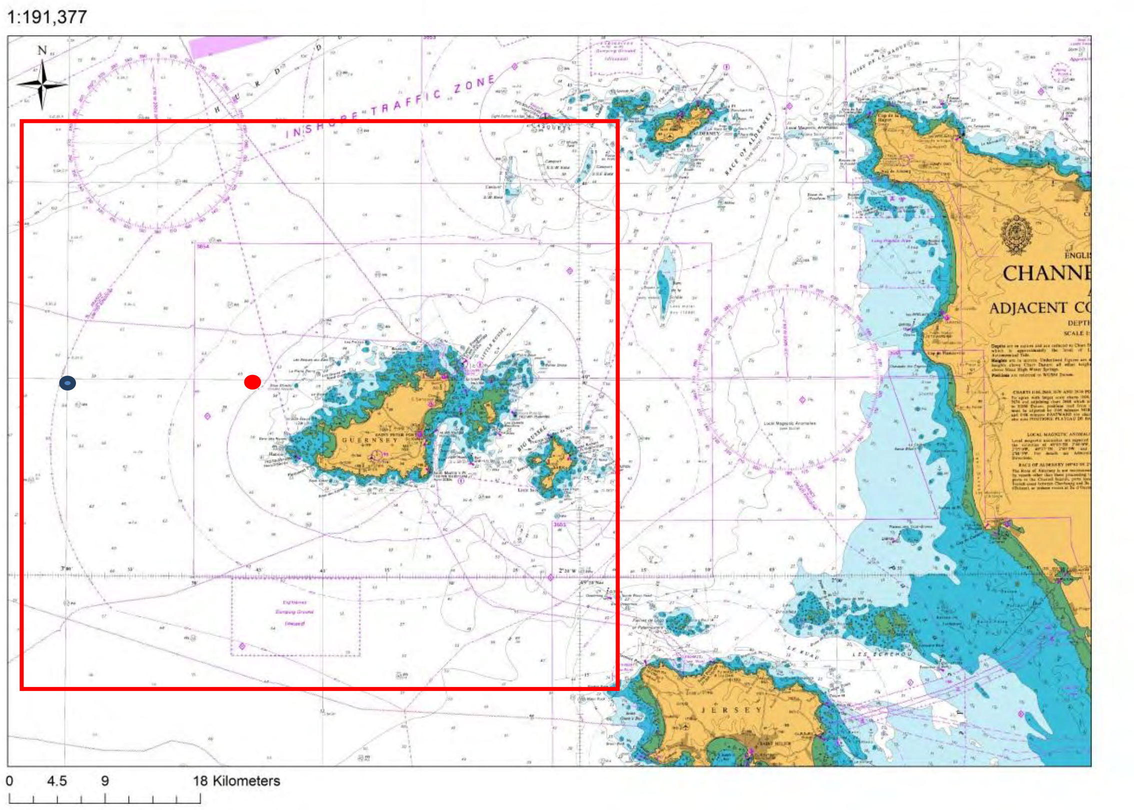
The second buoy was located 5 nautical miles South of Jersey Island (Station ID: 62027) and directional wave data was obtained through Jersey’s Met office for two years (January 2010 – January 2012). The data though directional, was also deemed insufficient to drive the model. This was due to location; the distance from the model boundary to the Jersey buoy was too far to propagate the waves to a sufficient level of accuracy, however it was considered as a validation point within the model itself. A one month validation model was run to assess its suitability; the correlation achieved a R^2 value of 0.46 for significant wave height H_s. This relationship is too low to provide a realistic relationship for a resource assessment.

Numerous other sources of wave data were also explored, for longer available periods and for in-situ wave buoy data - UK's Channel Coast Observatory, National Oceanic and Atmospheric Administration (NOAA), Guernsey's RET, UK's Met office and a number of French contacts through Guernsey's RET, like Lfremer (French Research Institute for Exploration of the Sea).

Taking into account the available funds, the UK Met office was contacted and directional wave data was freely extracted from their Wave Watch III NAE Model at Latitude: 49.530, longitude: -2.940 ,depth: 77m at 3 hourly intervals for the periods 1st January 2009 – 31st December 2011.

Times series directional data was also extracted from the same model at grid point latitude: 49.530 longitude: -2.770 depth: 66m for the same period. This location would be used within the computational grid to provide a validation point for an accuracy assessment against the model outputs, mainly H_s, T_p and Direction.

Figure 7 presents the locations where these extraction points exist in relation to Guernsey Island. Simple the' Blue dot' provided data to drive the model and the 'red dot' was checked against UK model data for accuracy.



4.2.2 Model inputs

Figure 7 Showing locations where data was extracted from the Met office WaveWatch III model (red – validation data & blue – driving force data) and the modelled area around Guernsey

Data supplied from the UK Met office model point is situated approximately 12 nautical miles from Guernsey Island. The boundary grid is 15 nautical miles away. The close distance and similar water depths provide sufficient reason to extend the model input location out to the boundary location.

4.2.3 Directional descriptions

Dominate wave and swell directions were researched to determine boundary conditions and local physical processes. Analysis plots show the boundary grid/orientation is sufficient to allow an accurate assessment of the selected climate, see Figures 8 and 9.

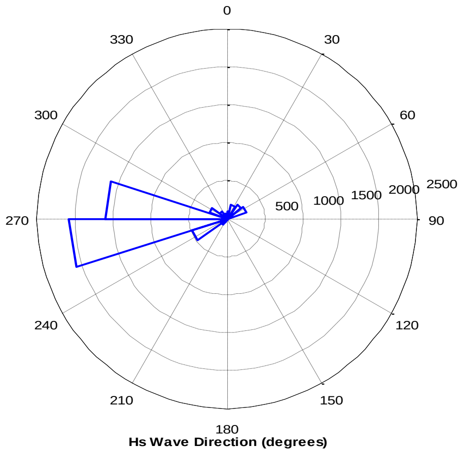


Figure 8 Rose diagram showing Hs wave direction at the offshore model boundary from the Met office WaveWatch III model

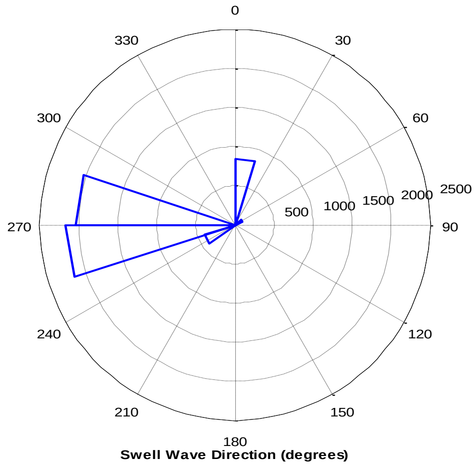


Figure 9 Rose diagram showing swell wave direction at the offshore model boundary from the Met office WaveWatch III model

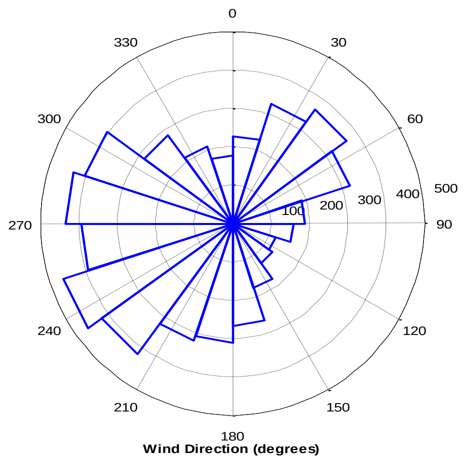


Figure 10 Rose diagram showing wind direction at the offshore model boundary from the Met office WaveWatch III model

4.2.4 Influence of wind

Delft3D can accommodate wind as a parameter within its computations. This physical input is seen to increase the run time of the computations, while also expecting an increase in wave heights in the open ocean. In addition, as seen in Figure 8 is also multidirectional surrounding Guernsey.

The majority of the wind is received between 215^0 – 310^0, leading to the wave, swell and wind directions feeding Guernsey waters to be west/south westerly. A trend expected in this geographical location, due to the close proximity of the Atlantic Ocean. Equimar protocols (Prevosto, 2011) state that the inclusion of wind always be included in detailed modelled studies where possible. However, if accurate data is scarce, a constant wind condition should be applied across the modelled area.

The use of directional wind as a parameter within this model was found to have no effect on significant wave height or period for any of the validations runs. Furthermore a constant wind, taken to be the mean wind speed and direction over the 2 years was applied to the model. However, once again no significant change was observed. In order to speed up the computations, wind was neglected as a parameter for final model runs.

4.2.5 Bathymetry requirements

Bathymetric data should provide a high enough resolution to resolve the appropriate seabed features, the stage of the project is also of concern. For early stage modelling, coarser resolution bathymetry (~1000–5000m grid spacing) will be acceptable (Venugopal, et al., 2010). For more detailed modelling for project development and operation over smaller geographic areas, the minimum grid resolution shall be 500m. The grid resolution for this project was resolved at 1,100 meters, which was the highest resolution obtainable with the resources available.

Obtaining the highest available resolution bathymetry proved to be a challenge. In the UK - Marine Digimap (Sea-zone) was explored but gridded bathymetry for the Channel Islands did not exist, and the gridded bathymetric data in the Sea zone tiles effectively stops at the international waters line. This means that with the available resources I had, the Channel Islands fall within the 'no data' area of the tile in Sea-zone. This was verified through personal communication with their support team.

30 arc second bathymetry is available through GEBCO but the scope of the project required higher level data. Further research unveiled data from EMODnet Hydrography where a grid size of .25 minute * .25 minute is available, geodetic system for the grid is WGS84. This 15 arc second bathymetry was extracted for the area covering the English Channel and was deemed adequate for deep water assessment. The downloaded data set was referenced to chart datum, further data manipulation took place in Matlab to correct the sea level from lowest astronomical tide to mean sea level (5.06m was used as per St Peters Ports).

The EMODnet Hydrography Portal data was found to be sufficient for offshore resource assessment but the shallower waters (<20 meters) surrounding Guernsey needed to be of higher quality in order for Delft3D to accurately resolve its computations. For this Hydrospatial - elevation & bathymetry files were selected from Marine Digimap, these shape files where manipulated using ARC GIS into rastor files and then further onto point files. These point files then contained depth values; Figure 13 shows the refined high resolution bathymetry surrounding Guernsey's shallow waters presented through Matlab.

Using Delft3D boundary grids where created and merged with bathymetric data, these boundaries would provide the bases on which the resource characterisation would build; Figures 11 and 12.

It should be noted that in later validation runs the high resolution bathymetry was neglected for the main two year runs. This decision was based on the offset surrounding contours between the two bathymetric files. Different bathymetric files set bands of where each contour lies, the EMODnet data and shape files did not overlap with the correct contours. This would provide an inaccurate assessment of the wave propagation; furthermore the depths the high level bathymetry covered were all shallower than 25 meters, an area unfeasible for wave energy but also an area that is too close to close to shore.

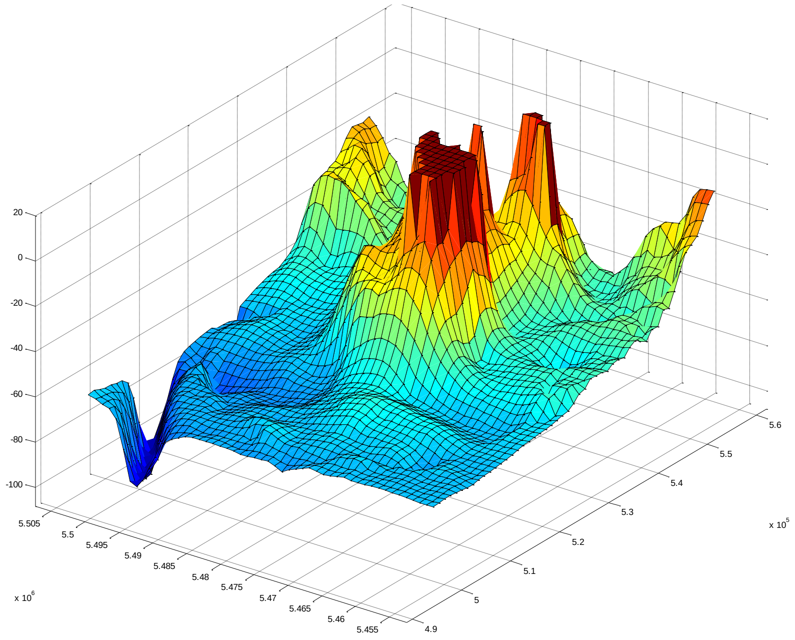


Figure 11 Main grid merged with bathymetry at a resolution of 15 Arc seconds

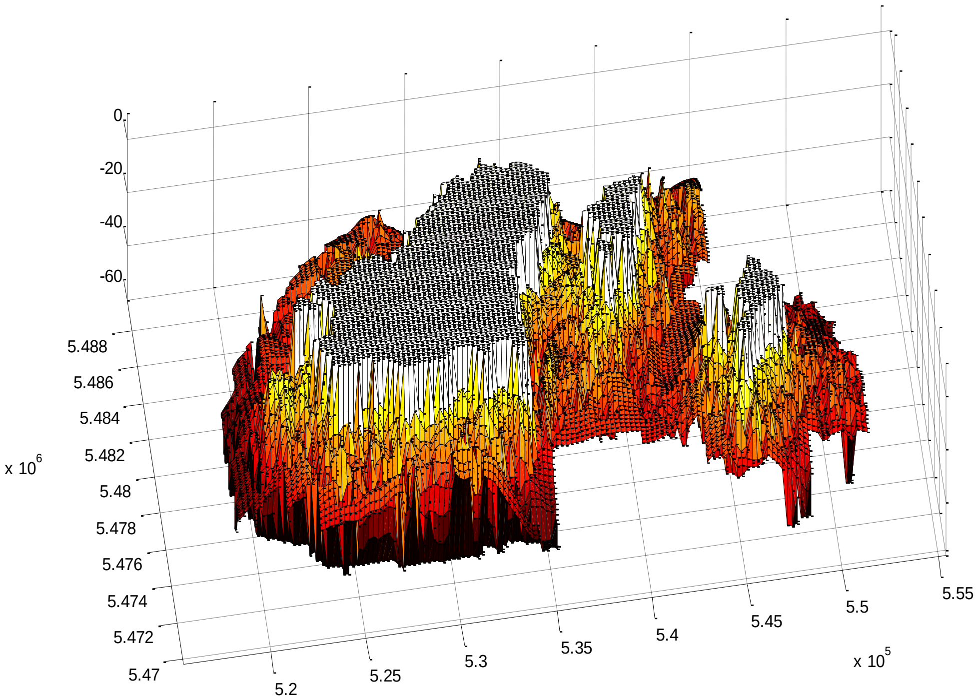


Figure 12 High resolution bathymetry formed from Marine Digimap shape files

4.2.6 Sea floor composition

For the project, the geographical make-up of the sea floor surrounding Guernsey's waters was not taken into account and assumed to negligible. Different rock strata have varying effects on waves as they propagate over the sea floor. It is suggested however that this consideration would be applied in the site specific assessment, especially for mooring design.

