Department of Naval Architecture, Ocean and Marine Engineering

An Integrated Framework for Resource Assessment and Operation and Maintenance Cost Modelling for Wave Energy Farm

By

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Emmanuel Edet Antai *Date: 25 September 2018*

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Nomenclature

Symbol	Quantity	Unit
α	Wave Amplitude	m
λ	Wave Length	m
ω	Angular Frequency	rad/s
k	Angular Wave Number	rad/m
C	Phase Velocity of Waves	m/s
C_g	Group velocity of waves	m/s
d	Local Water Depth	m
U	Velocity	m/s
ϕ	Velocity Potential	m^2/s
ξ	Wave Elevation	m
F	Force	N
M	Mass	kg
ρ	Density of sea water	kgm^{-3}
g	Gravitational Acceleration	m/s^2
E	Energy	J
P	Power	W
J	Wave Energy Transport	W/m
T_e	Mean Wave Energy Period	s
T_p	Peak Wave Period	s
θ_m	Mean Wave Direction	°
θ	Wave Direction	°
H	Wave Height	m
Hs	Significant Wave Height =($H_{1/3}$)	m
HRMS	Root Mean Square Wave Height	m
S	Spectral Density	m^2s or $(m^2H_z{}^{-1}$
f	Wave Frequency	Hz
f_p	Peak Wave Frequency	Hz
H_{m0}	Spectral Significant Wave Height	m
m	Spectral Moment	-
m_n	nth Spectral Moment	$m^2H_z{}^{-n}$

List of Abbreviations

Abbreviation	Meaning	Unit
CAPEX	Capital Expenditure	
CDF	Cumulative Distribution Function	
DF	Discount Factor	%
DR	Discount Rate	%
FIT	Feed In Tariff	
IRR	Internal Rate of Return	%
NPV	Net present value	£
O&M	Operation and Maintenance	
OPEX	Operational Expenditure	
PDF	Probability Density Function	
PMF	Probability Mass Functions	
PTO	Power Take-Off	
REFIT	Renewable Energy Feed in Tariff	
ROCs	Renewables Obligation Certificates	
ROV	Remote Operating Vehicle	
SFOC	Specific Fuel Oil Consumption	
TIC	Total Initial Cost	£
T_{mc}	Total Maintenance cost	£
WEC	Wave Energy Converter	-

Terms and Definition

Term	Definition
Array	This is used to refer to a set of multiple devices connected to a common electrical grid connection.
Capacity Factor	The ratio of the actual output of a power plant over a period compared to its theoretical power output if the plant was to operate at full load over the same period.
CAPEX	Capital Expenditure. The funds required at the beginning of a project for the purchase and construction of operating assets and necessary infrastructure.
Directionality	Wave directionality refers to distribution of waves from different directions.
Fetch	The length of water over which a wind has blown which, together with the strength of the wind determines the size of the waves produced.
Heave	Linear, vertical (up and down) motion
OPEX	Operating Expenditure. The financial cost of operating and maintaining the asset(s) over the lifetime of the project.
Pitch	Rotation about the horizontal sway axis
Practical Resource	This is the actual value of the technical resource that can be exploited once grid connection; military zone; shipping lane; wind energy development; fishing; environmental and economic constraints have been accounted for.
Rated Power	This is the peak power output of the device and each ocean energy device will be rated at a specific wave height and period.
Resource Sample	An estimate of the wave power at a specific time and place that may be obtained by measurement or computer simulation.
Roll	Rotation about the horizontal surge axis.
Surge	Linear, horizontal (front/back) motion.
Sway	Linear, horizontal (side to side) motion.

Technical Resource	The actual value of the theoretical resource that can be exploited using existing technology options, taking account of current technology limitations, constraints and assumptions.
Theoretical Resource	A high-level overview of the theoretical maximum potentially extractable energy contained within the overall resource.
Unidirectional waves	This is defined as the time-averaged energy flux across a line of unit length which is parallel with the wave crests.
Wave Energy-Resource	This is the time integral of the wave power which occurs at a position or in a particular area of interest, integrated over whatever timescales.
Wave power	This is defined as the time-averaged flux in a system of water waves.
Wave Power Climate	This is the statistical description of the variation of wave power on timescales of the order of months or years which is obtained by forming the statistics of the resource samples.
Yaw	Rotation about the vertical heave axis.

