Estimation of Wave Energy from Wind Velocity

Jonathan Blackledge
Technological University Dublin, jonathan.blackledge@tudublin.ie

Eugene Coyle
Technological University Dublin, Eugene.Coyle@tudublin.ie

Derek Kearney
Technological University Dublin, derek.kearney@tudublin.ie

Ronan McGuirk
Technological University Dublin

Brian Norton
Technological University Dublin, brian.norton@tudublin.ie

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Estimation of Wave Energy from Wind Velocity

Jonathan Blackledge, Eugene Coyle, Derek Kearney, Ronan McGuirk and Brian Norton

Abstract—**The aim of this paper is to report on a possible correlation between the Lévy index for wind velocity and the mean Energy Density of sea surface waves in the same location. The result is based on data obtained from 6 buoys located around the coast of Ireland and maintained by the Marine Institute of Ireland and a further 144 buoys located at various locations off the coast of the United States of America and maintained by the National Data Buoy Centre. These buoys provide historical data on the wind velocity, wave height and wave period as well as other data on an hourly interval. Using this data, we consider the relationship between a stochastic model for the time variations in wave height that in turn, is based on a non-Gaussian model for the wind force characterised by the Lévy index. The results presented in this paper indicate the possibility of developing a method of estimating the energy and power densities of sea waves from knowledge of the wind velocity alone.**

Index Terms—**Wave Energy Density, Wind Velocity, Lévy Index, Non-Gaussian Analysis, Sea Surface Wave Model.**

I. Introduction

OCEAN wave energy [2] has significant potential in terms of the contributions it can make to the development of a renewable energy resource [3]. Generating electricity from open sea surface waves has negligible environmental impact, increases the amount of electricity that originates from renewable energy technologies, minimises the use of fossil fuels in the long run and addresses climate change issues. One of the principal problems associated with ocean wave energy is how to make the generation of the energy economically viable. Part of this exercise includes the development of physical and engineering models to accurately predict the energy and power available from open sea surface wave patterns. It is in the context of this problem that the results discussed in this paper are presented.

The motion of sea surface waves (generated by the wind) is principally determined by the wind speed and, in particular, the gradient of the wind velocity which induces a force. Thus, understanding the temporal and spatial variations of the wind force regulated through different angles of incidence upon the sea surface is a fundamental issue. Another issue is the characteristic spectrum over which the wind force is converted into wave motion. Because it is not possible to uniquely simulate such complex interactions on an entirely deterministic basis (e.g. the wind velocity can not be known precisely as a function of time) over large scales, in this paper we consider a stochastic model to investigate a correlation between the energy associated with a sea surface wave stream and the wind velocity time series characterised by the Lévy index which is a non-Gaussian statistical metric used to model random processes with long-tail distributions.

In order to validate a stochastic model two approaches can be considered. The first is to use Computational Fluid Dynamics (CFD) to simulate sea surface waves over relatively small scale surface areas in order to confirm the statistical validity or otherwise of the stochastic models developed. The second and complementary method is to consider the statistical compatibility of the stochastic model with known data (e.g. wave height time series) which will inevitably be of a limited extent and validity (the use of CFD thereby being required). In this paper, we address the second approach using data obtained from the Irish Marine Weather Buoy Network [4] and the National Data Buoy Centre [5].

The principal aim of this work is to consider a model for time varying sea surface wave patterns generated by a wind velocity field that is compatible with known data for a given location. The purpose of this is to derive more precise estimates of the expected energy output from a given wave energy converter with known performance characteristics. The approach provides the potential to identify the optimal location of a wave farm from knowledge of the wind velocity alone. In this paper we provide evidence for a possible correlation between the expected wave Energy Density and the Lévy index for the wind velocity alone. As an introduction to the issues involved, Section II provides a brief overview of wave energy and Sections III and IV continue with a brief explanation and classification of wave energy convertors, respectively. The resource and environmental issues associated with wave energy technology are considered in Section V and in Section IV, the primary definitions for evaluating wave energy are introduced. Section VII provides the material which represents the principal contribution to the field given in this paper and introduces both the basic model and data analysis used to validate a new relationship between the energy density of sea surface waves and the Lévy index of the associated wind velocity. To the best knowledge of the authors, this provides an original contribution in terms of the data acquired and the analysis of the data undertaken and presented , the key result being that there exists a relationship between the mean wave energy density $\bar{E}$, the bandwidth of the waves Ω and the Lévy index of the wind velocity γ given by

$$\frac{\ln \bar{E}}{\mid \Omega \mid} \leq 3\left(\frac{2}{3\gamma}-1\right)$$

II. Overview of Wave Energy

Ocean wave power is a concentrated form of solar energy. Winds generated by the differential heating of the earth pass over open bodies of water push surface water particles along with it, setting up a rolling motion in the water and moving the water particles in a vertical and circular

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Jonathan Blackledge (jonathan.blackledge@dit.ie) is the Science Foundation Ireland Stokes Professor and Professor Eugene Coyle (eugene.coyle@dit.ie) is Head of Research Innovation and Partnerships at Dublin Institute of Technology. Derek Kearney (derek.kearney@dit.ie) is a Senior Lecturer in the Electrical Services Engineering Department at Dublin Institute of Technology. Ronan McGuirk (ronan.mcguirk@esbi.ie) is an electrical engineer with ESB International and registered for a PhD with the Dublin Energy Lab. Brian Norton (brian.norton@dit.ie) is President of Dublin Institute of Technology and a member of the Dublin Energy Lab.

path as illustrated in Figure 1 [6]. The energy and power

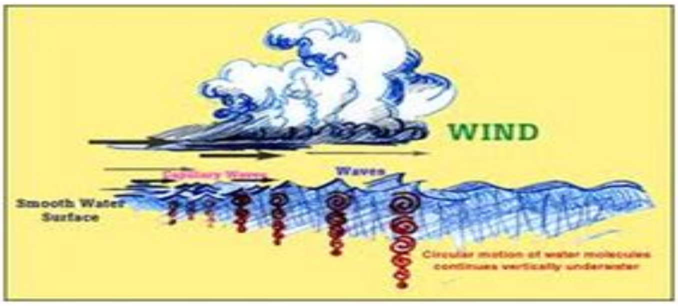

Fig. 1. Generation of sea surface waves.

densities of a wave are proportional to the square of the wave amplitude and knowledge of the average wave height is therefore important when considering where to place a wave farm. Figure 2 shows an average wave height map of the world where it is clear that the northern hemisphere (i.e. the northern Atlantic and Pacifc oceans) have the largest average wave heights. Further, in terms of the propensity of these waves to coast lines, there are two principal regions that stand out: (i) the Aleutian Islands; (ii) the west coasts of Ireland and Scotland. However, the latter coasts are regions with a higher population density and easier access to the infrastructure required to exploit wave energy technology. On the west coast of Ireland, wave heights can vary from 2-12 metres over a week depending on seasonal changes and the world's first commercial wave energy plant generating 0.5 MW (developed by *WaveGen*) is located in Isle of Islay, Scotland.

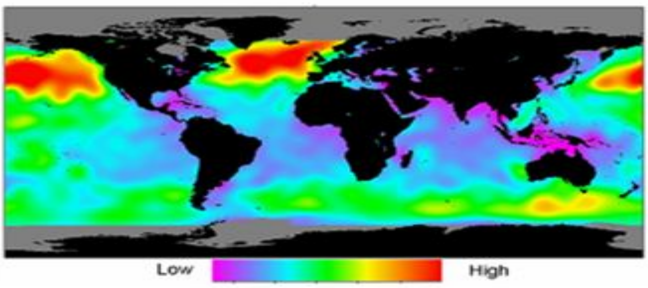

Fig. 2. Global average wave height map.

A. The Wave Energy Resource

The World Energy Council has reported [7] that approximately 2 Terawatts, approximately double the current world electricity production, could be produced by harnessing the oceans energy via wave power. For example, it is estimated that 1 million Gigawatt hours of wave energy is incident on Australian shores annually and that 25% of the UK's current power usage could be supplied by harvesting its wave resource . A detailed assessment of Ireland's wave energy resource in 2005 looked at the theoretical and accessible levels of wave energy in Irish waters [8]. The study indicated that a theoretical wave energy resource of up to 525 TWh exists within the total limit of Irish waters. For comparison, in 2006 the total electricity requirement for the Republic of Ireland was 27.8TWh of electricity. In 2011 the UK Carbon Trust estimated that the global marine energy sector could be worth US$760 Billion by 2050 and could support 68,000 jobs in the British marine energy sector alone. Industry estimates put annual marine energy revenues at nearly US$100 Billion by 2025.