4.2.7 Influence of tides and currents

Given the scope of the project and the time constraints associated with such a project, interactions with a tidal model were ignored. This process would drastically increase the model run time and complexity. The effect of such a process would potentially see the wave heights and available power reduce. This would be most noticeable in the shallows, in areas of high velocities, like to the East and South West of the Island, as seen in Figure 14. This collaboration would be suitable for a further MSc Project. (See Chapter - Further research)

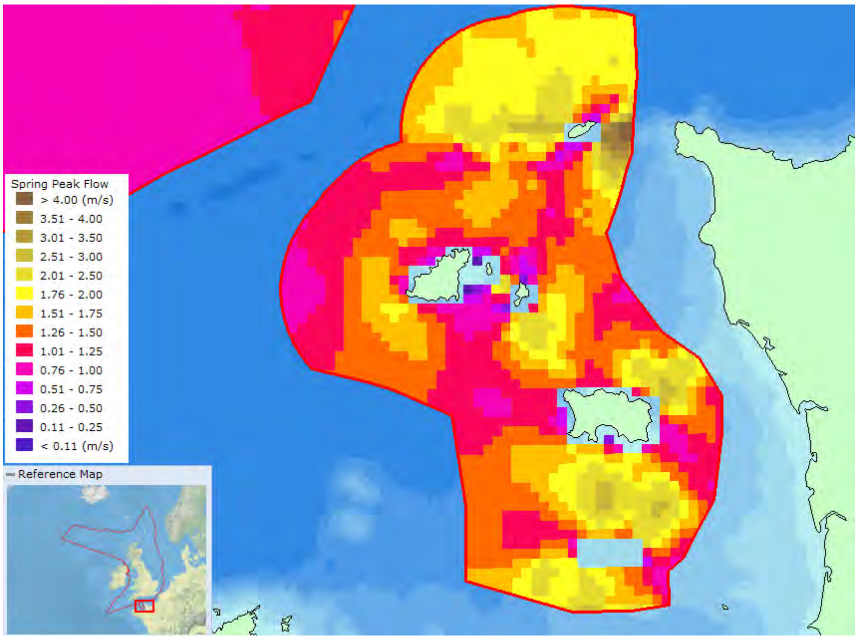


Figure 13 Spring Tidal velocities surrounding the Island in meters per second, (BERR, 2011)

The importance of tides at a given location is determined by the local tidal range and the water depth. In deep water areas, change of depth due to the tide will be unimportant and tidal data may be excluded. However, in intermediate and shallow water regions ($d < \lambda/2$) where the tidal excursion may modify the depth by more than 5%, (Prevosto, 2011) (and – remove word) should be included. Similarly it is also recommended that currents be introduced; if the velocity is greater that 2-3% of the local group velocity of the dominant waves.

Finally, a separate project solely concentrating on the tidal aspects of the waters surrounding Guernsey was undertaken by Sarah Bedingham (University of Plymouth) called: ‘An assessment of the Tidal Resource of Guernsey’ at the same time. A project combining both wave and tidal models to assess the interactions amongst both parameters would be of significant value and therefore advised. Such a project would be most beneficial if directional wave buoy data was also made available.

5. Model Calibration & validations

In order achieve the highest outputs from the model, validations runs took place. Firstly comparisons between significant wave heights (H_s) at the validation point were conducted; Figures 14 and 15. The statistical properties of R^2 and root mean squared error (RMSE) would assess the correlation of the compared values. This correlation assesses the suitability of the model created, ensuring the most accurate resource assessment.

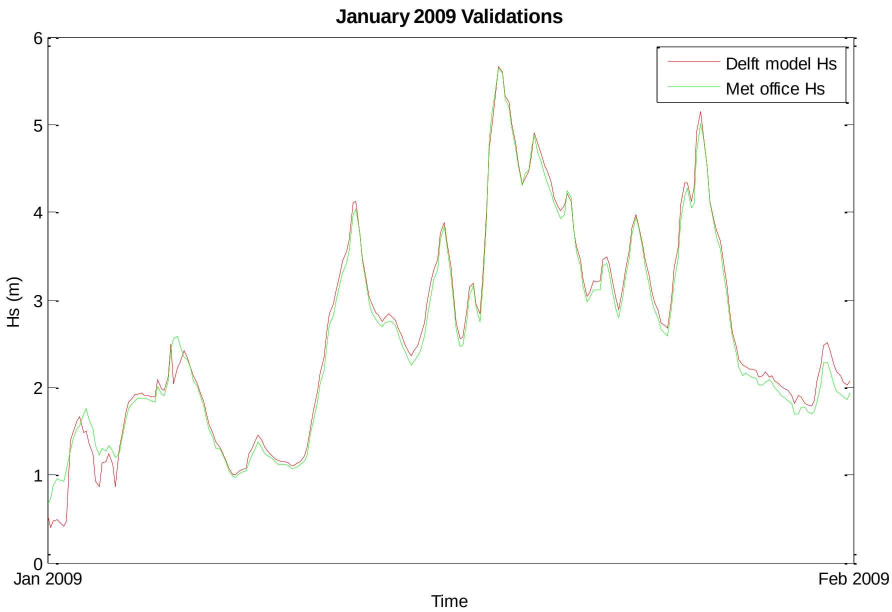


Figure 14 Wave height (Hs) validation for Delft3D model (JONSWAP spectrum, directional spreading of 10°) over 1 month time period (3 hourly data intervals)

Initial observations of Figure 14 show a close relationship between the Met office UK data and Delft3D output data. A RMSE value of 0.12 further confirms this correlation. This value represents the error between that of the two compared data sets. In this case, the value is the error, in meters, between Met office UK and Delft. This small error value is considered excellent for a numerical model.

Comparisons between Peak period was also conducted, to further confirm the models suitability. Figure 16 shows a similar correlation to that of H_s.

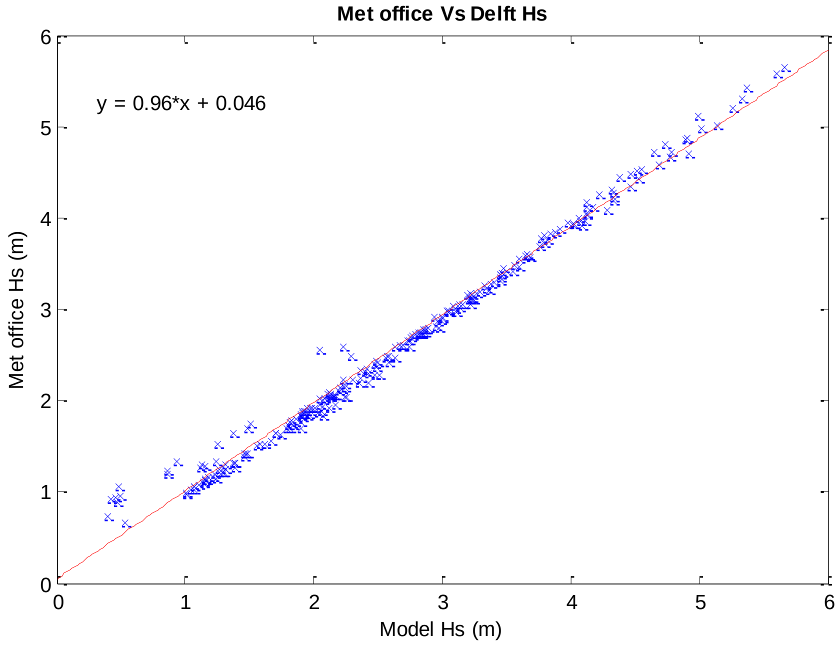


Figure 15 Linear regression analysis of measured and Deflt3D model Hs at the validation point R^2 = 0.98 (Red trend line).

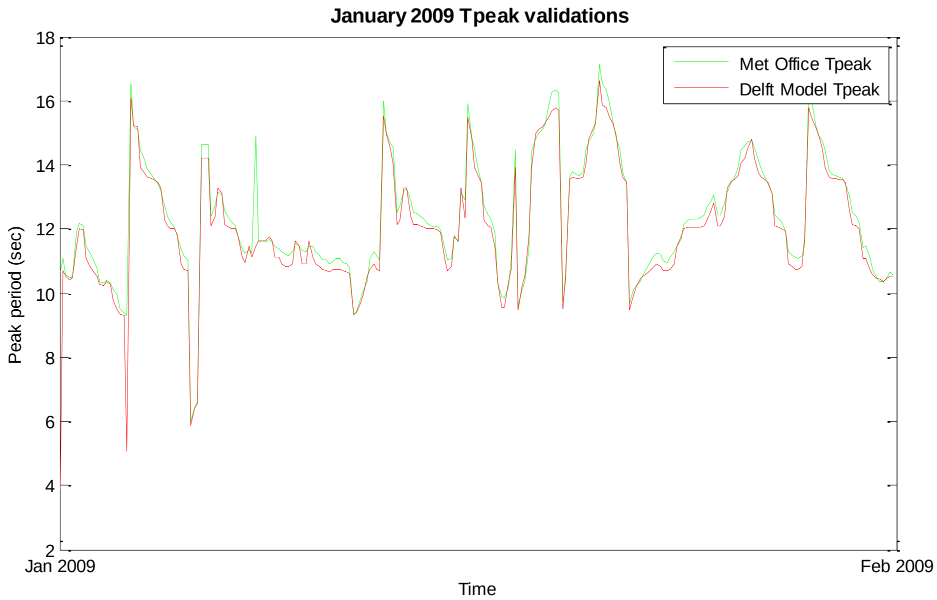


Figure 16 Peak period (Tp) validation for Delft3D model (JONSWAP spectrum, directional spreading of 10^{o}) over 1 month time period (3 hourly data intervals).

The relationship between the model hind cast data and Met office UK data achieved a R^2 value of 0.96 for one month validations, thus drawing a conclusion that the driving force of the model input location supplied from the UK Met office is well correlated with the wave climate surrounding Guernsey and outputs from the model can be assumed to give a good representation of conditions surrounding Guernsey's jurisdictional waters.

In addition numerous models simulations assessing the most suitable directional spreading value revealed no difference; values ranged from 5^0 – 30^0, whereby the higher value the more realistic the sea sate. Simulated spreading models revealed no difference between values and hence a directional spreading value of 10^o was selected due to good correlation and to increase the run time of the model.

Similarly runs were conducted with the influence of wind. Each 3 hourly data point had wind direction and speed; no significant change was seen in wave height (H_s) or period (T_p) and was therefore discredited, Figure 17. Furthermore a constant wind imposed across computational grid also revealed no substantial change. It should be noted that the data obtained from the Met office UK model would have had wind as a driving force. Point measurement validation would be the only method of fully insure the models accuracy. From this it is recommended that a wave buoy be deployed west of the island.

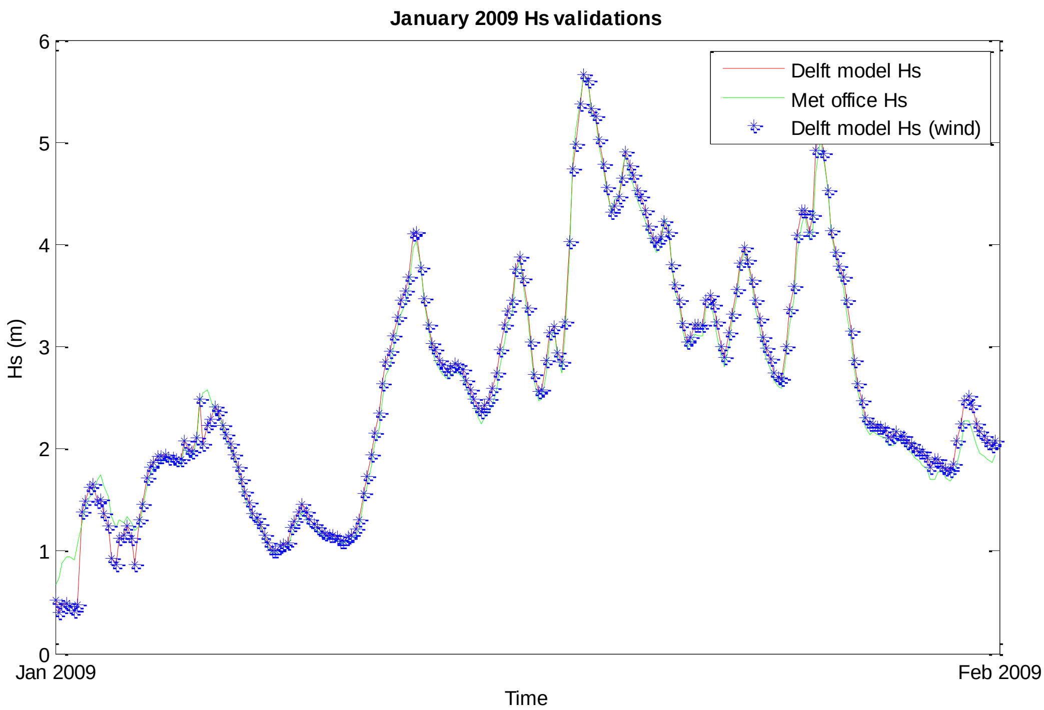


Figure 17 Wave height (Hs) validation for Delft3D model using the influences of wind (JONSWAP spectrum, directional spreading of 10^o) over 1 month time period (3 hourly data intervals)

With successful one month simulations, one year data runs where conducted for year 2009. Similar trends were experienced over the 1 year period for significant wave height (H_s) values and peak periods (T_p), Figure 18 and 19.

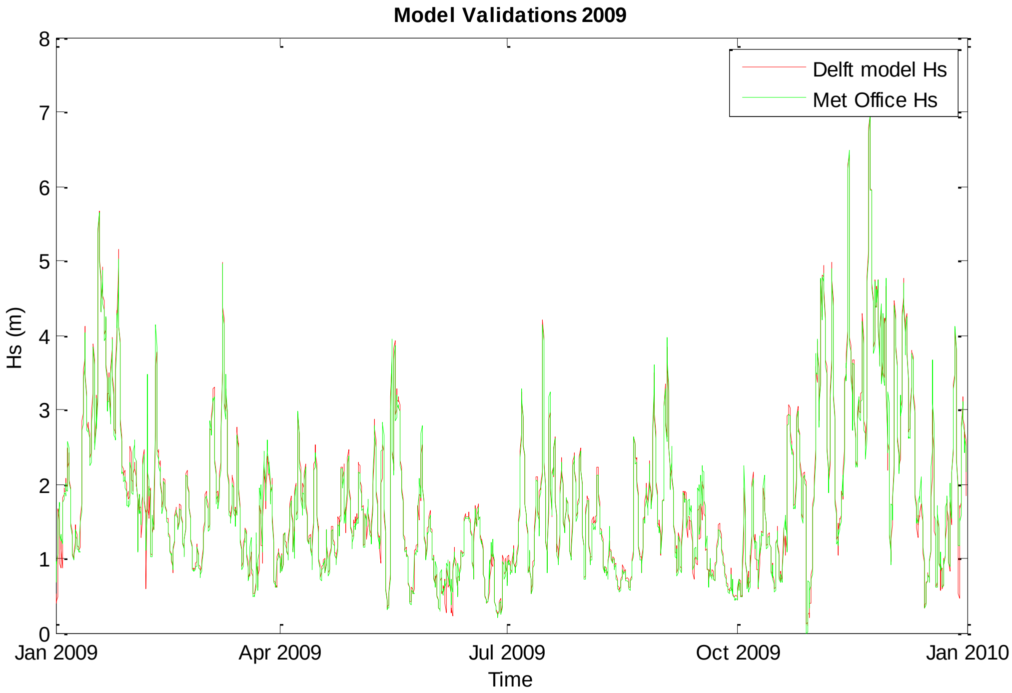


Figure 18 Wave height (Hs) validation for Delft3D model (JONSWAP spectrum, directional spreading of 10°) over 1 year (2009) time period, (3 hourly data intervals)