Abstract

There is need for a framework to support the development and application of Wave Energy Converter (WEC) as an alternative source for power generation. The gaps in existing literature reveal that, the issue undermining the growth of the wave energy industry is lack of a single consistent and well documented source of information; which clearly defines the approach for preliminary assessment. The Operation and Maintenance (O&M) aspect are often not included in the feasibility studies. This is the reason for the variation surrounding the cost of electricity production using WECs.

The research aims to bridge these gaps by providing an integrated framework that presents the methodology for preliminary assessment of a WEC farm project. In contrast to other studies, this research seeks to investigate the wave energy resource and contributes to providing the relevant tools to investigate the future market potential, together with opportunities for cost reduction of electricity generation using WECs. The need for understanding the offshore environment is highlighted to facilitate reliable energy yield predictions and strategies for O&M of the WEC farm.

The main contribution and novelty of this thesis in comparison to past studies is the integrated framework. This is significant to support investment decisions because as well as providing a solution to the problem of resource assessment, the issues associated with variation in the O&M cost estimates are critically analysed. Results suggest that variation in the O&M cost estimates can be attributed to the decision of employing the O&M vessel for maintenance of only a single device in a WEC farm.

The lack of operational experience in the wave energy sector, is identified as another problem experienced when attempting to quantify the profitability of a WEC farm project. This research addresses the problem by providing a basis and renewed support for potential wave energy industries and requirement for a generic methodology which considers the resource assessment, O&M cost and economic value of the WEC farm.

***Keywords**: Resource Assessment, O&M, Cost, Integrated Framework.*

Chapter 1-Introduction

1.1 Chapter Outline

This Chapter introduces the background information that sets the agenda for the work presented in this thesis. An integrated framework for resource assessment together with the procedure for modelling the Operation and Maintenance (O&M) cost of a Wave Energy Converter (WEC) farm is essential. This is relevant for preliminary considerations of a selected location for deployment of a WEC technology. The resource assessment focusses on the method used to describe the level of wave power available in the proposed location. The O&M cost modelling is relevant to address issues surrounding the O&M cost estimates.

Section 1.2 provides background information on wave energy resources potential and Section 1.3 presents the preliminary consideration for Site selection. In Section 1.4 an overview of the technical components of wave energy generation projects is presented. This is followed by challenges of wave energy generation projects in Section 1.5. The project rationale is presented in Section 1.6 and the thesis aim and objectives are presented in Section 1.7. This will set the stage for analysis of the main components of the resource assessment and O&M cost modelling that will be discussed in subsequent Chapters of this thesis. The scope and limitations of the study are presented in Section 1.8. The outline of the thesis layout is presented in Section 1.9. Section 1.10 summarizes the information in this Chapter.

1.2 Background

The world’s oceans covering $(2/3)$ of the earth’s surface present a massive energy resource. Wave Energy Converters (WECs) transform energy from the kinetic and potential energy of ocean surface wave into other forms of energy (e.g. electricity) (Dunnett and Wallace, 2009). Ocean waves are generated primarily by wind blowing across the ocean surface (ripples) and can propagate over deep water with minimal energy loss. These waves will combine and continue to gain energy from the wind over long open ocean stretches (leading to swells) (Kinsman, 1965).

The potential of wave energy is found to reach power densities of 60-70KW/m in some locations. For example, countries such as Australia, Chile, Ireland, New Zealand, South Africa, the UK and the US have excellent wave resources with average power densities of around 40-60KW/m (IRENA 2014). Studies (Hosna and Mohamed 2014) mentioned that the best wave conditions for exploitation are in medium-high latitudes and deep waters (> 40m deep). The most energetic wave conditions can be found primarily between latitudes of 30° to 60°, as can be seen in Figure 1, with the largest power levels occurring off the west coasts of continents.