B. History Of Wave Energy

The wave energy sector may not be as far advanced as other renewable sectors such as wind or solar, but the concept of harnessing energy from ocean waves is not new. The first ideas were patented as far back as 1799 [9]. Between 1855 and 1973, 340 patents for wave energy devices were placed. Modern era research into wave energy was greatly stimulated by the oil crisis of the early 1970's which generated a the dramatic increase in oil prices (see Figure 3). The increasing

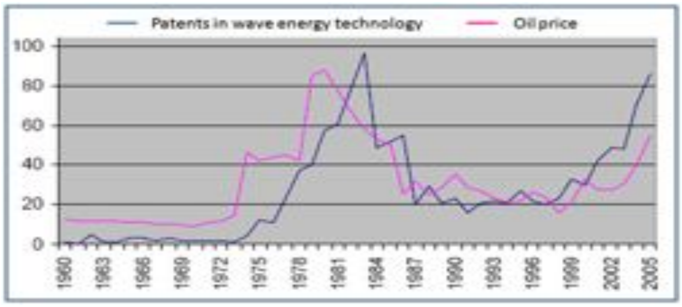

Fig. 3. Relationship between oil price and global wave energy patents.

oil prices panicked governments into stepping up research into alternative forms of power generation. Several research programs with government and private support were started mainly in the UK, Portugal, Ireland, Norway, Sweden and Denmark. However in the 1980's, the price of oil returned to more affordable levels and with it, the interest in wave energy research dwindled with funding being withdrawn from many projects. But since the mid 1990's, the increasing levels of CO_2 emissions and climate change awareness has captured the attention of governments and people the world over and in turn the generation of electricity from renewable sources has once again become an important area of research. In the last 10 years, there has been a resurgent interest in wave energy, particularly in Europe. Today there are over 1000 patents relating to wave energy world-wide and an installed capacity of approximately 2MW.

C. Why Wave Energy?

The use of ocean waves as a source of renewable energy presents many unique advantages over other forms of renewable energy generation. They include the following:

- Ocean waves carry the highest energy density of all renewable energy sources, roughly 1000 times the kinetic energy of wind [10], allowing for much smaller and less conspicuous devices to produce the same amount of power in a fraction of the space (it is the high power density of wave energy that suggests it has the capacity to become the lowest cost renewable energy source).
- Negligible environmental impact [11].
- Wave energy convertors are less visually obtrusive than wind turbines with negligible demand on land-use and

infrastructure costs are therefore significantly lower over other land-based renewables.
- There exists the potential for a significant contribution to energy production without carbon emissions.
- The natural seasonal variability of wave energy follows the electricity demand in temperate climates [12].
- Sea surface wave can travel large distances with little energy loss.
- Wave energy devices can generate power for considerably longer periods compared to other renewable sources such as wind and solar energy [11].
- Wave power production is much ‘smoother’ and more consistent than wind or solar energy resulting in higher overall capacity factors.

III. Wave Energy Converters

Unlike other renewable energy sectors such as wind, for example, which has settled on a three blade axis turbine design for all its devices across most locations, there is no such uniformity in the designs of wave energy devices. With patents for over 1000 wave energy conversion technologies in Japan, North America and Europe [12], there are a large number of conceptual designs competing for the right to be deployed on a mass scale. However, given the nature of the environment in which the devices have to be installed, it is very possible that no one design will be capable of adequately exploiting the wave energy resource across the globe. It is more likely that a handful of designs will provide enough scope for harnessing the oceans wave energy across all feasible environment types. With this in mind, wave energy devices are generally categorised by location and type.

A. Location

The placement of wave energy converters is broken into three separate categories [13], On-Shore, Nearshore and Off-Shore (see Figures 4 and 5).

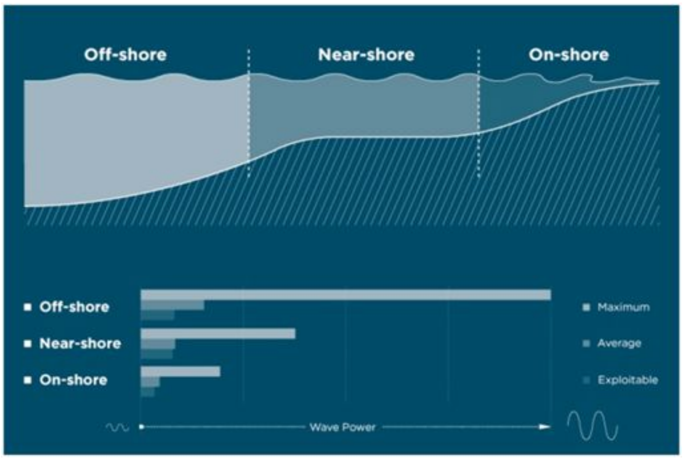

Fig. 4. Location to power representation for wave energy converters.

1) On-Shore: Wave energy devices installed onshore have the advantage of being closer to the utility network which naturally reduces initial grid connection costs. Devices installed near the shore are easier to maintain and are less susceptible to damage from extreme whether conditions as

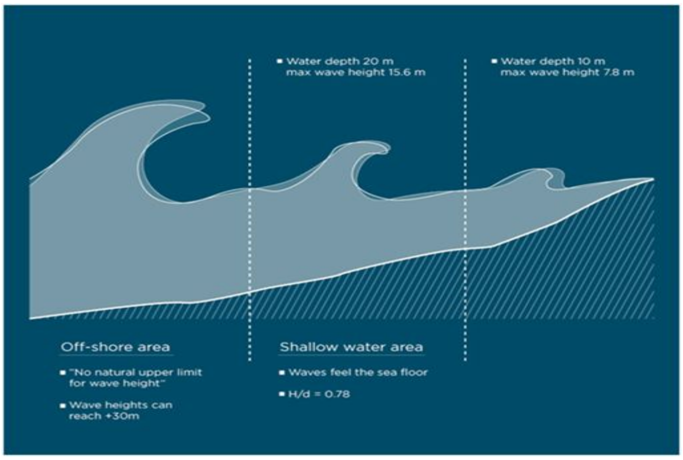

Fig. 5. Classification of wave energy locations.

waves are attenuated as they travel through the shallower water reducing potential stresses on the device. These advantages however come at a price as devices installed in shallower waters close to the shoreline have less energy to exploit (Figure 4). Nearer to the shoreline, the average energy density of a wave decreases due to their interaction with the seabed. In addition to this, the aesthetic quality of the wave energy device becomes an issue as it is more readily visible than a device installed out to sea. This can lead to many localised issues surrounding the visual impact of the devices on the local scenery making it more difficult to secure permission for the installation of large arrays of devices.

2) Near-Shore: Nearshore devices are defined as devices that are in relatively shallow water. While there is a lack of consensus as to what defines ‘shallow’ water, it is generally agreed that nearshore represents an area within 2km from the coastline. Devices located in this area are often directly attached to the seabed allowing for a stable and robust base from which an oscillating body can work. Like shoreline devices, a commonly perceived disadvantage is that shallow water leads to waves with reduced power, restricting the harvesting potential [1]. However, nearshore waves 500 m to 2 km from some coastlines off the west coasts of Scotland and Ireland, for example, can have 80-90% of the power potential of offshore waves. Offshore waves carry a power potential of around 18.5 kW per metre-slice, whereas nearshore waves carry around 16.5 kW. The contention is that to-date, readings from severe storms have pushed up the average power potential of off-shore areas. Also, nearshore waves tend to have uniform movement direction towards the coast whereas off-shore waves come from several directions making them harder to collect.

3) Off-Shore: Offshore devices are generally installed in deep water. Placing a wave energy converter in deeper water results in a greater amount of energy to be exploited as the energy content in deep water waves is higher. Offshore devices are more difficult to construct and maintain. However, the higher energy content and shear size of the waves encountered in these locations means the conversion devices have to be designed to tolerate the most severe conditions which inevitably adds cost to construction and maintenance. There is also the added disadvantage that the further away a device is from the land, the more expensive it becomes to connect said device to the utility grid.

IV. Classification Of Wave Energy Devices

Early research in wave energy converters primarily targeted floating devices. This resulted in three typical classifications of either a Point Absorber, a Terminator or an Attenuator [2]. The classifications were intended to describe the principle operation of and geometry of the device. These descriptors are still used today to a certain extent but the advent of new designs in recent years have added a few new classifications, primarily the Oscillating Water Column, Oscillating Wave Surge Converter and Overtopping Device.

A. Oscillating Wave Surge Converter

An oscillating wave surge converter usually comprises of a hinged deflector positioned perpendicular to the wave direction that moves back and forth exploiting the horizontal velocity of the wave.