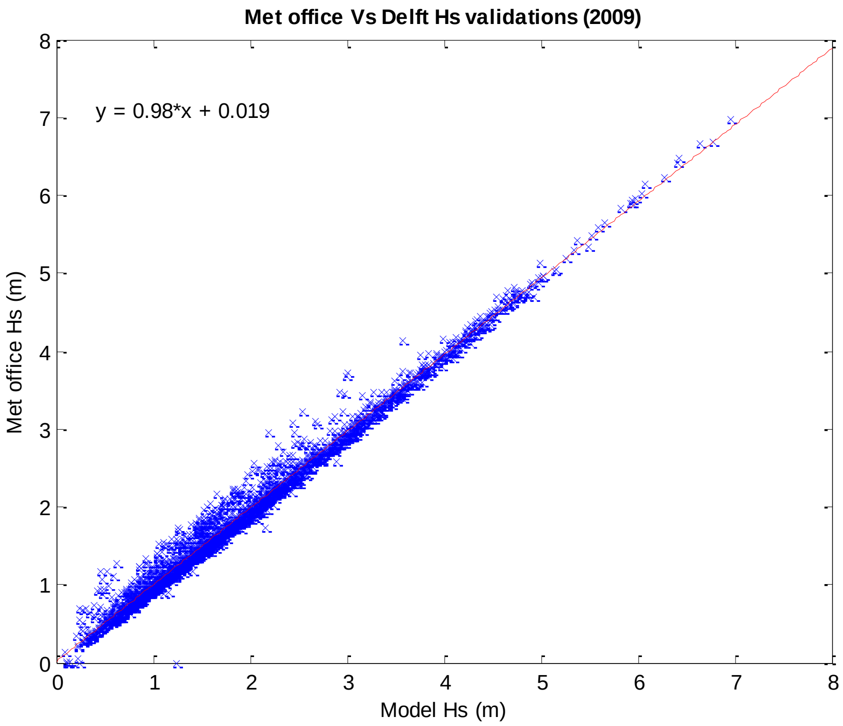


Figure 19 Linear regression analysis of measured and Deflt3D model Hs at the validation point for 1 year (2009) R2 = 0.98 (Red trend line), (3 hourly data intervals)

Similar to one month validations, the alignment between the two models is very accurate. A RMSE value of 0.11 further confirms the correlation. The one year validation run provided higher correlation, with both R^2 and RSME values increasing in accuracy.

Finally two full years of three hourly data was introduced within Deft3D for the periods - 1st January 2009 – 31st December 2011. Given the only validation point obtainable was in deep water it is assumed that data within these category is of sufficient accuracy, thus suitable for further analysis. However, locations within shallow water and within the wave shadow of the island are of somewhat inaccurate. It should be noted that within numerical models, waters shallower than 10 meters are very difficult to resolve the computations, and would therefore be an unrealistic source of data within the modelled area. In addition, no validation data is available within these locations.

5.1 Model limitations

The model does however have limitations. Firstly a constant water level was set which did not account for local tidal ranges and currents. Secondly water levels were set to mean sea level, as per St Peters port. This set the sea level for the entire modelled area to be at a mean water level, based on the local geographical properties.

Furthermore, the bathymetry used has restrictions; marine hydro space gridded bathymetry was used, which has the best available resolution. The bathymetry used was sourced from two data sets; firstly a high resolution bathymetry dataset from Marine Digimap shape files, as previously stated is point data and the only data found to be available for this project. The bathymetry used for the deeper waters (> 20 meters) surrounding Guernsey's coast is of 15 arc second resolution (grid size) and has been smoothed to increase the model efficiency. As the study site, and wave propagation is fed from the west coast, this will have no effect on wave propagation at this location.

Furthermore there are no wind parameters introduced into the model, the effects of wind would see an increase in wave height but only by a small factor. Preliminarily results from validation runs showed no increase or decrease in wave height (H_s) with wind (Figure 17) and was thus disregarded.

Diffraction was also neglected; this process can cause the model to be unstable. Delft3D uses numerical diffusion by default, which is a more efficient process for use in wave models. Using numerical diffusion will provide a computationally more efficient model and will therefore reduce run time which is a constraint given the scope of the project.

Finally the project had cost limitations where only publicly available data was used and is not as accurate as information directly source from the companies involved, however the project is the first high level resource characterisation of Guernsey's waters and thus the foundations on which further, more accurate assessments can be carried out.

6. Data Analysis

Following the completion of the model runs, analytical methods where discussed. In order to describe various sea states and to determine their characteristics relevant to wave energy utilization, the statistical parameters derived from the wave energy spectrum must be used. Sea states are often summarized in terms of wave height, period and directional parameters.

The spectral parameters used in the characterization of wave energy resource are the significant wave height H_s, energy (mean) period T_e (and spectral peak period T_p), mean direction and wave power level (P; i.e., the flux of energy per unit length of wave crest). For the following calculations, H_s is assumed to be the same as H_{mo}

Wave power analysis

Wave power levels at each location have been calculated using model outputs of significant wave height (H_s) and mean zero-crossing period (T_z) over the two year period from January 2009 – December 2011. An estimation of wave energy period (T_e) can calculate directly from T_z using Equation 1.

1

$$T_e = 1.162T_z + 0.3285$$

This relationship has been identified in (Davey et al., 2010) using calculations from spectral data at the wave hub site calibrated with physical measurements. Wave power is then calculated using the Airy wave equations (Reeve D et al., 2012), as the ratio of water depth to wavelength (h/λ) is greater than 0.5 at the validation site, but also in all areas identified for further analysis. All power estimates are assumed to have no intermediate or shallow water effects on the wave energy.

To calculate wave power using deep water approximations the total wave energy per unit crest and the wave propagation speed or group celerity must be calculated from H_{m0} and T_e (Eq.2 & 3).

2

$$E = \frac{pgH^2}{8}$$

3

$$C_g = \frac{gT_e}{4\pi}$$

Wave power per unit crest can then be calculated from Equation 4, therefore Equation 5 shows that wave power may be calculated directly from H_{m0} and T_e, assuming p = 1025 Kg m^{-3} and g = 9.81 m s^{-1}.

4

$$P = EC_g$$

5

$$P = \frac{pg^2}{32\pi} H_s^2 T_e$$

Using the above method, power per meter squared was calculated at the validation point. All power estimates assume no intermediate or shallow water effects on wave energy.

It should be noted that the calculations executed, as presented above, only produce the available energy and power. In order to calculate the power delivered from a wave energy device, the device power matrix is required. For the purposes of this study, the freely available Pelamis and Wave Dragon power matrixes will be used.

7. Results & Discussions

7.1 Power density map of Guernsey waters

Analysis of modelled data is complex; there are numerous locations at which power estimates could be conducted. In order to select the most suitable sites which will allow a more in depth assessment of power, which will be discussed later on; the following will be discussed throughout this chapter:

- Overall mean power density (kW/m) surrounding Guernsey
- The most energetic zones around the island
- Current marine renewable industry constraints
- Conflicts associated with the waters around Guernsey
- Predicted power from installed WEC's at each selected site
- Uncertainty of those power estimations

The overall available mean power density, which covers the modelled area, is displayed in Figure 20. This presents the most energetic zones surrounding the island by assigning a mean power value, calculated from the two year period. In order to achieve this plot, H_s and mean period T_m were extracted for each of the 2,500 points within the computational grid. Mean power was then calculated at each point, using the equations discussed previously, and the result was a mean power estimation map surrounding the island.

The map was created in ARC GIS, using Jenessant repeating shapes toolbox; each box was then assigned a value. First observations clearly outline that the most energetic zones are to the west. This was expected, given the influencing conditions prevailing from the Atlantic Ocean, also to the west. Furthermore rose plots, Figures 8 and 9, presented dominate swell and waves from a westerly direction, further confirming the highly energetic environment to the west of the island.

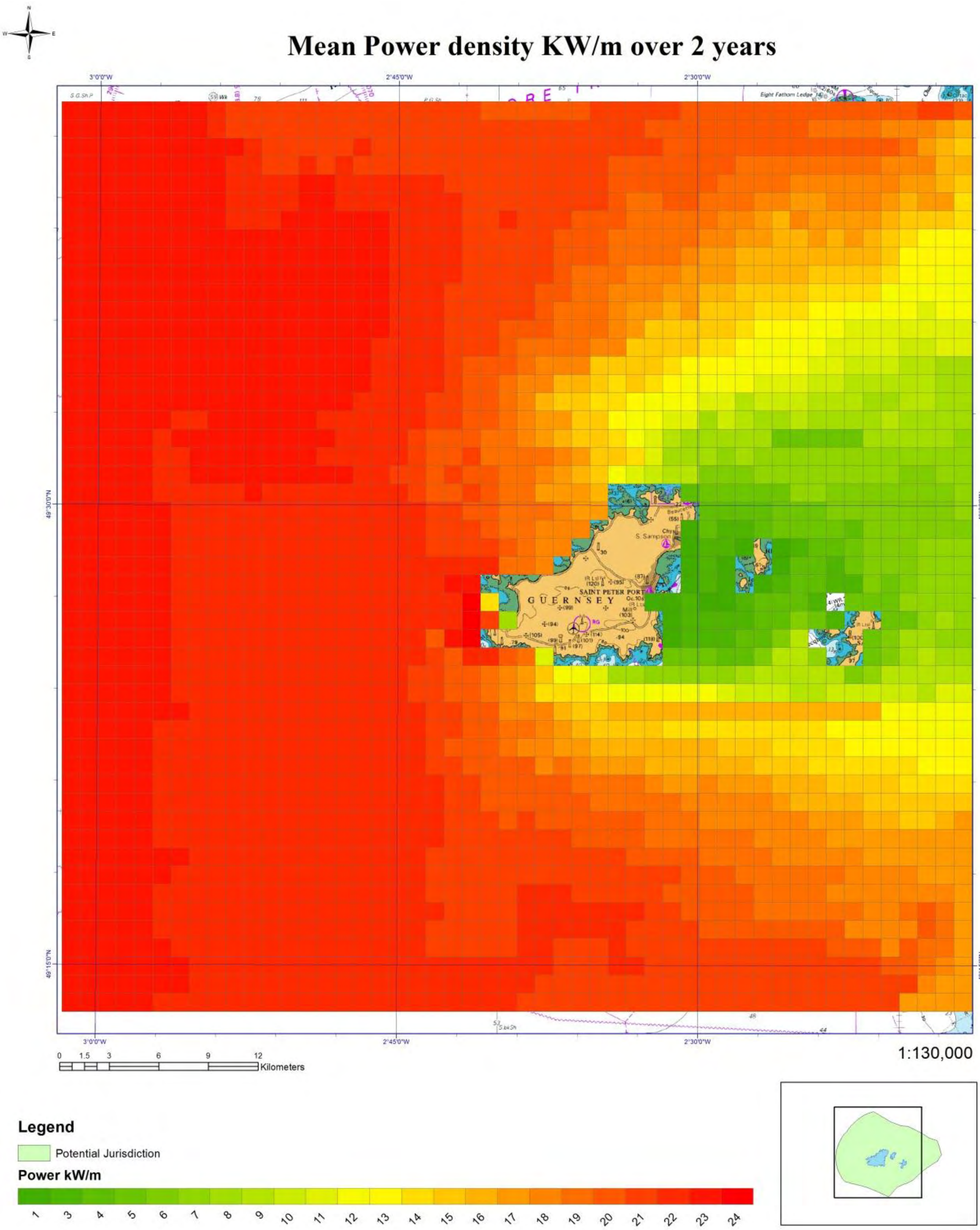


Figure 20 Mean power density (kW/m) surrounding Guernsey, as per the modelled area

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A closer look outlines the highest density of 23 kW/m blocks to be located north west of the island. A secondary location with similar, but not as dense, is directly to the west. Both locations are clearly visible in Figure 21.

Furthermore a third location, which is also the area where the highest mean value of 24 kW/m is observed. This is located just west of Hanois, near Pleinmont point and believed to be associated with close proximity of the depth contours, allowing for waves to gather energy over a short distance and time. Attention is also draw to Appendix B, Figure 42, where a wave height of approximately 5 meters propagates over the modelled area. It shows an increase in wave height at the same location, further confirming of the accuracy surrounding Figure 20.

It should be noted that the map is geo-referenced; the distortion surrounding the merging of the island with the power map is due to the resolution difference. The base map of this map in an Admiralty chart and Delft3D uses a much lower resolution grid, as previously discussed. However the map merely informs Guernsey's RET on where future investigations should be directed, in order to verify these findings.

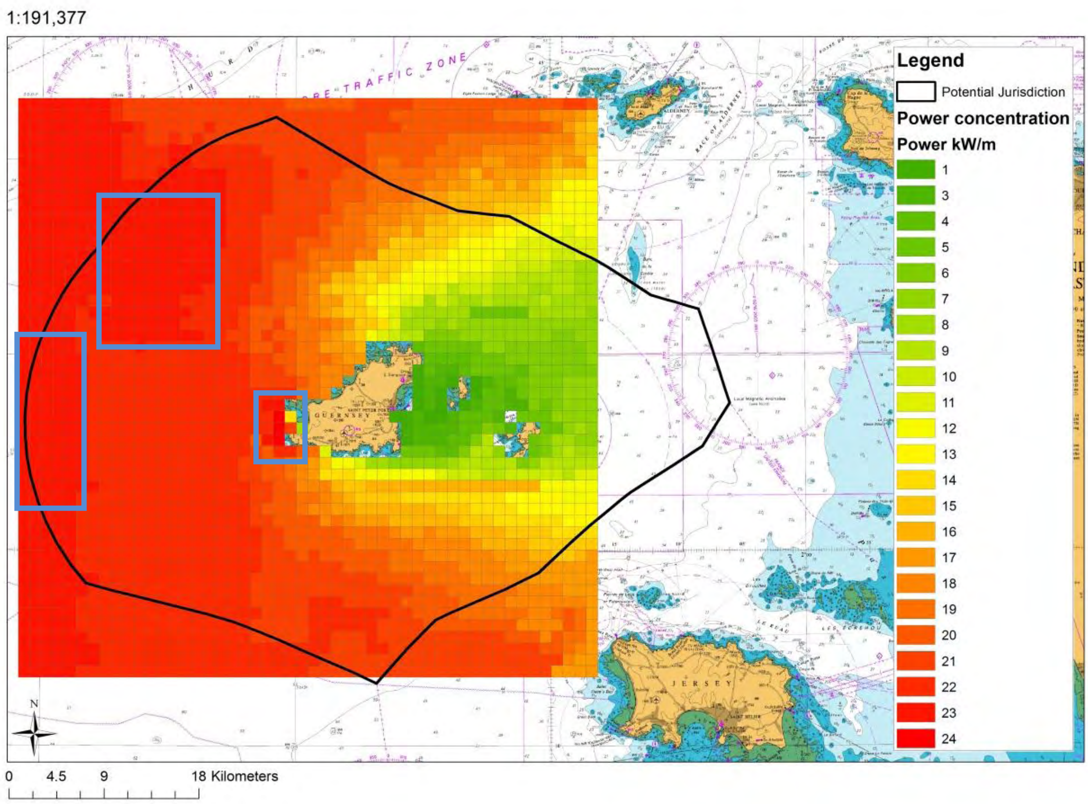

Figure 21 Mean power surrounding Guernsey, along with the potential jurisdiction (black) and with the most energetic zones (in blue) outlined

Before further investigation is carried out, a brief look into the significance of the model data is examined. The available power calculated within this project, provides a higher mean power estimation than that of the Atlas of UK marine renewable energy resources; technical reoprt. This presented, Figure 22, an estimated value of 10.1 – 15.0 kW/m of wave crest surrounding Guernseys western coastline.