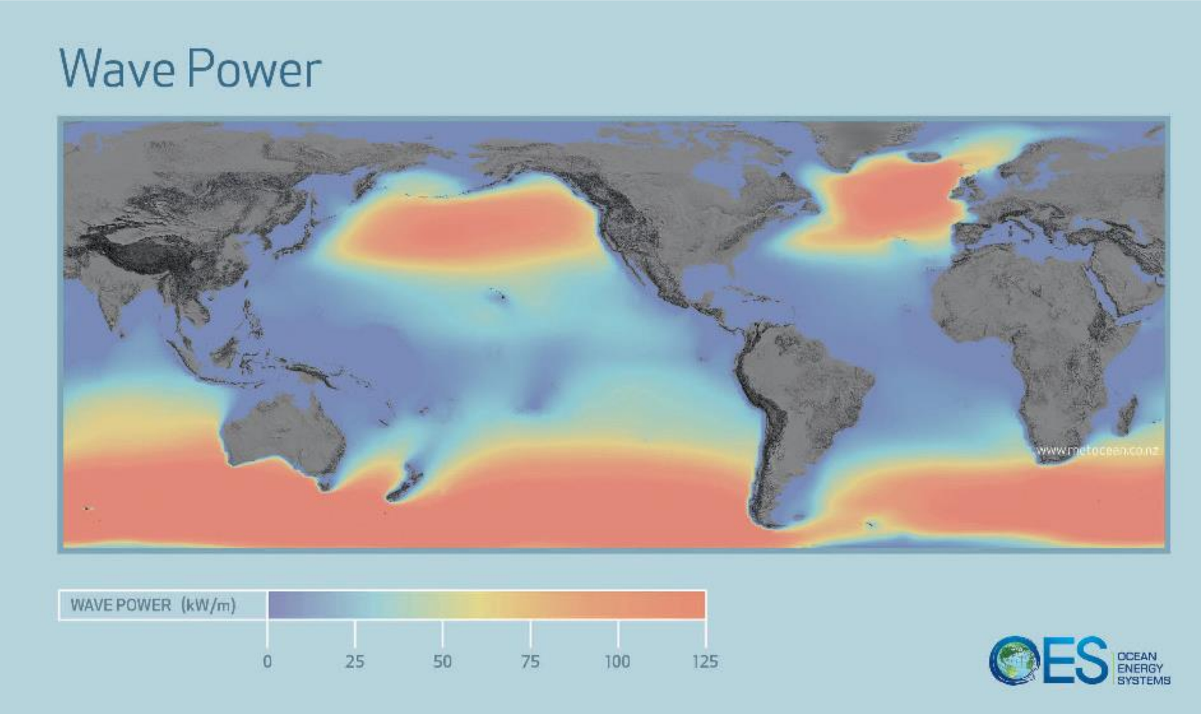


Figure 1: Global Annual Mean Wave Power Distribution (IEA-OES 2014; IRENA, 2014)

Figure 1 shows the global annual mean wave power distribution across different regions in the world. The global exploitable wave energy resource is approximately equal to 20% of current world electricity consumption (Cornett 2008). Although wave energy potential varies considerably depending on location; the IEA estimates on energy consumption in 2013, showed that total world energy consumption was 3.89×10^{20} joules, which is equal to an average power consumption of 12.3TW (IEA 2015).

Wave energy can be considered as a concentrated form of solar energy since the primary source of wind energy is the sun and the main source of wave energy is the wind. This implies that waves are energy in transition, stored in the ocean's surface in the form of waves being carried away from their origin. The global estimates for wave energy potential are still relatively uncertain. In 2012, the Inter-Governmental Panel on Climate Change (IPCC) reported a theoretical potential of around 29,500 Terawatt-hour per year (TW/h/yr.) considering all areas with wave energy densities higher than 5KW/m (JRC 2013).