1) WaveRoller: The WaveRoller device developed by AW Energy consists of a plate fixed to the seabed that uses the forward and backwards motion of the waves to drive a piston pump which pumps hydraulic fluid inside a closed hydraulic loop (Figure 6). The high pressure fluids are fed into a hydraulic motor that drives an electric generator. It is a modular system; hence, its capacity can easily be increased by simply adding more units. The device is fully submerged below sea level [14].

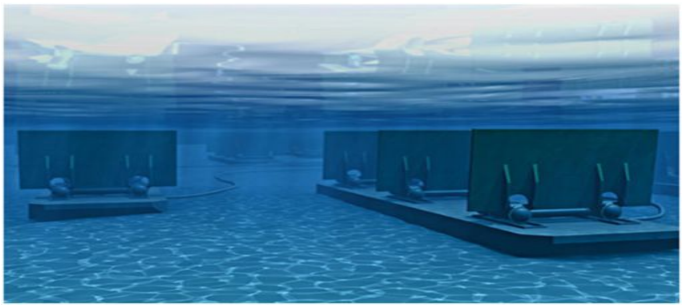

Fig. 6. Waveroller by AW Energy.

2) Oyster: The Oyster device developed by Aquamarine Power is an oscillating device for deployment near shore on the seabed in water depth of 10 to 12 meters with approximately 2 meters of the device exposed above the sea surface (Figure 7). Similar to the WaveRoller in design and operation, it uses multiple piston pumps to pump high-pressure seawater to the shore via a subsea pipelines. The water is then used to generate electricity through a hydro-electric turbine. The cost of the pipe line is low, because the device is deployed near shore. However, this decreases the efficiency of the device because a lot of the energy in the waves is depleted due to friction when the wave reaches shallow water [15].

Fig. 7. The Oyster device by Aquamarine Power.

B. Point Absorbers

Point absorber devices have a small horizontal dimension comparative to the longer wave length in which they operate. Point absorber devices utilise the rise and fall of the wave height at a single point. The devices can be floating structures that heave up and down on the sea surface or submerged below the sea surface utilising the pressure differential. These devices are generally quite small and as such are not reliant on wave direction.

1) PowerBuoy: The PowerBuoy, developed by Ocean Power Technologies (Figure 8) involves a floating structure with one component relatively immobile, and a second component with movement driven by the wave motion. In essence it is a floating buoy contained within a fixed cylinder. The relative motion is used to drive an electrical generator through Faraday Induction directly [16].

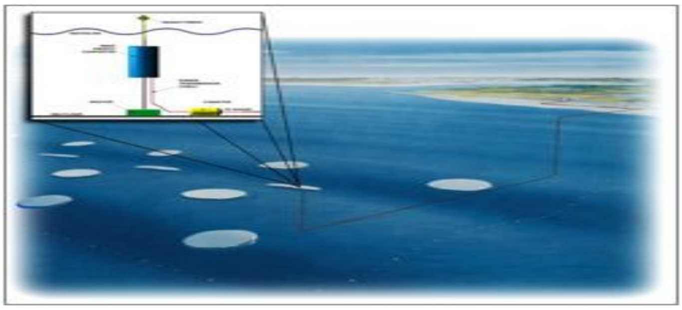

Fig. 8. PowerBuoy by Ocean Power Technologies.

2) WaveBob: Wavebob (Figure 9) works on the same principle as a bicycle pump. There are two main parts to the working apparatus: a round doughnut-shaped section called a torus; a separate float which is located in a hole in the centre of the torus and has a larger weight suspended from it located under the water. The larger weight moves up and down in the water at a different frequency to the lighter doughnut shaped torus. The two devices are connected together through a central column, and as the system moves up and down, it pressurises a hydraulic circuit which drives an electrical generator [17].

Fig. 9. The Wavebob device.

3) Archimedes Wave Swing: The Archimedes Wave Swing developed by AWS Ocean Energy is a submerged cylinder shaped buoy, moored to the seabed, at least six metres below the sea surface. Passing waves move an air filled upper casing against a lower fixed cylinder, with the up and down movement converted into mechanical energy and then electrical energy via a linear synchronous generator (Figure 10) [18].

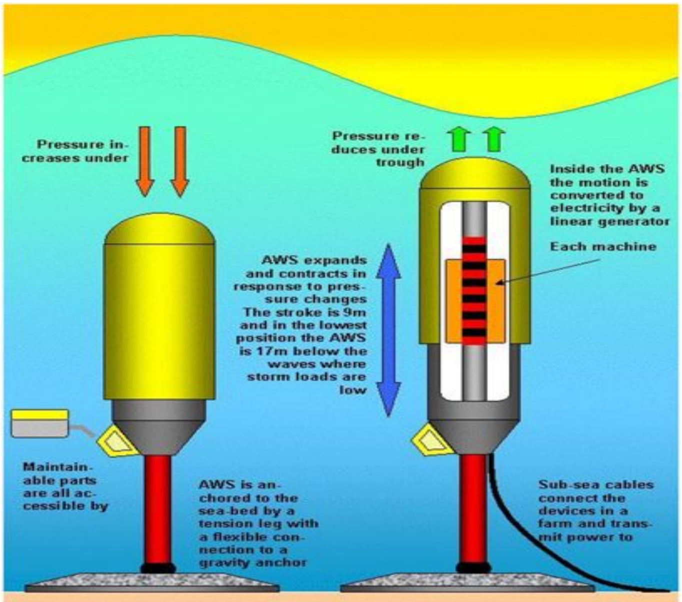

Fig. 10. Archimedes Wave Swing by AWS Ocean Energy.

C. Attenuators

Attenuators are long multisegment floating structures orientated parallel to the direction of the wave travel. The differing heights and force of the oncoming waves along the length of the device causes a flexing motion where the segments connect. This flexing is directly connected to hydraulic pumps or other converters. Attenuator devices have a relatively small area exposed to the face of the waves, enabling them to reduce the hydrodynamic forces of inertia, drag and slamming that have the potential to inflict significant damage to offshore devices.

1) The Pelamis: The Pelamis, designed by Ocean Power Delivery Ltd, is made up of four floating cylindrical pontoons connected via three hinged joints (Figure 11). The wave induced motion of these joints is resisted by hydraulic rams which pump high pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Several devices can be connected together and linked to shore through a single seabed cable with a typical 30MW installation occupying a square kilometre of ocean and providing sufficient electricity for 20,000 homes [19].

2) McCabe Wave Pump: Using a similar concept, the McCabe wave pump has three rectangular steel pontoons that point into the wave direction (Figure 12). There is a damping plate attached underneath the central pontoon in order to increase its inertia. The wave energy is converted by hydraulic pumps that are situated at the hinge points between the central pontoon and the two on its sides. The high pressure hydraulic fluid can drive a hydraulic motor that is coupled to an electric generator in order to generate electricity, or the pumps can pump high pressure seawater that can be desalinated in a reverse osmosis process.

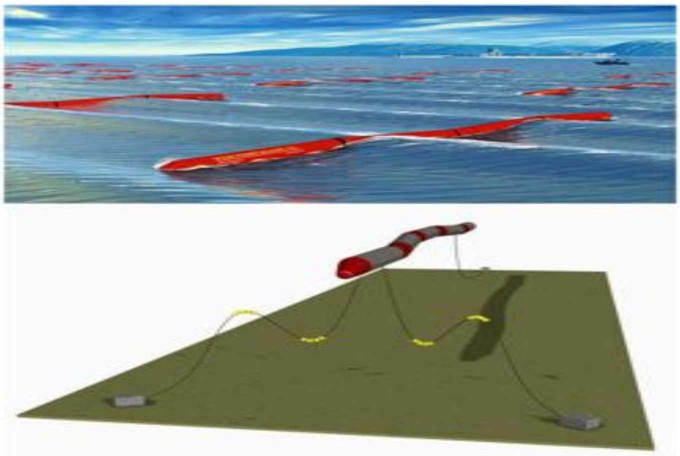

Fig. 11. Pelamis by Ocean Power Delivery Ltd.