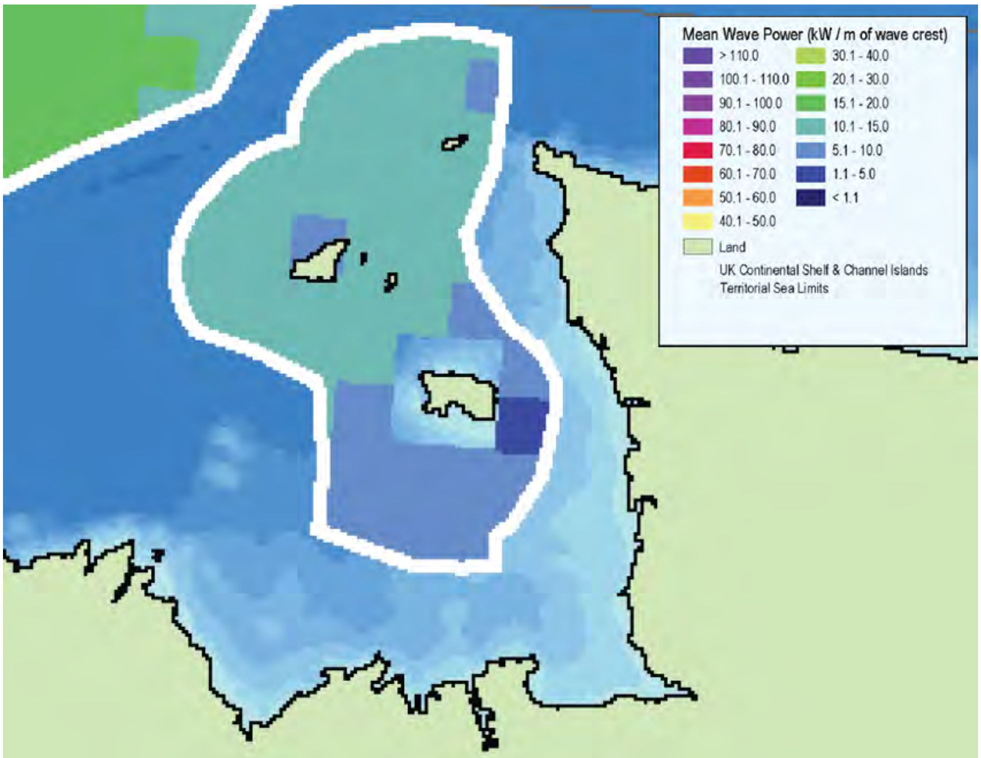

Figure 22 Map of annual mean power surrounding the Channel Islands (BERR, 2008)

The differences experienced between that of the Renewable Energy Atlas and this model are attributed to the grid size. The Renewable energy atlas grid size is approximately 12km along the edges. The grid size used in this assessment is 1.1 km. The refined nature of the grid has allowed for a more in depth investigation. A figure of 23kWm of wave crest, although higher by 8kW/m, is not unrealistic. The values are expected to be higher due to a more in depth study; a greater data set would confirm this as the model was only run for 2 years.

In comparison with other locations, Cornwall has annual power density value of 20.1 – 30 kW/m and the North West of Scotland between 40 – 70 kW/m (BERR, 2008). All these locations are subjected to direct influence from the Atlantic Ocean while Guernsey is somewhat sheltered by the regions of Cornwall and Finistere.

7.2 Constraints surrounding suitable Marine Energy Sites

With the known available mean power, further analysis is conducted in order to determine whether these high energy zones have conflicting uses, and thus suitable for further power investigations.

Firstly water depth is of key importance, for the purposes of this study, waters less than 40 meters were neglected due to the current capabilities of the industry, which is within depths of 40 – 70 meters. There is a device that has operated in shallower water (10 – 15 meters), called Oyster (www.aquamarinepower.com). This device is entering their second deployment this year since 2009 in Orkney, Scotland, but the device operates using the whole water column, thus obstructing a significant portion of the energy. However not proven, could restrict wave energy and sediment transport and it thus disregarded within this study. Furthermore the shallow waters have a constraints associated with them which will be discussed later on.

Water depths over 70 meters were also neglected, though the industry is moving forward, depths afar of this mark are not yet feasible, and thus unexplored. However in future years this may change. The remaining water depths, as seen in Figure 24, are open for further investigation. Furthermore the shallower depths (of between 10 and 20 meters), which are frequently seen around Guernsey are close to the shore and could thus hinder the visual landscape. It should be noted that zones of ordnance disposal and subsea cables are also presented on the map.

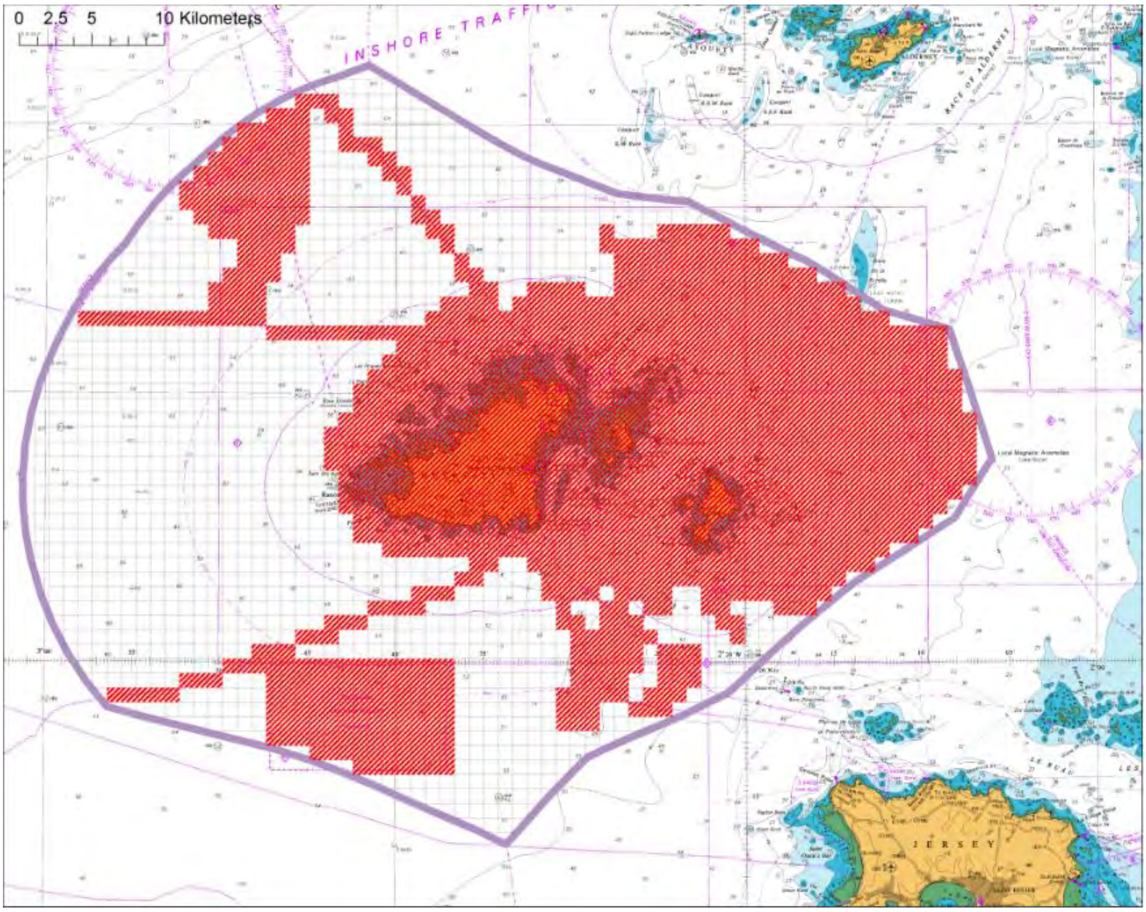

Figure 23 A constraint map showing the areas (in Red) where wave device deployment is restricted by depth (both deep and shallow), ordnance disposal areas and cables, (Sutton, 2012)

As previously stated in 4.4.7; Figure 13, It is common knowledge that the waters surrounding Guernsey have high tidal velocities, these areas are visibly focused to the east of St Peters Port, however tidal velocities in excess of 1.5m/s (BERR, 2011) are present off the west coast. Further investigation is required as to the significance of the tidal component on the wave power.

Brief attention is drawn toward other constraints surrounding Guernsey. As seen in Figure 24, the numerous constraints close to shore prevent much development. The navigation is of minimal importance, the available power in these regions is too small. In addition the shallow depths are also a contributing factor. The third location identified, with the highest extracted power values, is a location noted for marine mammals. This further confirms the notion to disregard this location for further assessments.

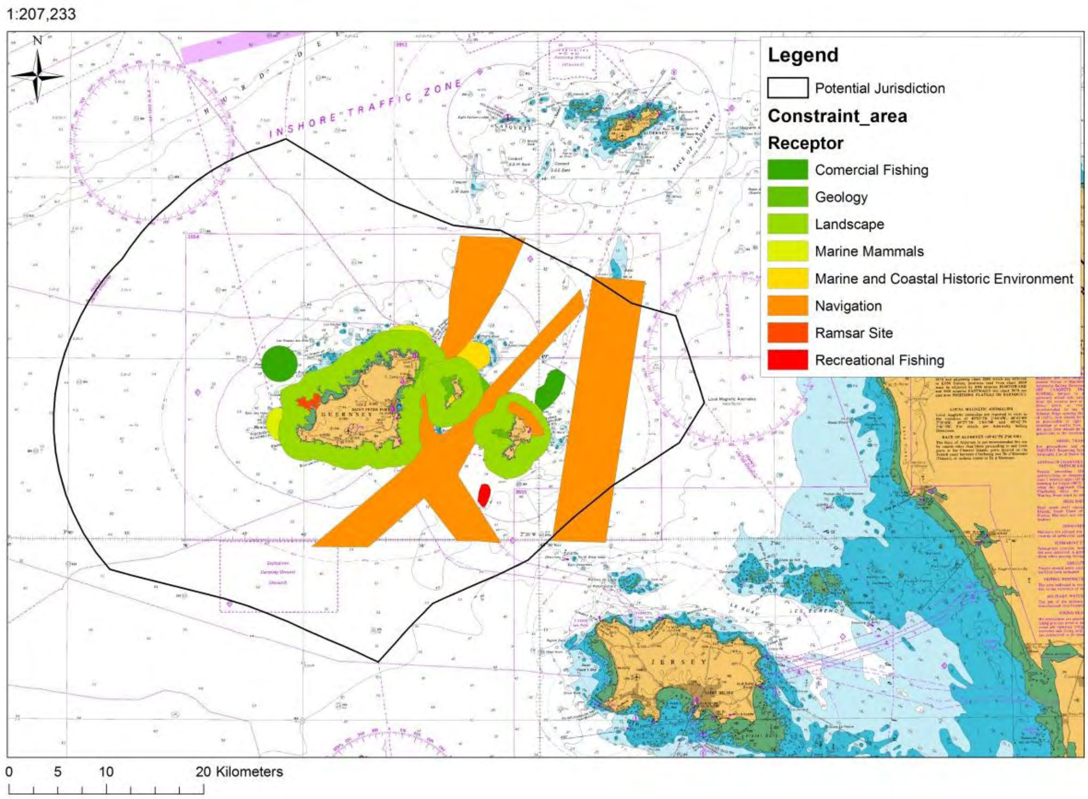

Figure 24 Map showing the most significant constraints that effect potential sites for wave energy convertors

As shown in Figure 24, protected areas of conservation must also be avoided, these high profile areas, like that of the Ramsar site - Lihou Island (Guernesiasie, 2009) must be deliberated during early stage marine energy projects. Major shipping lanes, ferry routes, high density recreational areas for water sports, fishing, etc must also be removed from consideration. Further information from Figure 24 shows that the majority of constraints are associated to the east of the island, with minimal loss to shore restrictions around the whole island. This works in favour for marine energy, as expected, the lowest power and depth restrictions are associated to the east. This leads us to confirm that the west coast is optimal for wave energy assessments.

Figure 25 and previous figures assign geo-referenced exclusions zones based on information obtained from Guernsey RET, using ARC GIS, these where overlaid with the modelled area mean power estimations. This outlines the most suitable locations, with minimal conflicts and those with the highest available energy.

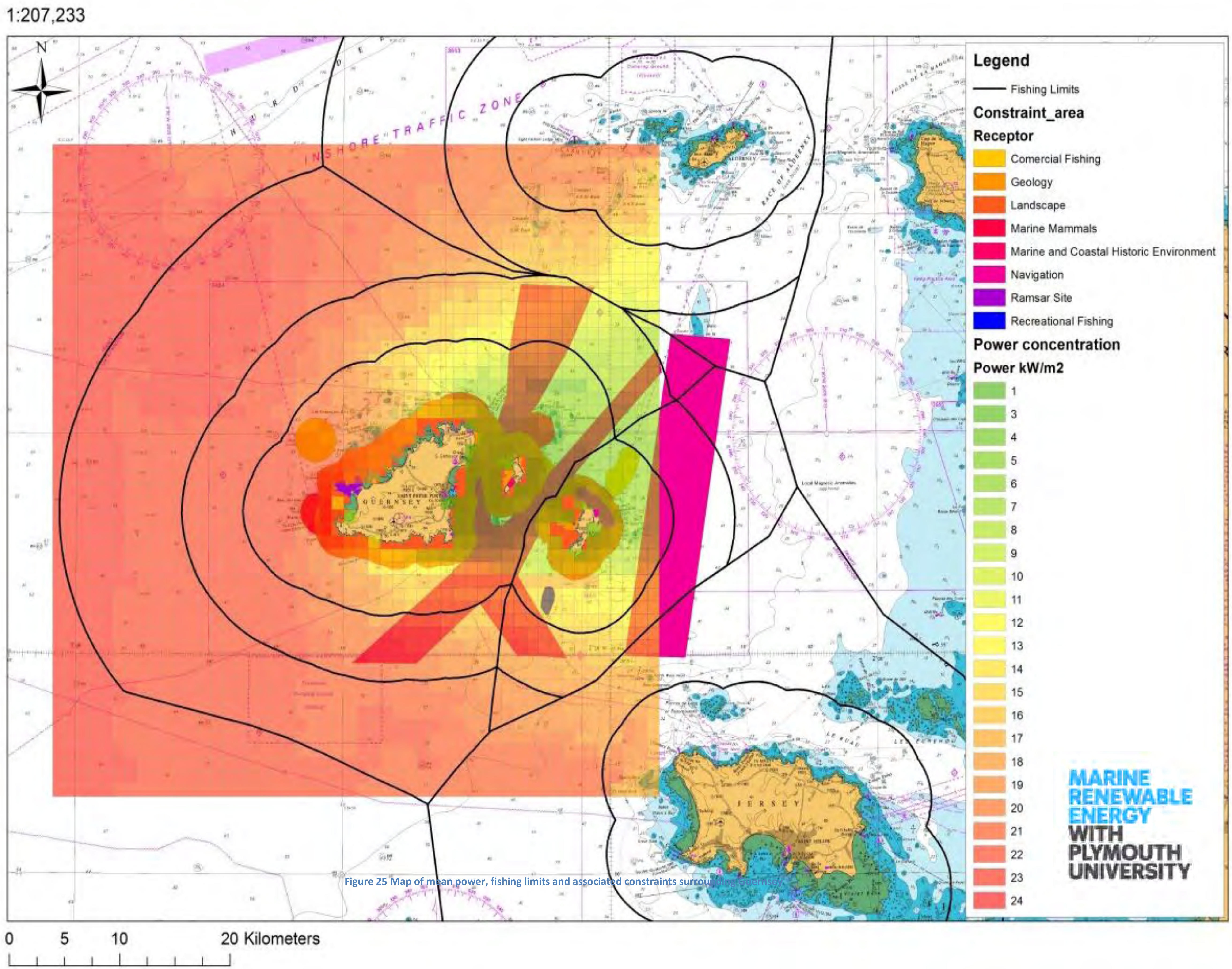

Figure 25 Map of mean power, fishing limits and associated constraints surrounding Guernsey

A pending application to obtain jurisdiction out to 12 nautical miles is awaited, if successful, fishing grounds maybe extended. If these fishing grounds overlap with the high energy zones, potential exclusion zones maybe considered. Using Wave hub, Cornwall as an example, shipping lanes where altered to accommodate the energy production site. This move required numerous stakeholder engagements, of which incorporated local, national and international representation. Similar alterations can be applied to Guernsey if the highest zone of potential power conflict in the future.

