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FEASIBILITY OF OFFSHORE WIND IN GUERNSEY WATERS

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ABSTRACT

The Bailiwick of Guernsey is located 80 miles south of England with a population of 65 068 (2011) and a base load of 23MW, this is predicted to rise to 28.5MW by 2020. Guernsey imports around 80% of its annual electricity through a cable link to France via Jersey, with the remainder supplied by slow speed diesel (65MW) and fast start gas turbines (50MW) where necessary.

In line with Guernsey's Energy Resource plan of gradual decarbonisation, diversification and sustainable secure energy supply; this project will look at the feasibility of offshore wind in Guernsey waters up to the 3nm limit. The scope of which includes environment, bathymetry, grid integration, analysis of the potential wind energy resource and the visual impact.

A potential deployment zone has been identified off the NW coast; this area consists of a rocky seabed with depths ranging between 20m and 30m. Monopile and gravity foundations have been compared focussing on environmental impact and installation cost; feasibility of alternative deployment zones are also discussed. Data from anemometers located at Chouet and the Airport underwent exposure correction and were found to correlate closely, mean wind speeds differ by only 0.27% and standard deviations by 3.8% (data collected between Nov 2011 and Apr 2012). This enabled the use of historical airport data, it was found that 115.31GWh and 125.16GWh would have been produced in 2010 and 2011 respectively had an array of 10 Vestas V90-3 turbines been installed.

A comparison has also been made between Enercon and Repower turbines in order to analyse the impact of drivetrain technology on energy capture; conventional geared drive is found to be more efficient than direct drive, however further work is suggested into the relative reliability of the two technologies and the associated maintenance costs. Augmented reality visuals have been generated for multiple deployment scenarios; it was found that by rearranging the turbine layout the visual impact can be significantly altered, further research is suggested on the effect this has on public perception and array efficiency.

Keywords:

Energy, Resource, Security, Island, Turbine, Renewable, Energy, Guernsey

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BWEA	British Wind Energy Association
CAPEX	Capital Expenditure
CU	Cranfield University
CVT	Continuously Variable Transmissions
DOC	Depth of Charge
EMF	Electromagnetic Field
PV	Photovoltaic
GHG	Greenhouse Gas
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
GEL	Guernsey Electricity Limited
GW	Gigawatt
EPRI	Electric Power Research Institute
SOC	State of Charge
VRB	Vanadium Redox Battery
Li-Ion	Lithium Ion
NA-S	Sodium Sulphur
MCP	Measure Correlate Predict
MW	Megawatt
OPEX	Operational Expenditure
DECC	Department of Energy and Climate Change
WTG	Wind Turbine Generators
RO	Renewable Obligation
OFTO	Offshore Transmission Operator
GBF	Gravity Base Foundation

1 Introduction

1.1 Background (To Guernsey)

1.1.1 Location

The Bailiwick of Guernsey is a British Crown dependency that encompasses the islands of Herm, Lihou, Jethou, Alderney and Sark. Along with the Bailiwick of Jersey it forms the Channel Islands, a group of islands situated approximately 80 nautical miles south of the English coast and 25 nautical miles North West of the French coast.

Figure 1-1 Map of Guernsey

(NASA, 2011)

Guernsey is the second largest of the Channel Islands at approximately 21km long and 8km wide.

The terrain is mostly low lying land, with beaches, coves and cliffs to the south being a primary attraction. There is also a large deep water port at St Peter and an industrial port at St Sampson with a drying area.

“There are about 4,500 tanker harbours around the world containing 25,000 tanker berths, of which only two dry out, and both are in St Sampson’s” document written by Fishers Associates suggests that the harbour needs to improve (This is Guernsey, 2012). St Peters Port on the other hand will benefit from significant refurbishment, including £13.75 million for new mobile harbour cranes and work to the berths where they will be located (States of Guernsey, 2012).

1.1.2 Industry and Commerce

In 2011 the business and finance sectors accounted for 27% of the total number of employed people on the island, 12% are working in construction and manufacturing, 14% in the retail sector. Tourism is another major industry, although bed spaces have declined over 20% between 2001 and 2011 (Environment Department, 2012).

Guernsey is not a member of the EU and as such does not benefit from EU funding and financial support, it does however benefit from participating in the Common Travel Area and is able to trade freely with Europe, this is of particular benefit to Guernsey’s fishermen who are able to sell at French ports.

1.1.3 Electricity Generation

The generation of electricity on Guernsey is the sole responsibility of Guernsey Electricity Ltd (GEL) which is entirely owned by the Guernsey Government. GEL can produce 65.3 MW using five slow speed diesel generators fuelled by heavy oil and 50 MW using three fast start gas turbine engines fuelled by gas oil (GEL, 2005) In December 2011 a £14 million investment was made to purchase a 17 MW Wartsila medium speed generator (GEL, 2012). This was deemed necessary to secure energy supply for the island in the long term.

In addition to on island generation, GEL have been importing electricity from France via a 90kV subsea cable through Jersey since 2000, the cable has a maximum capacity of 60 MW and is able to provide much of the islands base load supply. There is currently a contract in place to purchase 60 MW through this cable with the purpose of reducing Guernsey’s reliance on oil imports and the volatility associated with oil prices. Electricity prices rose 8.5% in 2010 and 2.5% in 2012 in part due to increased cost of on island generation caused by the price of oil. The cable also has the benefit of increasing energy security by having more redundant capacity.

1.2 Energy Security

With increasing population and ever more advancing technology our energy usage continues to increase at an unsustainable rate. Our dependence on energy is demonstrated primarily through the consumption of fossil fuels as this is still the primary source of fuel for electricity generation.

Our energy dependence can be seen even more clearly when looking at developing nations, for example, as countries like China bring billions of people out of poverty and into the middle classes (80% of its population is predicted to make this transition within the next 15 years (Farrell et al., 2006), this will put an immense strain on global natural resources. Even with two large scale power stations coming online every week in China (Harrabin, 2012), there is still insufficient installed capacity to meet peak demand. Peak demand deficit in 2011 was predicted to be between 44.85GW and 49.85GW with power use restrictions and rationing being put in place (Reuters, 2011).

Year on year economic growth in China for Q1 2012 is 8.1% per annum (National Bureau of Statistics of China, 2012) and suggests a significant increase in the demand for oil: "Its consumption and imports of hydrocarbons will continue to increase, with major implications for the world market for oil and gas." (Lester, 2007).

With the main trade off in deciding which technology to implement being between global climate change, energy security and global resource competition, this raises the question of how sustainable is our current electricity generation portfolio.

1.3 Greenhouse Gas Emissions

In addition to the aforementioned problems in securing a reliable long term source of energy, we must also consider the environmental impact of the current generation portfolio:

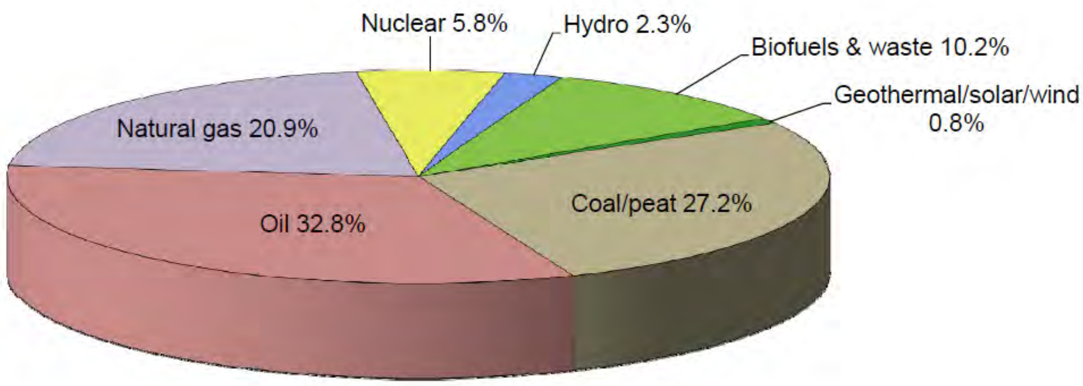

Figure 1-2 Share of total energy supply

[IEA Energy Statistics, 2009]

With approximately 81% of current global generation producing greenhouse gas emissions and global CO2 concentrations exceeding 396 ppm in 2012 (NOAA, 2012), climate change is becoming a major concern. As a result in September 2011, 191 states signed and ratified the Kyoto protocol to reduce greenhouse gas emissions by an average of 5.2% between 2008 and 2012. An extension of the commitment is being discussed in Mexico, South Africa and Qatar in the years 2010, 2011 and 2012 respectively.

In 2009, emissions in developing countries rose by over 3%, although developed countries saw a reduction of 6.5% during the same period, this figure is expected to change when economic conditions improve (IEA, 2011). Intergovernmental panel on climate change (IPCC) [fourth assessment report] predicts average global temperatures to increase by 2.4-6.4 degrees by 2100, this would have profound environmental and ecological impacts that would be felt across the globe.

1.4 Renewable Energy

The two points/sections mentioned above are major factors driving the uptake of “renewable energy technologies”. In Europe and western countries, the uptake of such technologies has been significant with an EU27 target of 20% energy consumed from renewables by 2020.

To date, solar and wind have emerged as favourable technologies receiving significant deployment and representing a large proportion of installed capacity across Europe. Both experience similar drawbacks which need to be addressed if this type of renewable energy is to provide base load capacity, the most prominent of which is intermittency.

1.4.1 Solar Photovoltaic (PV)

Solar power has made significant progress over the last few years and remains the world’s fastest growing power generation technology with installed capacity increasing 72% in 2010 (REN21, 2012) and 86% in 2011 (BP, 2012). It is also interesting to note that in 2010, Europe added more PV capacity than wind, and continues to lead the way in the PV market with 84% of global installed capacity occurring within the EU (REN21, 2012).

In a recent cost update report, the Department for Energy and Climate Change (DECC) shows significant cost reductions when comparing 2011 data to current costs in 2012. Reductions of up to 20% are seen for domestic systems and up to 50% for installations of 50 kW and above (PB, 2012).

According to Bloomberg (2012), there was a 51% drop in solar panel prices for the same time period driven by a doubling in the output capacity of the ten largest manufacturers, this has resulted in India being able to produce electricity more cheaply using solar cells than by burning diesel (Pearson, 2012). It is important to note that demand and therefore price is not only affected by an increase in supply, but also changes in tariffs. This is particularly true in the UK where panels may operate less efficiently due to lower levels of sunlight, resulting in an increased dependency on ‘feed in tariffs’.

1.4.2 Wave and Tidal

Wave power is a highly predictable resource, more so than wind. Tidal range and tidal stream are also highly predictable with a potential resource of 16TWh per year in the UK alone. Despite the vast potential of tidal resources, the technology is not mature, with only a handful of in-stream tidal current generators in operation.

Clean current Renewable Energy Systems deployed a tidal current generator at the Race Rocks Ecological Reserve in Canada in 2006, its Tidal In-Stream Energy Conversion (TISEC) is now licensed to Alstom who are industrializing the technology (Clean Current, 2012). SeaGen installed the world's first commercial scale 1.2 MW tidal stream generator in Strangford Lough in April 2008.

The UK has 3.4 MW of marine energy installed in 2011 with 60 MW planned for deployment by 2014 (Renewable UK, 2011). According to renewable UK numerous deployment scenarios exist for installed capacity by 2020 some of which are in the multiple GW scale. However to reach the point where hundred MW scale arrays are deployed the risk currently associated with marine energy must be removed, this will allow more rapid expansion and deployment of the technology.

Korea are also investing heavily in tidal power with several multiple-hundred MW barrages including 812 MW by Daewoo near Ganghwa Island and 1.32 GW proposed at a site west of Incheon. With regards to tidal stream, Hyundai Heavy Industries installed a prototype 500 kW tidal current generator at Uldolmok Passage in south west Korea. Hyundai are part of a government backed project to develop a 90 MW tidal current farm by 2014 (Hyundai, 2012).

1.4.3 Wind Power

Wind power currently has a global installed capacity of 239 GW with 42 GW of new generation installed in 2011 (WWEA, 2012). Europe is at the forefront of wind turbine research and development, represented by 44% of global installed capacity in Europe. Denmark produced 28.3% of its power in 2011 from wind (BP, 2012).

China has experienced immense growth in its wind industry, with an annual growth rate of 39.4% in 2011. This makes it not only the largest but also the fastest growing wind market in the world. As was the case with solar PV, this rapid growth is likely to result in reduced costs due to economies of scale. The difference being that wind turbines are not only produced in China but are also being consumed by the domestic market therefore giving Chinese developed wind turbines provability on a very large scale.

Despite its benefits in terms of energy security and greenhouse gas emissions, the issue of intermittency can be highlighted by using Portugal and Spain as an example, where, in 2011 electricity generated fell despite an increase in installed capacity, this was due to lower than normal wind speeds.

Concerns regarding offshore installation vessels - a lack thereof may result in a bottle neck until vessel construction catches up.

1.5 Previous Studies

1.5.1 Wave and Tidal REA

A regional environmental assessment (REA) has been undertaken on marine renewable energy, the scope of which includes all territorial waters of Guernsey, Herm and Sark to within 3 nautical miles of the coast. The REA however excludes the development of wind energy (Commerce and Employment, 2009).

1.5.2 Halcrow Consultancy Report

An initial feasibility study has been produced by consulting engineers Halcrow Group Ltd with the aim of understanding the constraints that are applicable to the development of offshore wind energy on Guernsey. It was concluded that there is a viable wind resource; energy yields and their associated costs are likely to be comparable to other offshore generation sites within the UK.

The study states that there is only one suitable deployment zone which is off the North West coast of Guernsey, at the time of writing there was no local weather station close to the potential deployment site. The following recommendations were made by Halcrow to allow the development to be taken forwards:

- The wind resource should be verified by a weather station with close proximity to the potential deployment site.
- Environmental risks that have not been covered by Halcrow should be evaluated and addressed.
- A landscape and visual assessment should be undertaken.
- Further study into public attitudes.

1.6 Scope and Objectives

This study is limited the 3nm limit of Guernsey's territorial waters.

On 3rd November 2011 an anemometer located at Chouet started generating data; this is the closest onshore site to the potential deployment zone outline by Halcrow. To date, this gives a total of 6 months of wind data at close to the potential deployment zone. This report will verify the Chouet data against that of the airport, by establishing a close correlation between data from the two sites ensure its accuracy and viability in quantifying the potential wind resource can be verified.

Further to the recommendations made by Halcrow, a more comprehensive assessment of current wind turbine technology will be undertaken to ensure maximum efficiency in the wind climate around Guernsey.

Other areas to be covered include analysis of grid integration including the impact of intermittent generation on the Guernsey grid, calculating the predicted power output of an offshore turbine array and assessing the possible requirement for balancing technologies such as energy storage.

As a very comprehensive environmental scoping study has already been undertaken for wave and tidal, this document will compare and contrast the differences between the two technologies (wind vs wave/tidal) with respect to the their environmental impacts with the aim of highlighting possible ways to mitigate the impact.

Visual impact is seen as a significant barrier to the implementation of near-shore wind in Guernsey waters. This report aims to provide visual representations of multiple deployment scenarios from different onshore perspectives, then analyse the possibility of mitigating the impact through alternative site selection or modifying the deployment layout at the current potential deployment site.

2 Technology

2.1 Wind Turbines

Siemens AG are the world's largest manufacturer of offshore wind turbines, in terms of overall megawatts sold Vestas, Sinovel Wind Group and Xinjiang Goldwind are the top manufacturers; according to new energy finance analyst Eduardo Tabbush, they will remain so through to 2015.

2.1.1 Reliability

Offshore turbines need to be more robust when compared to onshore; this is particularly the case on Guernsey due to its relatively remote location. Other access problems that can affect schedules maintenance includes weather conditions at sea.

Whether or not offshore wind turbines are feasible therefore depends significantly on the reliability of the turbines and associated drivetrain, this is often quantified by proven installations and the track record of a particular model. The following sections will discuss the various wind turbine technologies currently in use with an emphasis on reliability and provability.

2.1.2 Direct Drive

It is well known that the gearbox of a wind turbine can be prone to failure and is both costly and time consuming to repair or replace. This can therefore incur significant costs not only in replacing parts and costs associated with transportation and installation, but also as a result of the turbines downtime i.e. the cost of backup generation.

Nordex, GE Energy, MTOI, Enercon, Multibrid, Alstom and Siemens are all working on direct drive turbines with the aim of reducing component failure simply by reducing the number of components. They have no gearbox and fewer bearings, however as a result of this the chance of failure of components within the generator may be increased, this includes generator gearings, windings, laminations etc.. Interactions between magnetic loads in the generator, turbine loads and bearing reliability are not fully understood (Coultate, 2009)

The gearbox functions to convert the slow rotational speed of the rotor (~10 rpm) into the fast rotational speed required by the generator (~500+ rpm depending on number of poles etc.). Removing it therefore requires use of an annular generator with many poles rotating around the stator, enabling it to produce similar power figures but at lower rpm (Enercon, 2012a).

Slower rotational speeds should reduce wear also the reduced number of components also increases reliability, however lack of a gearbox also results in increased variability in the generator speed and therefore output voltage. As a result of this, more complex power electronics may be required to properly regulate the output electricity supply. This is particularly the case for permanent magnet generators (PMGs) which can be used in direct drive turbines to do away with need for very large diameter nacelles that result from the high number of copper windings required. (Increased number of windings increases the size and weight of the nacelle).

Siemens, GE energy and Alstom use PMGs in their new offshore turbines whereas Enercon use electromagnetic (EM) pole shoes. Alstom claim their high density PMG is more compact and lighter than previous generations.

In March 2012 Alstrom inaugurated the largest offshore wind turbine in the world. The 6 MW Haliade 150 uses direct drive, following year-long tests and a second turbine to be installed off the Belgian coast, full scale production of this model is expected in 2014 (Alstom, 2012).

2.1.3 Hybrid Systems

At halfway between direct drive and geared systems, hybrid drive attempts to take the benefits of both. They use a simplified gearbox with perhaps one or two geared stages (making it simplified and lighter compared to standard gearboxes). The generator used then has less poles than with direct drive but more than with a normal gearbox system, this results in the gearbox and generator being of similar size facilitating maintenance. Areva has incorporated hybrid technology into its M5000 turbine; this is a turbine that has been exclusively designed for large offshore wind farms.

2.1.4 Redundancy

This can be another potentially effective method for mitigating reliability issues at sea, it essentially uses the opposite strategy of direct drive systems. Rather than decreasing the part count key components are duplicated making the turbine partially redundant, remote monitoring systems then improve the overall management of the system ensuring improved uptime.

This strategy has been adopted by WinWind whose WWD-3 turbine (3 MW) uses two 1.5 MW converters running independently in parallel, its auxiliaries are also independent and redundant. Losses are reduced by only using one converter during times of low wind speed, this also improve the longevity of the other converter as it is subject to less wear when under standby duty. (WinWind, 2012).

Clipper Wind's 2.5 MW liberty design has a single speed gearbox driving four compact and lightweight generators, not only does this provide redundancy as the powertrain can run on only two or three generators, but it also aids in maintenance as the lightweight generators can be serviced by Liberty's onboard jib hoist. So there is no need for costly cranes etc.. (Clipper, 2012).

2.1.5 Vertical Axis Wind Turbine (VAWT)

Some still argue that using horizontal axis wind turbines (HAWT) still has a number of disadvantages compared to vertical axis (VAWT), namely, if a blade is rotating perpendicular to the ground it has to overcome gravitational loading. This increased load increases the wear and fatigue on drive train components. Other advantages include lack of requirement for a yawing mechanism and easier construction methods when out at sea. Wind Power Ltd believes that offshore turbines can be made more robust if a VAWT design is used. Conceptual designs are currently being developed by the Energy Technologies Institute (ETI) in the UK with a Novel Offshore Vertical Axis (NOVA) system to be installed in 2015 as a demonstration (ETI, 2012). From its design the system is said to be significantly cheaper to construct and more reliable.

2.1.6 Conventional Multi Geared Drive

This is by far the most proven technology; all the other technologies described here have limited experience offshore as a result of this it is often the technology of choice.

For this reason, Vestas have opted to go down this more conservative route when developing their next generation V164 7 MW turbine. It uses a medium speed drivetrain with a multiple stage planetary/helical gearbox similar to the one found in their V112 3 MW turbine.

As the industry continues to grow and direct drive and hybrid systems become more proven in offshore environments, they may become more economically viable and represent a viable option for Guernsey.

2.2 Foundations & Structures

Things to consider when looking at foundations are the water depth, turbine and wave load, installation demands and installation time. These will also determine the overall cost of the project.

As the majority of conventional structures have been covered by the Halcrow, this report will concentrate on novel designs including those that made the final shortlist in the Offshore Wind Accelerator (OWA) initiative (Carbon Trust, 2012). This is to give an idea of the potential technology that may be applicable to Guernsey in the near future.

2.2.1 Suction Bucket

Suction buckets are a novel foundation type that are said to benefit from over 40% less weight than the equivalent monopile at the same location, a prototype has been installed at Frederikshavn with a Vestas V90-3 (Ibsen et al., 2005). A similar test project also underway in Qidong (NW of Shanghai) developed by DaoDa Heavy Industry Group.