In absolute terms Table 1 illustrates how Asia and Australasia receive the largest quantity of wave energy. South and North America also have impressive amounts despite its rich resource on its western seaboard. Western and Northern Europe performs moderately well given its relatively small size. However, Central America and the Mediterranean Sea and Atlantic Archipelagos perform poorly given their mid-latitude position. As a resource, wave energy has the advantage of relatively good predictability for sea state conditions (utilising methods and measurement developed for the benefit of existing offshore industries) (Cornett, 2008).

Table 1: Regional Theoretical Potential of Wave Energy (Cornett, 2008)

REGION	Wave Energy TW/h/yr.
Western and Northern Europe	2,800
Mediterranean Sea and Atlantic Archipelagos- (Azores, Cape Verde, Canaries)	1,300
North America and Greenland	4,000
Central America	1,500
South America	4,600
Africa	3,500
Asia	6,200
Australia, New Zealand and Pacific Islands	5,600
Total	29,500

Figure 2 shows the regional distribution of the global annual mean wave power estimation in KW/m spanning 10 years' period. This demonstrates how this resource is most abundant in the mid to high latitudes of both hemispheres. On the other hand, the World Energy Council in 2013, estimated the global technical potential of wave energy to be at 11,400TW/h/yr., while it's sustainable generating potential is 1,700TW/h/yr. (World Energy Coucil 2013). This equates to about 10% of global energy needs. Other global estimates vary between 2000-4000TW/h/yr. (Cruz 2008; Falcao 2010; Bahaj 2011; Kadiri 2012).

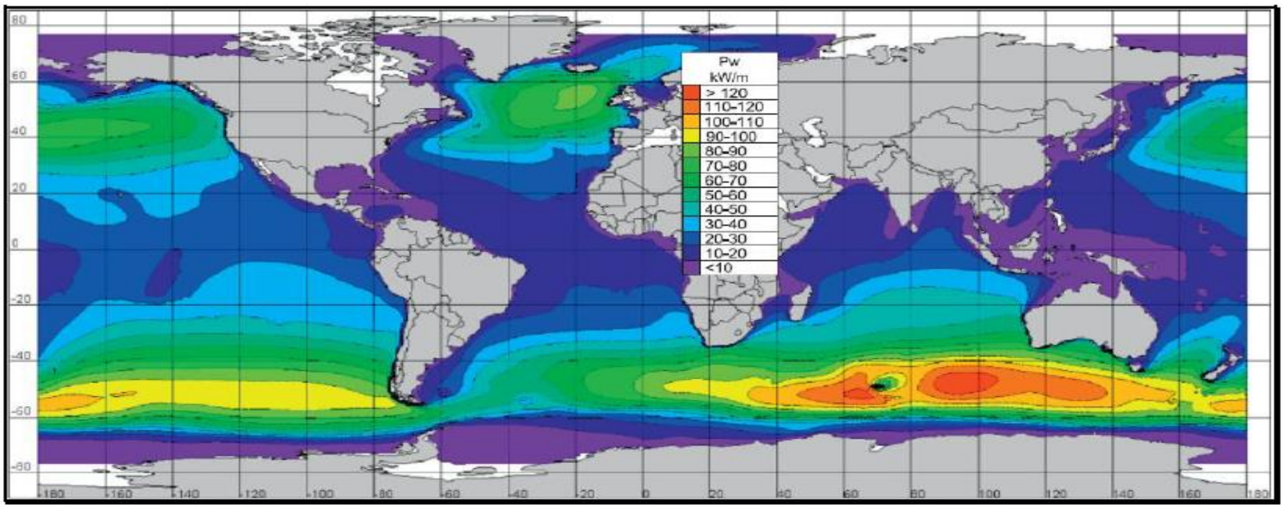


Figure 2: Global Annual Mean Wave Power Estimation in kW/m Spanning 10 Years' period (Lopez et al. 2013)

In contrast, the total European wave energy resource is estimated to be around 2800TW/h/yr., with available wave energy power resource for the North Eastern Atlantic (including the North Sea) estimated to be around 290GW. For the Mediterranean, it is 30GW (EU-OEA and Association. 2010). In addition, studies (Boud and Thorpe 2003) estimated the deep water resource to be approximately 1.3TW. This estimate ignores the small-scale resource located in seas such as the Baltic and Mediterranean.