7.3 Selection of sites for further investigation

Overlaying water depth restrictions with that of conflicts presented in Figure 25, and consulting the power map of Guernsey (Figure 20), two of the most energetic zones were selected for further assessment. These are both out towards the 12 nautical mile limit, a third, for a comparison was also selected. This location is the same as the model validation point, selected to in still confidence to the power estimations. The location may also serve as a potential site. The site would also provide data, allowing the effects of wave propagation in shallower water to be discussed. Selected sites are presented in Figure 26.

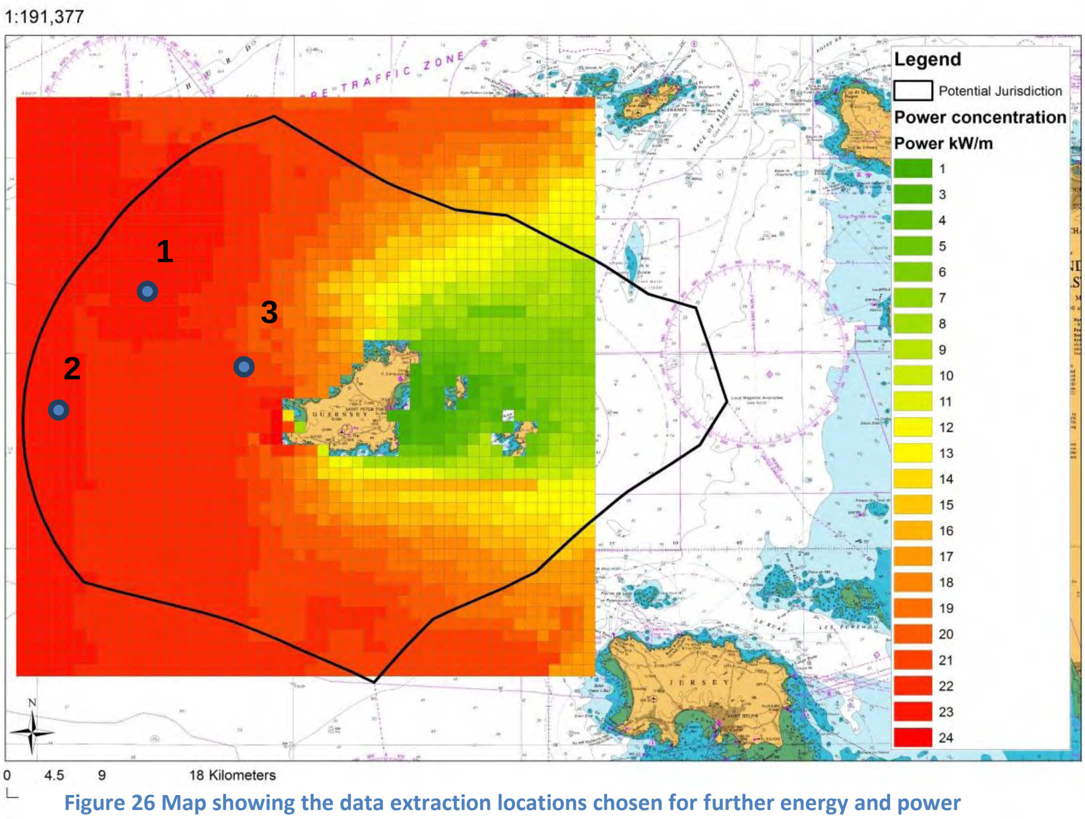

Figure 26 Map showing the data extraction locations chosen for further energy and power assessments within 12 nautical miles

Prior to individual discussions on each of the three locations, a comparison between all locations is briefly drawn, Figure 27. The available energy, calculated for the two year period show similar trends. With close examination, slight peak and trough differences are visible. All locations are within a close proximity of each other, hence the similarity. First predictions would anticipate insignificant differences for further calculations.

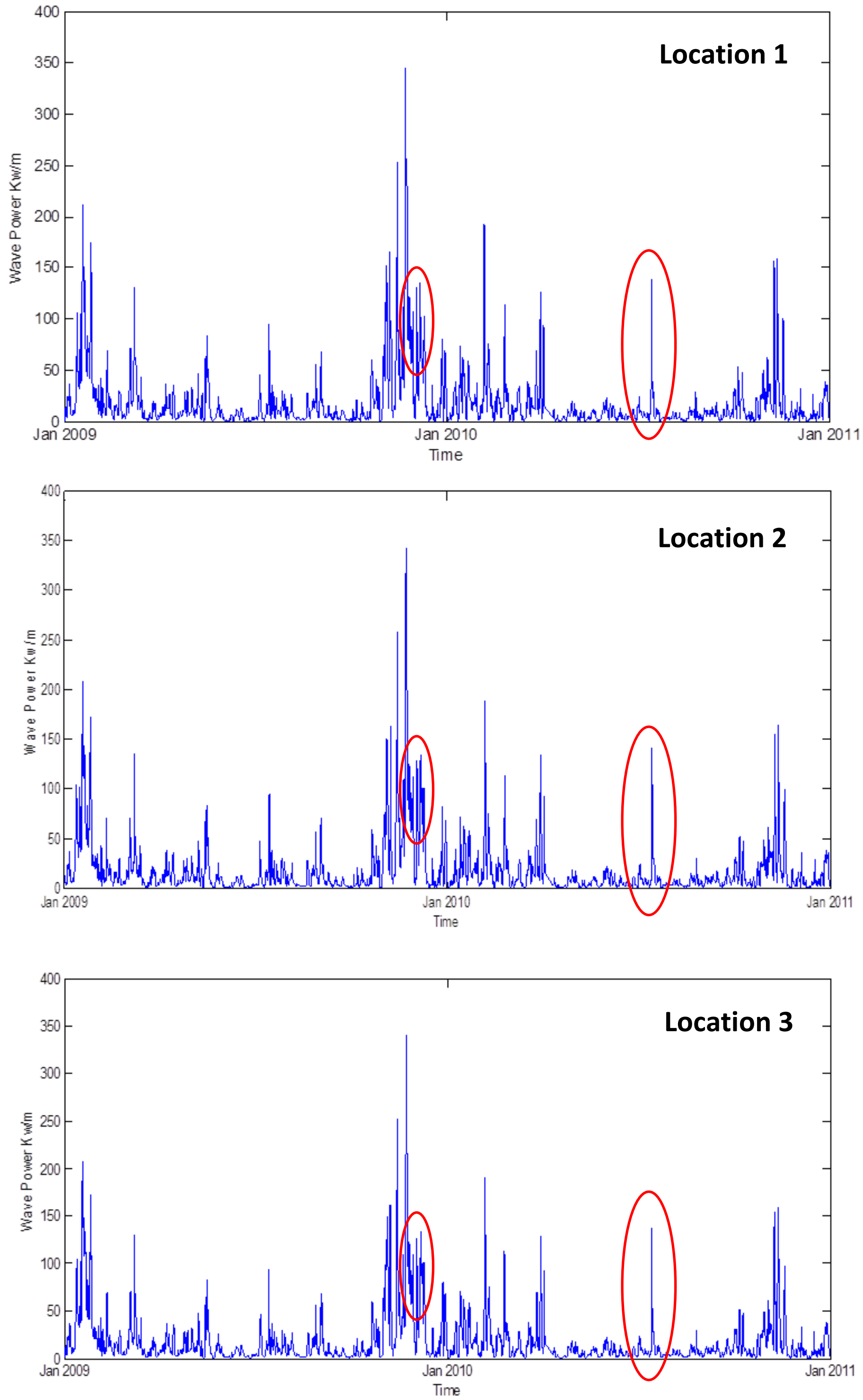

Figure 27 Figures showing available power at each location selected for further investigation, red circles merely outline small differences.

7.4 Location 1

Located 10 nautical miles from the coastline, Figure 28, this location was selected based on the surrounding high concentration of mean power. The depth of the site is at the upper limit of the industry, close to 70 meters, however the deployment of marine energy convertors off Guernsey's shores is not imminent, and operating depths may change in coming years. This section merely assesses the potential extractable energy of the site. The mean wave height for location 1 was calculated at 1.66 meters.

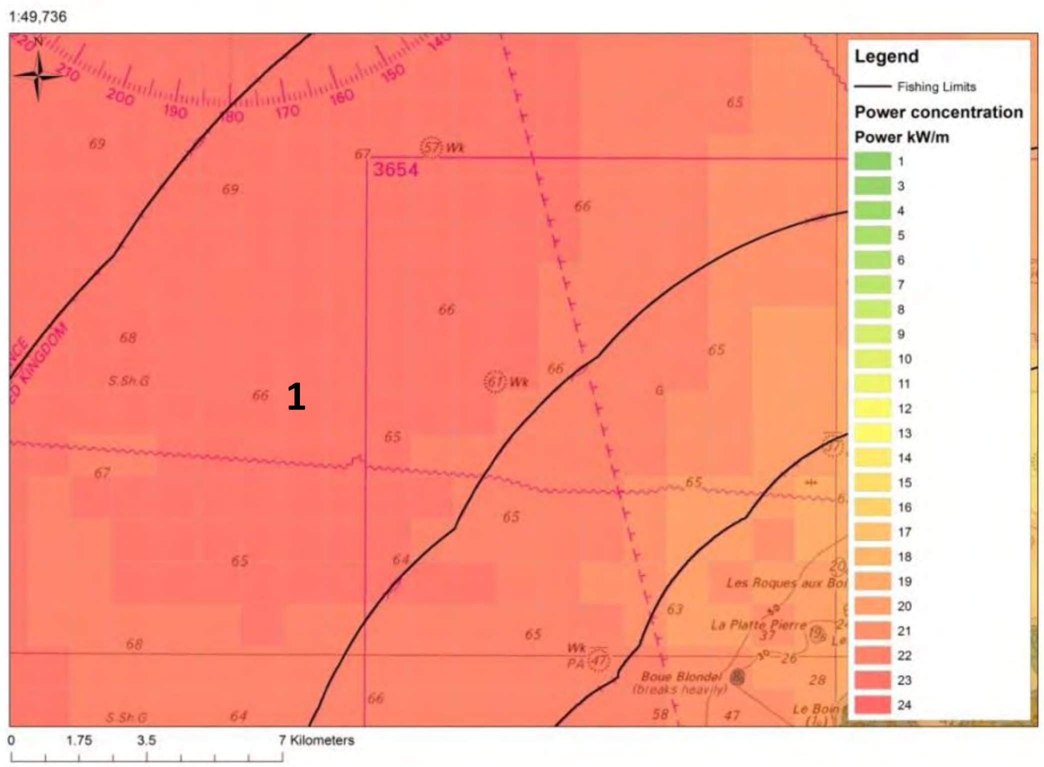

Figure 28 Location 1: Showing the available mean power (per meter wave crest) with an admiralty chart base map and the fishing limits surrounding Guernsey

Using maltab, plots presenting frequency of occurrence, percentage occurrence and finally power were created. Integration with the freely available Pelamis power matrix for their 750kW P1 device was conducted. Firstly, Figure 29 shows the frequency of each significant wave height H_s and energy period T_e occurrence over the two years. It is clearly visible that the most frequent wave conditions are experienced within the 2 meter at 9 – 11 second period. A trend expected of the region, due to the sheltering nature of Cornwall and the Finistere, France.

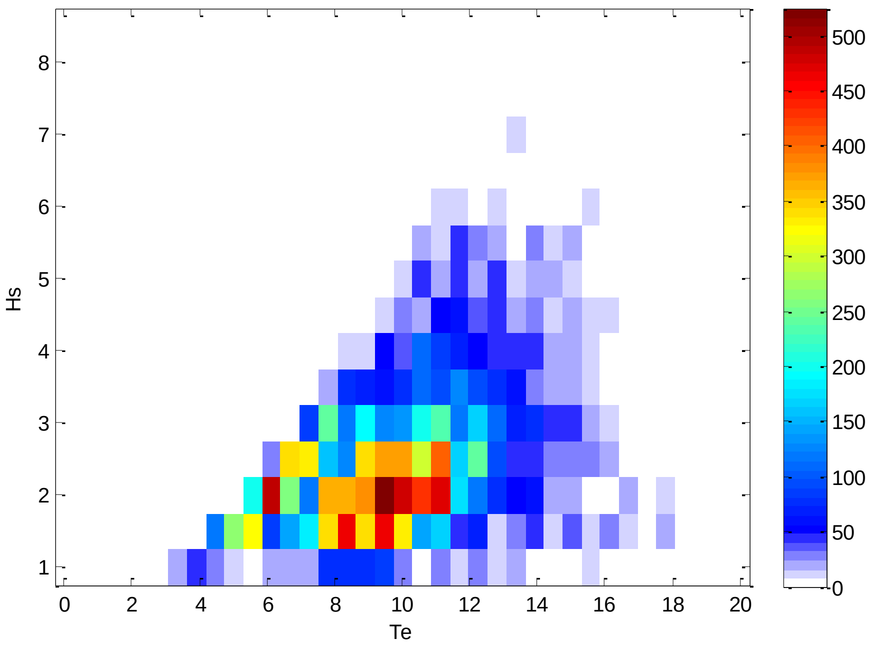

Figure 29 Frequency of occurrence over the 2 year period of investigation for location 1

Figure 30 presents the percentage that each of those conditions occur over the same period. Once again the most energetic zones are experienced within the lower range of wave heights. Preliminarily conclusions would recommend a device with a power spectrum tuned to lower wave heights.