Suction lowers the pressure between the bucket and the sea surface therefore reducing the penetration resistance around the tip of the skirt. Large horizontal loads and overturning moments are said to be overcome by the vertical bearing capacity of the bucket and earth pressures on the skirt (Ibsen et al., 2005).

More simple welds and lack of a transition piece reduce the overall complexity. The reduced weight allows for installation by smaller vessels, also as no pile driving is required, installation costs are reduced.

SPT Offshore have developed suction pile clusters (SPC) which use three separate interconnected piles (tribucket), they represent a higher capacity versus weight ratio compared to single suction piles (SPT Offshore, 2012). The tribucket system has benefits to the single bucket, i.e. the entire foundation structure is assembled in port.

2.2.2 Gravity Structure

Use of concrete foundations is both cost effective to manufacture and more stable in terms of market price fluctuations. Standard technologies are used which are proven within the offshore industry (GBF, 2012) to depths of 20-55m.

Slipforming stem reduces production time; a consistent mix is required so that it behaves in a predictable way. This allows for fast production by conventional land based civil engineering contractors (Brook-Hart et al.,). The entire structure can be cast in a dry dock which is then flooded allowing for easy transportation to the deployment site.

A major barrier to implementation is the practical handling of large concrete structures; section 5.1 contains information on installation and the potential lack of available specialised vessels. However work is underway to develop bespoke vessels (Carbon Trust, 2012), avoiding the need for jack up barges or floating cranes.

Although gravity structures can be installed on a variety of sites with a range of seabed conditions, they are sometimes associated with an increased environmental impact due to their footprint and the extensive seabed preparations that are required. For example in the Thornton Bank wind farm, an average of 90 000m^3 was dredged per foundation pit (measuring 50m by 80m); a depth of 7m below the surrounding seabed was achieved. Once the pits had been dredged a gravel foundation was laid and some the dredged material was used as infill for the foundation (Peire et al., 2009).

French engineering firm, ‘Rockmat’, aim to reduce both the deployment and decommissioning costs through the use of a novel installation technique which removes the need for site preparation and specialist installation vessels. A 100-Te tug boat is used to tow the GBF to the deployment zone, then three 10-Te tugs are used to accurately position GBF during ballasting. Hydraulic jacks are used to adapt to seabed irregularities that are greater than 1m, concrete is then sequentially injected into flexible cofferdam bags around the perimeter of the foundation then through its centre, ensuring a perfect fit with the seabed (Rockmat, 2012).

2.2.3 Monopile

Monopiles are by far the most mature technology for offshore wind with 75% installed by the end of 2008 and 50-60% projected for 2011 to 2015/20 (NRG Bluewater, 2010). Halcrow identified monopiles being used in depths of up to 20m, with increasing depths possible due to vessels being able to carry the extra weight.

In September 2010, IHS Emerging Energy Research stated in an advisory note that dissolved grouting has caused turbines with monopile foundations at 600 out of Europe’s 948 offshore turbines to be prone to shifting, for example the transition piece on Egmond wind turbine generators were discovered to have slid down the pile (Nordheim, 2011). Retrofitting problematic foundations could cost up to 120k euros per turbine (Deign, 2011).

In new developments a possible solution is to change the shape of the grouted section, forming a cone shape (this was implemented in the London array). Other offshore farms which do not suffer from the problem include Scroby Sands which uses a bolted flange connection rather than grouting, and the Beatrice wind farm in Scotland, using a technique known as ‘Hydra-lok’ (Hydraulic force is used to make a structural connection between foundation and pile). It seems that the only structures not affected are those using shear keys (Stancich, 2011).

2.3 Electricity Grids

Historically, the design and structure of electricity grids were strongly influenced by the location of power stations (which themselves are strategically located according to availability of a fuel source) and proximity to demand centres. Modern grid infrastructure is highly interconnected, and while this has the benefit of improved power smoothing; there is an increased vulnerability to cascading effects that may result in wide-area power outages (CRO Forum, 2011).

In the past, spare infrastructure capacity served as a shock absorber; however as competition between utilities drives profit margins, spare capacity is reduced (Amin and Wollenberg, 2005). The nature of renewable energy generation further complicates matters as it is intermittent and deployment locations are often where the natural resource is greatest making interconnection difficult.

The following subsections will review smart grids and energy storage, along with their role in dealing with intermittent generation.

2.3.1 Smart Grids

A ‘Smart’ Grid can mitigate the issues associated with renewables by making every node in its network adaptive and responsive in real-time. In order to achieve this there needs to be independent processors in every component, enabling the component to assess its own condition through the use of sensors and communicate this to nearby components (Amin and Wollenberg, 2005). Such intelligent equipment allows the use of decentralised or hybrid distributed control negating the requirement for central control which can be slow and unresponsive. The use of ‘peer to peer’ connectivity in this fashion will allow more and more grid connected devices to be installed with minimal impact, improving stability, capacity and enabling a self-healing type of infrastructure.

Benefit-to-cost ratio of the Smart Grid was estimated by the Electric Power Research Institute (EPRI) in 2011 to be between 2.8 and 6. Benefits include:

- A reduction in power disturbances,

- Reduced CO_2 emissions,
- Improved operational efficiency,
- Optimised utilisation of current generating capacity
- Accommodation of all types of generation and storage options.

(Amin and Wollenberg, 2005; EPRI, 2012)

A real-world example of where intelligent systems may be implemented to wind generation is in the real time monitoring of wind speed and thermal properties of over-head power lines. During periods of high wind speed and therefore increased generation, transmission lines have increased dynamic thermal ratings allowing them to be more efficiently utilised by carrying more load. (EPRI, 2012; Birkbeck and Nicholson, 2012).

Renewable resources, particularly wind generation offers a high level of controllability, power is instantly available and can be throttled during periods of high wind speed, smart systems would be able to take advantage of this.

2.4 Energy Storage

Energy storage is becoming increasingly more important as we increase the proportion of intermittent generation that is supplied to the grid. Currently we only store around 10-20% of the energy produced by a renewable energy system (Laird, 2012), this is used to smooth out the variability experienced from this type of generation and reduces the ramp rate both up and down. The ramp rate is the amount of load you can add to a generator per unit time, the faster this is the more flexible the power source. So decreasing this value enables greater compatibility of the power source with the grid and gives more control to preventing spikes from hitting the grid.

Wind resources respond on the timescale of seconds and can be unpredictable. Turbine power is shown by (Leadbetter and Swan, 2012) to vary from 20% to 95% of monthly averages within only a 10 minute time period. In addition the wind resource may decrease as electricity demand increases requiring conventional generation to have quicker ramp rates compared to simply meeting normal demand alone (Leadbetter and Swan, 2012).

- System Regulation – meet short term demand spikes and fluctuations, can alleviate or avoid the need for frequency regulation by the plant.
- Time Shifting
- Load Levelling – Storage of energy where generation exceeds demand (e.g. wind energy generated at night), in order to meet increased or peak demand. (Dell and Rand, 2004)
- Peak Shaving – “Energy storage accommodates the minute-hour peaks in the daily demand curve.” (Dell and Rand, 2004)

There are a number of storage solutions that are capable of performing the above, all of which have the aim of providing more reliable and higher quality power, cost savings by deferring potential grid upgrades or the implementation of new generating capacity. Emissions are also reduced by reducing the requirement for backup generating capacity.

Due to standardisation of battery chemistries, batteries are usually considered by technology rather than the manufacturing company so decisions are driven by the requirements of the consumer and there is little brand loyalty (Peterson, 2012), for this reason a study has been made on the different types of energy storage technologies currently available, details of this can be found in Appendix F.

3 Quantifying the Wind Resource

For the purposes of this study, it is important to properly quantify the available wind resource on Guernsey, at present the measurement equipment available includes an anemometer at the airport (Long/Lat: 49.4331°, -2.5981° (Gladstone, 2012) which is centrally located, 10m above the runway (Crozier, 2012). Following the Halcrow report, there was a second anemometer installed at Chouet in the north east of Guernsey. This started generating data on 3/11/2011 and records wind speed and prevailing direction on a minute by minute basis.

In addition to the methods already employed by Guernsey, there are a number of methods that can be used to measure wind speed, with varying degrees of accuracy. Measurement techniques such as SODAR and LIDAR have already been reviewed by the Halcrow report; this report will therefore only cover wind models, a review of factors affecting wind speed will also be undertaken to improve our understanding of wind data that has already been obtained from anemometers on Guernsey.

3.1 Wind Models

3.1.1 Measure Correlate Predict (MCP)

MCP refers to an algorithm that predicts the wind resource at a target location for wind energy development. It uses physical data as an input such as long term data from the National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR).

The MCP module for windPRO is capable of full MCP analysis including: ‘Measure’, using time series data. ‘Correlate’ by extraction of concurrent data with correlation analysis, and ‘Predict’ through the use of linear regression, matrix method, wind index and Weibull scale.

As models are better understood and their accuracy is improved, NCEP, NCAR and other such datasets are often reanalysed.

3.1.2 Atmospheric motion vectors (AMV)

Satellite imagery is used to identify targets such as clouds and water vapour; these are tracked using advanced pattern matching techniques based on cross correlation statistics. Sequential images are taken at regular time intervals with a target being selected from the first image, the images that follow are analysed for well-matched areas. However if the gap between images is too long then the cloud pattern and characteristics can change reducing the number of matched areas (Park et al., 2012).

Once processed, these atmospheric motion vectors are used to identify synoptic scale motion for weather analysis (Jedlovec et al., 2000): Use of high resolution visible channel images can also be used to estimate mesoscale flows (Bedka and Mecikalski, 2005), motions of this order would be more applicable at the scale of offshore wind generation, however the resolutions are still likely to be too low for use at a specific deployment site.

3.1.3 Virtual Met Mast

Virtual met mast is a wind velocity prediction tool developed by the met office that provides mean wind speed, wind direction, wind shear, turbulence intensity and air density with long term historical data available up to 21 years in a 10 year time series. The system can produce site specific data down to a resolution of 100 m and at a specified height above sea level, even finer resolutions possible using high resolution downscaling.

The data is known to be accurate as it has been proven against 60 UK sites, accuracy is said to be within 0.1 meters per second in the case of offshore wind speeds (Met Office, 2012).

3.1.4 3Tier Prospecting Model

3Tier is a company specialising in renewable energy risk analysis including project feasibility, energy marketing and asset management tools for wind, solar and hydro (3Tier, 2012a).

The wind component of the 3Tier dataset is created through the incorporation of advanced mesoscale NWP (Numerical Weather Prediction) and wind data from meteorological towers based worldwide (3Tier, 2012b). Hourly values are available down to a resolution of approximately 5km covering all continental and near shore areas between 60°S and 70°N. It is acknowledged by 3Tier that regardless of the high resolution data available, small spatial features are not well resolved, as a result, local sheltering may result in lower than predicted wind speeds and similarly isolated bluffs and hills will likely have higher wind speeds (3Tier, 2009).

For the purposes of validation, wind speeds have been compared with 764 meteorological stations within Europe from National Centres for Environmental Prediction (NCEP) Automated Data Processing (ADP) surface observations dataset. NCEP ADP data is compared to 3Tier data at a level of 10m although some sites may be slightly lower than this, European data is considered to be of high quality (3Tier, 2009).

3.2 Factors Affecting Wind Speed

Forecasting of wind is very important as it has implications to maritime and aircraft operations, and weather prediction. Pressure gradient is a key parameter in understanding wind speed, the difference in air pressure between two locations results in the flow of air from high to low pressure. A larger difference in air pressure would therefore result in increased wind speeds.

The sun combined with atmospheric forces drives almost all physical processes at sea. Solar energy is the dominant source of energy; this in turn heats the oceans which drives atmospheric circulation. Non-uniform heating of the ocean's surface coupled with uneven heat gain and heat loss gives rise to winds in the atmosphere. Synoptic scale circulation in the atmosphere is driven by solar heating in the equatorial region and cooling at higher latitudes.

Surface winds change with the season, although the earth's mean distance from the sun is 1.5×10^8 km, its orbital eccentricity means that its actual distance from the sun varies by 5×10^6 km (NASA, 2012) therefore resulting in varied solar intensity at different times of the year. Furthermore, the earth has an axial tilt of 23.45° (IERS, 2012) which results in maximum solar heating between the tropics of Cancer and Capricorn which lie 23.45° north and south of the equator respectively, depending on the time of year.

Infrared emission from the sea surface and sensible heating of the sea surface by hot or cold winds are important exchanges of energy that occur at this boundary. Sea surface interaction is therefore a very important contributor to weather and climate patterns namely wind speed and direction.

Sea to air heat flux is related to the mesoscale convective system and prevailing synoptic pattern (Kung and Siegel, 1979), it also depends on the profiles of wind, temperature and moisture in the atmospheric boundary layer all of these parameters are encompassed by the bulk transport equations**.**

3.2.1 Weibull/ Rayleigh distribution

A continuous probability distribution used to describe the size of particles, but can be applied to describe wind speed distributions as the natural shape often closely correlates with the Weibull shape. Knowing the average wind speed at a particular location will enable us to predict how often different wind speeds will be experienced and the probability distribution of this to occur.

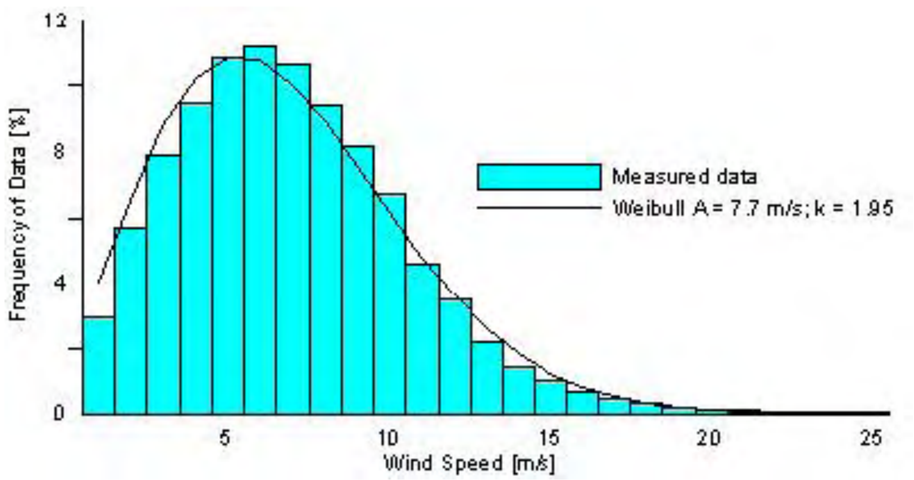

Figure 3-1 Weibull Distribution of Wind Speeds (Mean: 7.7ms^{-1})

(EMSD, 2012)

The distribution depends on the shape parameter often denoted by *k*. At most locations in the world the shape factor is around 2. A shape factor of 2 results in a Rayleigh Distribution.

3.2.2 The Planetary Boundary Layer

This refers to a thin viscous layer just above the sea surface that is affected by frictional forces and heat fluxes. The thickness of this layer depends on a number of factors such as wind speed and sea surface temperature, for example where the water temperature is less than that of the air and wind speeds are slow, the boundary layer thickness may be of the order of only a few 10s of meters. For a warmer sea and faster wind speeds, the boundary layer may be up to a kilometre.

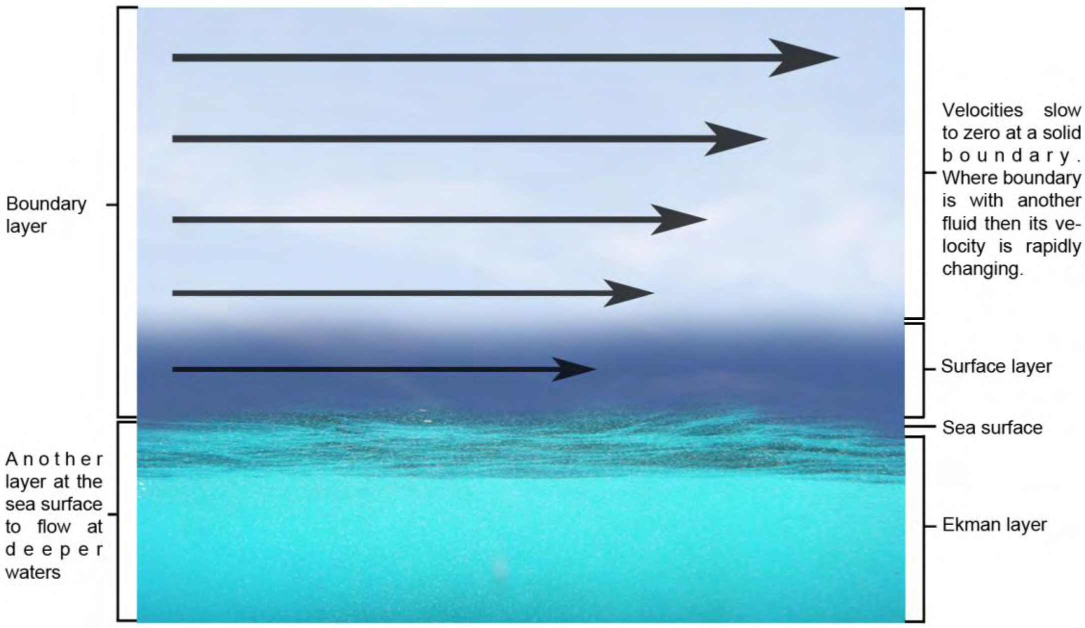

Figure 3-2 Planetary Boundary Layer

The surface layer above occupies approximately 10% of the overall boundary layer, vertical heat flux and momentum are almost uniform in this region and wind speed increases as a log of height. It is for this reason that wind speed measurements acquired at a height of 10m need to be extrapolated up to the hub height of a potential wind turbine.

The Gradient Height refers to the height at which wind is no longer affected by frictional forces, i.e. the height of the planetary boundary layer.

The wind stress (τ) is a shear force exerted by the wind on the sea surface, it can be defined as follows:

$$\tau = \rho C_D U_H^2 \tag{3-1}$$

Where:

$\mathrm{C_D}$	Drag Coefficient
$\mathrm{U_H}$	Wind Speed (U) at height (H) above water
ρ	Density of air (1.3 kgm^{-3})

3.2.3 Turbulence

Turbulence is the influence the boundary has on the interior flow. It is an eddying motion that causes continuous mixing of fluid elements resulting in a major source of energy loss (Apsley, 2009).

It arises from the nonlinear terms in the momentum equation, the importance of which is defined by Reynolds number (the ratio of non-linear terms to viscous terms). Turbulent effects are only relevant within the boundary layer (Anderson, 2005).

A process known as Reynolds averaging can be used to predict turbulent flow; this is achieved by first decomposing each flow variable into a mean value ($\bar{u}$) plus a fluctuation (u'). Turbulence contributes a factor to this value (Equation (3-1)) known as the turbulent stress or Reynolds stress (τ'):

$$\tau' = -\rho \, \overline{u'v'} \tag{3-2}$$

Stress is the net flux of momentum per unit area. Any fluid moving along a boundary will experience shear stress at that boundary, at sea this results from the wind blowing across the sea surface and it is how the momentum of the wind is transferred to the sea. The wind stress is defined in equation (3-1).

3.2.4 Surface Roughness Length

This refers to the relief characteristics (or roughness) of the terrain, the value of which depends on the frictional effect of the ground on the wind passing over it. It is technically defined as "the height at which the wind speed reduces to zero when extrapolated down using Monin-Obukhov similarity theory." Put simply, it is a one dimensional length (height in meters) relating to the surrounding terrain (Peña, 2009).

Where an even and homogeneous surface is present, the mean velocity profile can be calculated from the logarithmic wind profile:

$$U(z) = \frac{u^*}{k} l_n \left(\frac{z}{z_0}\right) \tag{3-3}$$

Where:

z	Measurement Height (m)
z_0	Roughness Length (m)
u^*	Friction velocity/ Shear velocity (sometimes denoted (u_τ)
k	0.4 (Von Karman constant)

Due to surface layer friction, the analysis of wind speed data from a particular site must first be normalised to account for anomalies in the terrain downstream of the mast. It is advised that exposure correction in this manner can only be effective where the roughness length is around 0.5m or below (EPA, 2000). As the Chouet mast is situated in a coastal location, it experiences wind from both land and the sea, so both scenarios must be accounted for.

Where wind has fetch over open sea, the aerodynamic roughness length is significantly reduced due to the more homogeneous nature of the sea surface. In this scenario it is possible to use Charnock's relationship to express sea surface roughness as a function of friction velocity:

$$z_0 = \alpha \frac{u^{*2}}{g} \tag{3-4}$$

Where:

g	9.81 (Gravitational constant)
$\propto$	0.014 (Empirical constant)

Surface roughness over land is more difficult to estimate and depends on a number of factors; The effective roughness length can be calculated by taking a standard deviation of the wind speed (s_u) and wind direction (s_d):

$$\frac{s_u}{U} = c_u k \left[ln \left(\frac{z}{z_{0u}} \right) \right]^{-1} \quad \textbf{(3-5)}$$

$$\frac{s_v}{U} = c_v k \left[ln \left(\frac{z}{z_{0u}} \right) \right]^{-1} \quad \textbf{(3-6)}$$

Where:

z_{0u}	Effective roughness length of the terrain upstream (station specific)
z_0	Roughness length (Grid value)

If it is assumed that raw unfiltered wind data is used then values, $k = 0.4$, $c_v = 1.9$ and $c_u = 2.2$ can be used. However if a degree of filtering is applied due to the measuring technique used by the anemometer then values of c_v and c_u will need to be reduced accordingly.