Figure 3 shows the wave energy distribution and potential power density worldwide. Although there is seasonality, with higher wave conditions experienced in the winter than in the summer at most locations, there is tremendous energy potential in the ocean. From Figure 3 it is apparent that the energy potential in the ocean is much higher than that of solar power, with energy densities reaching 60KWh/m^2. Solar energy has an ideal energy density of 1KWh/m^2 (Previsic and Bedard 2007).Wave energy has a higher level of predictability in addition to higher energy density.

Waves arrive day and night, 24 hours a day, and sea states have more inertia than solar/wind conditions, with less potential for sudden changes in the resource potential (Cornett, 2008). WEC systems have over the years shown promising potentials to deliver cleaner energy in the world. It is only recently that a proliferation of technology developers have started to produce full-scale prototypes and therefore truly demonstrating the potential utility of this form of power production (Cruz, 2008).

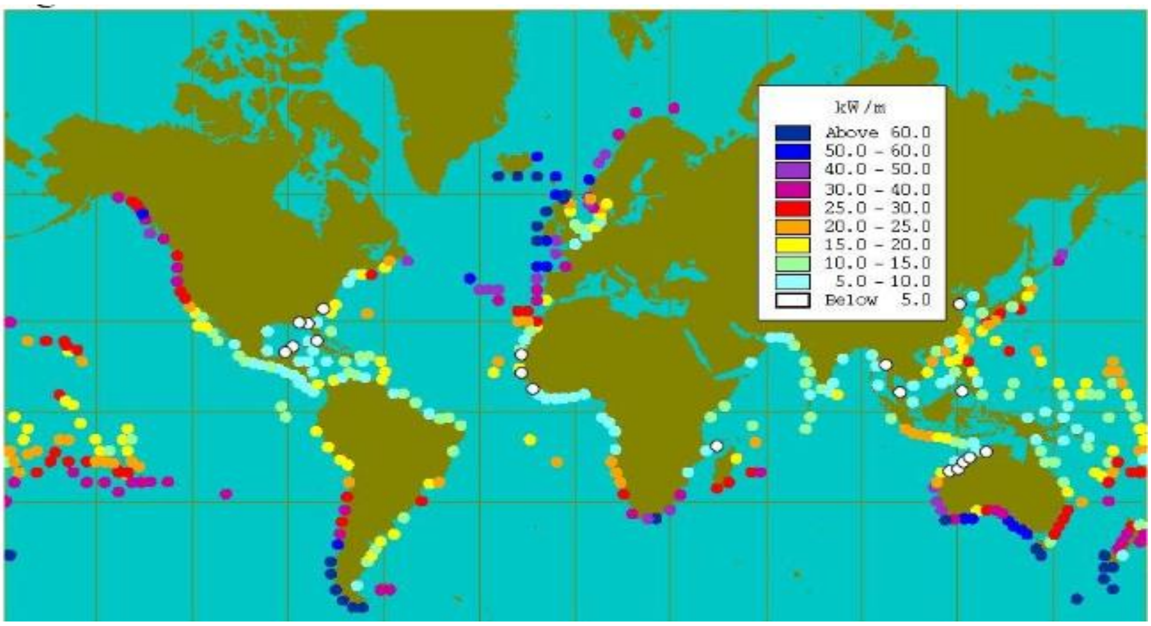


Figure 3: The World Wide Wave Energy Distribution and Potential Power Density (Previsic and Bedard 2007)

The global wave energy resource is taken to be total power intercepted by a line along the coasts of countries facing major oceans. In addition, it voids the assumption of advanced arrays such as devices located in the mid-Atlantic Ocean. Figure 4 shows the resources distribution of the annual average wave power levels (KW/m) measured for different locations around the world. The largest resource with the highest power level exists along the parallels of latitude of approximately 55° North and South of the equator.