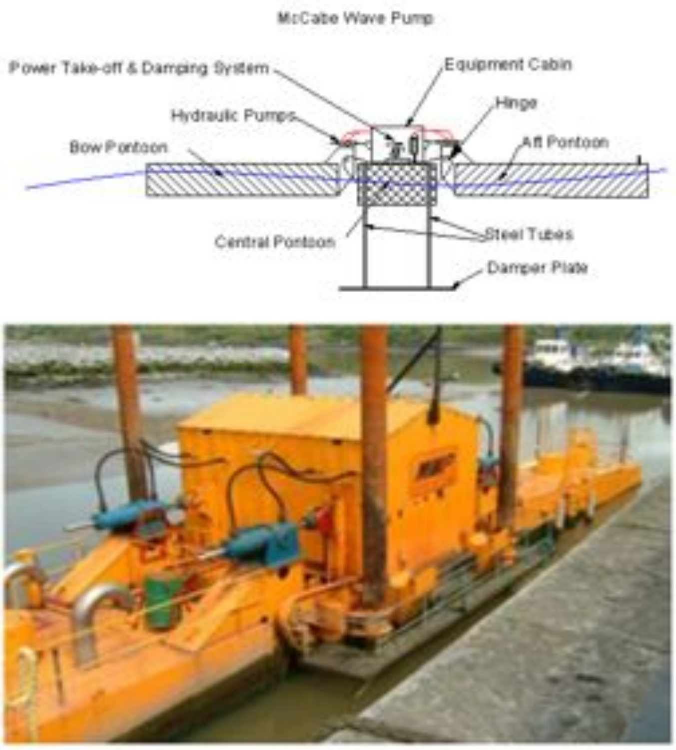

Fig. 12. McCabe Wave Pump device.

D. Overtopping Device

Overtopping devices have reservoirs that are used to capture sea water by impinging waves to levels above the average surrounding sea level. The water is then released back to the sea and in doing so is used to drive turbines. Overtopping devices can be designed and tested for both onshore and floating offshore applications.

The ‘Wave Dragon’ is an offshore overtopping device shown in Figure 13. This device uses a pair of large curved deflectors that concentrate the waves toward a central raised reservoir and thus raises the effective wave height. Kaplan turbines are used to convert the low head of the water into mechanical energy. The turbines drive permanent magnet generators, thereby generating electricity on the same principal as conventional land based hydropower plants [20].

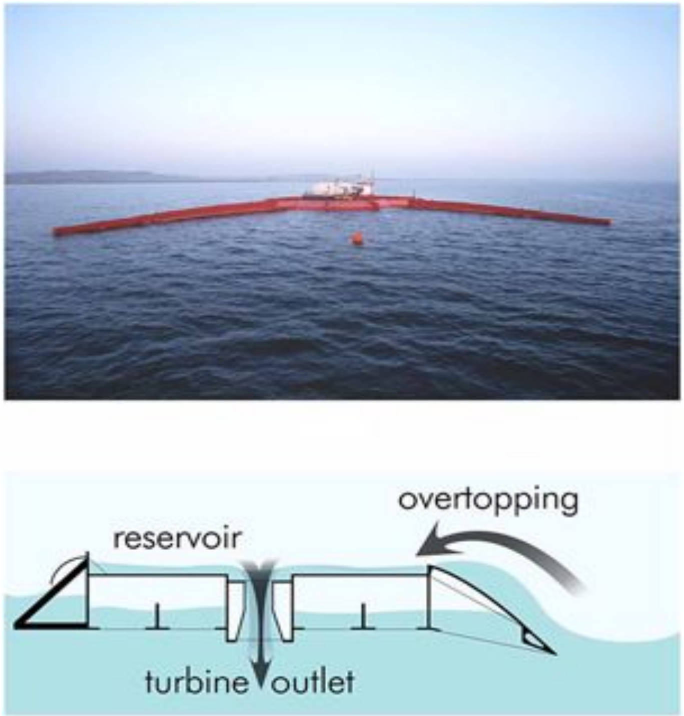

Fig. 13. The Wavedragon device.

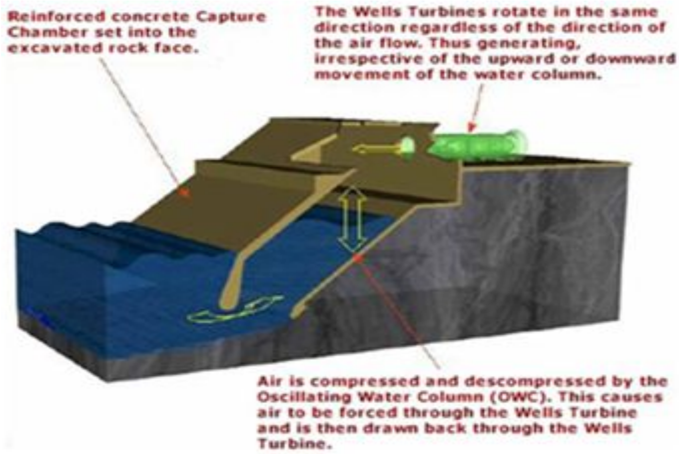

Fig. 14. Limpet Device by Wavegen.

Fig. 15. Oceanenergy OWC.

E. Oscillating Water Column

An Oscillating Water Column (OWC) is made up of a chamber with an opening to the sea below the waterline. When waves approach the device, water is forced into the chamber which applies pressure to the water within the chamber. The wave action results in the captured water column within the device moving up and down like a piston which alternatively compresses and depressurises the chamber forcing the air through an opening connected to a turbine. A low pressure Wells Turbine is often used in this device as it rotates in the same direction regardless of the air flows direction. One of the main advantages of the oscillating water column device is it's simplicity in design and robust construction. Figure 14 illustrates the Wavegen Limpet device which is a shore mounted OWC [21]. There are examples of OWC's being used as point absorbers such as OceanEnergy's OWC illustrated in Figure 15 [22]. This device uses the same operational characteristics as the Wavegen Limpet but is designed for deployment offshore.

V. Environmental Considerations and Resource

The benefits of wave energy are undeniable but, as with any technology at such an early stage of development, there are a number of technical challenges that need to be overcome to fully realise the potential of, and most importantly, the commercial competitiveness of wave energy devices. Waves produce a slow ($\sim$0.1 Hz), random and high in energy density oscillatory motion. Converting these characteristics into a useful motion to drive a generator capable of producing a quality output that will be accepted by the utility provider presents a considerable challenge. As waves vary in height and period, so do their respective energy levels. Gross average power levels may be possible to predict in advance but the variable input needs to be converted into a smooth electrical output which usually requires the addition of some form of energy storage or ideally a large array of devices. Predominantly, in offshore locations, wave direction is highly variable and so wave devices have to be aligned accordingly. For point absorber devices such as the PowerBuoy or WaveBob this is less of an issue but closer to the shoreline, alignment is required and can be realised. This is because wave directionality becomes more uniformly predictable due to the refraction and diffraction experienced as the the water depth shallows and is in essence funnelled towards the shoreline.

Fundamentally, and, as has been eluded to in the previous paragraphs, the biggest barrier to the effective operation of wave energy converters is the environment in which they are placed. The irregular and highly unpredictable nature of the sea surface has an impact on the design of all devices. To operate efficiently, each device must be designed to operate for the most common wave levels. The device also has to be capable of withstanding the stresses induced by freak weather conditions and in the case of wave energy converters, freak waves. These conditions may only occur very rarely but when they do, they can deliver power levels in excess of 200 $\mathrm{kW/m}$. This design requirement throws a very costly barrier in the way of developing wave energy converters. The device itself may only be rated to capture the energy from the most commonly occurring waves but has to be engineered to withstand the very high and destructive level of power produced, albeit it infrequently, by extreme weather events.

A. Environmental Considerations

The capture of wave energy for electrical power generation is generally considered to have negligible environmental impact. The exact nature and extent of any potential impact however still remains uncertain as the technology is still in its infancy. The marine habitat could potentially be impacted upon depending on the nature of the device being installed, be they totally submerged structures, above sea level platforms or seabed mounted devices. Above sea floating platforms can potentially provide a resting platform for sea mammals as well as a nesting area for birds. The underwater surfaces of wave energy devices can provide for substrates or various biological systems. Changes made to the seabed for mounting devices and for the provision of submarine cables can also produce potentially negative effects on the local marine habitat. Offshore wave energy devices may be a source of conflict with commercial shipping and recreational boating. Careful consideration needs to be taken when selecting potential areas for the sitting of wave energy devices. Nearshore devices have the potential to interfere with recreational activities as well as having a negative visual impact on the coastline. Any impact that may occur can also be very site specific and it is only with the development of large scale wave farms that the devices impact becomes better defined.