Roughness effects can be normalised by first calculating the site specific effective roughness length according to sector averaged wind directions using equations (3-5) (3-6) and (3-4)**.** These can then applied to the equation for logarithmic wind profile (3-3) to extrapolate up to the appropriate height, in our case the hub height is circa 80m (Vestas V90-3MW has a hub height of 80-90m).

Use of the logarithmic wind profile equation (3-3), however, requires calculation of the wind shear velocity or friction velocity(u^*).

In practice, a value for wind shear is rarely evaluated for a given site (Anonymous2000); given the data available on Guernsey, a more simplified approach can be adopted by using the terrain classification chart Table 3-1 to provide estimates for the roughness length (z_0). This is achieved by simply undertaking a visual survey of the area and comparing these observations to the terrain descriptions.

Terrain Description	z_0 **(m)**
Open sea, fetch of at least 5 km	0.0002
Completely open terrain with a smooth surface, e.g. concrete runways in airports	0.0024
Open flat terrain; grass, few isolated obstacles, softly rounded hills, very scattered buildings	0.03
Agricultural land with some houses. 8m tall hedgerows within a distance of 1.25km	0.055
Agricultural land with some houses. 8m tall hedgerows within a distance of 0.5km. Low crops, occasional large obstacles, $\frac{X'}{H} > 20$	0.1
Agricultural land with many houses. 8m tall sheltering within a distance of 0.25km	0.2
High crops, scattered obstacles, $15 < \frac{X'}{H} < 20$	0.25
Small towns, forests, very rough and uneven terrain	0.4
Parkland, bushes, numerous obstacles, $\frac{X'}{h}$ 10	0.5
Regular large obstacle coverage (suburb, forest)	0.5 - 1.0
Very large cities with tall buildings and sky scrapers	1.6

Table 3-1 Terrain Classification

Modified from (EPA, 2000; Ragheb, 2012)

x	Typical distance to upwind obstacle
h	Height of obstacle

It is then possible to use the simplified logarithmic wind profile equation:

$$U(z) = U_{10}\ \frac{ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{10}{z_0}\right)} \tag{3-7}$$

This assumes an anemometer measurement height of 10m. In all cases, when applying the above formulae, strong wind speeds of above 4 meters per second should be used. Raw wind data will need to be filtered so that only wind speeds above this value are included in any analysis.

3.2.5 Other types of exposure correction

It is also possible to correct exposure using factors that account for flow distortion $(\mathrm{C_F})$ and topographic effects $(\mathrm{C_T})$:

$$U_c = U.C_F.C_T.\frac{ln\left(\frac{10}{z_{0u}}\right)}{ln\left(\frac{z}{z_{0u}}\right)}\ \frac{ln\left(\frac{60}{z_{0u}}\right) ln\left(\frac{10}{z_0}\right)}{ln\left(\frac{10}{z_{0u}}\right) ln\left(\frac{60}{z_0}\right)} \tag{3-8}$$

3.2.6 Averaging Wind Direction

It is important to note that exposure correction is a function of wind direction, as mentioned earlier this is particularly true for the Chouet mast. Conventionally wind data is averaged into sectors; this allows for the calculation of roughness length depending on upstream conditions, and eliminates the problems that may arise from averaging wind that has a highly variable prevailing direction. For example, wind prevailing from 0° and then from 180° would cancel out, similarly wind prevailing from 330° to 30° would average at 180° using conventional averaging methods. Three scenarios have been compiled each of which applies different values of surface roughness; this is outlined in more detail in section 7.1.

It is possible that the direction vane on the anemometer may fluctuate between two points; if this is the case then direction should be estimated using an average of the two points through which the vane was fluctuating.

For the purposes of this study sector sizes of 60° have been used giving a total of 6 sectors each represented by a different roughness length. Being a small island, there isn't a wide range of land use to justify using a greater number of sectors. The wind monitoring mast at Chouet is situated on the tip of a small peninsula and benefits from having the majority of its exposure to the sea, this between approximately 258° and 57°, with fetch of at least 5km over the sea a z_0 value of 0.0002 can be utilised.

For Chouet, Scenario 2 maintains a surface roughness length of 0.0002 between 240° and 60° (clockwise) due to exposure to the sea. As shown in Figure 3-3, between 60° and 120° there is 1km to 3km of land before the sea, the contours show low lying land with minimal relief. This has therefore been assigned a z_0 value of 0.0024 as per Table 3-1.

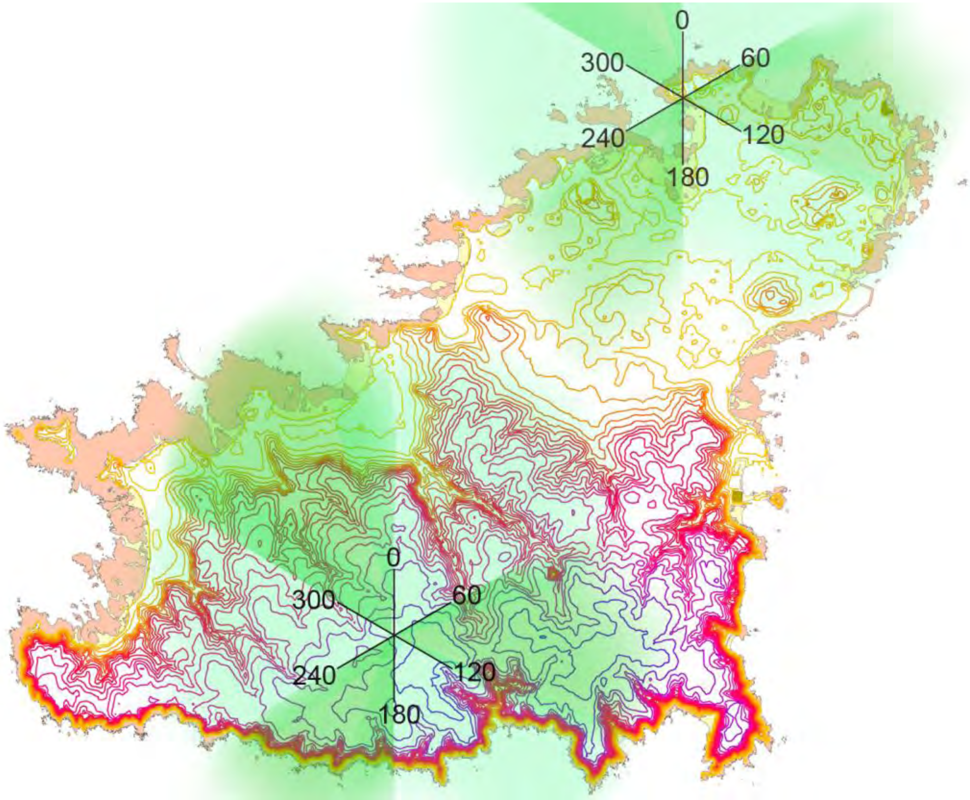

Figure 3-3 Contour map of Guernsey showing sectors

Between 120° and 180° there is 3km of land before the sea increasing to almost 9km from 170° on to 180°, the last 10° is also significantly more rough as wind has to pass over the lower half of the island which comprises of hills and valleys, a z_0 of 0.1 has been applied.

Finally between 180° and 240°, the majority of incident wind has to pass over the entire island for 9km to a maximum of around 12km. Again there are significant relief characteristics to consider, z_0 is considered to be 0.2 to account for this.

For the airport a similar method is used, for example between 0° and 60° there is a rather steep valley with close proximity to the airport (See Figure 3-3) followed by around 3km of hilly land and a further 6km of low lying land. These roughness conditions are assumed to warrant a z_0 of 0.3 in this scenario.

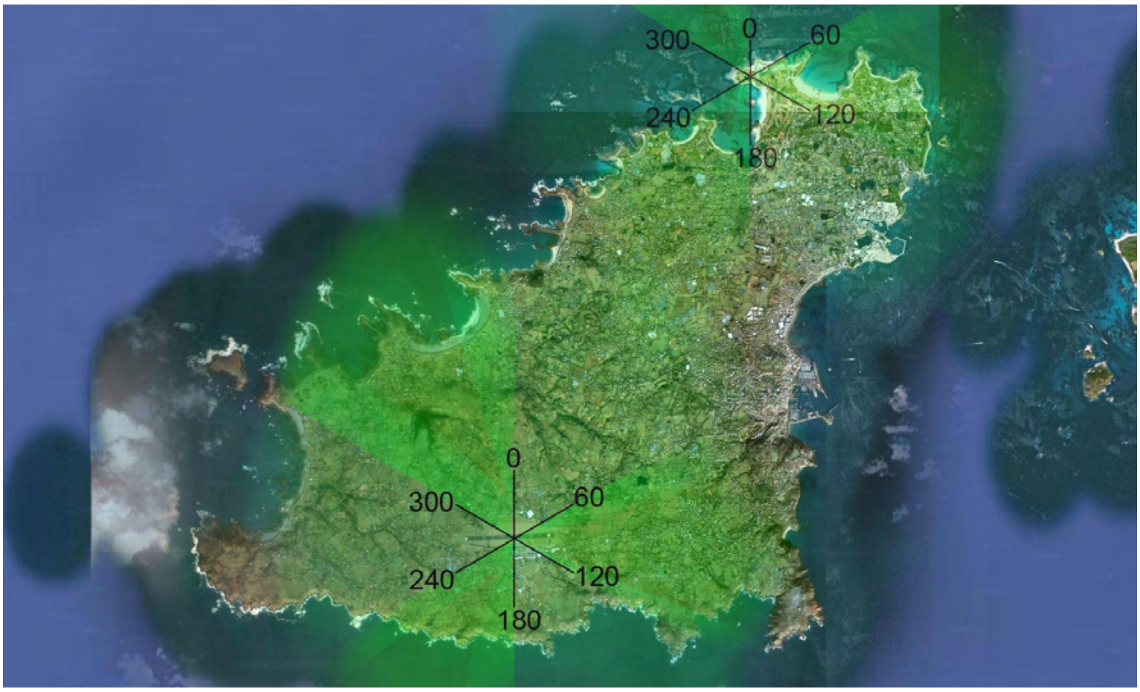

Figure 3-4 Satellite image of Guernsey showing sectors

Scenario 3 differs from scenario 2 in that it assumes lower values of surface roughness around the Chouet site, and uses more aggressive values for z_0 around the airport, this can be justified by looking at the contour map (Figure 3-3). Terrain around the Chouet site is significantly smoother and a larger proportion of sectors have prevailing wind with fetch over the sea.

4 Potential Energy Resource

After taking into account wind direction, surface roughness and extrapolating it up to hub height, it is possible to quantify the potential energy resource available. Power curve data from different manufacturers, using different types of turbine technology can then be used to evaluate their suitability at a potential deployment site.

The turbines that have been analysed can be split into three main groups according to their designed power output and swept area. The first has a rated power of around 3MW and blade diameter of 90m, the second maintains the rated output but increases the swept area by increasing the blade diameter, this yields a much improved power curve and promises improved energy capture and therefore efficiency. The third category is next generation, very large offshore turbines. These have blade diameters of up to 164m in the case of the Vestas V164.

A comparison has been made between Vestas, Enercon and Repower turbines. Vestas was recommended by the Halcrow report and provides a good baseline figure due to their use of traditional planetary gearboxes. Enercon use exclusively direct drive technology, and have a range of turbines comparable in rated output to that of Vestas. It would therefore be useful to make a comparison between the two technologies using real-life wind speed data. Repower has been included simply because of its significantly higher cut-out wind speed.

4.1.1 Average Power

The average power at a given site can be calculated by grouping historical wind data by frequency of occurrence, yielding frequency and probability distributions, Appendix A.1.3 explains the excel formula for this in more detail. A resolution of 1 m/s was deemed sufficiently accurate as manufacturers only provide turbine power curve data on this basis.

Plotting the wind speed probability distribution of a given site will yield a Weibull probability density function; if this is convoluted into the power curve of the turbine using equation (4-1), then the average power of the wind turbine can be estimated. This assumes 100% reliability of the turbine.

$$\bar{P} = \int_{U=0}^{\infty} p(U)\, P(U) dU \tag{4-1}$$

There are a number of ways to evaluate the above integral within excel, using direct summation is not very accurate, the step must be very small to approximate well and can easily lead to truncation errors.

The trapezium rule (4-2) is closer to the curve and therefore provides a better approximation, the Simpson method (4-3) is even closer as it fits a quadratic of three points (x_1, x_2 and x_3) the trapezium rule is simply a first order polynomial version of the Simpson method thus the coefficients are $\frac{1}{2}$.

$$\int_a^b f(x)dx = \sum_a^b \frac{1}{2}[f(x_1) + f(x_2)]\Delta x \tag{4-2}$$

$$\int_a^b f(x)dx = \sum_a^b \left[\frac{1}{3} f(x_1) + \frac{4}{3} f(x_2) + \frac{1}{3} f(x_3)\right] \Delta x \tag{4-3}$$

The values for average power will give a good indication as to the site specific suitability of a particular turbine model. For example, at a site of frequently low wind speeds, a turbine with a lower rated output but low cut-in wind speed will compare favourably to one with a higher rated output but an equally high cut-in wind speed. Comparing average power in this way will eliminate this bias.

4.1.2 Energy Production

As stated in (Anonymous2000), if a record of hourly average wind speeds is available from a site then this can be used directly with the turbine power curve to estimate the energy that would have been generated had the turbine been installed at the respective site.

As before appendix A.1.4 contains the excel method used. For each turbine analysed the total energy produced in kWh and capacity factors are calculated, it is important to note that these values assume 100% availability of the turbine and no downtime for maintenance etc..

Minute by minute wind data is averaged into hourly figures as per A.1.1. The use of hourly averages is significantly more accurate than using daily or monthly figures which can produce incorrect values for energy produced. For example consider a Vestas V90-3 installed at a location where the wind blows at 16m/s for 12 hours and then 10m/s for another 12 hours. Using daily averages would yield:

$$E_1 = 2837kW \times 24hrs = 68.1MWh$$

Whereas using hourly averages would yield:

$$E_2 = (3000kW \times 12hrs) + (1710kW \times 12hrs) = 56.5MWh$$

The value for daily averages is 20% greater than using hourly data. Although minute data is available on Guernsey at both the Chouet and Airport sites, this was not deemed practically feasible to analyse in excel as the volume of data would be too great.

The above also provides good justification for using a wind duration curve rather than simply estimating the parameters of a Weibull or Rayleigh distribution.

5 Costs

Offshore wind energy is inherently more expensive than its onshore equivalent both in terms of CAPEX and OPEX. Table 5-1 shows the various markets that impact on the deployment and maintenance of offshore wind.

Foundations	Interdependencies
There are only 2-3 monopile suppliers in the offshore market; however industry consensus is that there is potential for expansion/ redeployment of existing facilities. Supply chain for jacket and alternative structures is immature but experience from other industries can be applied as demand increases. Use of concrete foundations can reduce exposure to commodity risk.	• Currency [V. High] • Steel [V. High] • Recession [High] • Vessel Market [Low] • WTG Market [High] • Learning/Scale [High] • Project Demand [High]
Electrical Equipment	
Components required for electricity transmission and grid connection are in short supply in the near term. A mature and broad supply chain ensures a less volatile price. High levels of future deployment in the offshore sector will rapidly increase the demand for subsea HVDC cabling, possibly leading to increased pricing.	• Currency [V. High] • Project Demand [High] • Recession [High] • Stimulus [High] • Innovation [Moderate] • Learning/Scale [Low] • WTG Market [Low]
Installation Vessels	
Most of the cost is associated with the lease of	• Project Demand [V. High]

the main installation vessel. There is a significant lack of purpose built vessels for foundation deployment and turbine installation. Sourcing additional capacity from other industries such as oil and gas increases exposure to global oil markets and is only feasible when there is reduced construction activity in the respective industry.	• Oil [V. High] • Currency [V. High] • Recession [High] • Innovation [High] • WTG Market [High] • Foundation Market [High] • Learning/Scale [Moderate]

Table 5-1 Interdependencies of Markets related to Offshore Deployment

Modified from (BWEA, 2009)

5.1 Installation

Historically, offshore wind capital costs have been relatively stable between 2000 and 2004, early competition between manufacturers help maintain low prices early on however from 2005 onwards they have spiralled upwards; a number of factors have contributed to this:

A reduction in competition throughout the supply chain combined with competition from onshore wind for supply.

In the UK offshore wind industry over 80% of capital products are imported (BWEA, 2009) foreign exchange rates therefore plays a major role in the CAPEX of new projects, this is shown in Table 5-1 where currencies have a ‘very high’ influence on all three market sectors. Between 2008 and the beginning of 2009 the British pound (Sterling) fell almost 20% against the euro (Google Finance, 2012) resulting in significant effects on project CAPEX (DECC, 2009), especially due to the fact that offshore wind has a high euro content (BWEA, 2009).

As per Table 5-1 capital installation competes with onshore wind for the construction of wind turbines, the oil and gas industry for foundations and installation vessels, and transmission and distribution industries for electrical equipment. As the offshore market matures and there is increased confidence, a dedicated supply chain may be developed, this would reduce the interdependency seen above and stabilise the overall CAPEX.

Increased competition from growing economies in Asia; the price of lead, steel and copper has increased 376%, 100% and 200% respectively (Blanco, 2009) This has driven up the price of foundations by over 180% since 2007 (DECC, 2009).

In a study by Ernst & Young for the DECC (DECC, 2009) the megawatt-weighted average of CAPEX was £3.2m per MW, this is composed of £1.5m for the wind turbines (~47%), £0.7m for foundations (~22%), £0.6m for electrical infrastructure (~19%) (Quinonez-Varela et al., 2007) and the remaining £0.4m for planning and development costs (~12%). The British wind energy association (BWEA) also concludes a CAPEX of £3.1m per megawatt installed in 2009 with future trends showing a slight rise, followed by a fall from 2009 levels in 2015 (BWEA, 2009).

At the time of the Halcrow report, the installed price of offshore wind was described as moving from £2m/MW to nearer the £3m/MW region, it is now well above the £3m mark and looks to continue rising in the near future, with cost reductions expected further in the future, when technologies and supply chains become more mature. Arup predicts a fall of 24% between 2010 and 2020, and capital cost of between £2.3m/MW to £3.2m/MW at financial close 2010 (DECC, 2011).

5.2 Maintenance & Reliability

The reliability and availability of offshore wind turbines is of primary importance to their economic feasibility, operational costs for offshore wind are considerably higher than a comparable onshore wind farm. Costs are exaggerated by high prices present in the oil and gas industry (I.e. the daily rate of an offshore lifting crane can be 10 times higher than the onshore equivalent) and access difficulties.

For smaller offshore farms it is not feasible to purchase expensive offshore lifting vessels for maintenance, scheduling the hire of such vessels is important and has to take into account vessel location and movement as well as weather conditions. This can result in increased downtime and reduced availability. It should be noted that general maintenance tasks can be carried out with less specialised vessels, which can be purchased for the lifetime of the farm.

Windstats is a good quarterly newsletter which publishes operating information from over 12000 wind turbines operating in The Netherlands, Spain, Sweden, USA, Belgium, Germany and Denmark. Where manufacturers have turbines in full production, then fleet average availability is said to be 97% however it is not known what maintenance effort is required to achieve this level of reliability. (Cambridge Econometrics, 1999) suggest that in practise, this translates to visiting the turbine four times a year for servicing or repair.

For example, Vestas quote 99.3% availability of their Fjaldene wind farm, but this is due to its close proximity to the Vestas central service department (Petersen,). 95% availability warranties (excl weather) have been seen at around £30 000 per annum per turbine (Hassan, 2001).

5.3 Cost calculation

Calculating the cost of electricity generated can be achieved by combining actual data, using the methods discussed in sections 4 and 5, with estimated values for capital and maintenance costs discussed above.