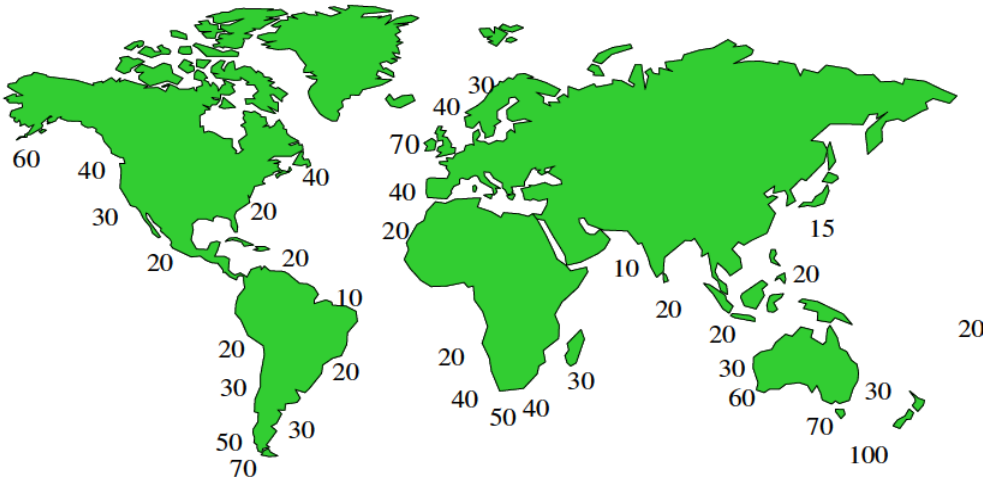


Figure 4: Global Distribution of Wave Power Levels in Kw/m of Wave Crest Length (Thorpe 2001)

Wave energy generation technologies are developing rapidly with experiences from offshore wind turbines. This is due to their attractiveness in contributing to the global energy mix. Ocean wave energy is one of the most concentrated and widely available forms of renewable energy in coastal areas. The wave energy forms as kinetic energy from the wind transmitted to the upper surface of the ocean. Although the air-sea interactions and energy transfer mechanisms are complex, ocean surface wave formation is primarily influenced by the speed of the wind, its duration and the fetch (the distance of open water over which the wind blows).

As it is solar energy that creates the differences in air temperature that cause wind, waves energy can be considered a concentrated form of solar energy (Hasselmann *et al.*, 1973). The spatial concentration of energy is one key advantage of wave energy in comparison to other renewable energy resources. A report (Minerals and Management Service 2006), confirmed the significant advantage of wave energy over other renewable energy resources. The authors acknowledged that ocean wave has the greatest power density and as such provides relatively continuous and predictable power. This advantage makes the ocean wave energy more suitable for electrical grid operation.

Ocean wave energy could be a potentially significant contributor in the effort to meet growing demands of energy by humans and about 10% of worlds electricity demands could be met by ocean wave energy (Barstow et al. 2009). A prominent reason for this consideration is due to its characteristic importance to generate electricity efficiently. On the other hand, over 70% of the earth's surface is covered by water, most of which is in the world's seas and oceans. About half the world's population (approximately 37%) lives within 60km of the coastline, three-quarters of all large cities are located on the coast (UNEP 2016); these facts make wave energy a good match between resource and demand.

Figure 5 shows the annual average wave-power density flux (kW/m at the deep water). This is used to presents an idea of the global market for WECs; this can also present the motivation for developing new and alternative markets for WECs. In Figure 5, it can be observed that the best wave-energy climates have deep water power densities of 60–70 kW/m but fall to about 20 kW/m at the foreshore. However, there is seasonality and this can cause higher wave conditions to be experienced in the winter than in the summer at most locations (Barstow *et al.*, 2009).