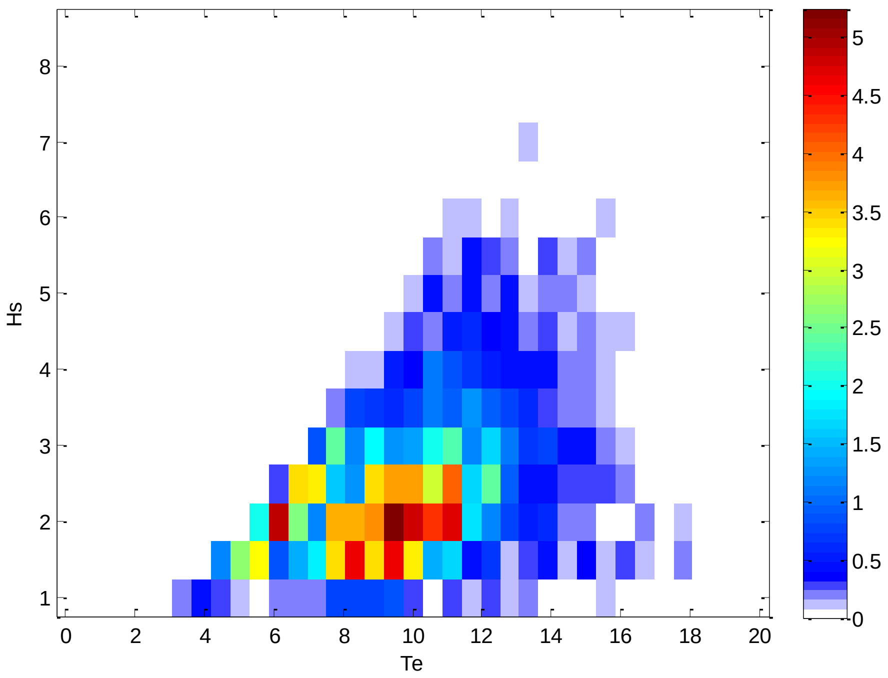

Figure 30 Wave activity during the 2 years. The elements indicate the number of occurrences, in percentage from the total

With the frequently occurring zones of high activity in the lower wave height range, as expected, the most extractable portion of energy is thought to be within this zone. Figure 31 confirms this, the integration with the Pelamis power matrix confirms that the most extractable potential is with the lower range. Wave the device is most active in the 2.5 meter, 8/9 second period range. Over the two years a total calculated extractable power, through the P1 750kW device is calculated at 1,959MW/h. It should be noted that this figure does not include maintenance and downtime, a discussion which will be carried forward.

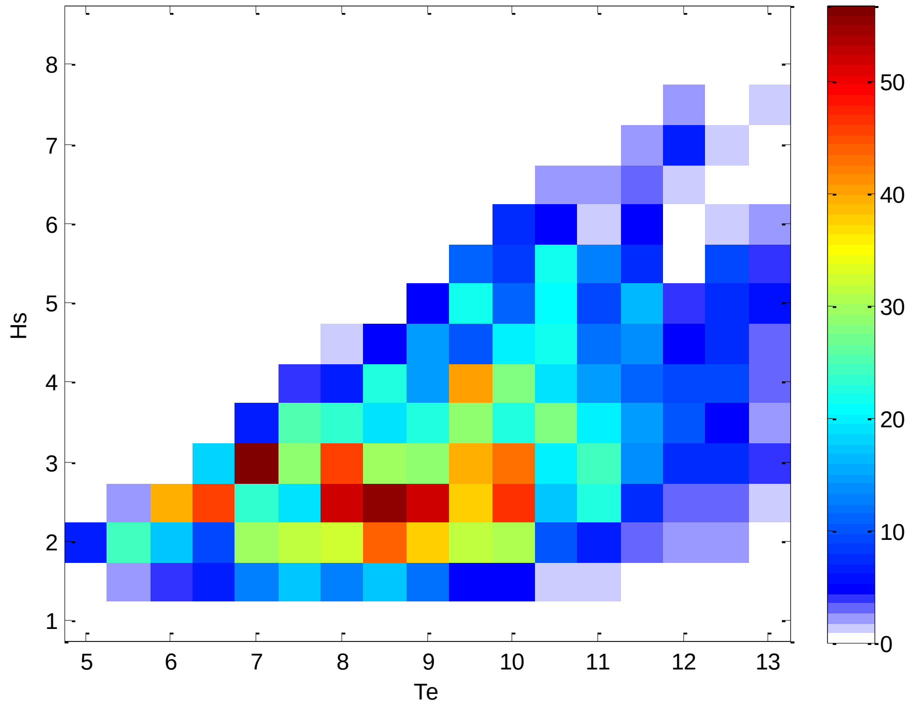

Figure 31 Total extractable power in MW/h over the 2 year investigated period, using Pelamis power matrix

In should be noted that the original data contain values of 3 hourly data, the values presented for frequency of occurrence, percentage occurrence and extractable power are all hourly. This was obtained by assuming the sea sate would hold for the whole 3 hours. A acceptable method discussed throughout Equimar guidelines.

7.5 Location 2

Located furthest to the west, 11 nautical miles from the coastline, location 2 is the deepest of the three. However, still within the 70 meter range of the industry, the site is investigated for reasons similar to that of location 1. The mean wave height for location 2 is calculated at 1.65 meters. Similar expectations are thought, in comparison with location 1, this is based on the similar water depths and mean power kW/m of wave crest previously calculated, Figure 20.

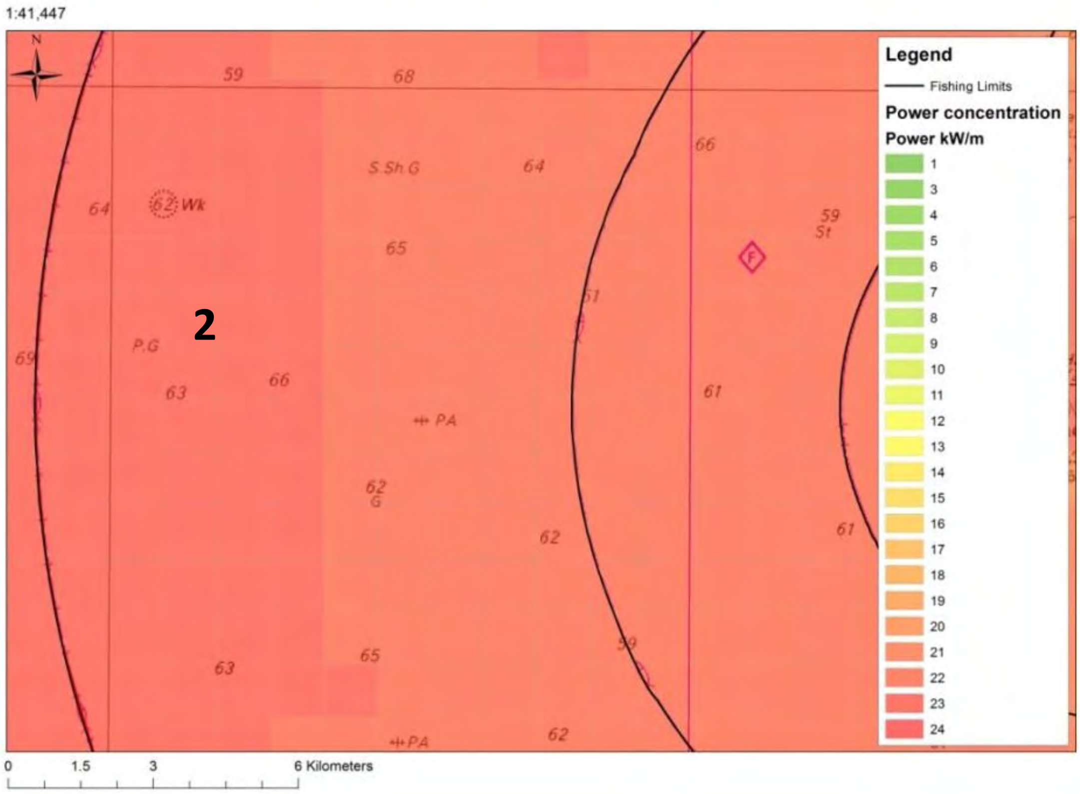

Figure 32 Location 2: Showing the available mean power (per meter wave crest) with an admiralty chart base map and the fishing limits surrounding Guernsey

Firstly the, Figure 33 shows the frequency that each significant wave height H_s and energy period T_e occur over the two years. Once again it is clearly visible that the most frequent wave conditions are experienced within the 2 meter at 9 – 10 second period. A trend previously disucssed, thus confirming the water depths and wave climate surrounding Guernsey carry similar properties.

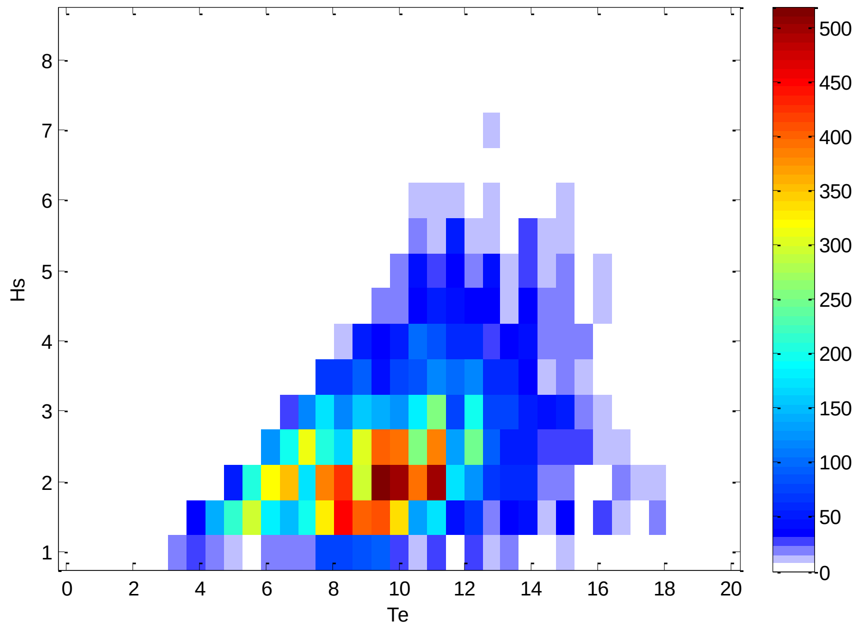

Figure 33 Frequency of occurrence over the 2 year period of investigation for location 2

Figure 34 presents once again the percentage that each of those wave conditions occur over the same period. Once again the most energetic zones are experienced within the lower range of wave heights.

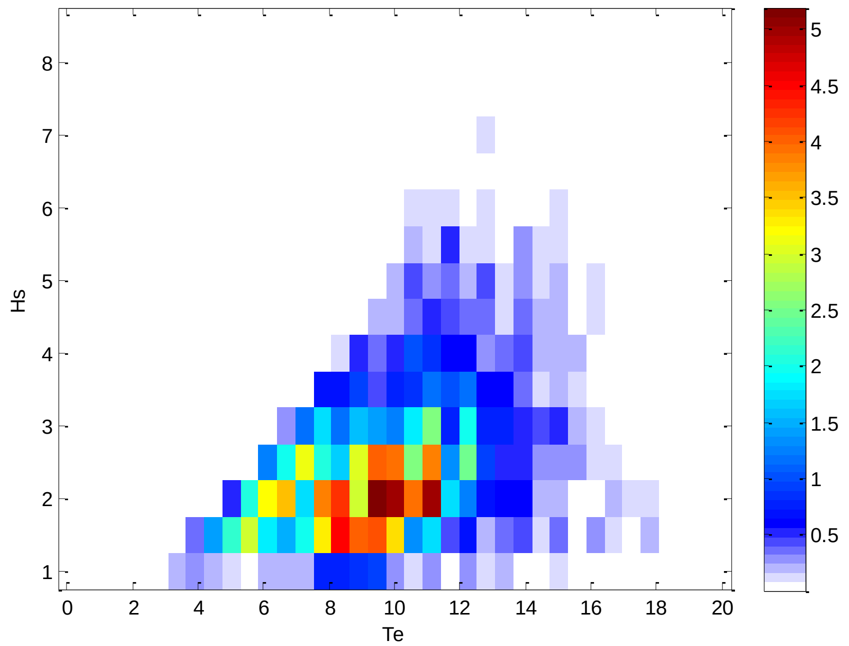

Figure 34 Wave activity during the 2 years. The elements indicate the number of occurrences, in percentage from the total

Though closer to the model boundary, Figure 35 confirms a greater range of power generation, greater values of power MW/h are visible in the less than 3 meter range. The total calculated extractable power, once again, through a 750kW device is calculated at 1,978MW/h. A difference of 17 MW/h is noted between each location. The location is the furthest from shore, thus greater cable costs and greater maintenance costs are foreseen. However the distance would also have the least visual implications standing from the island.

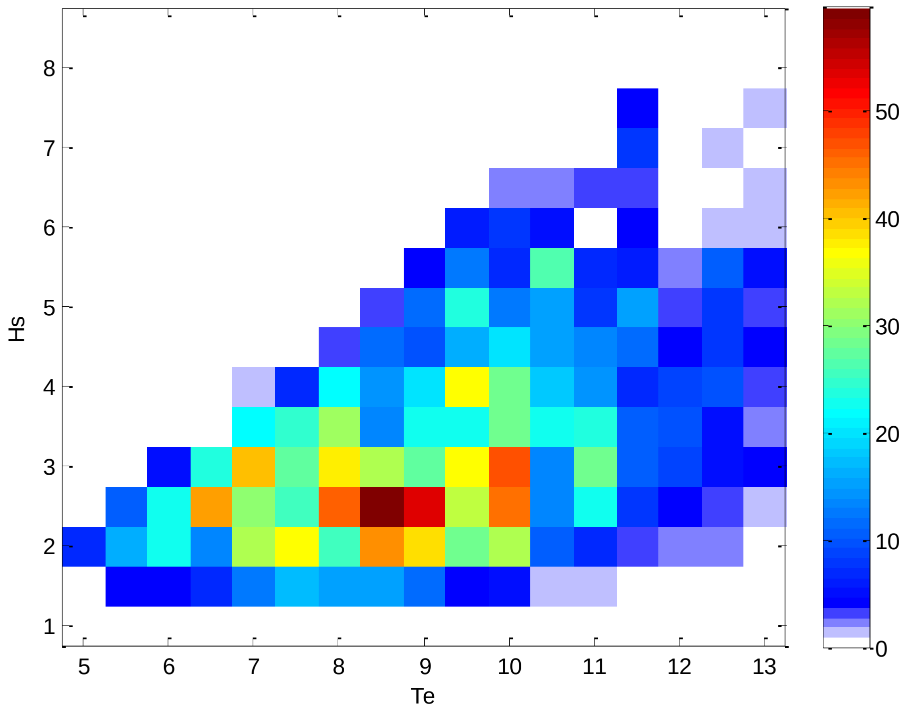

Figure 35 Total extractable power in MW/h over the 2 year investigated period, using Pelamis power matrix

7.6 Location 3

Location three, 5 nautical miles from Guernsey's coastline, is the point at which the model was validated. This aims to bring confidence to the power assessments and the project. The mean wave height for this location is calculated at 1.63 meters. Though close to shore, the site is shallower that previous and could yield higher power levels; a prediction based on the focusing effects of waves over decreasing water depths. The site also has further positives, lower cable costs and lower maintenance costs. However the location would be visible from the shore line. Public perception could hinder any marine development.