By using the 2010 and 2011 wind data to estimate energy production as discussed in 4.1.2, the cost per unit of electricity generated can be estimated for a specific turbine had it been deployed on Guernsey during this timeframe. This will provide an accurate estimation of E which can be substituted into equation (5-1):

$$g = \frac{CR}{E} + M \tag{5-1}$$

Where

g	The cost per unit of electricity generated (£ per MWh)
C	The capital cost of the wind farm (£)
E	The annual energy output of the wind farm (MWh)
M	Operating and maintenance cost per unit output

The maintenance cost can then be estimated using equation (5-2), this gives the operating and maintenance cost per unit output of the wind farm. The factor K represents the annual operating costs as a fraction of the total capital cost. For example a maintenance cost of £79k per annum per MW installed results in a K of 2.47% assuming a capital cost of £3.2m.

$$M = \frac{KC}{E} \tag{5-2}$$

The capital recovery factor is calculated using the required annual rate of return, a baseline value of 12% was used by Ernst & Young in their analysis of levelised cost and RO banding (2009). Where x is the annual return rate and n is the number of years over which the investment is to be recovered, the recovery factor (R) is defined by equation (5-3) below:

$$R = \frac{x}{1-(1+x)^{-n}} \tag{5-3}$$

As a means for comparison, using 12% post tax nominal required rate of return, E&Y calculated the levelised cost at £144 per MWh, assuming wholesale prices of £60 per MWh they recommended 2.5 ROCs/MWh. This is assuming a baseline export rate of 38%, some industry players are suggesting load factors of 44% resulting in £124 per MWh if using the same financial model (DECC, 2009).

6 Wind Farm Layout & Visual Impact

As this report is currently limited to 3nm offshore, the visual impact of a potential offshore wind farm is of great importance to Guernsey. The benefits of installing near-shore include reductions in installation and running costs due to reduced electricity infrastructure and sea transport.

Wind farm layout is also important; a higher degree of packing can cause interference due to wake effects (González et al., 2011b). Wind flow in the wake of a turbine is slower and more turbulent so by citing turbines close together, the overall efficiency of the farm can be reduced.

A number of mathematical algorithms have been developed in order to optimise the layout of a wind farm, (Marmidis et al., 2008) uses a Monte Carlo based simulation, and (Mosetti et al., 1994) an evolutive algorithm. A recent paper by (González et al., 2011a) outlines a cost model including accounting for the main features of infrastructure design.

Figure 6-1 below demonstrates an example mutation operation performed by an evolutive algorithm (González et al., 2011b). A turbine is selected and possible feasible locations are determined, one of which is selected at random.

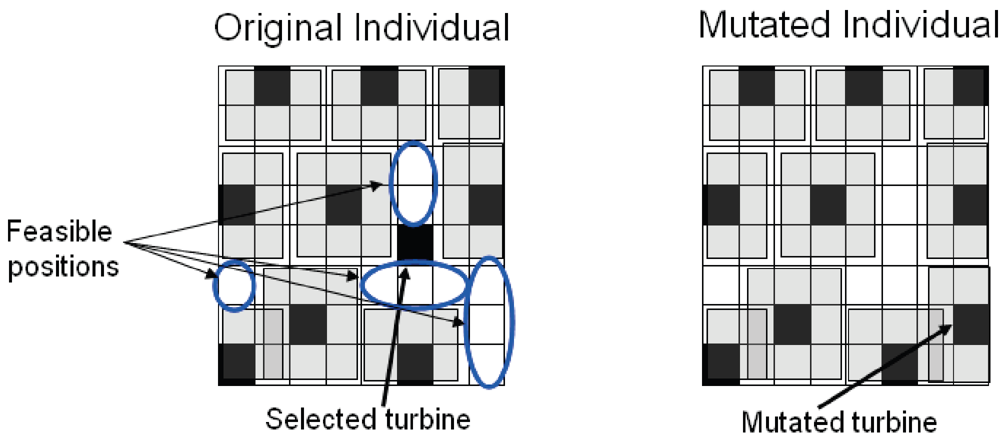

Figure 6-1 Graphic representation of a mutation operator

Above: (González et al., 2011b). Use of an optimisation algorithm as described above will result in a stochastic wind farm layout, this is shown by (Neubert et al.,) to potentially achieve a 1% improvement in array efficiency when compared to a symmetrical layout with optimised orientation.

Figure 6-2 Visual of a stochastic layout at a distance of 1.5km (80m rotors)

Figure 6-3 Visual of a symmetric layout at a distance of 1.5km (80m rotors)

(Neubert et al.,)

Figure 6-2 and Figure 6-3 above show the difference in visual impact, the significance of this was exemplified during the planning stages of the Middelgrunden offshore wind farm in Denmark.

Figure 6-4 shows a conceptual arrangement of 27 turbines in 3 rows when viewed from the beach at Kastrup (Labelled in Figure 6-5). Even though the turbines adopt a symmetrical layout, they still appear unorganised when viewed from the beach, this layout was criticised at a public hearing in 1997 (Sørensen et al., ; Vikkelsø et al., 2003).

Figure 6-4 Visual representation of 27 turbines in 3 rows at a distance of ~3.5km

(Vikkelsø et al., 2003)

The layout was then changed to 20 turbines in a curved line as defined in Figure 6-5; the circle shown has a radius of 5km.

Figure 6-5 Deployment layout of the Middelgrunden offshore wind farm

(Sørensen, 2006; Google, 2012)

Figure 6-6 shows how the single curved line leads to a more organised view when observed from the same perspective as Figure 6-4. A second hearing took place in September 1998 which focussed on the visual impact due to the controversial site selected, the hearing was passed and the layout approved.

Figure 6-6 Visual representation of 20 turbines in a single row at a distance of ~3.5km

(Vikkelsø et al., 2003)

Installing turbines in a straight line limits the mutual interference among the turbines and also the potential longevity of this interference.

Reduction in mutual interference increases turbine availability reducing the chance a turbine is in the wake of a neighbouring turbine, this decreases the risk of wind load fluctuations and therefore the potential damage of mechanical components due to fatigue.

7 Site Selection

7.1 Wind Resource

In order to properly estimate the potential wind resource, at least one year of wind data is required; the Chouet anemometer has been strategically placed close to the potential deployment zone in order to quantify the wind resource. There is currently only 6 months of data from this site, however, by observing a close correlation with airport wind data it may be possible to utilise historical airport data to get an idea on the availability of the wind resource.

7.1.1 Wind Speed

Figure 7-1 shows wind speed (m/s) as recorded by the airport and Chouet anemometers between November 2011 and April 2012. As a point of reference, the data is shown at the height as recorded by anemometer (10m) and assuming a surface roughness length (z_0) of 0.0002 from all directions (Scenario 1).

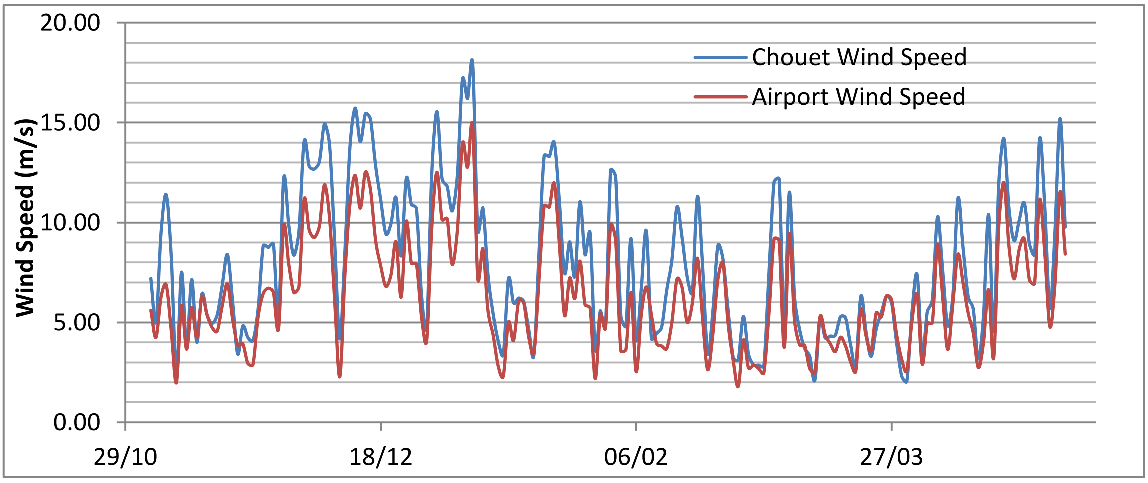

Figure 7-1 Chouet/ Airport wind speeds, averaged daily (10m)

In order to make a comparison, equation (3-7) has been applied to extrapolate the data to a hub height of 80m, again assuming a surface roughness length (z_0) of 0.0002 from all directions. Figure 7-2 is compiled from daily averages, more detailed hourly averages can be found in Appendix B.1, Figure 9-1 to Figure 9-6.

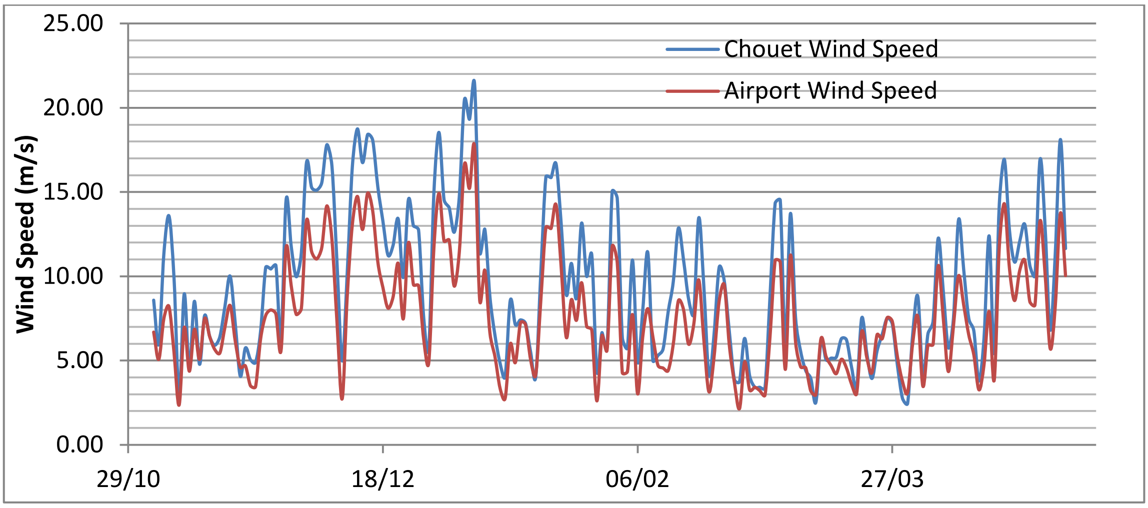

Figure 7-2 Chouet/ Airport wind speeds, averaged daily (80m)

When comparing Chouet data to that of the airport (Figure 7-1) that has not undergone exposure correction (scenario 1), a correlation can be seen between the two data sets, with the Chouet data exhibiting higher and more peaked wind speeds but still following a similar trend to that of the airport. When looking at more detailed hourly averages, the correlation is at times less clear with some time shifting i.e. Chouet will sometimes experience higher wind speeds and for longer periods of time compared to the airport. This is likely as a result of the predominant south westerly wind direction and due to the fact that the Chouet is significantly more exposed from the south west. This attribute is most evident between 5th and 8th November (Figure 9-1).

The next step was to break down the wind into six sectors according to its prevailing direction; individual values for surface roughness length (z_0) can then be applied to each sector according to downstream terrain conditions. Figure 7-3 shows the variation in wind speed as a function of height when different values of z_0 are applied to equation (3-7). A reference speed of 10 m/s is used, as this is extrapolated upwards, it can be seen that larger values of surface roughness have a greater impact on the predicted wind speed value, this is to account for the increased frictional forces that may be experienced due to downstream conditions, as described in section 3.2.4.

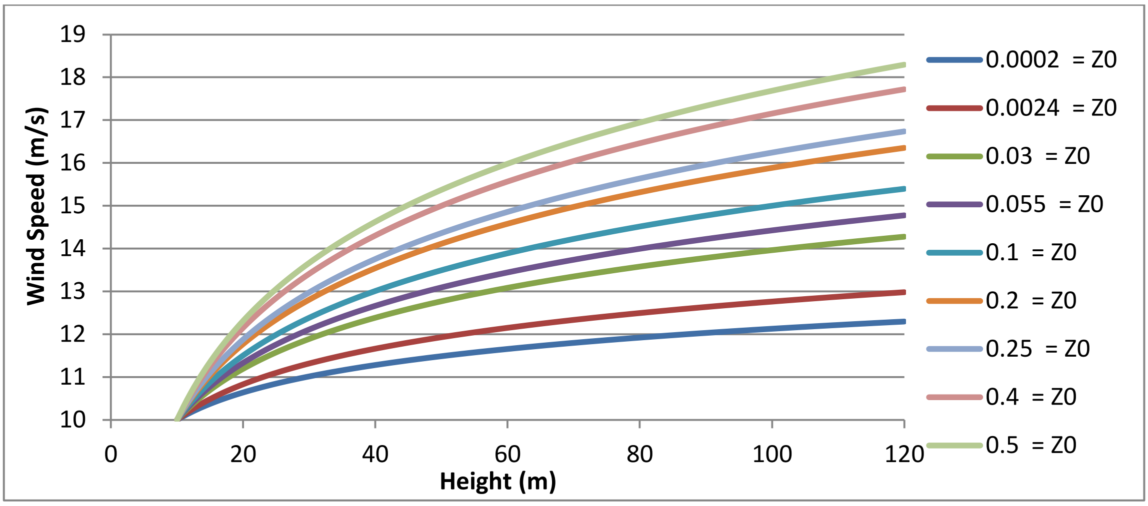

Figure 7-3 Wind Speed Vs. Height for varying surface roughness lengths

As only a visual inspection will be undertaken it is important to note that there may be significant error in the predicted values of z_0, as a result of this, three scenarios have been run to account for different possible downstream values of z_0. As described earlier, scenario 1 will assume z_0 values of 0.0002 from all directions, that is, Figure 7-1 and Figure 7-2 use z_0 values from Table 7-1. Table 7-2 and Table 7-3 show the statistical similarity between the two sites.

Chouet	z_0	Airport	z_0
Wind Speed: [0<x<60]	0.0002	Wind Speed: [0<x<60]	0.0002
Wind Speed: [60<x<120]	0.0002	Wind Speed: [60<x<120]	0.0002
Wind Speed: [120<x<180]	0.0002	Wind Speed: [120<x<180]	0.0002
Wind Speed: [180<x<240]	0.0002	Wind Speed: [180<x<240]	0.0002
Wind Speed: [240<x<300]	0.0002	Wind Speed: [240<x<300]	0.0002
Wind Speed: [300<x<360]	0.0002	Wind Speed: [300<x<360]	0.0002

Table 7-1 Scenario 1 (Sector values for z_0)

Month	2-Tailed T-Test	Chi-Squared
November	6.34275E-19	0.999183472
December	2.10152E-45	0.999256853
January	5.85738E-18	0.796814605
February	3.85429E-21	0.999996237
March	0.000114808	1
April	2.0383E-18	0.991231029

Table 7-2 Two tailed T-Test and Chi-Squared for Scenario 1

	Airport	Chouet
Variance	14.71339084	24.88323238
Mean	7.56	9.46
Standard Deviation	3.84	4.99

Table 7-3 Comparison of Airport and Chouet data for Scenario 1

Scenario 2 has been compiled by adjusting the surface roughness length to the values shown in Table 7-4, these are described in more detail in section 3.2.6. As before, Table 7-5 and Table 7-6 show the statistical similarity between the two sites.

Chouet	z_0	Airport	z_0
Wind Speed: [0<x<60]	0.0002	Wind Speed: [0<x<60]	0.3
Wind Speed: [60<x<120]	0.0024	Wind Speed: [60<x<120]	0.1
Wind Speed: [120<x<180]	0.1	Wind Speed: [120<x<180]	0.05
Wind Speed: [180<x<240]	0.2	Wind Speed: [180<x<240]	0.05
Wind Speed: [240<x<300]	0.0002	Wind Speed: [240<x<300]	0.2
Wind Speed: [300<x<360]	0.0002	Wind Speed: [300<x<360]	0.2

Table 7-4 Scenario 2 (Sector values for z_0)

Month	2-Tailed T-Test	Chi-Squared
November	1.32704E-11	1
December	2.67971E-07	1
January	0.071584524	1
February	0.002641047	1
March	0.124358104	1
April	0.005276348	1

Table 7-5 Two tailed T-Test and Chi-Squared for Scenario 2

	{Airport}	{Chouet}
Variance	23.82890381	29.30509709
Mean	9.47	10.18
Standard Deviation	4.88	5.41

Table 7-6 Comparison of Airport and Chouet data for Scenario 2

When applying scenario 2 to account for surface roughness, the difference in mean wind speed over the 6 month period is seen to reduce from 1.9ms^{-1} (a difference of 25% between the two sites) to 0.71ms^{-1} (a 7.5% difference). The standard deviation also reduces from 1.15ms^{-1} to 0.53ms^{-1}. So the difference in the standard deviations between the two sites is reduced by 18%. There is also a significant improvement in the Chi-Squared statistic.

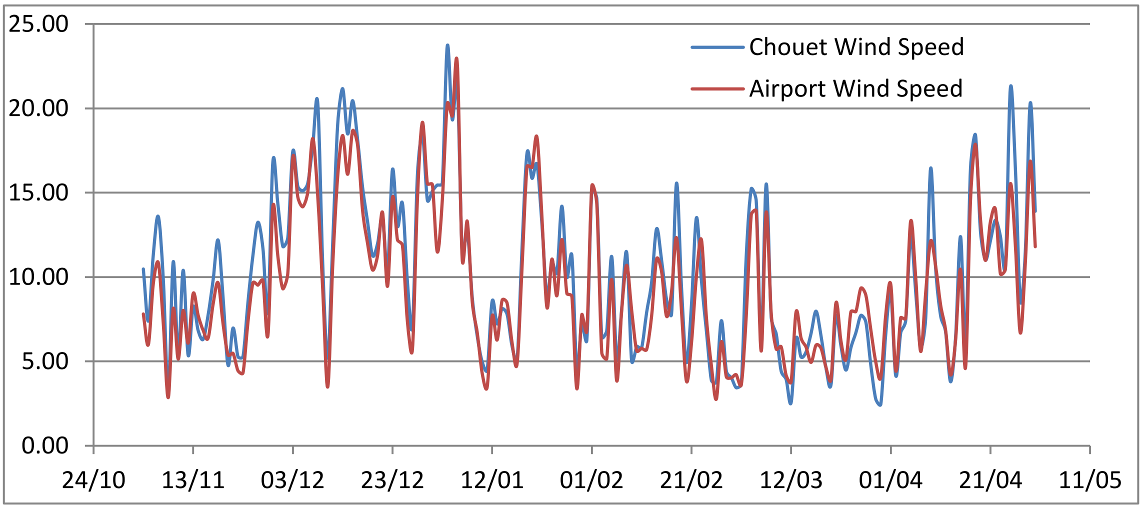

Figure 7-4 Chouet/ Airport wind speeds, averaged daily (Scenario 2 @ 80m)

Scenario 3 has been compiled by adjusting the surface roughness length to the values shown in Table 7-4. As before, Table 7-5 and Table 7-6 show the statistical similarity between the two sites.

Chouet	z_0	Airport	z_0
Wind Speed: [0<x<60]	0.0002	Wind Speed: [0<x<60]	0.5
Wind Speed: [60<x<120]	0.0024	Wind Speed: [60<x<120]	0.25
Wind Speed: [120<x<180]	0.0024	Wind Speed: [120<x<180]	0.1
Wind Speed: [180<x<240]	0.05	Wind Speed: [180<x<240]	0.1
Wind Speed: [240<x<300]	0.0002	Wind Speed: [240<x<300]	0.25
Wind Speed: [300<x<360]	0.0002	Wind Speed: [300<x<360]	0.25

Table 7-7 Scenario 3 (Sector values for z_0)

Month	2-Tailed T-Test	Chi-Squared
November	0.055314939	1
December	0.02012399	1
January	0.868255589	1
February	0.431207738	1
March	2.78004E-05	1
April	0.742905571	1

Table 7-8 Two tailed T-Test and Chi-Squared for Scenario 3

	Airport	Chouet
Variance	24.95745816	26.9121074
Mean	9.80	9.83
Standard Deviation	5.00	5.19

Table 7-9 Comparison of Airport and Chouet data for Scenario 3

Figure 7-31 below shows wind speed as a function of time for the six months of data available at the Chouet site, this is using scenario 3 with z_0 applied as shown in Table 7-7. More detailed graphs compiled from hourly averages can be found in Appendix B.2, Figure 9-7 to Figure 9-12.