As with any emerging technology, the challenge eventually must be to reduce the cost of wave energy generation. The barriers listed herein may largely be technical, but every time a barrier is overcome, wave energy generation becomes increasing economically viable and with that, moves a step closer to widespread commercialisation. In this context, the principal issues are as follows:

- engineering challenges;
- construction costs;
- installation costs;
- maintenance costs;
- transmission costs and losses;
- environmental impacts;
- Scale of electricity production

B. Measuring the Resource

The power in a wave is proportional to the square of the amplitude and to the period of the motion. Large amplitude ($\sim 2\mathrm{m}$), long period ($\sim 7-10\mathrm{s}$) waves have energy densities commonly exceeding 40-50 $\mathrm{kW/m}$. However, due to its variability, a wave climate is difficult to measure. Wave buoys can give accurate estimates of the sea state but are expensive to maintain for long periods of wave climate estimation [2]. Resource assessment studies are essential when evaluating possible locations for a wave energy project and site specific measurements and surveys are necessary before deciding on the final location for any wave farm. In this context a fundamental question is: How is the wave amplitude spectrum related to the wind velocity (at least on a statistical basis)? The results presented in this paper suggest a possible method for evaluating potential wave energy sites using existing wind velocity data alone and thus requiring considerably less capital outlay. This is based on a linear wave theory for the ocean surface.

C. Linear Wave Models

Linear wave spectrum models assume that the distance over which the waves develop and the duration over which the wind blows are sufficient for the waves to achieve their maximum energy for the given wind speed. It is assumed that waves can be represented by sinusoidal forms. This relies on the following:

- waves vary in a regular way around an average wave height;
- there are no energy losses due to friction or turbulence, for example;
- the wave height is much smaller than the wavelength.

These principal assumptions provide the basis for predicting wave amplitudes on a statistical basis and it is upon this basis that many wave energy converters are designed in which the wave amplitude is taken to conform to a Rayleigh distribution. However, this distribution is known to be inaccurate which is primarily due to a lack of understanding of how, on a statistical basis, wind energy is converted into wave energy.

From a statistical point of view, what is required is a physical model that can accurately predict the distribution of sea surface waves given knowledge on the distribution of the wind velocity. A solution to this problem can then be used to estimate the 'power quality' from a wave farm given statistical parameters that reflect the environmental conditions in which the wave farm is operating. The quality of power is based on measures that include the energy and power densities of the ocean surface. These measures are discussed in the following section but, in general, and. on the basis of a linear wave theory, focus on the following:

- developing a stochastic model for the wind velocity that is statistically significant;
- using this model to simulate the wind velocity and sea surface waves (time signature);
- use the model to develop a wave energy estimator based on wind velocity data alone and hence establsih an answer to the basic question: Can we estimate energy density from knowledge (a statistic) of the wind velocity?

VI. Energy and Power Density of a Sea Surface Wave

The Energy Density (energy in Joules per unit area) of a continuous sea surface wave can be obtained by considering the oscillation of a column of water perpendicular to the plane. Let h be the height of the column with area A above the plane at $h = 0$. Denoting the density of water by $\rho \simeq 1000\mathrm{kgm}^{-3}$ and with $g = 9.81\mathrm{ms}^{-2}$ representing the acceleration due to gravity, the downward force is give by $F = hA\rho g$. Thus we can write (from Newton's second law) the time dependent wave equation

$$\frac{d^2h}{dt^2} = -\omega^2 h, \quad \omega^2 = \frac{A\rho g}{m}$$

where m denotes mass and whose general solution is given by

$$h(t) = a\exp(\pm i\omega t), \quad \omega = \sqrt{\frac{A\rho g}{m}}$$

where ω is the angular frequency and a is the amplitude of the wave. The energy is then (from Newton's energy formula) given by

$$E = \frac{1}{2}m \mid v \mid^2 = \frac{1}{2}m\left|\frac{dh}{dt}\right|^2 = \frac{1}{2}A\rho g a^2$$

which provides an expression for the Energy Density $E := E/A$ of the form

$$\begin{aligned} E &= \frac{1}{8}\rho g H^2 \quad \mathrm{Jm}^{-2} \\ &\simeq 1.23H^2 \quad \mathrm{kJm}^{-2} \end{aligned} \tag{1}$$

where $H = 2a$ is the wave height in metres. The Power Density is then given by

$$P = \frac{E}{T} \quad \mathrm{Wm}^{-2} \tag{2}$$

where T is the period of the wave in seconds.

This result refers to the simplistic case of a continuous wave oscillating at a single (angular) frequency ω. It also assumes linearity where the wave amplitude is taken to have relatively small amplitude. In reality the time signature of a surface wave stream measured at a spatial location on the sea surface will be composed of a range of amplitudes that vary in time reflecting a characteristic frequency spectrum. In this case, we can consider $H$to be given by the mean or root-mean-square of the wave stream. Similarly the period of the waves will vary and we may consider T to be the mean of periods. Thus, if we consider an average wave height of say 1 metre, then the Energy Density is 1.23 kJm^{-2} giving a Power Density of $1\mathrm{kWm}^{-2}$ for a mean wave period of 1 second. These energy and power density estimates are relevant measures for wave energy conversion devices that exploit the primarily vertical movement of a wave such as the *McCabe Wavepump*, the *Archimedes Wave Swing* and the *PowerBuoy*.

A further measure of a wave energy resource is the power per meter of the wave front (wave crest) or Energy Flux. This measure can be calculated by multiplying the Energy Density by the wave front or group velocity to give

$$F \simeq 0.5H^2T, \quad \mathrm{kWm}^{-1} \tag{3}$$

The energy flux is a more relevant measure for devices such as the *Pelamis*, the *Oyster* and *Waveroller*.

VII. Analysis of Sample Data from the Irish Marine and NDBC Weather Buoy Networks

The Irish Marine Weather Buoy Network [4] maintains six weather buoys (M1-M6) that are located as shown in Figure 16. The National Data Buoy Centre (NDBC) [5] is part of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). NDBC designs, develops, operates and maintains a network of data collecting buoys and coastal stations as illustrated in Figure 17. The buoys are operated by both associations and record data on the Atmospheric Pressure (mb), Wind Direction (in Degrees), Wind Speed ($\mathrm{m/s}$ or in the case of the Irish Marine Network, in Knots where 1 Knot = 0.514444 $\mathrm{m/s}$, Gust (Knots), Dry Bulb Temperature (^oC), Dew Point (^oC), Sea Temperature (^oC), Wave Period (seconds), Wave Height (metres) and Relative Humidity (%). The data obtained from this data mining exercise is given in [27] which provides values for the mean wind velocity, mean wave height and period and the Energy and Power Densities and the Energy Flux.

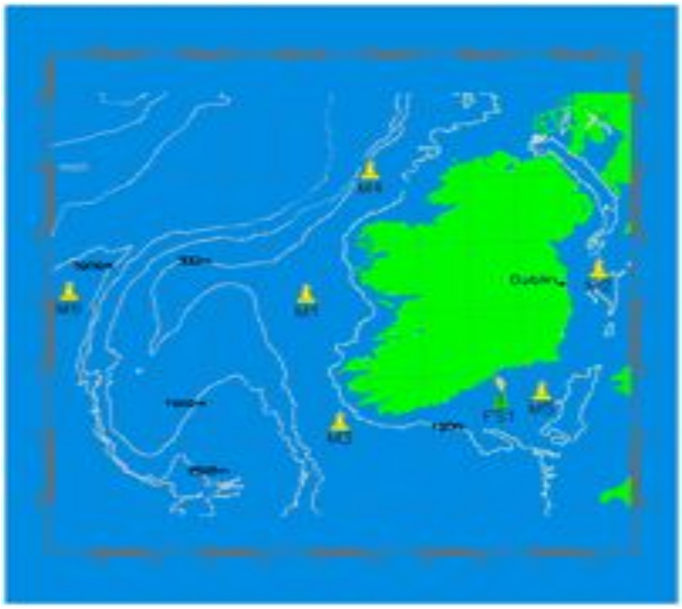

Fig. 16. Location of the Irish weather buoys M1-M6.

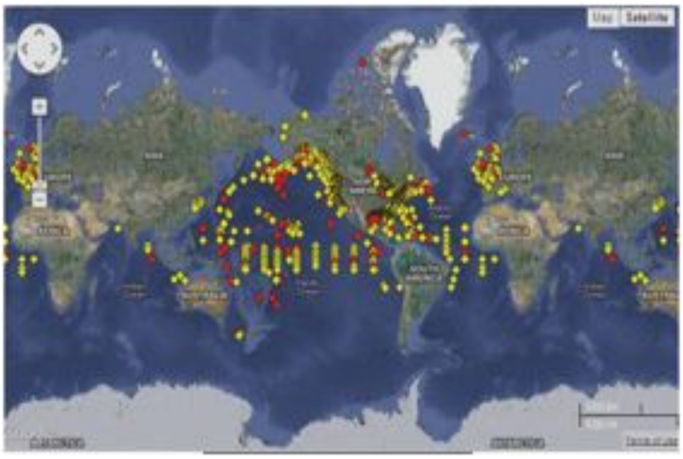

Fig. 17. Location of the NDBC maintained weather buoys.