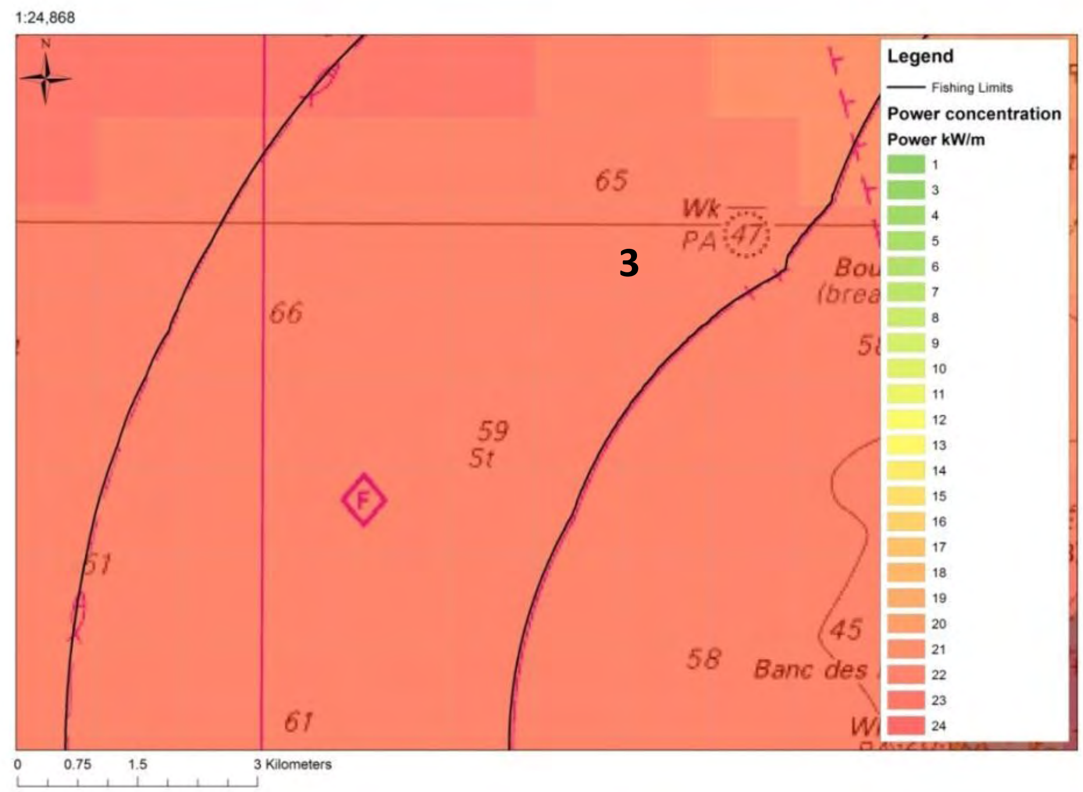

Figure 36 Location 3: Showing the available mean power (per meter wave crest) with an admiralty chart base map and the fishing limits surrounding Guernsey

Once again, Figure 37 shows the frequency that each significant wave height H_s and energy period T_e occur over the 2 years. As with the latter two, the most frequent wave conditions are experienced within the 2 meter at 9 – 11 second period. With three locations producing similar trends, a conclusion can be drawn; the wave climate surrounding Guernsey is most frequent between 1.5 - 2.5 meter wave heights with periods between 8 – 11 seconds. Renewable atlas UK predicted mean wave height of 1.51 – 1.75, confidence should now be applied to the projects method.

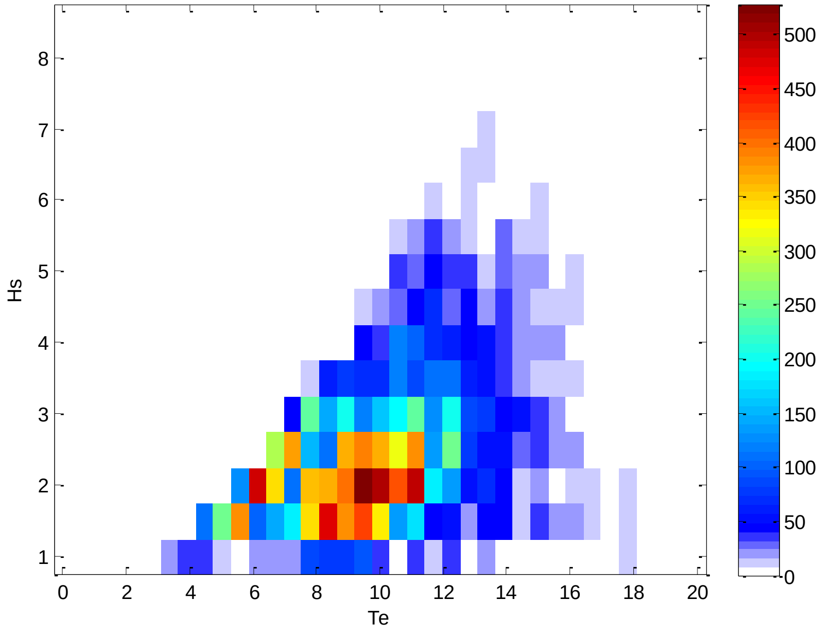

Figure 37 Frequency of occurrence over the 2 year period of investigation for location 3

Figure 38 presents the percentage that each condition occurs over the 2 year period. Once again the most energetic zones are experienced within the lower range of wave heights, as previously discussed.

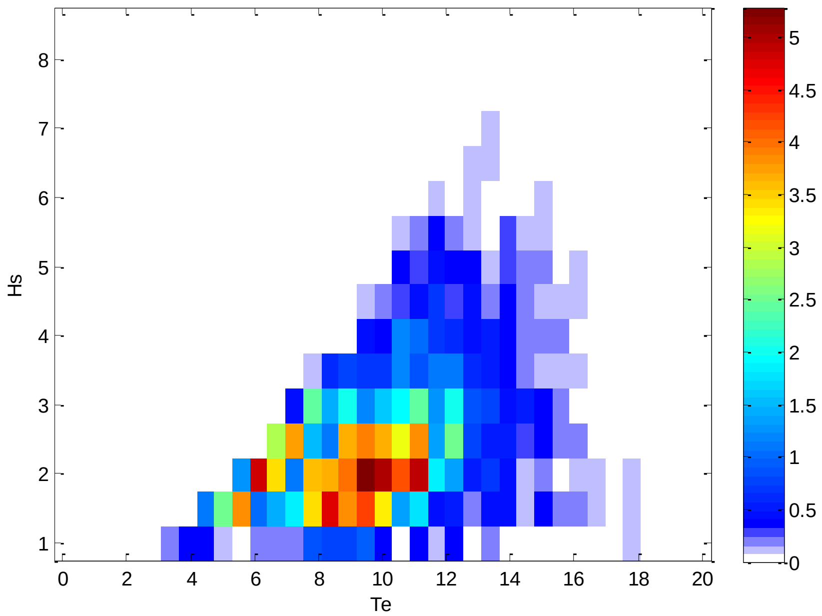

Figure 38 Wave activity during the 2 years. The elements indicate the number of occurrences, in percentage from the total

Finally, Figure 39 presents the power findings for location three. Firstly it can be seen that, of the three locations, location three has the lowest potential for power extraction. With comparisons of Figure 31 & 35, it is visible that location three has lower activity than its deeper counter parts. In addition the extractable energy is calculated at 1,933MW/h over the 2 years, 26MW/h lower than location 1 and 45MW/h lower than location 2. In conclusion, the deeper, more offshore waters of location 2 are the most suitable of the selected sites.

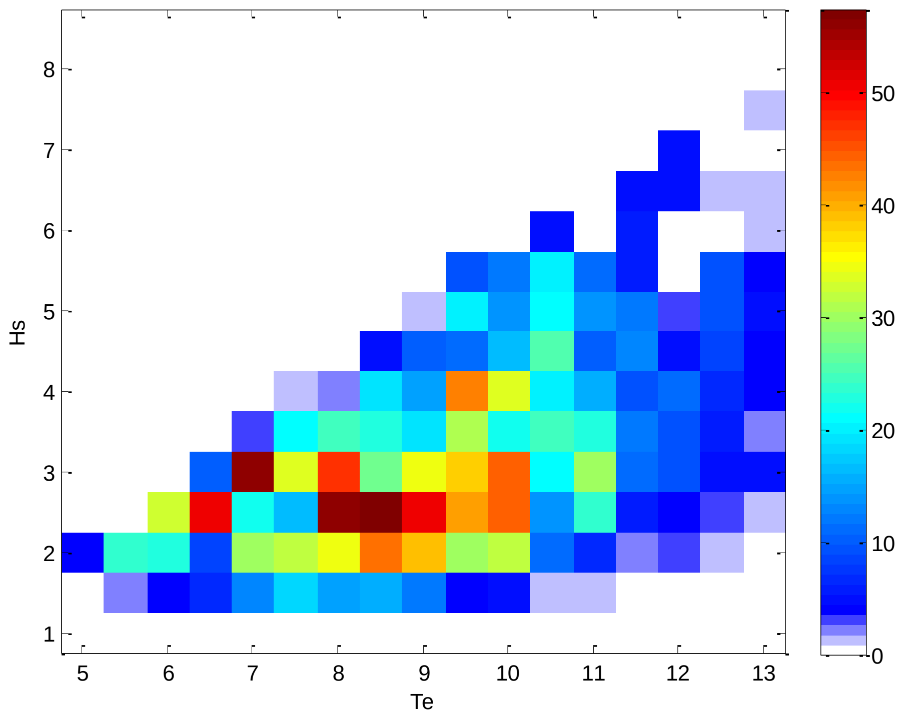

Figure 39 Total extractable power in MW/h over the 2 year investigated period, using Pelamis power matrix

To summarize, the three locations have similar waters depths, location 2 (the deepest) and location 3 (the shallowest). The site with the most energy potential is that of location 2. The deeper waters are more exposed, have no physical structures hindering wave propagation and are constantly fed directly East from the Atlantic Ocean.

Though the difference between each site is no greater than 45MW/h, all three sites have potential. Cable costs, public perception, zones of constraints, which have largely been accounted for, could change in future years. This may push the marine energy projects further off shore, currently the most suitable location.

Finally, when compared against Figure 13, taking into account the tidal components, location 1 and 2 are located in areas of the lowest tidal velocities.

7.7 What can Pelamis contribute to Guernsey

Taking location 2 as the optimal location, further investigation is conducted to identify the potential contribution from wave energy convertors compared with Guernsey estimated annual consumption of 400,000MW/h/yr.

Firstly the calculated value of 1,978MW/h over two years is based on extracting the total available energy. This is however not possible given the current maturity of the industry. Capacity factors vary for each device. According Pelamis technology – they state their devices have capacity factors between 20 – 40%, (Pelamis, 2012) depending on sea state. For the purposes of these calculations, a device capacity factor of 35% is applied and a further 15% of the total available energy is discredited. The latter is the expected loss each year allowing for maintenance and device downtime.

Taking into account the computational grid use to assess this point in time, of 1.1 km long & wide, an estimated 4 devices are installed for electrical investigation at location 2 based on 300 meter spacing. Table 1 outlines the expected contribution from a Pelamis P1 750Kw device to Guernsey Electric Limited (GEL).

Estimated power from Pelamis devices	
Power over 2009	1190MW/h
Power over 2010	788MW/h
Power over 2 years	1,978MW/h
Device capacity factor 35%	695MW/h
Discredited 15 % (loss of 104MW/h) 2yrs	591MW/h
4 devices deployed (2yrs)	2,364MW/h
12 devices deployed (2yrs)	7,092MM/h
Guernsey's electrical consumption (yr)	400,000MW/h
Contribution - 4 wave power devices (2yrs)	0.29%
Contribution - 12 wave power devices (2yrs)	0.88%

Table 1 Estimations of power using the Pelamis P1 750Kw device matrix

7.8 What can Wave Dragon contribute to Guernsey

A paper dated 2012, discussing the wave energy pattern around the Madeira Islands revealed a power matrix for the Wave Dragon 7MW device and Aqua buoy 250kW device. A comparison between the Wave Dragon and Pelamis was decided. Aqua buoy was left out due to the lower rate capacity of the device. Wave Dragon was assessed for the same location as Pelamis, Location 2. The power matrix is presented in Figure 40 below.

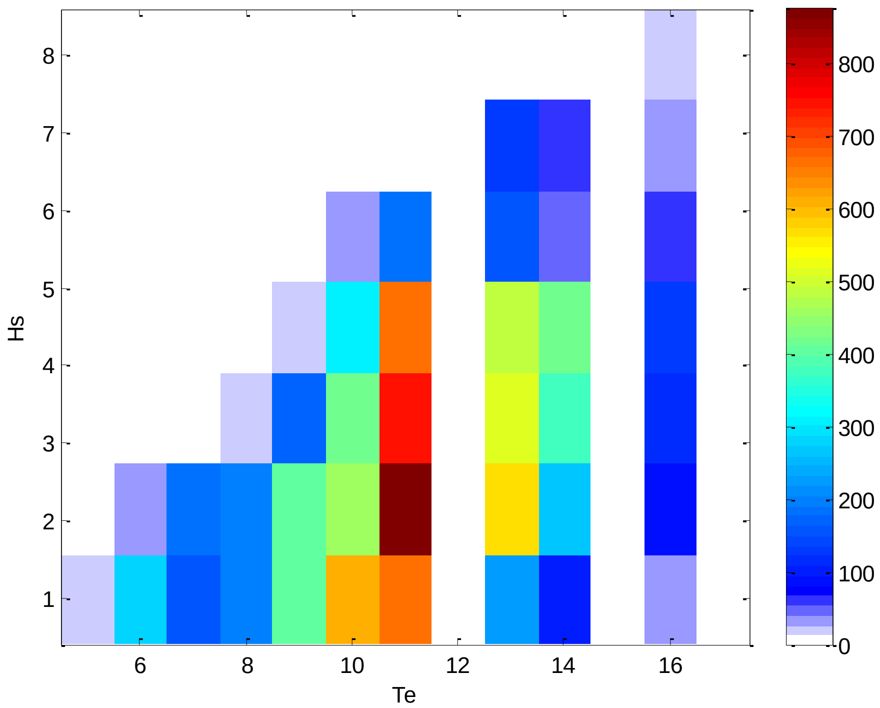

Figure 40 Wave Dragon power matrix for a 7MW device at location 2 in MW/h over the 2 years

Initial observations show no values for a period of 12 and 15 seconds. An in depth investigation yielded that the data set extracted from Delft3D, for Peak Period are true and do not contain values of 12 or 15. The statistical method in matlab was also checked for errors. The Wave dragon power plot yields a much higher power value for the same sea state. Firstly the device is rated higher, over 6MW in difference and secondly the device is much larger and of an over topping design. Pelamis is an attenuator device. The extractable power was calculated at 10,962MW/h over 2 years for one device. Once again, Table 2 outlines the expected contribution to GEL from one Wave Dragon 7MW device. A brief investigation into Wave Dragons capacity factor yielded various values. The same capacity factor, of 35%, was selected.

Estimated power from Wave dragon devices	
Power over 2009	6,928MW/h
Power over 2010	4,034MW/h
Power over 2 years	10,962MW/h
Device capacity factor 35%	3,837MW/h
Discredited 15 % (loss of 575mW/h) 2yrs	3,261MW/h
2 devices deployed (2yrs)	6,522MW/h
8 devices deployed (2yrs)	26,088MW/h
Guernsey's electrical consumption (yr)	400,000MW/h
Contribution - 2 wave power devices (2yrs)	0.81%
Contribution - 8 wave power devices (2yrs)	3.2%

Table 2 Estimations of power using the Wave Dragon 7MW device matrix

It should be noted that both devices have associated positives and negatives; this report merely outlines their potential contribution. Further investigation is recommended on each device, their environmental effects, wave shadow effects and industrial readiness closer to deployment.

From Table 1 and 2 it is clear that 2009 was the more energetic of the two years. Figure 27 allows for the comparison, where the summer months of 2010 are visibly less active. An increased data set would allow for a greater in depth seasonal and monthly comparison.