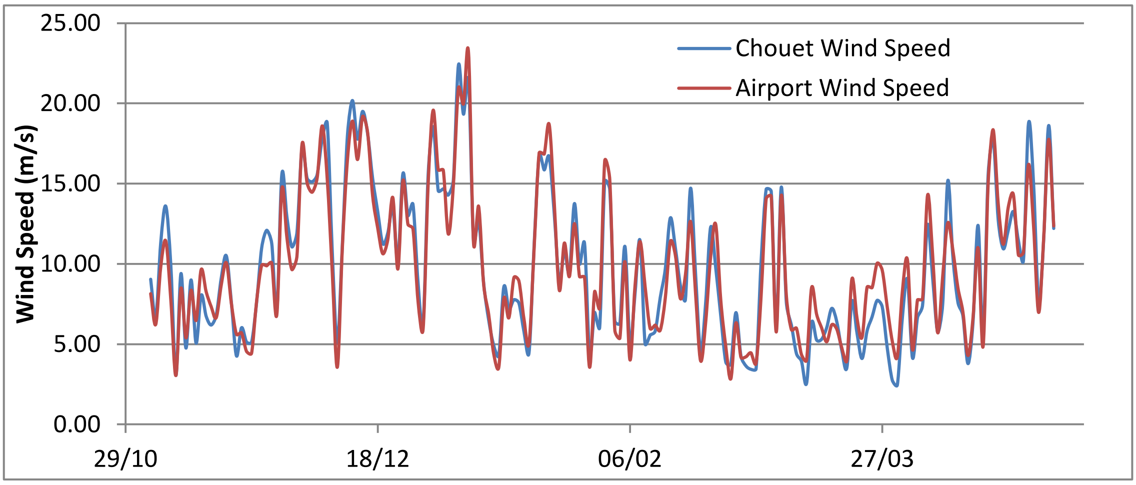

Figure 7-5 Chouet/ Airport wind speeds, averaged daily (Scenario 3 @ 80m)

Scenario 3 further reduces the difference in mean wind speed between the two sites to $0.03ms^{-1}$, a difference of only 0.3%. Standard deviation is also improved, showing a difference of $0.19ms^{-1}$ or 3.8%.

The improved statistical significance seen in scenario 3 results from the use of more aggressive values for z_0 around the airport and slightly lower values at Chouet, it is therefore evident that the values given in Table 7-7 more accurately represent surface roughness conditions around the two sites.

7.1.2 Wind Speed (3Tier Model)

As scenario 3 has shown the closest relationship between the Airport and Chouet sites, this data will be used to make a comparison with data obtained from 3Tier's wind prospecting tool (3Tier, 2012b). As the airport site has the most comprehensive set of historical data this has been plotted in Figure 7-6 against the 3Tier data. Again, more detailed comparison using hourly averages can be found in Appendix B.3, along with a comparison showing all three data sets (Chouet, Airport and 3Tier).

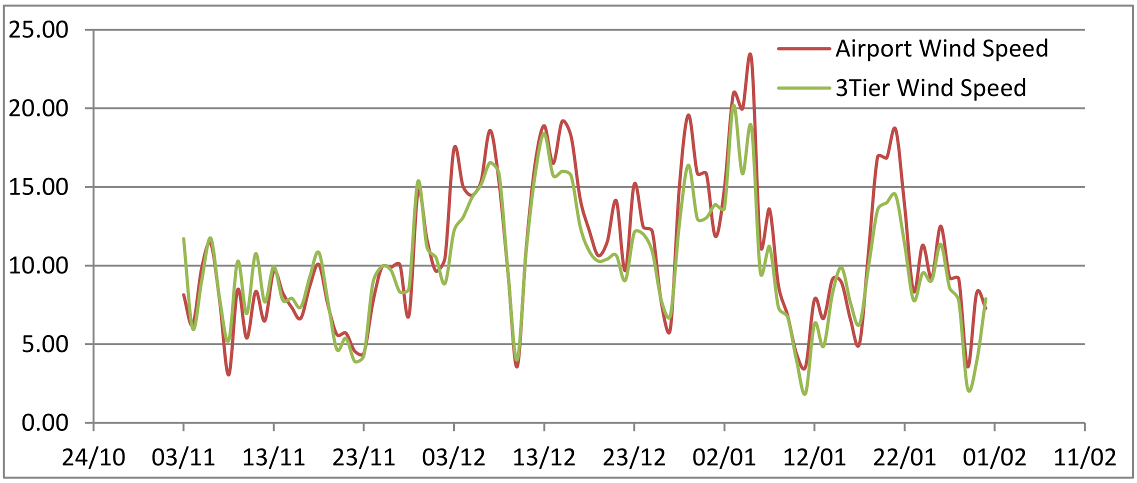

Figure 7-6 Airport/ 3Tier wind speeds, averaged daily (80m)

A good agreement is also seen when comparing scenario 3 airport data to that of the 3Tier wind prospecting model, small changes in wind speed appear less well resolved by the model, peaks are smoothed (Figure 7-6). The three month average was $10.18ms^{-1}$ for 3Tier and $10.95ms^{-1}$ at the airport, a difference of 7.6%.

It is important to note that wind calculations here do not account for the air mass type or temperature, as described in 3.2.2 the effective height of the planetary boundary layer reduces where the sea is cooler that the air and where wind speeds are slow, this may therefore result in less accurate results where temperature or wind speed reach extremely high or low values.

Assumed values of z_0 are thought to be most accurate where wind direction is coming from over the sea, this will also give rise to wind of the highest quality with minimal turbulence resulting from surface roughness.

It is understood that wind speed is most constant over periods of 10 minutes to one hour (Anonymous2000); taking hourly averages therefore provides the best compromise to accurately display wind data for large periods of time. Averaging over one hour also removes the effect of turbulence.

7.2 Energy Resource

It can be seen from section 7.1 that the two sites exhibit a sufficiently close relationship to allow the use of historical airport data in analysing the energy resource at the potential deployment zone by extrapolating the data up to hub height, and using appropriate exposure correction.

First the results for average power are shown for the period November 2011 to April 2012, this is so that the potential energy generated at both sites can be compared therefore verifying the accuracy of wind speed extrapolation techniques used predict surface roughness and wind shear.

When calculating average power, both the trapezium rule and Simpson method were applied, this yielded 3230.61kW and 3209.99kW respectively for the Enercon E126 (Using airport wind speeds from Nov 2011 to Apr 2012). As the Simpson method showed better accuracy, this was used to calculate average power values. Figure 7-7 shows average power in kW for each turbine assuming a hub height of 80m and surface roughness lengths are as per scenario 3.

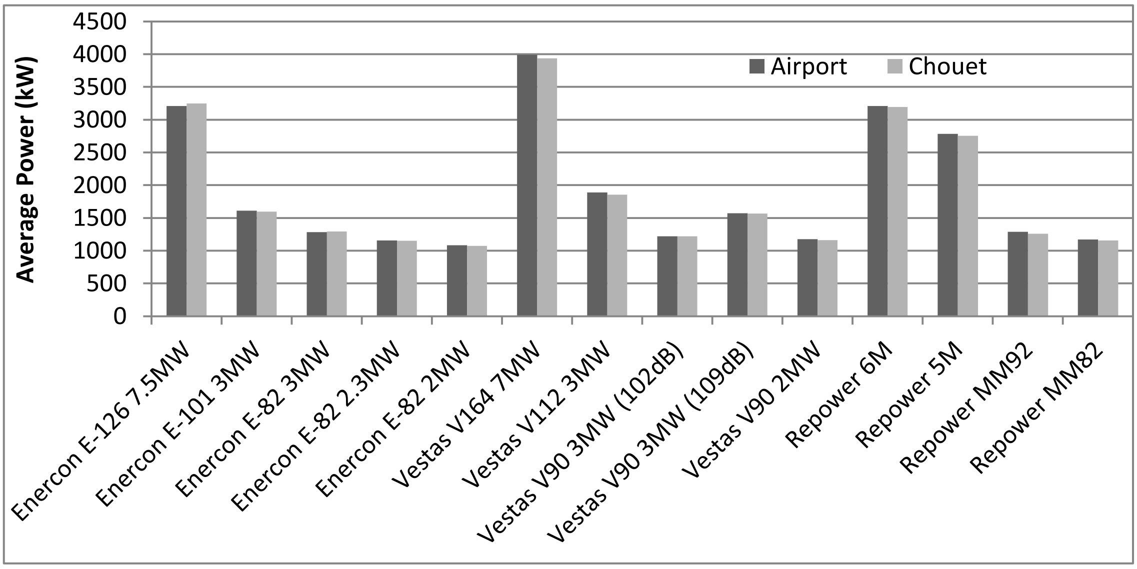

Figure 7-7 Average Power for November 2011 to April 2012

Looking at Figure 7-7 and taking the Vestas V90-3 (109db) as an example there is a difference of 0.3% between the predicted powers generated at the two sites over the six month period.

Figure 7-8 shows the capacity factors corresponding to the above. Table 9-1 shows the numbers for the above and below charts.

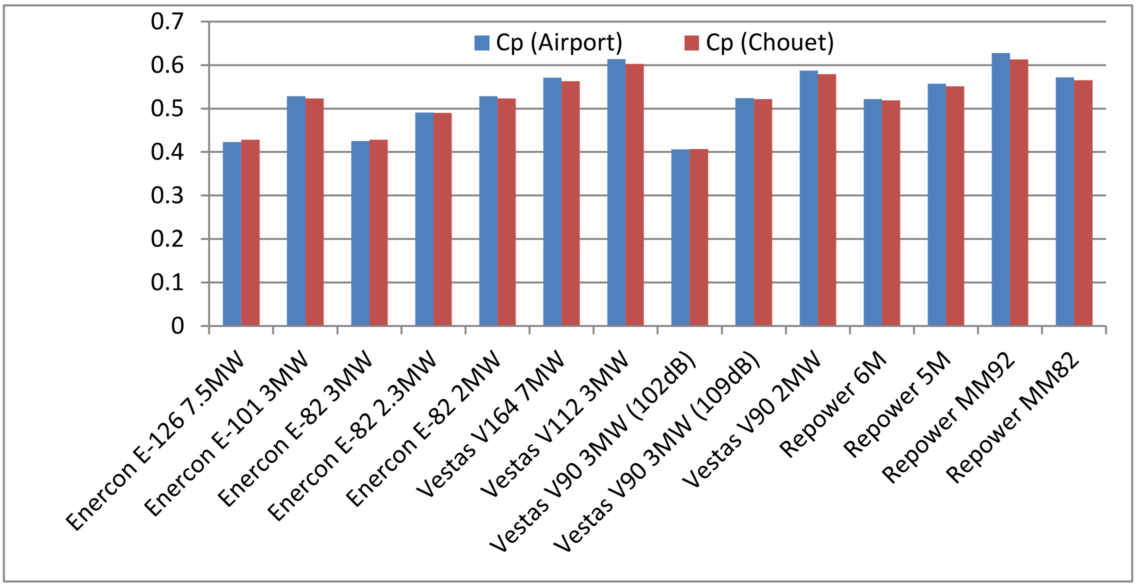

Figure 7-8 Capacity factor for November 2011 to April 2012

It is important to note that the capacity factors shown in Figure 7-8 are simply calculated by dividing the predicted output between November and April, with the rated power of the turbine assuming 100% efficiency and no downtime.

As per section 4.1.2 the energy production potential has been calculated. The data assumes scenario 3 and a hub height of 80m, airport data has been utilised. There is 8693 hours of data in 2011 and 8754 hours in 2010; this is due to the fact that 3 days of data is missing from the beginning of November.

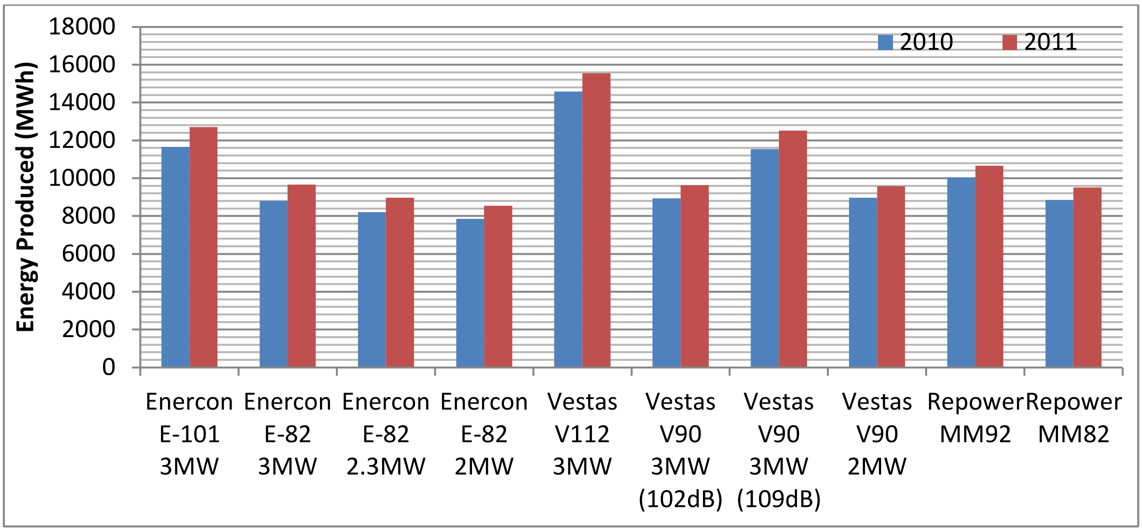

Figure 7-9 Energy Produced in 2010 and 2011 (Turbines < 5MW)

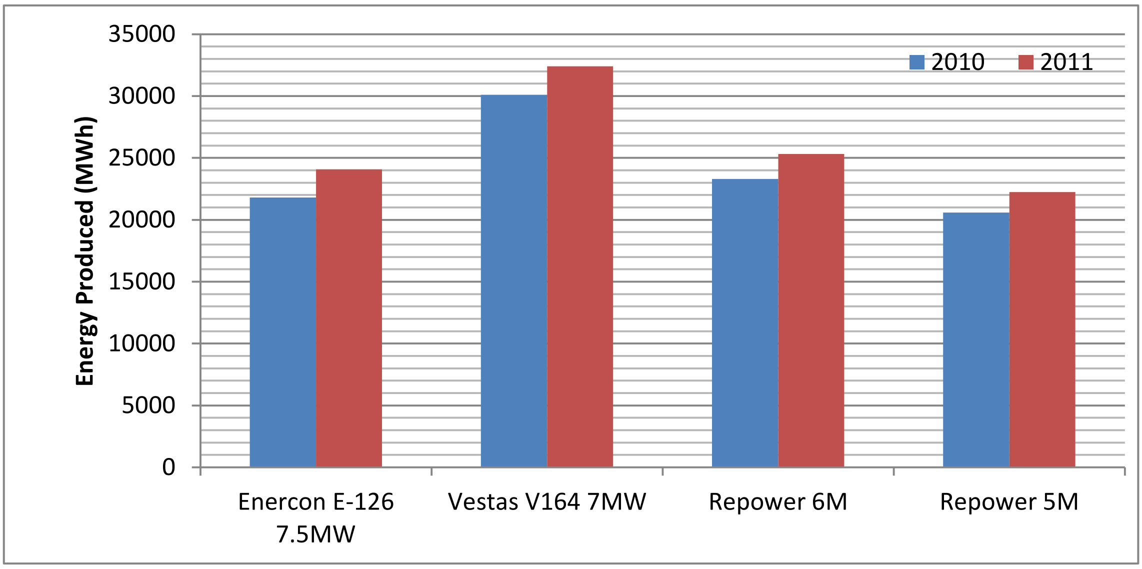

Figure 7-10 Energy Produced in 2010 and 2011 (Turbines > 5MW)

As shown in Figure 7-3 when applying the modified log law, the increase in wind speed does not vary linearly with height, this has important implications to both the design of the wind turbine, particularly the blade strength and also the accuracy of WTG power curves.

It is assumed that the stated wind speed on the power curves used are measured at hub height and that the wind speed is constant over the cross-sectional area of the turbine blades, this is clearly not the case especially when considering blade diameters of next generation turbines are approaching 164m.

Even using a Vestas V90 with 90m rotor diameter and at a 80m hub height as an example, the effect of wind shear between the blade tip at its upper most position (135m) and bottom position (35m) are still significant:

$$V(125) = 10\frac{ln\frac{125}{0.3}}{ln\frac{80}{0.3}} = 10.8ms^{-1} \quad \textbf{(7-1)}$$

$$V(35) = 10\frac{ln\frac{35}{0.3}}{ln\frac{80}{0.3}} = 8.5ms^{-1} \quad \textbf{(7-2)}$$

In order to achieve high levels of reliability; turbine blades should be sufficiently strong to withstand shear forces at their specified deployment location.

Wind speed can be shown to have more of an impact on energy generated as a result of an increase in swept area rather than an increase in the rated power of the turbine; this may be because the turbine is often operating at lower wind speeds. Repower, Vestas and Enercon turbines have been analysed in order to give an idea of the impact different turbine technologies have on predicted power output.

All Vestas turbines analysed have a cut-out wind speed of 25ms^{-1} and a restart speed of 20ms^{-1} (Vestas, 2004). Enercon on the other hand uses their 'Storm Control' technology which does not shut down the turbine until a 10-minute average wind speed of more than 34 m/s is reached (Enercon, 2012c). It works by pitching the blades out of the wind so that they can be quickly turned back when wind speeds drop (Enercon, 2012b), this is supposed to prevent abrupt shutdowns and reduce the need for shutdown and start-up procedures which can reduce yield. Repower has a cut-off speed of 30ms^{-1} on all turbines tested.

Data from 2010 and 2011 suggest that there is no requirement for an increased cut-out speed, as wind speed doesn't exceed 25ms^{-1} during this time period. The above technologies therefore have no impact on predicted power output.

Another focus is on drivetrain technology, there is a clear trend towards simplification of gearbox components and achieving economies of scale

(BWEA, 2009). Enercon turbines exclusively use direct drive technology which lack a gearbox and are therefore simpler and potentially more robust compared to Vestas who use multiple stage planetary gearboxes.

When comparing Repower MM92 (92m rotor) with the Vestas V90-3 (90m rotor) the power curves show similar performance, however making the same comparison with the Enercon E-101 shows that even with an increased rotor diameter of 101m, the Vestas turbine still outperforms the Enercon in low wind speed conditions (under $10ms^{-1}$). But above this speed the Enercon has the advantage, which is shown by a 1.1% and 1.47% increase in power generated in 2010 and 2011 when compared to the V90-3.

The E-101 is only able to achieve these figures due to its increased swept area, if we look at the specific output of the above turbines in 2010 and 2011; the V90-3 produces 1.81 MWh/m^2 and 1.97 MWh/m^2 whereas the E-101 only manages 1.45 MWh/m^2 and 1.59 MWh/m^2 respectively. So the Vestas unit is around 24-25% more efficient in energy capture per m^2 of swept area.

For areas with very high wind resource a smaller swept area may be advantageous when compared to a larger one as it may lead to less risk of damage during periods of sustained high speed wind, it may also be able to operate to a higher maximum wind speed, resulting in less downtime. Around Guernsey there is not a sufficiently large wind resource to warrant using smaller blades to prevent damage, however as we are currently limited to 3nm offshore the visual impact associated with using larger turbines is an important factor to consider.

Although there is currently little evidence to suggest Enercon's direct drive turbines will be more reliable, there is evidence to show the importance of experience and provability of a turbine manufacturer. For example Repower have increased the rated power and improved the power curve of their 6M compared to their 5M turbine, but without increasing its swept area.

7.3 Cost

As per section 5.3 the respective cost of the Enercon and Vestas wind turbines have been calculated using a required annual rate of return of 12%. Historical wind data was used from 2010 and 2011; Figure 7-11 shows the cost per MWh produced during this time period assuming a turbine availability of 95% and maintenance costs of £79k per MW of installed capacity.

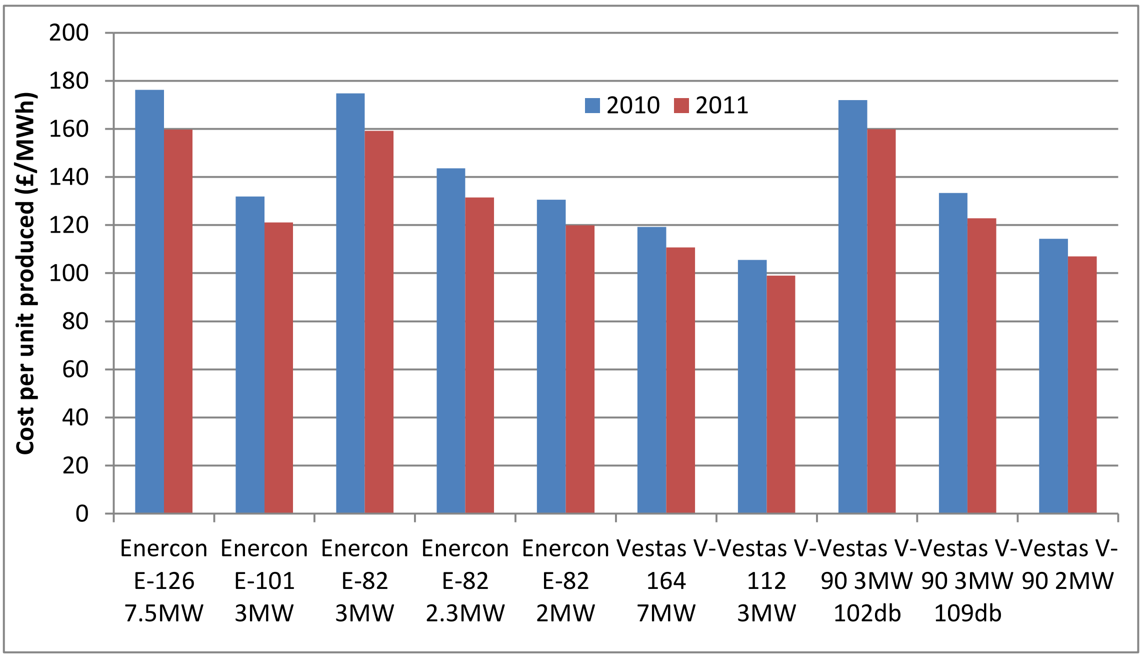

Figure 7-11 Cost per Unit (£/MWh) assuming CAPEX £3.2m/MW

Appendix E contains a more complete breakdown of figures including cost of generation for the above turbines assuming 90%, 95% and 99% availability for both 2010 and 2011.