Figure 18 shows an example of data taken from the M1 buoy which is located off the west cost of Ireland (see Figure 16) at position 53.1266^oN 11.2000^oW. This Figure shows a signal consisting of approximately 8000 samples of hourly data on the wind velocity in metres per second, the wave height in metres and the wave period in seconds. The data available from the Irish Marine weather Buoy Network and NDBC is not always contiguous as some samples or sequences of samples are the product of null returns. The data therefore needs to be filtered to eradicate any null entries. In cases when different data streams are being used on a comparative basis, as in Figure 18, each data stream needs to be filtered consecutively eradicating all data points in all array groups when ever a single null return is detected in any single array. Thus, the signals given in Figure 18 do not represent a contiguous stream of data output from the M1 buoy but a null entry filtered version of the data. However, this does not effect the statistical characteristics of the data, and, in each case, the data is seen to be Rayleigh-type distributed as illustrated in Figure 19 which shows 100-bin histograms of the signals given in Figure 18. Figure 20 shows plots of the Energy Density, the Power Density and the Energy Flux computed from equations (1), (2) and (3), respectively, using the samples of data from the M1 buoy shown in Figure 18. Note that all three signals have similar time signatures, and, apart from scaling, their statistical characteristics are similar. However, the signals are significantly erratic with Energy Fluxes, for example, ranging from long periods of a few $\mathrm{kW/m}$ to short periods in excess of $300\mathrm{kW/m}$. Data of this type can be acquired from all Marine Institute buoys and in reaching the conclusions to follow, data from an additional 144 buoys operated by the NDBC was also collected and processed.

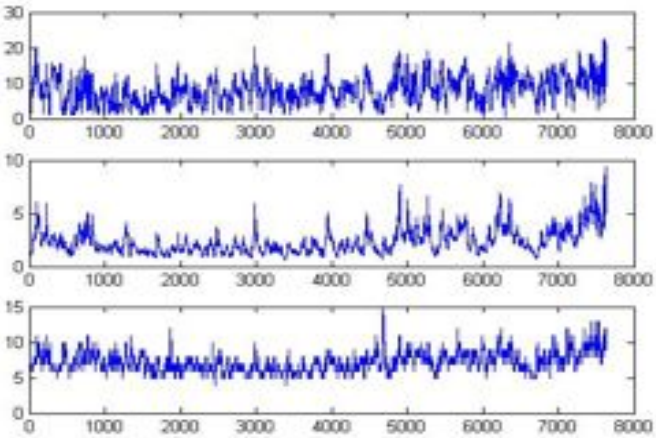

Fig. 18. Time series of the wind velocity in $\mathrm{m/s}$ (top), wave height in metres (centre) and the wave period in seconds (bottom) hourly sampling.

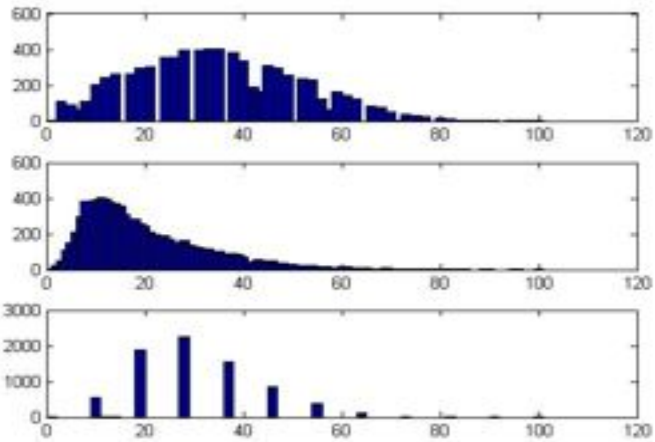

Fig. 19. 100-bin histograms of data on the wind velocity (top), wave height (centre) and the wave period (bottom) as given in Figure 18.

We consider an evaluation of the energy/power parameters given by equations (1)-(3) and the wind velocity. The results

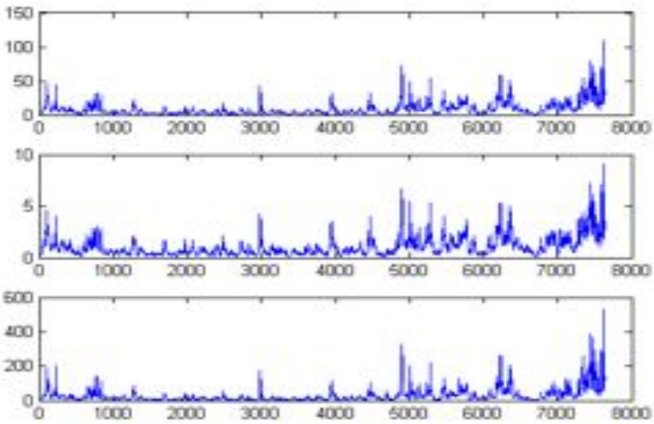

Fig. 20. Plots of the energy density in $\mathrm{kJ/m^2}$ (top), power density in $\mathrm{W/m^2}$ (centre) and the energy flux in $\mathrm{kW/m}$ (bottom) using data obtained for the M1 Marine Institute buoy. The sampling rate is hourly.

TABLE I
SAMPLES OF THE TABULATED MEAN VALUE PARAMETERS COMPUTED FROM THE TIME SERIES DATA OBTAINED FROM THE MARINE INSTITUTE AND NDBC BUOYS.

Buoy ID	Wind Velocity $\mathrm{m/s}$	Energy Density $\mathrm{kJ/m^2}$	Power Density $\mathrm{W/m^2}$	Energy Flux $\mathrm{kW/m}$
MI	8.1308	6.8692	0.9447	20.3029
M5	8.3263	3.6468	0.6715	8.0507
41010	5.7575	2.3441	0.4252	5.2521
42007	5.2905	0.4743	0.1204	0.7638
42040	5.2788	0.998	0.229	1.7673
44005	4.8762	2.7465	0.5286	5.8002
44011	6.2231	5.4719	0.9334	13.0396
45005	5.2992	0.4696	0.1595	0.5619
46045	2.9771	1.0394	0.1717	2.5573
46080	7.0217	6.6112	1.036	17.1486
51100	6.1413	6.5918	0.9135	19.3344
CHLV2	7.7713	1.3278	0.2604	2.752

are shown in Figure 21 which gives scatter plots of the mean wind velocity for the mean values of the Energy Density, the Power Density and the Energy Flux using filtered time series of the type given in Figure 18 for 144 buoys. Samples of the tabulated data is given in Table I.

From this Figure, we observe the following:

1) the scatter of the mean wind velocity and the mean values of the Energy Density, the Power Density and the Energy Flux is similar in all cases;
2) there is no clear scaling relationship between the mean wind velocity and these parameters other than a general expected trending between the wind velocity and energy/power output, i.e. the scatter is wide within then context of the expected trend;

It is in this context that we now investigate a possible scaling relationship between the Energy Density and the Lévy index for the wind velocity using models discussed in the following section.

A. *Scaling Relationship for Sea Surface Waves*

We consider the model derived in [23] for time varying sea surface waves which is compounded in the following result:

$$u(t) = \frac{\Omega}{\pi}\mathrm{sinc}(\Omega t) \otimes f(t) \tag{4}$$

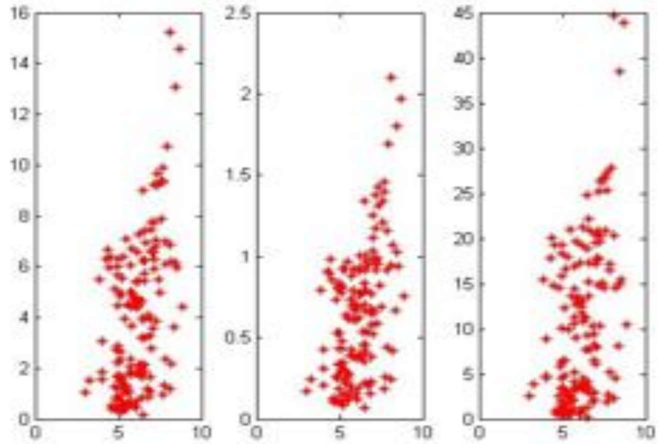

Fig. 21. Scatter plots of the mean wind velocity in $\mathrm{m/s}$ (horizontal axis) versus the mean Energy Density in $\mathrm{kJ/m^2}$ (left), mean Power Density in $\mathrm{W/m^2}$ (centre) and the mean Energy Flux in $\mathrm{kW/m}$ (right) for data obtained from the Marine Institute and NDBC buoys.

where $\otimes$ denotes the convolution integral over time t, $u(t)$ is the wave amplitude, $f(t)$ is a source function (the force generated by the wind as a function of time) and Ω is the bandwidth that is characteristic of the conversion of the force of the wind on the surface of the sea into wave motion.