Around 2% of the world's 800,000km of coastline exceeds 30kW/m, giving a technical potential of around 500GW assuming offshore wave-energy devices have 40% efficiency (WEC, 2004a). The total economic potential is estimated to be well below this (WEC, 2004b) with generating cost estimates around 80–110 US$/MWh highly uncertain. Extracting electrical energy from marine currents could yield more than 10TWh/yr (0.4 EJ/yr.) if major estuaries with large tidal fluctuations could be tapped, but cost estimates range from 450–1350 US$/MWh (IEA, 2006).

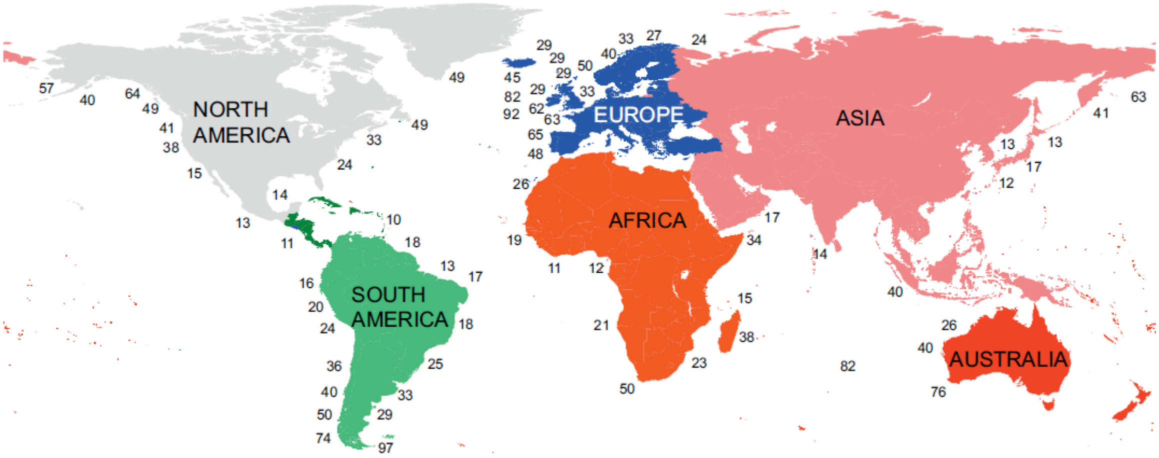


Figure 5: Annual Average Wave-Power Density Flux (Kw/M At Deep Water)(Max 2009)

To accelerate the rate of deployment of wave energy technology, it is necessary to investigate the future market potential, together with opportunities for cost reduction given the nascent stage of the ocean energy sector. Ideas for wave energy conversion have been around for some time. Serious academic attention began in the early 1970s, extraction of wave energy at useful scales and costs has proven challenging. In recent times, progress in wave energy research began to generate more interest due to the over-dependence on the burning of fossil fuels and subsequent issues on climate change.

In that respect research groups and industry have been developing new solutions which could result in decreasing the cost of electricity generated by WEC. Thorpe (1999) predicted that the cost of electricity generated by wave energy is likely to decrease further in the future as the industry continues to expand with more developments in the technology. In order for new WEC technologies to enter the market and reach competitive levels with more mature renewable energy sources such as wind power, sustained government and public support are needed.

Ocean energy technologies are designed to achieve a rated power output when design conditions are met. At any point in the ocean, the wave climate is the result of waves arriving from different directions. The wave energy is the time integral of the wave power and both terms ‘power’ and ‘energy’ are used in this thesis. For time averages, ‘power’ and ‘energy’ are numerically equal. The term ‘power’ and ‘energy’, are used relatively e.g. ‘power matrix’ and ‘energy matrix’, to emphasize that the presentation or statistic takes account of the duration of the relevant conditions as well as the power or energy.

1.3 Preliminary Consideration for Site Selection

This refers to the generic information that should be gathered with relevance for wave energy conversion and generation project. It is often necessary to gather general information on the site after which the data is integrated into the GIS (Geographic Information System) tool which will provide an accurate and convenient visual aid for choosing a suitable area (Zubiate et al. 2009). This information is necessary to provide the background understanding of the requirements for deployment and development of a wave energy farm.