The Enercon E-101 and Vestas V112 achieved the highest energy capture per MW of installed capacity, as the assumptions made have been based on a figure of £3.2M per MW installed these turbines have also proved the most cost effective costing £121.09/MWh and £98.98/MWh respectively (2011 data assuming 95% turbine availability). This increases to £134.31/MWh and £109.78MWh if electrical and array losses are assumed at 2 and 8% respectively.

The above yields 13.4p/KWh and 11p/KWh for the E-101 and V112-3, or 11.9p/KWh and 9.7p/KWh if the annual rate of return is reduced to 10%.

With this in mind Figure 7-12 shows cost of generation for 2010 and 2011 wind data, but this time assuming a reduced annual rate of return (10%) and a reduction in CAPEX to £2.4m/MW in line with 2020 cost predictions suggested by Arup (DECC, 2011).

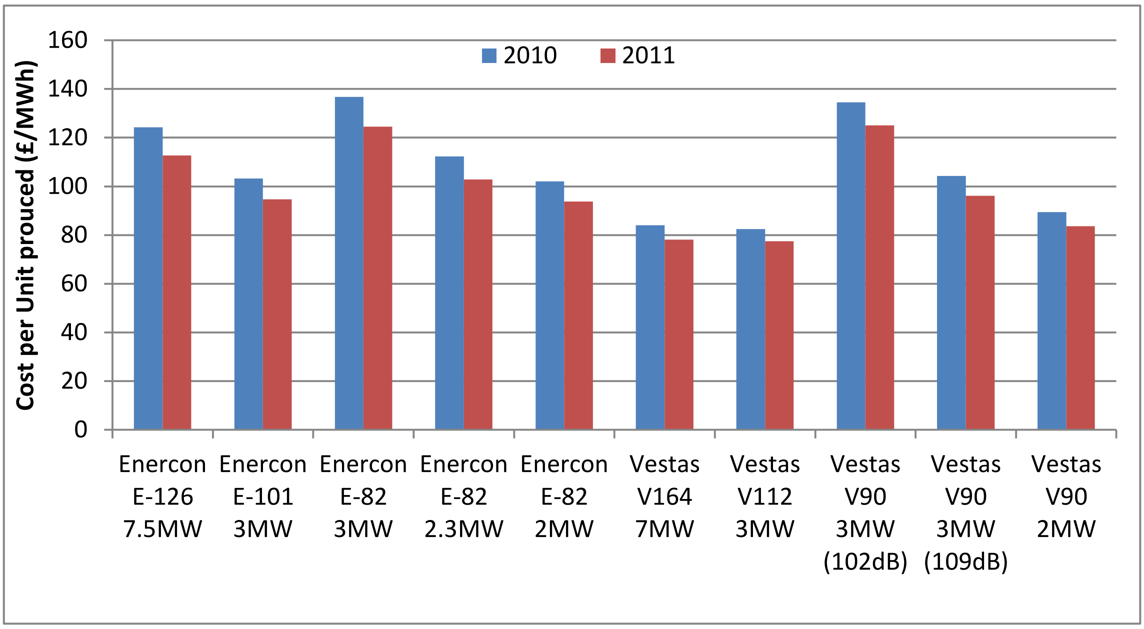

Figure 7-12 Cost per Unit (£/MWh) assuming CAPEX £2.4m/MW

Since Guernsey does not currently have any financial incentives in place for the uptake of renewable energies, a significant reduction in CAPEX as described above would significantly improve the economic feasibility. In order to make a comparison costs for the Enercon E-101 and Vestas V112 are reduced to 9.5p/KWh and 7.7p/KWh, a reduction of almost 30%.

Reductions to maintenance costs are also expected as the industry becomes more developed, further driving down the cost of generation.

The above does not include transmission costs on the GEL grid, it is understood that the grid will need to be fortified should a 30MW development be approved.

7.4 Bathymetry

Water depth and sea bed conditions are of primary importance when analysing a potential deployment location. The admiralty chart below (Figure 7-13) shows the bathymetry around Guernsey, the potential deployment zone contained within the yellow box is shown in more detail in Figure 7-14.

Chapter 4 of the Wave and Tidal REA, should be referred to for a detailed review of geology around Guernsey including maps of solid geology distribution.

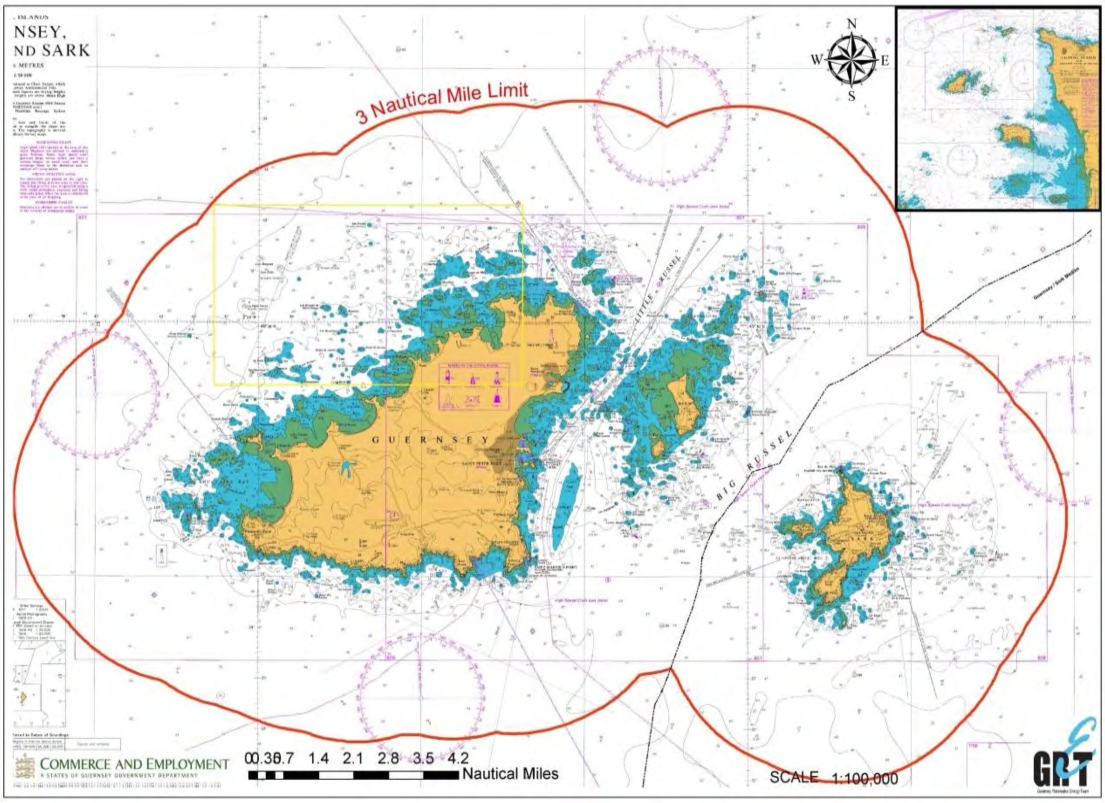

Figure 7-13 Admiralty Chart showing water depth around Guernsey

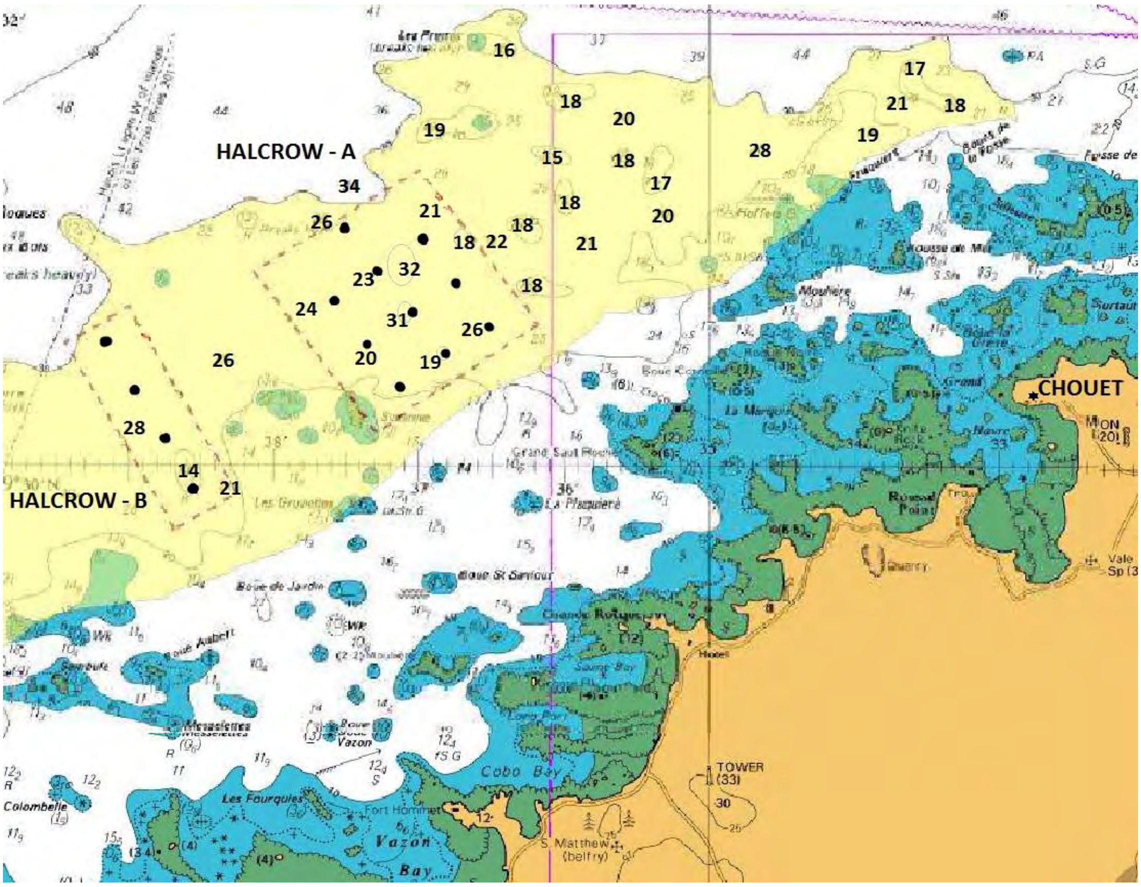

Figure 7-14 Water depth off the NW coast of Guernsey

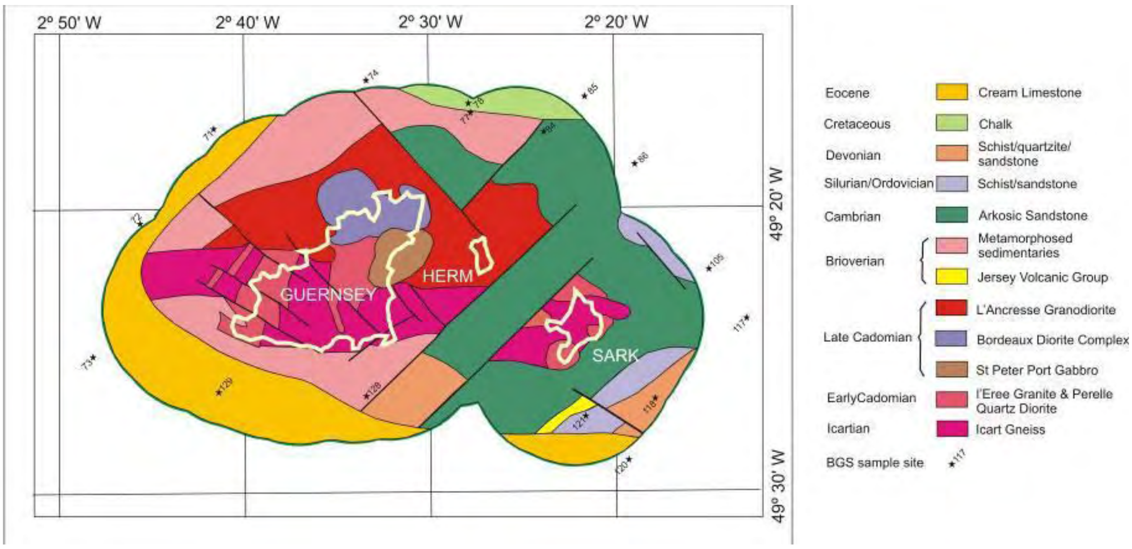

Figure 7-15 Map showing the Geology of Guernsey up to the 3nm limit.

7.5 Visual Impact

The original turbine layouts as proposed by Halcrow are shown in Figure 7-14, in order to assess the visual impact, a number of visuals will be generated from different points on Guernsey's west coast.

A scale model of Vestas V90 has been created using the computer aided design (CAD) software 'Sketch Up' (Howes, 2012), by loading a high resolution satellite image of Guernsey and its surrounding waters onto the CAD software, it was possible to place the 3D model of the turbines at their proposed locations. At this point, the orientation of the blades and overall direction the turbine is facing can be altered.

Once a particular layout is set up, a number of scenarios can be run from different points of view. Using a tool designed for the film industry, 'Film and Stage' ACT (Advanced Camera Tools), it is possible to alter the aspect ratio, focal length, height from the ground and angle of a 'virtual camera'.

Two reference points of view will be used; the first is from The Rockmount in Côbo bay is shown below (Figure 7-16).

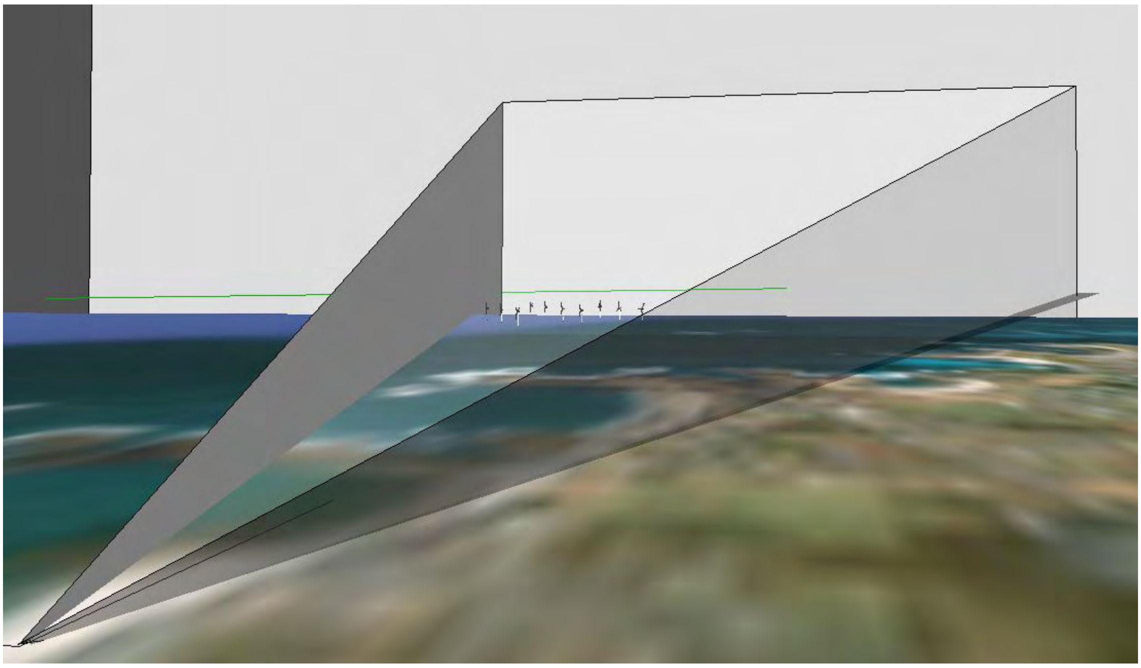

Figure 7-16 Scope of image using a 28mm camera from The Rockmount

And the second perspective is from Chouet, where the anemometer is installed. As before, Figure 7-15 shows the scope of the image taken from this perspective. All photographs were taken using a Canon EOS 550D or equivalent using a focal length of 28mm.

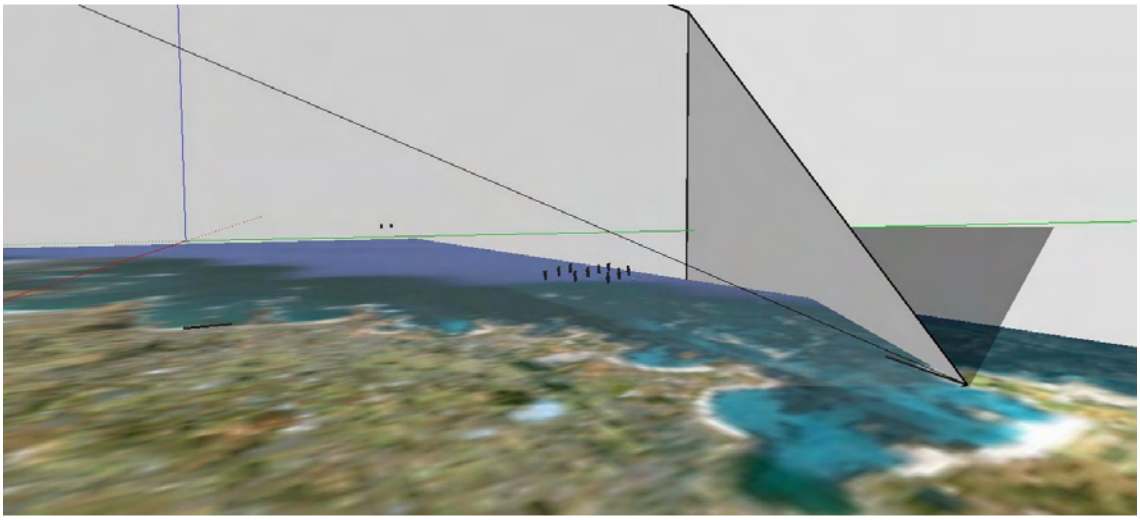

Figure 7-17 Scope of image using a 28mm camera from Chouet

The first layout to be analysed is the 10 turbine deployment scenario defined as Halcrow-A in Figure 7-14. An aerial view of this deployment scenario has been exported from CAD and rendered in Photoshop (Figure 7-18):

Figure 7-18 Visualisation of a 10 turbine array in a symmetrical grid (Halcrow-A)

The ACT function on CAD is setup to output a 2D graphic matching the specification of the camera that has been used to take the real picture (Canon 550D). For the purpose of accuracy, the ‘image size’ tool in Photoshop is used to set the resolution of both the real photograph and the 2D graphic. A value of 200 pixels per inch was applied to both in order to ensure the relative size and proportionality remains equal.

Figure 7-19 Visual of ‘Halcrow-A’ when viewed from The Rockmount

2D output from CAD was found to be of very low quality and not accurately representative of the real turbine when viewed from a distance. In order to improve the quality of the images, high resolution photographs of the turbine were combined with the real photograph using Photoshop. For accuracy, the aspect ratio and size of the turbine were maintained according to the CAD output image.

Figure 7-20 Visual of ‘Halcrow-A’ when viewed from Chouet

The visual above (Figure 7-20) was taken from the Choet on a cloudy day; visibility on this day was quite poor therefore significantly reducing the impact of the turbines. Figure 7-21 shows a cropped version of the above (Figure 7-20)

Figure 7-21 Close-up visual of ‘Halcrow-A’ when viewed from Chouet

Figure 7-22 Visualisation of a 9 turbines arranged in a curved line

Following research into the Middelgrunden wind farm in Denmark, a number of visuals were created with turbines arranged into a curved line as shown in Figure 7-22. Due to a predominant south westerly wind direction around Guernsey, it was not possible to have the primary axis of the curved line parallel to the coast, as this would result in excessive wake interactions.

Instead the layout ‘Curved-1’ was arranged with the primary axis at 338° as shown in Figure 7-23, this is in order to improve energy capture and reduce array losses.