Equation (4) is based on the following limiting observations:

1) the sea surface consists of a spectrum of two-dimensional waves oscillating at different frequencies;
2) all sea surface waves have relatively low frequencies $\sim$1Hz or less, equation (4) being predicated on the asymptotic condition $\Omega \to 0$;
3) the waves are not correlated in the sense that the wave pattern is locally dependent on the interaction of the wind with the sea surface over a limited area particularly in the higher frequency range.

Point 3 above also means that any attenuation of the surface due to the viscosity of sea water can also be neglected (at least within the immediate locality of the wave motion). Point 2 above is predicated on assuming an Impulse Response Function for the sea surface of the form $-2\ln(\omega r)$ where ω is the angular frequency and $r = \sqrt{x^2 + y^2}$. This is the asymptotic form of the two-dimensional Green's function for the case when $\omega \to 0$.

For unit mass, the wind force is given by the gradient of the wind velocity. In [24] and [25], a model for the wind velocity is considered that is based on a Lévy distribution for the wind force. The Lévy distribution generally provides a more accurate and statistically significant characterisation of the wind force compared to a Gaussian distribution. This is because it is an example of a 'long tail' distribution that includes rare but extreme events, i.e. freak weather conditions. It is shown that this approach leads to a stochastic model for the wind velocity $v(t)$ given by [25]

$$v(t) = \frac{1}{\Gamma(1/\gamma)} \frac{1}{t^{1-1/\gamma}} \otimes n(t) \qquad (5)$$

so that (for unit mass) the wind force is then given by

$$f(t) = \frac{1}{\Gamma(1/\gamma)} \frac{1}{t^{1-1/\gamma}} \otimes \frac{d}{dt} n(t) \qquad (6)$$

TABLE II

TABULATION OF LÉVY INDEX FOR SAMPLE WIND VELOCITIES AS PER TABLE I

Buoy ID	Lévy index
MI	1.6019
M5	1.6171
41010	1.6059
42007	1.6115
42040	1.7787
44005	1.7352
44011	1.6053
45005	1.7103
46045	1.6600
46080	1.5491
51100	1.6431
CHLV2	1.6002

where Γ denotes the Gamma function, $n(t) \in [0,1] \forall t$ is 'white noise' (a stochastic function whose Power Spectral Density Function is a constant) and $\gamma \in (0,2]$ is the Lévy index. The Power Spectral Density Function of the wind velocity given by equation (5) is

$$P(\omega) = \frac{C}{\mid \omega \mid^{\frac{2}{\gamma}}}$$

for an arbitrary scaling constant C and where

$$P(\omega) = \mid V(\omega) \mid^2, \quad V(\omega) = \int_{-\infty}^{\infty} v(t) \exp(-i\omega t) dt$$

Thus, taking logarithms, we can write

$$\ln P(\omega) = \ln C + \frac{2}{\gamma} \ln \mid \omega \mid$$

and by applying a data fitting algorithm to the logarithm of the Power Spectrum of the wind velocity data, an estimate is obtained for γ. Table II, tabulates the value of γ for the wind velocities associated with the buoys using data from the [4] and [5] (as per Table I using the Orthogonal Linear Regression (OLR) method [26]. A complete list of the values of the Lévy index computed is available from [27]. This database also includes references to data obtained form locations that introduce potential rouge values where the data is associated with non-oceanographic locations such as shallow waters, lakes and sheltered inlets etc. In order to filter out data of this type all values associated with location where the calculated Energy Density < 1 are ignored, the resulting data streams for the (filtered) Energy Density and associated Lévy index for the wind velocity being given in the 'Filter Data' document available from [27].

B. Basic Statistical Analysis of Filtered Wave Energy and Lévy Index Data

Using the filtered data given in [27] we present some basic statistical results with regard to the energy density of waves and the Lévy index of the wind velocity that 'drives' them. Tests for normality (which include the Chi-square, the Jarque-Bera and Lilliefors goodness-of-fit tests for composite normality) indicate that the Null Hypothesis can be rejected at the 5% level. Neither data sets can therefore be taken to conform to a normal (Gaussian) distribution. Analysis of the goodness-of-fit associated with probability plots show that the data conform best to a Rayleigh distribution (compared with the normal, lognormal, exponential, extreme value and the Weibull family of distributions). This is demonstrated in Figure 22 which shows that both the energy density and Lévy index appear to be Rayleigh distributed accept at the extrema. Interestingly, the Lévy index is better Rayleigh distributed than the energy density. The Rayleigh distributed characteristics of the energy density is to be expected as it maps to the distribution of wave heights which, for a linear wave model, are Rayleigh distributed (see Figure 19). The deviation of data points from this distribution (as shown in Figure 22) is a possible reflection of non-linearities which are known to occur from time to time in sea surface waves especially with regard to deep water ocean waves and can lead to the generation of 'Freak Waves' (see [28] and references therein). However, application of the Wilcoxen Signed Rank Test (which removes information on the shape of the distribution given that Ranks are resistant to outliers) yields a 'p-value' of 1.1442×10^{-21} and validity of the Null Hypothesis in this case (i.e. that the population medians are equal or the difference in population medians is zero) can be taken to be false. Thus although the energy density and Lévy index appear to conform to the same distributions, they are from 'different populations' and therefore independent. This is reflected in the scatter-plot given in Figure 23 which shows no clear correlation between parameters plotted. Thus, in the following section, we consider a new relationship between these parameters which is based on an analysis of the linear wave model compounded in equation (4) and (6).

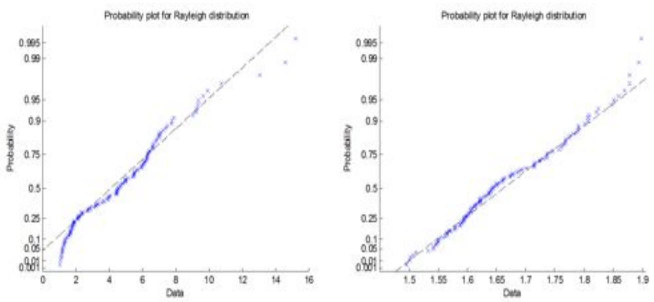

Fig. 22. Rayleigh probability plots comparing the distribution of the data to the Rayleigh distribution for the Energy Density (left) and the Lévy index (right).

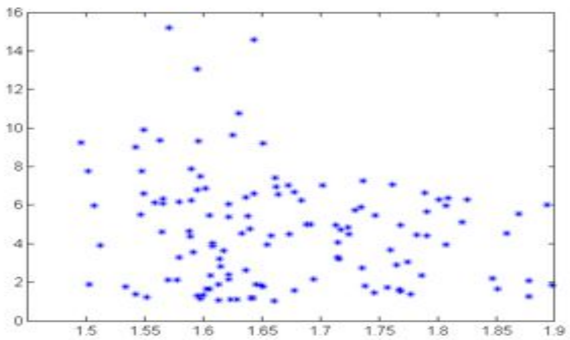

Fig. 23. A plot of the Lévy index of the wind velocity (horizontal axis) against the wave energy density obtained from the data for 125 buoys as sampled in Tables I and II.