Finally the power estimations within this report, for both devices, I feel are too high. The industry is too immature and the calculated method has numerous assumptions. The specific device capacity factors are not taken in to account; these can vary depending on rated capacity, devices and various sea states.

7.9 Uncertainty of energy calculations and future progression

The idea that 3.2% of Guernsey's Energy could be achieved through the exploitation of waves is an exciting prospect. However the ocean and tidal industry is not yet at a level of maturity to support extraction at a commercial scale. 2010 was expected to be a year to remember, the move to a commercial demonstration scale, (Wiese, et al., 2011). This evolution has still not been realised, also the installed capacity that was predicted has not been achieved, as seen in Table 3.

Table 3. Summary of the ocean and tidal energy market – as the end of 2010

	Cumulated Installed capacity 2010 (GW)	Installed capacity 2010 (GW)	Estimated electricity generation 2010 (TW/hy)
Europe	<0.26	0	<0.6
North America	<0.04	0	<0.1
South America	0	0	0
Asia	0	0	0
Africa	0	0	0
Oceania	0	0	0
World total	<0.3	0	<0.7

Table 3 Summary of the ocean and tidal energy market, as of the end of 2010

In addition, through personal communication with Mr Monk, as a previous employee at the Pico OWC plant in the Azores, which is grid connected. The industry matrixes are not accurate for achievable energy extraction, at best they are an over estimated anticipation of device performance, at this point in time. He is however in no doubt that this will improve as the industry develops.

Renewable Energy Focus (2011) estimates that it will be another five to 10 years before commercialisation can hope to take place. Having said the progression amongst, researchers, device developers, government backing and public perception is driving the industry forward. 2012 has seen numerous advances, the South West of England is now a Marine Energy Park, Scotland's Pentland and Firth is making head way, and scale model testing is being conducted on new emerging devices. Commercially available wave energy devices will become available, and supply clean and cost effective energy. When, is only a matter of time!

Furthermore the wave industry is at a position where wind was a decade ago, uncertainty of the resource (due to lack of accurate measurements), technical issues with devices and the limited knowledge surrounding the effects on marine life from these devices is something which can significantly delay the approval and permitting of marine developments.

8. Potential devices for deployment

When recommending wave energy converting devices suitable for deployment surrounding Guernsey Island or in any location of that matter, local conditions and accessibility are of primary concern. With an immature industry there are few well established market leaders that have full scale devices, which both are grid connected and have long deployment periods. A brief discussion into the potential wave energy devices available, and suitable, today will aid the wave resource assessment.

Taking the market leaders and given their current operational state; Pelamis, Wave dragon, Power buoy, and OE buoy were selected for further analysis due to progress, deployment history, power generation and future developments secured. The above devices all have positives and negatives associated with each of them, each device will be discussed individually.

Wave Dragon is an over topping device. Seagoing trials of the Wave Dragon 20 kW prototype proved its offshore survivability since March 2003 and verified the potential for commercial feasibility with large scale power generation below the costs of offshore wind power (UK, 2010). However, it does have the largest wave shadow and thus may carry most negative public perception and environmental effects. (www.wavedragon.net)

Ocean Power Technologies Power buoy is well proven in America after surviving hurricane Irene thus proving the survivability of the system, but the current device has a maximum power capacity of 150W which makes it a bottom contender when supplying sufficient energy to the national grid. (www.oceanpowertechnologies.com)

Ocean Energy buoy on the other hand is an efficient and powerful device, with an installed capacity of 2.25 MW but it is currently only at quarter scale and thus not fully developed. It has had great success off the West coast of Ireland and the development to a fully commercial scale is in progress with deployment, potentially this year at Wave hub. (www.oceanenergy.ie)

Pelamis is firmly embedded in the marine renewables industry; however the length of the device and the visual aspects from the shoreline are of concern when considering Guernsey. Furthermore the device presently has to be disconnected and towed to shore as every large storms draw in. (www.pelamiswave.com)

In summary, device selection should incorporate aspects relating to specific sites, water depths, user constraints, power rating, and public perception – through stake holder engagement. It is recommended that a full investigation be carried out prior to the project commencing. The industry will change and emerging technologies may prove more suitable.

A full list of all currently known devices is available through the U.S department of energy; Marine and Hydrokinetic Technology Database at http://www1.eere.energy.gov/water/hydrokinetic/default.aspx.

9. Further Research

As a preliminary study into Guernsey's wave resource, there are numerous aspects where improvements can be made, addressed below are some of the areas of which would benefit.

- Firstly the model is recommended to have a longer run time. This increased period of time would provide a more significant data set, with yearly and monthly statistics over a potential 5 years, allowing for a better understanding for the wave climate.

- The increased need for high level bathymetric surveys in territorial waters, this would increase the resolution of the model, allow the grid size to be reduced from 1.1 km wide to a potential 150 meters. Obtaining the data would be costly through surveys, a precise figure is unknown, direct contact with companies is recommended. A rough time frame to achieve this bathymetry would potentially be 2 years.

- A deployed wave buoy/rider would provide point measurements, though spatially challenged, would allow any model outputs to be directly compared against in-situ wave buoys instead of modelled data. This would greatly increase the accuracy of all power estimates. The longer deployment time the better, but as previously stated in literature review, has numerous constricts. The cost of such a deployment is expected to run into the thousands.

- Validation points in other areas, like that of the shallow waters would increase the accuracy of the model. Preferably located in the wave shadow of the Island, to the south or east, this would bring confidence to the resource estimates by supplying shallow water validation points. However as the UK Met office model does not extend that far, such data would be obtainable only through point measurement.

- Though this is an early stage resource assessment, it is recommended a specific site assessment be carried out. This should address the available power, downtime for maintenance, geology for moorings, water depths, suitable devices, any constraints and accessibility through ports and supply chains. This would be most suitable for an MSc project and is potentially free, depending on freely available data.

10. Conclusion

The project achieved all objectives, a high level analysis across the computational grid yielded average available power density of 20 – 24kW per meter of wave crest. This is an increase on the original estimations from the BERR Renewable Energy Atlas. Model validations achieved high success rate, with R^2 values of 0.98 when compared against Met office UK WaveWatch III model data over the two year investigated period. This brings confidence to the estimations of the model, the methodology and power estimations

From previous figures it is clear that the wave resource is, at its most energetic, to the west of the island. The energy east of the island is too low to consider deployment wave energy devices, due to shallow waters and the many associated constraints. The most significant of these are the shipping & navigation routes and local tidal velocities.

Of the three most energetic zones identified within Guernsey's potential jurisdiction, the waters directly west of the island (location 2) contain the highest estimated extractable power. One Wave dragon 7MW rated device produced 10,962MW/h of electricity and 1,978MW/h of electricity through one Pelamis P1 750kw device. Taking in account maintenance, downtime and device capacity factors, the total estimated electrical contribution to Guernsey electric is 3.2%, using 8 Wave dragon 7MW devices over two years.

Locations 1 & 2 are far enough offshore to have little or no effect on the islands constraints. Furthermore the sites carry the least associated effects when considering visual aspects and public perception. Views on public perception require an in depth assessment with local communities, water users, businesses and the government. Though the investigation period is only two years, the predicted contribution, however low, will drive the RET a step closer to considering future deployments of wave energy convertors.

Despite significant progress in recent years, ocean wave energy conversion technology remains in an early stage of development. Similar to wind power a decade years ago, a large number of very different device concepts are currently pursued at various scales by various developers and there is no consensus as to which technology is superior. This is typical for emerging industries.

The benefits for Guernsey Island for wave energy projects include:

- Wave-derived energy could supply up to 3.2% of the State's Energy needs. As such the wave climate is a significant renewable energy source that should be tapped into strategically. In reality, this technical potential is limited by environmental, economic and current technology but should be reviewed as the industry develops.

- Wave energy is predictable, some say accurate 48 hours in advance, and is more consistent than most other renewable alternatives. Wave energy is a renewable energy source with obvious long-term benefits, including: reducing dependency on foreign sources of energy, reducing electricity price volatility, displacing more polluting generation alternatives and reducing greenhouse gas emissions.

- Finally Development of a renewable energy industry creates jobs locally and reduces trade deficits, by keeping money in the local economy.

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Appendix A

Frequently asked questions regarding Guernsey's wave resource

1. Where is Guernsey RET considering wave energy devices?

Currently Guernsey RET is in the early stages of assessing the potential contribution of their energy from waves. As the industry develops and more assessments, in conjunction with Plymouth, Exeter and Cranfield Universities are carried out, sites of suitable and high potential can be confirmed. Until more scientific studies can confirm the findings of this report, numerous locations are open for discussion. However, what is clear is that the highest resource is concentrated to the West of the island.

2. What areas are not suitable for wave energy deployments as far as the government are concerned?

The positioning of wave energy convertors at sea requires a thought process that is anything but simple. Devices must be positioned in areas of high and constant power but must also be easily accessible in order to optimise the power extraction and any required maintenance.

Sites that must be avoided are waters shallower than 40 meters, unless the Oyster device is considered, and depths beyond 70 meters, due to current industry constraints. Furthermore, as previously stated in the Results and Discussion chapter, there are numerous other constraints that need to be considered. Outlined below are just some of those;

- Marine mammals
- Protected areas of conservation
- Commercial shipping
- Leisure craft and water users
- Shipping / ferry lanes
- Geological constraints
- Ordnance disposal zones
- Areas of high tidal velocities

3. Distance from the shore which is too far for deployment or too close?

As previously stated, consider thed constraints mentioned. Further to this, the most expensive part, at present, of any marine energy deployment is cable cost. Simply the longer the cable is, the higher the price. As an example, the 25km cable for the Wave hub, Cornwall amounted to 9 million British pounds.

Once ashore, a substation is required in order to convert/supply the electricity to the grid. Specific site selection should include an assessment of the existing power frame work of the island. In summary the grid connection point should be as simple and short as possible to minimise cost but should have wave energy convertors in the most energetic and optimal locations.

4. What contributing portion would you like from wave?

With the current state of the industry, only minimal contribution is to be expected from wave energy convertors. There are numerous devices which are supplying power, have commercial prototypes and developing new designs. In the coming years many of these may become capable of supplying power that is constant, reliable, and ultimately at a cheaper tariff. Until this time the industry is not at a commercial stage, and thus only minimal portions of energy are to be expected from wave energy devices.

Appendix B

Outputs from Delft3D model for water depth and wave height

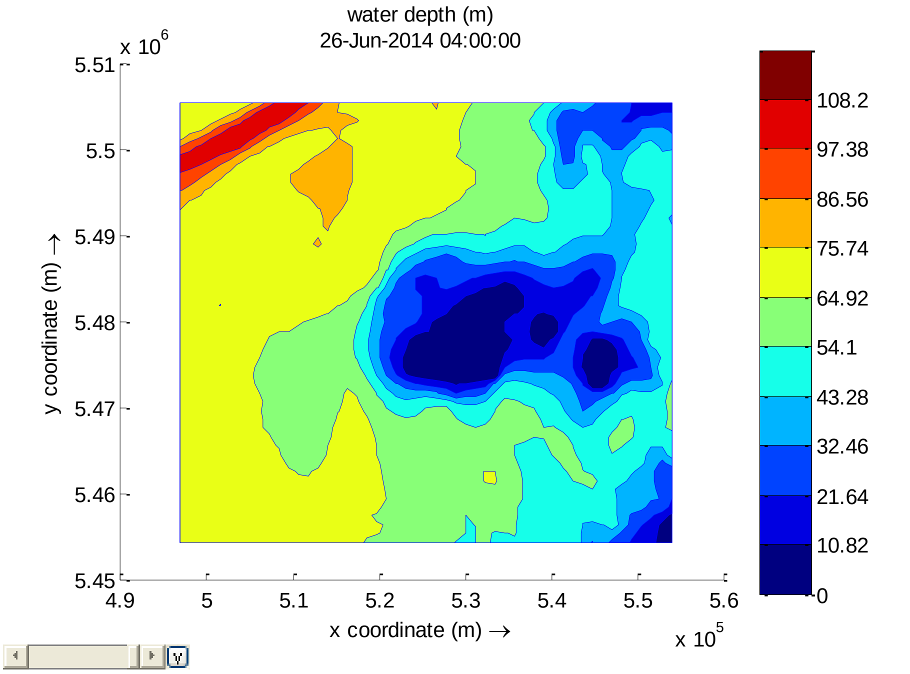

Figure 41 Water depths surrounding Guernsey Island, taken from the model, originally from EMODnET bathymetry

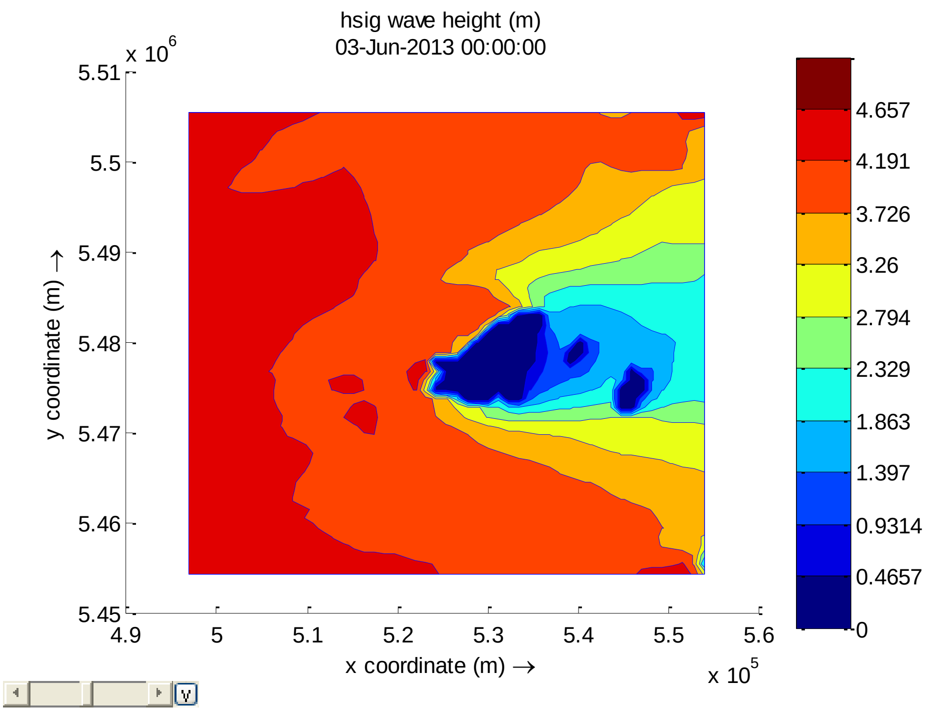

Figure 42 Showing a wave height of approximately 5 meters entering from the West of Guernsey and the reduction in wave height as the shore nears

Appendix C

Pelamis power matrix

H_s (m) \ T_e (s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Wave dragon power matrix

Tp (s) Hs (m)	5	6	7	8	9	10	11	12	13	14	15	16	17
1	160	250	360	360	360	360	360	360	320	280	250	220	180
2	640	700	840	900	1190	1190	1190	1190	1070	950	830	710	590
3	0	1450	1610	1750	2000	2620	2620	2620	2360	2100	1840	1570	1310
4	0	0	2840	3220	3710	4200	5320	5320	4430	3930	3440	2950	2460
5	0	0	0	4610	5320	6020	7000	7000	6790	6090	5250	3950	3300
6	0	0	0	0	6720	7000	7000	7000	7000	7000	6860	5110	4200
7	0	0	0	0	0	7000	7000	7000	7000	7000	7000	6650	5740