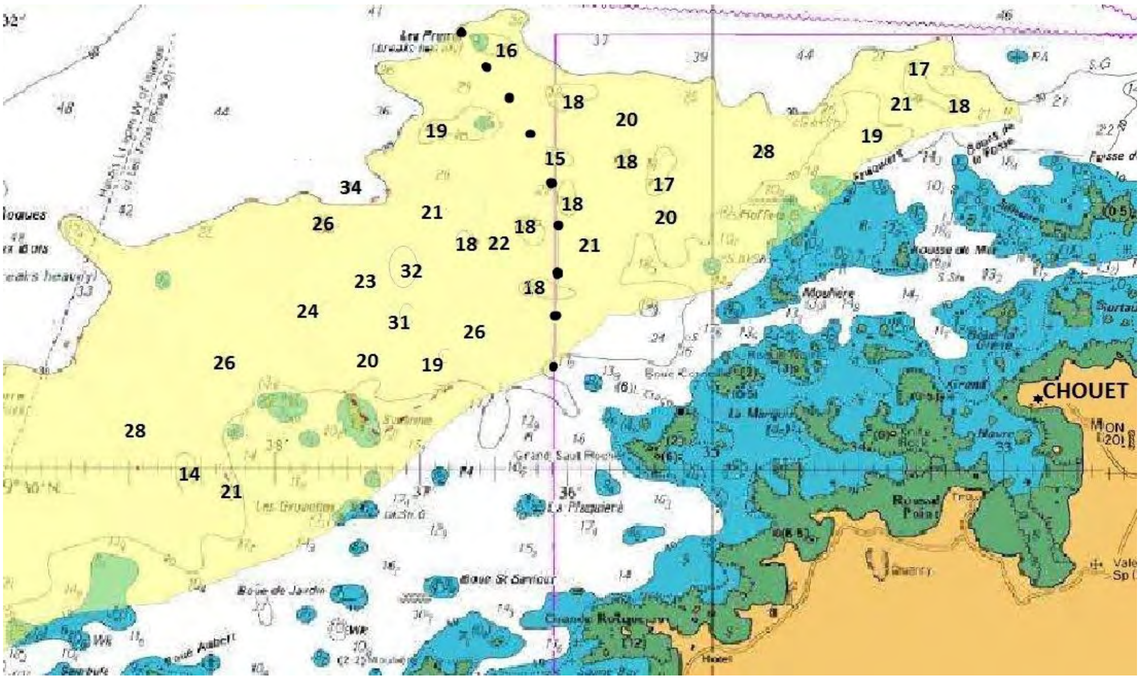

Figure 7-23 Map showing 'Curved-1' deployment locations

Figure 7-24 Visual of 'Curved-1' when viewed from Chouet

As the deployment scenario 'Curved-1' is almost perpendicular to the coast line, the view from The Rockmount is less organised:

Figure 7-25 Visual of ‘Curved-1’ when viewed from The Rockmount

Next, the axis of the curve was rotated clockwise to 22°. The resulting layout, ‘Curved-2’ has a similar visual impact when viewed from Chouet, but appears more organised when viewed from other points along the coast. In order to make a comparison Figure 7-26 shows the ‘Curved-2’ layout when viewed from The Rockmount in Côbo Bay.

Figure 7-26 Visual of ‘Curved-2’ when viewed from The Rockmount

7.6 Grid Connection

Guernsey operates a fast acting automatic load shedding system which acts to quickly reduce load if a generator unexpectedly fails. Currently, the interconnector cable to Jersey is capable of immediately balancing the power lost by using additional import. Due to technical reasons there is a minimum transfer of approximately 5MW (GEL, 2005), and due to a contract to buy, a minimum of around 16MW is imported the majority of the time.

According to GEL, the interconnector cable lands at Havelet Bay and connects into the grid between Les Amballes and the power station at St. Sampson. Distribution around the island is at 33kV to the main supply points, this is to minimise transmission losses. Kings Mills is the point at which voltage is stepped down to 11kV to supply the south and west coasts.

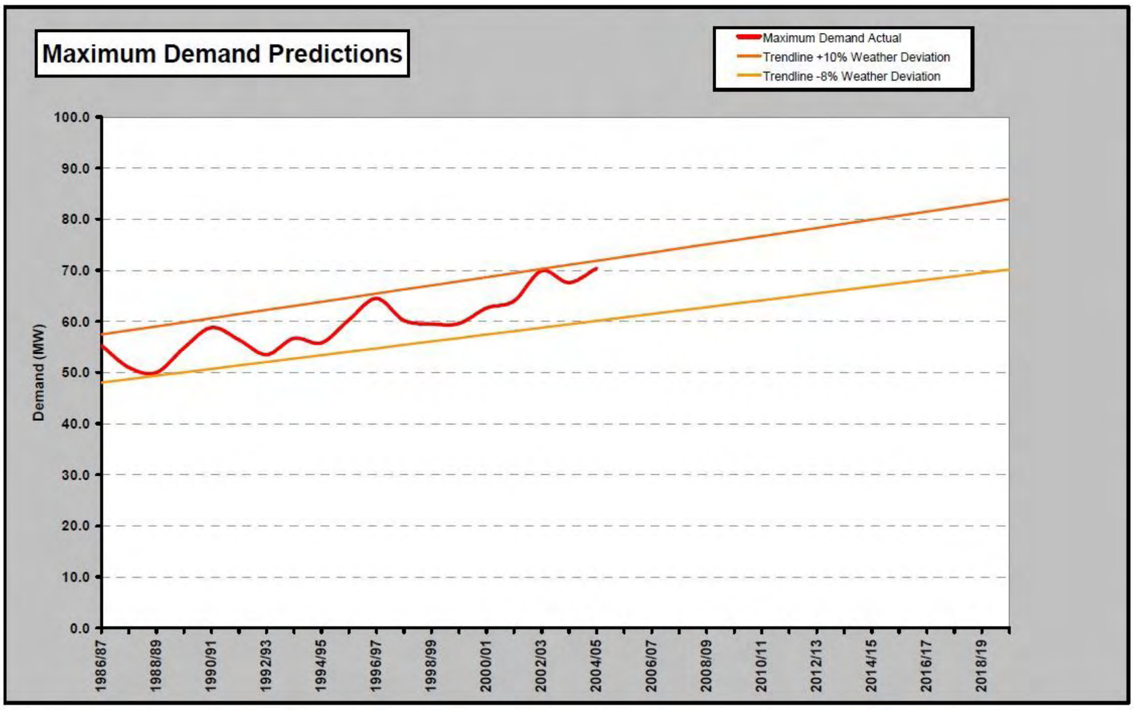

Figure 7-27 Maximum demand predictions for Guernsey

(GEL, 2005)

January 2007 saw a peak of 71.3MW and December 2007 saw a peak of 76.3MW (GEL, 2007) These peaks represent the upper limit of the +10% trend line (Figure 7-27); they are mostly due to periods of cold weather and a large number of households using electric heating.

As an example, Figure 7-28 shows the electricity demand for a typical day in December (GEL, 2005). The base load supply is shown to be 'imported' via the cable link, in this case providing an average of 29MW. Peak demand is then met by on island generation, reaching a maximum of just over 60MW in the evening. The winter months are considered the windiest, which coincides well with the increased demand experienced during these months.

Figure 7-29 shows potential power generated on the 1st of December 2011, integrating this line yields 551.6 MWh of energy generated assuming an array of 10 Vestas V112 turbines, enough to supply 60% of Guernsey's requirements (assuming demand is as per Figure 7-28). However this particular example highlights the potential requirement for load levelling or energy storage as maximum demand corresponds to a time of minimum generation.

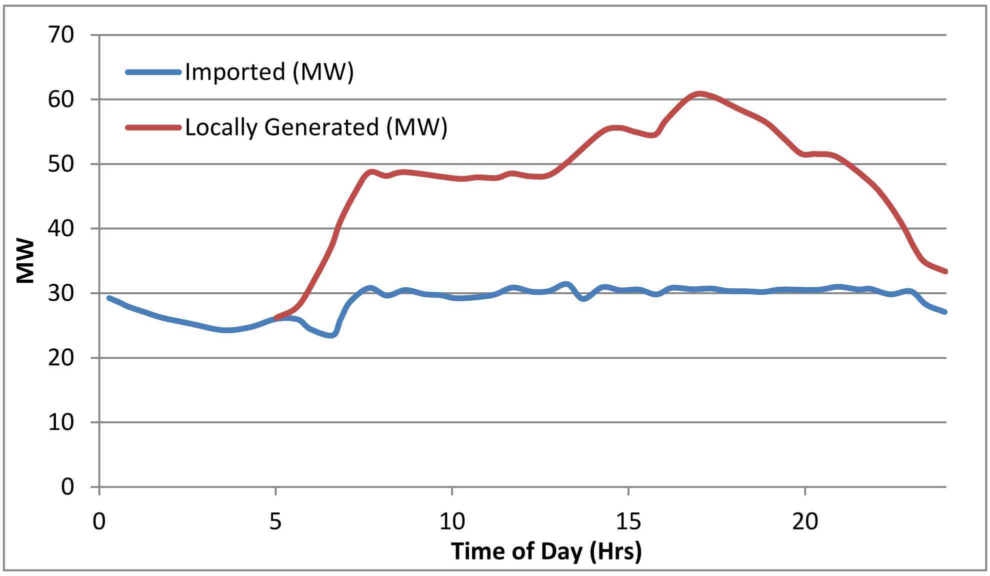

Figure 7-28 A typical day in December showing generated and imported energy

(GEL, 2005)

With load levelling, energy generated during the early hours of the morning could be stored to meet peak demand during the evening. Imported energy could then continue to meet the base load requirements.

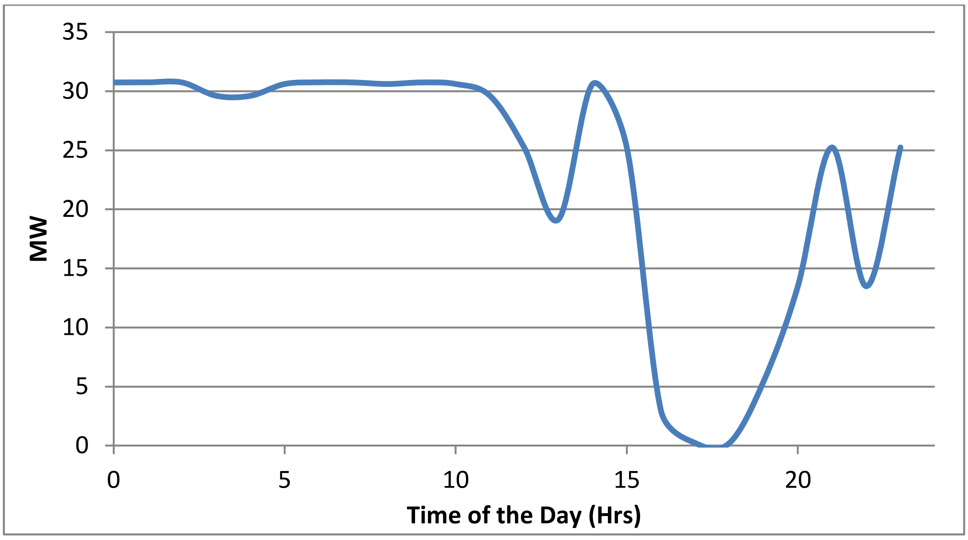

Figure 7-29 Estimate of power generation using an array of 10x V112-3 (1/12/2011)

Figure 7-30 shows a power generation estimate for the following day (2nd December 2011), in this case peak generation coincides well with peak demand and energy storage would not be required. In this case the turbine array can produce the majority of base load supply with the cable importing energy to meet peak demand.

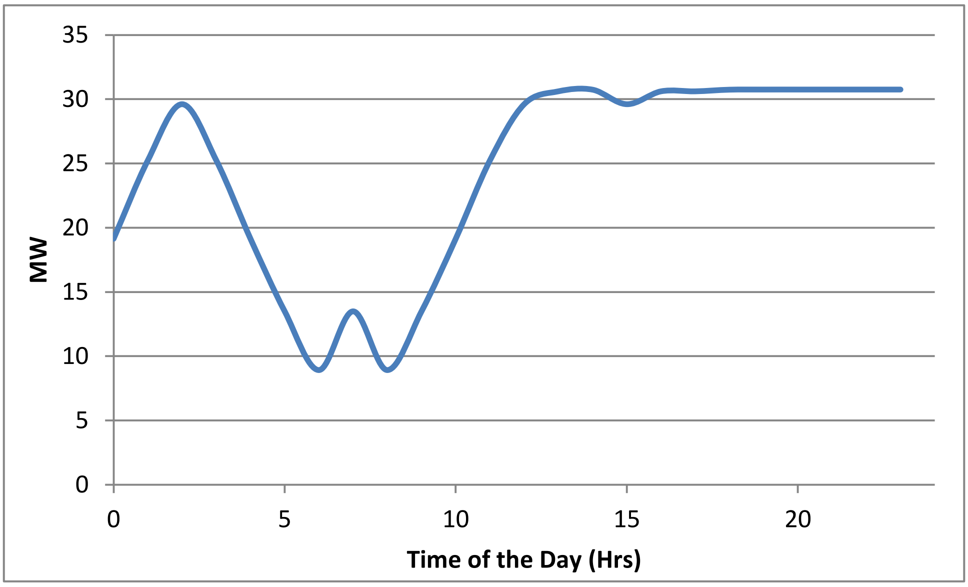

Figure 7-30 Estimate of power generation using an array of 10x V112-3 (2/12/2011)

The above shows the importance of when energy is generated; it is shown that in order to take full advantage of wind energy then some form of load levelling or energy storage technology is required. However the presence of a cable link is highly advantageous as this can be used to meet peak demand or ramp up on island diesel generators where necessary.

Given the current cost of energy storage technologies at the scales required by Guernsey, an agreement with Jersey to use the cable link for both import and export would ensure more complete utilisation of wind energy generated; excess generation at night for example could be used to supply some of Jersey's base load, limiting their requirement for importing energy from France.

As the interconnector cable has not proven 100% reliable the implementation of energy storage may become feasible in the future, especially considering the advancements in the field and likely cost reductions associated with this. The most suitable technology for Guernsey would be very fast acting battery storage in order to bridge the gap until fast start gas turbines can come online, therefore forming a hybrid type configuration as described in Appendix F.7.

Storage of distributed energy at the point of use also has the advantage of load levelling the supply network as well as the generating plant, therefore reducing the cost of additional cabling.

7.6.1 Hybrid and Smart Power Systems

There are a number of power management strategies that could be implemented to account for the issues seen in the above section. Barley and Winn suggest hybrid systems using diesel, battery and an intermittent renewable resource such as wind:

For example the ‘Frugal Dispatch Strategy’ aims to find a balance between the monetary costs of increasing battery wear and the cost using diesel generation. So when generation by the renewable resource does not meet demand on the grid, and this shortfall is below a critical point at which the cost of battery wear intersects the cost of diesel generation, then the batteries are used to balance the grid. A charge level of 50:50 gives optimal ability to react to grid conditions either pushing or pulling power (Dell and Rand, 2001)

Another example is the ‘Full power minimum runtime strategy’ (Lujano-Rojas et al., 2012). In this scenario diesel generators are run for a set amount of time, with excess energy used to charge the batteries, at this point the generators are disconnected.

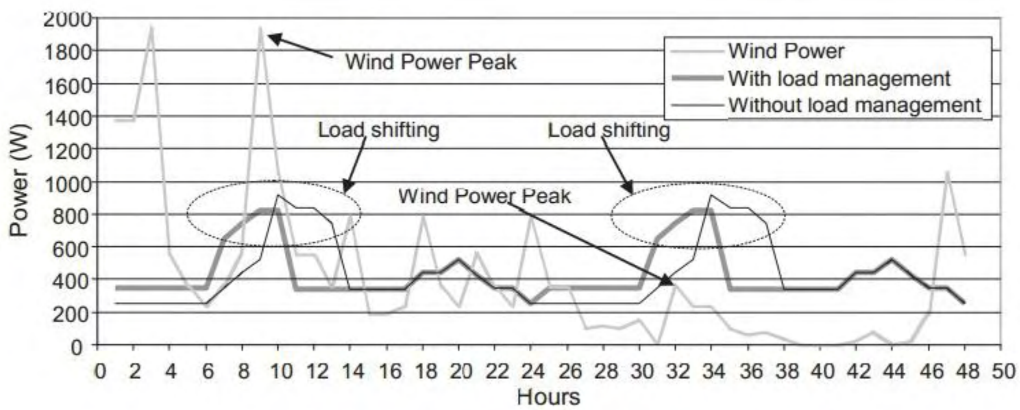

Figure 7-31 Wind power and load profiles as a function of time

[Lujano-Rojas et al; 2012]

It is concluded that by using an optimised load management strategy the usage of wind power can be improved by shifting controllable loads on the grid to the respective peaks in wind power thereby increasing the SOC in the battery. This in turn reduces the need for diesel generation. It is obvious from this conclusion that the forecasting of wind speed must be accurate in order to achieve optimal conditions; errors in forecasting would result in incorrect load shifting.

7.7 Environmental Impact

The potential impacts of offshore wind have been omitted from the wave and tidal REA in order to concentrate on wave and tidal exclusively. Some elements of the study will be applicable to offshore wind.

As offshore wind does not interact with the sea bed in the same way as tidal stream for example, marine processes such as sediment movement and impacts on benthic and pelagic ecology are not all relevant to this study. During the installation phase however, the environmental impact can be considered similar to that of wave and tidal and the REA can be referred to for a detailed analysis of potential environmental impacts.

Sediment may be released during construction phases also during trenching when laying cables. In addition to this there may be accidental release of contaminants during construction which can be more toxic; this includes lubricating oils, fuels and other chemicals. Release of such contaminants when operational is not likely as wind turbines do not have any submerged moving parts that utilise hydraulics or may require lubrication.

The operational impact of wind turbine foundations and their associated subsea cables is likely to be limited to the physical presence of devices, both technologies share the presence of subsea cabling etc. which can result indirect benthic habitat loss and/or disturbance due to scouring (GREC, 2010). However due to a minimal footprint within the water and significantly less interaction with benthic and pelagic ecology, offshore wind would compare favourably to wave and tidal.

Acoustic impacts of installing offshore wind foundations can be greater than wave and tidal especially where monopoles are driven into the sea bed, this can temporarily displace local fish communities with knock on effects for benthic communities. High intensity sound at close range has been shown to cause some sort of physiological effect to fishes, at further distances of a few kilometres behavioural effects can be observed (Gill et al., 2012), the significance of this is not fully understood but would depend on the nature of the sound and the species affected. A study by (Halvorsen et al., 2012) for example aims to quantify the threshold for the onset of injury to salmon. It was found that the equal energy hypothesis (EEH) could be rejected as the sound energy level (SEL) for a single strike resulted in a different severity of injury despite being equivalent to the SEL for cumulative strikes, as a result both of these parameters should be taken into account when aiming to mitigate the effect of sound exposure during construction phases.

Fish using the earth's magnetic field to navigate such as diadromous fishes are likely to interact with the electromagnetic field (EMF) associated with subsea cables but only if they pass over the cables. The effect is particularly true in shallow waters (of less than 20m) and has the effect of a temporary change in direction for the fish. The significance of this is not yet known (Gill et al., 2012).

It has also been suggested that if properly managed then offshore renewable structures be beneficial to fisheries, enhancing biodiversity by acting as artificial reefs (Inger et al., 2009)

With regards to pelagic ecology is difficult to analyse at a local scale; local knowledge suggests that location of fish stocks is highly variable and where one year they may be located at a particular location, by the next year they may have moved (Wilkinson, 2012), it is for this reason that it would also be difficult to quantify any financial loss incurred by fishermen as a result of fishing exclusion zones. Trawling does not occur in any of the potential deployment zones as defined in Figure 7-14 or Figure 7-34, however netting and long line fishing do occur.

Fish spawning areas occur off the west coast of Guernsey; this is confirmed by local fishermen and (Pawson et al., 2008) this does not conflict with our NW site.

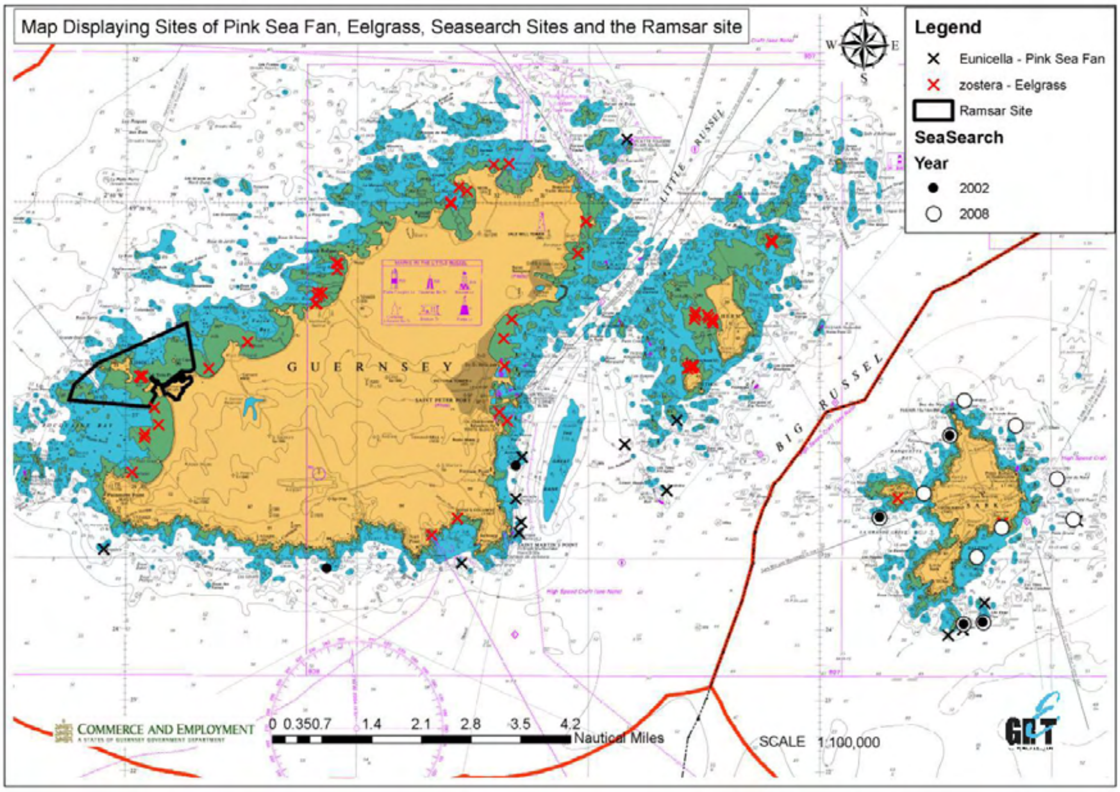

Figure 7-32 Location of Guernsey Ramsar Site (Lihou Island), Pink Sea Fan & Eelgrass

(GREC, 2010)

Potting is common in Guernsey waters, it occurs all year round but increases in activity in the period April to September with the SW of Guernsey and parts of the Big Russel most intensely used for potting (GREC, 2010). Figure 7-33 outlines the main potting areas around Guernsey.