C. Correlation Between Wind Velocity and Wave Energy

Given equations (4) and (6), the model for the wave amplitude becomes

$$u(t) = \frac{\Omega}{\pi}\text{sinc}(\Omega t) \otimes \frac{1}{\Gamma(1/\gamma)} \frac{1}{t^{1-1/\gamma}} \otimes \frac{d}{dt} n(t)$$
$$= \frac{\Omega}{\pi} \frac{1}{\Gamma(1/\gamma)} \left(\frac{1}{\gamma} - 1\right) \text{sinc}(\Omega t) \otimes n(t) \otimes t^{\frac{1}{\gamma}-2} \quad (7)$$

Equation (7) provides the basis for developing a scaling relationship between the Lévy index of the wind velocity γ and the wave energy that has been generated by the wind in the same locality (and whose Lévy index has been computed using the method reported in [24]). From equation (7) it is clear that the wave amplitude is proportional to $1/\gamma$. However, to quantify the a scaling relationship in terms of the wave energy we consider the spectrum of the wave amplitude - obtained by taking the Fourier transform of equation (7) and using the convolution theorem - which is given by

$$U(\omega) = N(\omega) \frac{i\omega}{\mid \omega \mid^{\frac{1}{\gamma}}}, \quad -\Omega \leq \omega \leq \Omega$$

where

$$U(\omega) = \int_{-\infty}^{\infty} u(t) \exp(-i\omega t) dt$$

and

$$N(\omega) = \int_{-\infty}^{\infty} n(t) \exp(-i\omega t) dt$$

Using Hölders inequality, we have

$$\|U(\omega)\|_2^2 \leq \|N(\omega)\|_2^2 \frac{\Omega^{3-2/\gamma}}{3-2/\gamma}, \quad \gamma > \frac{2}{3}$$

where

$$\|f(\omega)\|_2^2 \equiv \int_0^{\Omega} \mid f(\omega) \mid^2 d\omega$$

and hence, from Rayleigh's Energy Theorem, we can define the mean Energy Density $\bar{E}$ in terms of the inequality

$$\bar{E} \leq \|N(\omega)\|_2^2 \frac{\Omega^{3-2/\gamma}}{3-2/\gamma}$$

Thus, for $\gamma > 2/3$

$$\ln \bar{E} \leq \ln \|N(\omega)\|_2^2 + \left(3 - \frac{2}{\gamma}\right) \ln \Omega - \ln\left(3 - \frac{2}{\gamma}\right)$$

so that

$$\ln \bar{E} \leq 3\left(\frac{2}{3\gamma} - 1\right) \mid \ln \Omega \mid, \quad \Omega \to 0 \quad (8)$$

This asymptotic result is compatible with that used to derive equation (4) and equation (8) is therefore consistent with the original wave model. From equation (8) it is now clear that $\ln \bar{E}$ is proportional to $1/\gamma$ and to $\mid \ln \Omega \mid$. Normalising by the factor $3 \mid \ln \Omega \mid$ so that $\ln \bar{E} := \ln \bar{E}/3 \mid \ln \Omega \mid$ we consider the scaling relationship

$$\ln(1 + \ln \bar{E}) = -m \ln \gamma + c \quad (9)$$

where c and m are arbitrary (real) constants. Figure 24 shows a plot of the data (samples of which are given in Tables I and II) and a linear fit to the data based on equation (9) where (working to 4 decimal places) $m = -0.42699$ and $c = 1.0236$ (the norm of residuals being 3.5562). This result is an indication of a possible correlation between the Lévy index for the local wind velocity and the corresponding Energy Density of the wave patterns for the same area as quantified by equation (9).

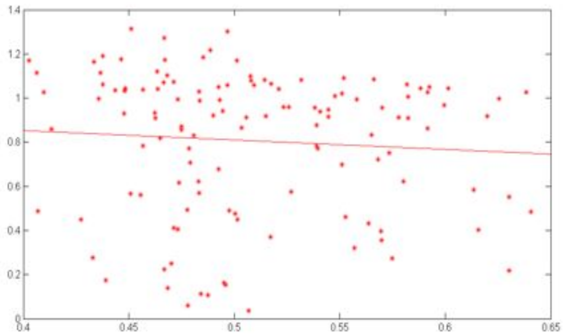

Fig. 24. A plot of the logarithm of the Lévy index of the wind velocity (horizontal axis) against the logarithm of 1 plus the logarithm of the wave energy density obtained from the data for 125 buoys as sampled in Tables I and II (red point stars) and a best linear fit (solid red line) to the data.

VIII. Conclusions And Future Work

The results given in Figure 23 are an indication of the possible validity of the scaling given by equation (9). The results provide the potential for developing a computational procedure to predict the mean Energy Density of a sea surface from data obtained on the wind velocity alone. This has a number of practical advantages in the assessment of regions suitable for the exploitation of offshore wave energy. Future work must include the validation (or otherwise) of the results presented in this paper.

Whilst the data is largely only available in hourly sampled intervals and includes null returns that need to be filtered, the stochastic models used in this study provide a statistical measure that is not dependent on the sampling rate. This is because the wind velocity model is scale invariant, i.e. one of the fundamental properties of equation (5) is that

$$\Pr[v(\lambda t)] = \lambda^{\frac{1}{\gamma}} \Pr[v(t)]$$

for a scaling factor λ where $\Pr$ denotes the Probability Density Function. The wind velocity is therefore taken to be a stochastic self-affine field (a random scaling fractal) whose statistical properties are the same (accept for scaling) at different sampling rates.

Future applications could include use of the approach to estimate the expected supplementary energy available by developing wave farms in the same regions as the offshore wind farms being planned by the European Wind Energy Association (EWEA) for the 2030 offshore super-grid. As the EWEA vision becomes a realisation, the added concentration of HVDC terminals, offshore wind farms and increased grid interconnection will help drive forward the competitiveness of wave energy as they will be able to exploit the infrastructure of wind farms in what are otherwise no-go marine areas. (Figure 25).

Fig. 25. Representation of the proposed offshore wind farms planned by the EWEA.

We conclude this paper with the following points:

- a linear model for sea surface waves depends on the accuracy of the source term (wind force);
- application of Lévy statistics yields a random fractal model for the wind velocity that is scale invariant;
- the Lévy Index can be used to quantify the non-Gaussian statistics of the wind velocity from which we obtain the following fundamental scaling law: *the logarithm of the Energy (or Power) Density/Flux is proportional to the inverse Lévy Index of the wind velocity*;
- analysis of global experimental data used to date appears to validate this relationship.

Acknowledgments

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Jonathan Blackledge holds a PhD in Theoretical Physics from London University and a PhD in Mathematical Information Technology from the University of Jyvaskyla. He has published over 200 scientific and engineering research papers including 14 books, has filed 15 patents and has been supervisor to over 200 MSc/MPhil and PhD research graduates. He is the Science Foundation Ireland Stokes Professor at Dublin Institute of Technology where he is also an Honorary Professor and Distinguished Professor at Warsaw University of Technology. He holds Fellowships with leading Institutes and Societies in the UK and Ireland including the Institute of Physics, the Institute of Mathematics and its Applications, the Institution of Engineering and Technology, the British Computer Society, the Royal Statistical Society and Engineers Ireland.

Eugene Coyle is Head of Research Innovation and Partnerships at the Dublin Institute of Technology. His research spans the fields of control systems and electrical engineering, renewable energy, digital signal processing and ICT, and engineering education and has published in excess of 120 peer reviewed conference and journal papers in addition to a number of book chapters. He is a Fellow of the Institution of Engineering and Technology, Engineers Ireland, the Energy Institute and the Chartered Institute of Building Services Engineers, was nominated to chair the Institution of Engineering and Technology (IET) Irish branch committee for 2009/10 and a member, by invitation, of the Engineering Advisory Committee to the Frontiers Engineering and Science Directorate of Science Foundation Ireland, SFI.

Derek Kearney graduated in 2007 from Ulster University with a First Class Masters Degree in Renewable Energy, and is currently working on a PhD in the area of wind energy. He is a lecturer in the College of Engineering and Built Environment at Dublin Institute of Technology and is programme manager for the MSc courses in Energy Management, Sustainable Electrical Energy Systems and Sustainability, Technology and Innovation. He is also programme manager for the BSc in Electrical Services and Energy Management. His principal area of specialty for both teaching and research is in the area of renewable energy and energy conversion systems. Recent achievements include winner of the 2006 President's Award for Teaching Excellence. He was chairman of the Honours Degree in Electrical Services and Energy Management for three years and previously worked on mainland Europe for a number of years.

Ronan McGuirk graduated with a first class Honours Degree in Electrical Services and Energy Management from Dublin Institute of Technology in 2012 and is currently a PhD researcher in the Dublin Energy Lab, Dublin Institute of Technology. He is an electrical engineer with ESB International in the High Voltage Cables Department. His PhD research, under the supervision of Professor Jonathan Blackledge, is in the area of Ocean Energy, mainly the simulation of sea surface waves for the evaluation of wave energy conversion technologies and has to date completed a number of projects in the area of renewable energy. Mr McGuirk is an Associate Member of Engineers Ireland.

Brian Norton is President of Dublin Institute of Technology. Irelands largest third-level institution. Its new city-centre campus will bring together its 2,300 staff and over 20,000 students. He has contributed to 5 books and over 350 research papers in the field of solar energy. He chairs 'Action Renewables', responsible for developing renewable use in Northern Ireland. Originally qualified as a physicist at University of Nottingham, he has doctorates in engineering from Cranfield University and the University of Nottingham. He is a Fellow of the Energy Institute, Engineers Ireland, the Irish Academy of Engineering, and the UK Higher Education Academy. Among his honours are the Napier Shaw Medal and Honorary Fellowship of CIBSE and the Roscoe Prize from the Energy Institute. He is an Honorary Professor by University of Ulster and Harbin Institute of Technology, China and University of Houston, USA.