Potting is considerably easier to quantify in terms of loss of income to the fisheries operating in the area, charts are used to map out the areas worked by different individuals (Wilkinson, 2012). It would simply be a case of defining the potential deployment area and quantifying the potential loss of income using these charts.

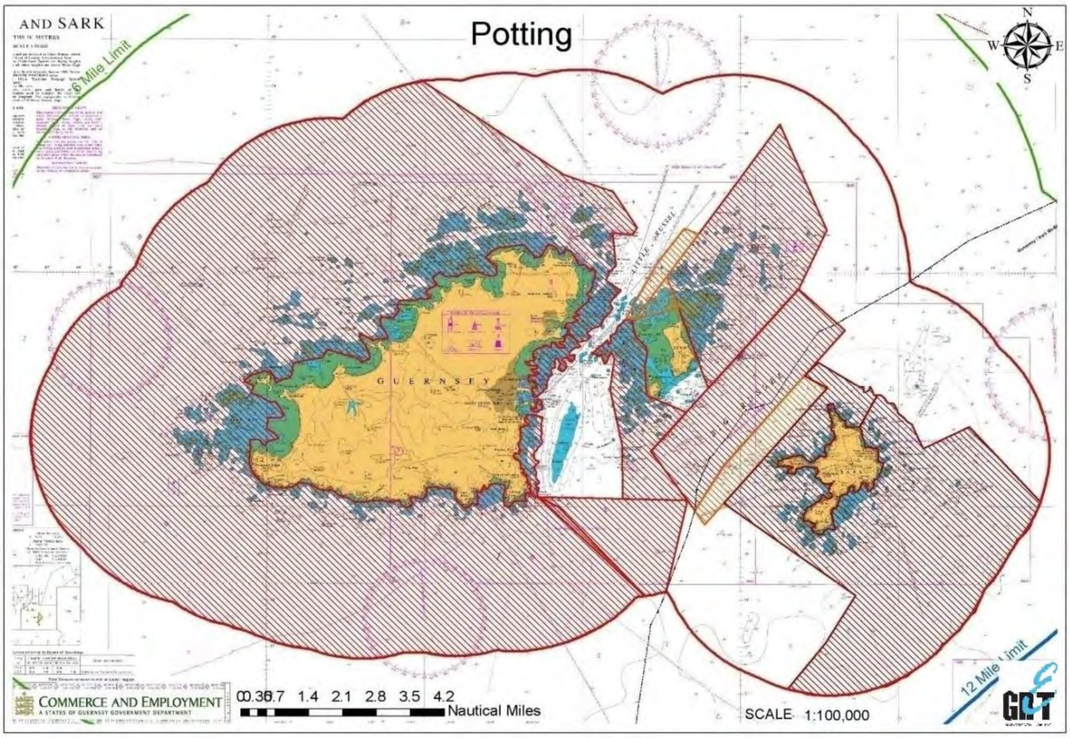

Figure 7-33 Primary potting areas around Guernsey

(GREC, 2010)

7.7.1 Birds

Birds tend to have a migrating height 500m or less, this can be 1000m or more depending on weather, terrain or species. Height tends to drop when approaching land. The Bailiwick is not situated on a busy or important migration route, but they do arrive and depart the island in large numbers with 60 different bird species breeding on the Bailiwick each year.

A study looking at the mortality rate of migratory birds off the NW coast of France has found that when the turbines are running birds clearly deviate and fly around them, and when they are stopped then roughly half fly through the farm and half around it (Galuen et al., 2010). The study was carried out at a ZPS special protection zone migratory route, only three mortalities were found during the study period, however the study highlights the risk associated with implementing large numbers of offshore farms along narrow migratory passages.

Although there is evidence of birds being forced to the ground due to the vortex of moving rotors (Winkelman, 1992), most studies have low recorded levels of mortality (Galuen et al., 2010; Winkelman, 1992; Erickson et al., 2001). It is noted by (Langston and Pullan, 2003) that the majority of these statistics rely on finding bird corpses and that they do not account for birds removed by scavengers.

Collision risk is somewhat associated with visibility and so increases at night, but also due to weather conditions that may act to decrease visibility (i.e. fog or rain) (Erickson et al., 2001). Risk is also said to increase with species, so birds that natively fly during times of poor visibility (dusk or dawn) may be at greater risk (Drewitt and Langston, 2006), also larger species with poor manoeuvrability may have a greater collision risk (Brown et al., 1992).

Displacement of birds can occur around wind farms during installation or operational phases as a result of noise, visual or vibrational impacts. The impacts of course vary depending on the specific location and species involved and should therefore be evaluated specifically for a particular site.

As Guernsey is not located on any major migration paths ('flyways') we do not need to consider the potential impacts of extra energy expenditure of the birds flying around the farms.

Pleinmont, Jerbourg, Icart and L'Ancresse are identified as important areas for migrant birds with the beach at Belle Greve, seen as an important feeding area for overwintering birds (overwintering has been seen to increase due to milder conditions)

Seabirds can survive short periods of high turbidity, but not prolonged periods of several weeks (Drewitt and Langston, 2006) (GREC, 2010)

7.7.2 Mitigation of impacts

Careful site selection, consider not only the location of RAMSAR sites but also locations that sustain diverse range of species and habitats, for example important breeding areas have been identified to the south of the island. REA defines most significant impact as the disturbance during breeding, installation works were recommended to take place outside of this time, which is defined as March to July.

Pile driving noise impact can be mitigated by precise timing of installation works to minimise the disturbance, for example by avoiding mating and spawning activity time periods.

Fishing exclusion zones may have a positive impact on fish stocks having a resulting knock on effect to species that feed on them. Equally this may cause a shift in the location of feedstock species therefore impacting on local bird colonies that feed on them.

It may be possible to reduce the overall footprint of the offshore wind farm by citing the turbines closer together (Drewitt and Langston, 2006). As there are no flyways to worry around Guernsey this may be an acceptable recommendation, however this may also lead to lower array efficiency due to the effect of turbine wake interactions

A post development monitoring programme is suggested; this is in place at a number of other wind farms and can also be used for future further development of the area.

A general lack of data has been identified on the topic of bird behavioural patterns, especially with regards to sea birds; further research should be undertaken in this area in order to properly mitigate the potential impact, for example by optimising installation and maintenance schedules.

7.8 Site One

Site one is defined as the potential deployment zone throughout this paper and refers to the site off the NW coast of Guernsey as recommended by the Halcrow report.

The REA for wave and tidal identifies this site as being mostly exposed rock. Halcrow propose the use of grouted monopiles due to a lack of industry experience with caisson foundation. In addition to this standard GBF's require significant sea bed preparations, dredging and levelling of the sea bed would be difficult at the NW site due to the exposed rock and is likely to be costly due to increased installation time. GBF foundations would also have a more significant impact on marine ecology due to increased sediment movement during installation. Once the seabed is flattened a gravel foundation is normally laid, this suggests the GBF would also require some form of scour protection.

Novel gravity structures such as 'Rockmat' described in 2.2.2 do not require sea bed preparations and can adjust to irregularities of up to 1m, this would significantly reduce the environmental impact and lengthy installation times mentioned above, however the technology has yet to be proven in offshore wind installations. If it is to be considered, a more detailed bathymetric survey of the seabed would be required, Figure 7-13 shows how water depths off the NW coast vary significantly between 20m and 30m. As 'Rockmat' GBF's are limited to 1m variations, the deployment pattern may be dictated by bathymetry rather than an optimised layout that reduces visual impact and improves energy capture.

Monopile foundations would therefore be more suited to this site, a drill and drive installation method would be required resulting in less seabed disruption and for a significantly shorter period of time (see 'Offshore Wind Farms' tab in Excel output sheet). The shorter installation times also reduces installation costs. In addition to this other similar installations have not required scour protection, for example at the North Hoyle wind farm monopiles are drilled and driven 25m into a rocky sea bed and no scour protection is used, instead seabed alterations are monitored one time per year.

Halcrow have suggested an optimised turbine layout using a symmetrical grid configuration, a number of iterations have been suggested in section 6 in an attempt to reduce the visual impact. Micro-siting of turbines also has implications to the electrical layout, primarily affecting cost and reliability. For example use of a radial collection system on a single row of 9 turbines offers the most cost effective solution, however reliability is poor as there is no redundancy for upstream turbines, should a fault occur downstream. Given increased repair times offshore, this can lead to substantial losses.

If a single row layout is to be used then a ‘single-sided ring’ would be required to provide some level of redundancy, this configuration is the most expensive as it requires a cable back to the collection hub from both sides of the row (Lumbreras and Ramos, 2012).

At the NW site the proposed grid layout contains two rows of 3 and one row of 4 giving a total of 10 turbines, with this layout using a radial collection system would therefore provide some level of redundancy as not all the turbines are connected to the collection system through the same cable. It also opens the possibility of using a ‘double-sided ring’ in which one row is connected to another and that neighbouring row is used as a redundant circuit, this option is said to be up to 60% more expensive than a simple radial design (Quinonez-Varela et al., 2007).

At the proposed site, use of either a single row of turbines with a ‘single-sided ring’ or a symmetrical grid with a radial collection system is likely to yield similar costs and levels of redundancy. However further improving redundancy and therefore reliability is likely to be more cost effective where a grid layout is used.

7.9 Other Potential Sites

Deployment to the South West of Guernsey is not an option due to the RAMSAR site located around Lihou Island (Figure 7-32). The beaches, coves and cliffs to the south are of high recreational value, also the water depth drops much more quickly compared to the NW site, reaching 40m to 50m after only 0.5nm in places.

Deployment sites off Guernsey's south west coast have not been considered as the water depth falls off rather quickly, turbines that are cited too close to the shore may experience sheltering, especially considering the predominant south westerly wind direction and the fact that the southern half of the island has significantly higher terrain than the north.

To avoid the effect of sheltering, a study by Exeter has identified two sites, one to the north of Guernsey and the other to the north west of Herm. These are defined in Figure 7-34. Site 'A' is approximately 0.5nm closer to shore when compared to the closest turbines from the Halcrow deployment scenario. This has the benefit of reduced cabling cost and also an easier route to interconnect with high demand centres on the east side of the island.

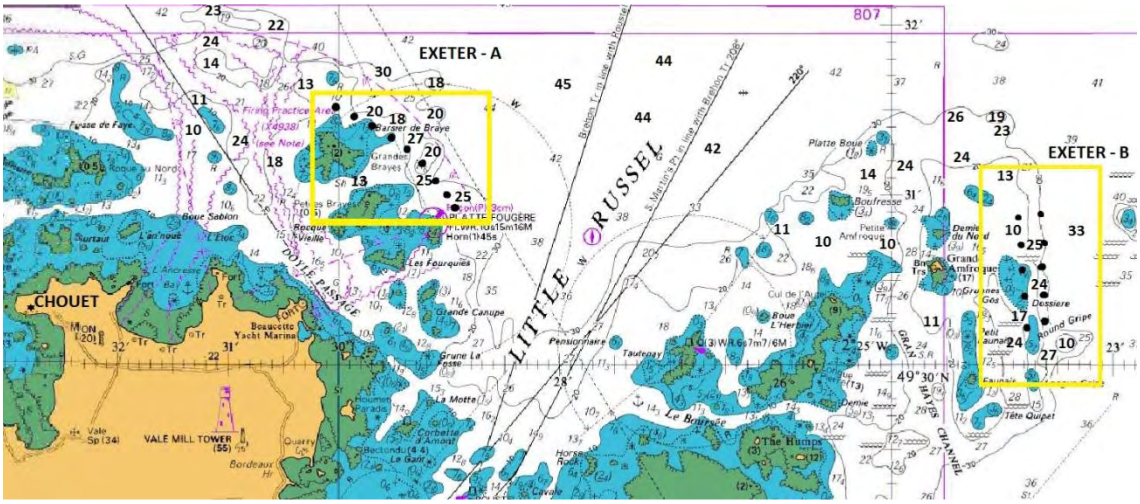

Figure 7-34 Water Depth off the NE coast of Guernsey

Site 'B' is approximately 5nm from Guernsey's east coast, any cable interconnection would have to cross the 'Little Russel'. Scallop dredging takes place north of this area and may be affected by the laying of a cable. The deployment layout is in two rows and does not appear optimised for the predominant wind direction. Considering this, and the distance from shore, a site at this location is not likely to be feasible when considering a deployment scenario of only 10 turbines.

A large export scale array has been suggested to the NE of Guernsey but outside the 3nm limit, this location is approaching depths of 40m or more and would therefore require alternative foundation technologies such as jackets or tension-leg-platforms (TLP's) which at the present time can be very costly and are not covered here. Cost reductions are expected as the technologies and supply chains mature.

The proposed site 'Exeter A' is likely to have a greater visual impact when compared to the layout at the NW site (Halcrow-A or Curved) as it is significantly closer to the shore. Deployment at this site is limited as the water depth breaks heavily to over 40m as you move further offshore.

7.10 Site Comparison

Wind resource is likely to be significantly higher at the NW site and of higher quality with reduced turbulence etc. as it has significant fetch over the sea. Both sites have similar bathymetry as they have been selected with current foundation technology in mind.

It would not be possible to cite a wind farm off Guernsey's east coast due to constraints such as environmentally sensitive areas, increased sea traffic, fishing activities, and potential sheltering by the island (predominant south westerly wind direction). This suggests cable landing will occur on either the north or North West of the island, leading to potential issues with grid balancing due to proximity to demand centres. A development off the north coast could potentially overcome this issue by interconnecting near the power station at St Sampson; fortification of the grid is not likely to be required at this point.

Decision between the two sites would depend very much on the financial viability and availability of funding for different scaled projects. It may be possible to piggy back off another larger development in French waters, sharing the usage of specialist vessels. Appendix G contains a list of nearby wind farms and ports both in French and British waters. A larger scale export array outside the 3nm limit could be installed as a standalone site giving more flexibility with regards to installation schedules etc.

Guernsey is currently looking at proven technology and would rather be a fast follower than implementing pioneering technologies. With regards to foundations monopiles were considered a safe and proven technology, but have now been shown to be unstable with grouting being worn away. The result is changes being made to design regulations to improve structure stability and longevity; this is a good example of how maturity of a particular technology can lead to improved reliability.

When analysing foundation types, it can be seen that a significant emphasis is placed on installation method and the simplicity of installation, there are two important reasons for this, the first is that installation time is directly proportional to installation cost, the second is that there is a shortage of specialised offshore installation vessels such as jack-up barges. If this becomes a key requirement then project scheduling may be adversely affected, if weather and environmental windows are also factored in then there may be significant financial risk associated.

8 Conclusion

Overall, offshore wind is feasible in Guernsey waters within the 3nm limit. Even without the use of energy storage, an array of 10 turbines would diversify Guernsey's power generation portfolio, improving flexibility and energy security.

- A new anemometer has been installed at Chouet due to its close proximity to a potential deployment zone off the NW coast of Guernsey; this has generated 6 months of data so far. Applying exposure correction for site exposure to wind data from both the Chouet and Airport anemometers, and extrapolating to a hub height of 80m has provided data with a sufficiently close correlation to enable the use of historical wind data; this is shown by a chi-squared fit approaching 1.

- Two years of historical wind data have been analysed and have shown that there is a sufficient wind energy resource on Guernsey to warrant the development of offshore wind energy within the 3nm limit. An estimated 103GWh of electricity may have been produced annually in the years 2010 and 2011 when considering an array of 10 Vestas V90-3 turbines and taking into account appropriate values for array and electrical losses as well as turbine availability.

- It is shown in this report that the energy generated by a turbine array will not be fully utilised as the time of peak generation does not always coincide with peak demand. However the flexibility provided by the cable link does substantially help with power balancing on the island, with this in mind it is considered too expensive to implement energy storage using currently available technology.

- It is also acknowledged that on island generation does not only serve as a backup but also as an important part of the energy supply, whilst the cable link has served to dramatically improve the islands carbon footprint, an offshore instalment would further improve the islands carbon footprint in line with their aims for gradual decarbonisation and energy security.

- Two sites have been examined and the recommended deployment location is off the NW coast with the deployment pattern as defined in section 6, this aims to reduce visual impact whilst not having a significant effect on the overall array efficiency. Exeter site B would not be feasible due to its increased distance from shore and sheltering by the island from the prevailing wind direction.

- At present it is recommended that the Vestas V112-3 turbines are used due to them being around 20% cheaper per MWh when compared the Enercon E-101 and 21% cheaper than the V90-3, however as direct drive technology matures and its reliability is proven then this is likely to become a more viable option.

- An alternative turbine arrangement has been proposed for the NW site with visuals from Côbo Bay and Chouet. It was found that the visual impact could be altered significantly; however it is not clear if this has a significant improvement on visual impact, a public survey would have to be undertaken. It is also unclear how an alternative layout affects overall array efficiency.

- Regardless of deployment pattern, the electrical layout of a potential offshore array should exhibit some form of redundancy. Where a grid layout is implemented (such as Halcrow-A), it is suggested that a radial collection system is used, and where a single line of turbines is used then a ‘single-sided ring’ should be used.

- At the present time monopile foundations (drilled and driven into the rocky seabed) offer the least risk at the NW site. They are a mature technology and continued widespread deployment is developing their supply chain. Also many of the potential problems have already been identified. As a result of this, use of a flanged connection is suggested, rather than a grouted one.

- Gravity base foundations avoid the risk associated with high steel prices, however current installation methods are more time consuming and environmentally damaging compared to monopiles. Novel installation methods are being developed to overcome these issues, which may make GBF’s a viable option.

- Based on wind data and selected turbines above the Cost of electricity generation using offshore wind turbines will be higher than current on island generation. A reduction in CAPEX to £2.3m/MW and a reduced return on investment rate of 8% would be required to reduce the cost to a level comparable with on-island generation.

- The financial loss incurred by fisheries due to deployment off the NW coast is easily quantifiable and mostly as a result of restricted potting activities in the area.

- Environmental impacts would be less than those outlined in the wave and tidal REA due to there being no submerged moving parts, installation impacts are comparable but can be somewhat mitigated through careful planning. This includes implementing a baseline monitoring system and an onsite ecologist during construction phases to give comprehensive briefing to site personnel.

- Site selection has been planned with environmentally sensitive areas in mind; the potential deployment zone is not located on any major migration route (‘flyways’) for birds therefore reducing the potential for bird collisions. However scheduling of construction and maintenance works should also be optimised in order to avoid sensitive periods such as breeding which usually occurs from March to July.

9 Recommendations

- When more detailed wind data is available at the Chouet site this should be analysed and taken into consideration. Also, use of a wind speed model such as virtual met mast would provide good means of verifying data. This also provides information on wind shear which can be applied to equation (3-3).

- Use of smaller sector averages when defining surface roughness length in order to more accurately account for upstream conditions.

- Assess the possibility of small scale export via the cable link, is it possible to have an agreement with the Channel Islands electricity grid (CIEG) for a potential array to supply excess generation to Jersey when demand on Guernsey is low. Given the research into Guernsey's extensive wave and tidal resource further research into energy export should be undertaken.

- It is suggested that a more complete economic appraisal of energy storage is undertaken, particularly since it can also serve the purpose of grid balancing. Cost savings may therefore be possible where grid upgrades are no longer necessary.

- Further study into nearby wind farms in French waters and the possibility of sharing resources during installation phases, the hire of specialist vessels is identified as a major contributor to project CAPEX.

- Once a deployment zone is selected, further study is suggested on how micro siting of turbines within this zone affects array efficiency. Electrical layout should also be analysed further depending on the degree of redundancy required and the financial resources available.

- Further research into bird behavioural patterns should be undertaken in order to identify the least sensitive periods of time during which installation and maintenance works can occur.

- Tourism forms an important part of Guernsey's economy, although the potential visual impact have been discussed in this document, the associated public perception has not. A further study on public perception is suggested including surveys in the local area and at different times of the year, this is to gain the opinion of a wide demographic including tourists.

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