A considerable effort is needed to accurately assess a wave energy resource, particularly where the focus is on generation and supply of renewable energy (electricity). The accurate assessment of the resource potential is closely linked to thorough analysis of all the information gathered, particularly information relating to the factors that may interact or impinge on the actualisation of the wave energy project (Beaudoin et al. 2010; World Energy Council 2013). Issues such as scarcity and unavailability of in-situ measured data for detailed resource assessment and the difference in local legislation have been pinpointed as factors that could affect the siting, deployment and installation of a wave energy project.

These factors which have in summary been grouped into technical, environmental and socioeconomic factors are further divided into exclusive and limiting factors. For the development of an integrated framework for resource assessment and modelling of the O&M cost estimate for preliminary assessment of a prospective wave energy farm, the most relevant information required include the resource description, consideration of existing infrastructure, accessibility for the project team, characteristics of the environment and interaction with other human activities. These factors are highlighted and summarised in the following pages.

Resource description refers to the method of describing the level of wave power available in the proposed area. A good wave climate is estimated to have an average intensity of approximately 20KW/m at a depth of 10m (Zubiate et al. 2009). In other studies (WaterTechnology 2004) extraction of wave energy may be considered viable in areas where the potential annual wave power exceeds 30KW/m. WECs could be placed in any location to harness the energy from the ocean waves. Figure 6 illustrates the possible location with respect to water depth, whereby WECs could be placed to harness the energy from the waves.

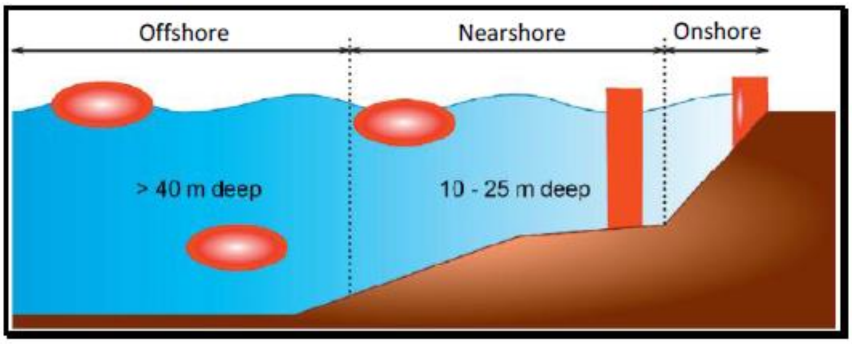


Figure 6: WECs Location With Respect To Water Depth (Lopez et al. 2013)

The information relating to parameters for describing the resource is discussed with more details in Chapter 4 methodology and modelling of this thesis. In addition, existing infrastructure refers to facilities that could contribute to the development of the wave energy farm. This is particularly proximity to existing harbour and good road network for ease of transportation. Existing grid connection for supply and distribution of the wave energy harvested from the selected location.

In this context, it is crucial to have an existing grid connection, because part of the main objective of a wave energy farm is to be able to transport and distribute the energy harvested from the resource to the final consumers. Therefore, the proximity of the resource to the consumption point should also be ascertained as part of the preliminary consideration for selecting a suitable site (Lopez et al. 2013). On the other hand, accessibility for the project team refers to the essential requirement of having a good road network in the local area.

Proximity to harbours is also necessary to facilitate the development of the wave energy farm project. The proximity is considered in terms of distance of the wave farm to the nearest port and harbours (Iglesias and Carballo 2011). It is important for the prospective site to have access connecting the local roads, access via transport or ferry should also be available for the transportation of equipment and technicians/personnel’s needed to perform O&M activities (Falcao 2010).

The characteristic of the environment is an important factor that needs to be considered. This is relevant to account for any eventualities which may arise during the planning, installation and operation process. In this context, it is essential to have a good knowledge of the geographic and atmospheric conditions of the area (Watson 2008). For example, these conditions may include geographical elements such as cliffs, beaches, rivers, and deltas. Climate conditions, e.g. wind regimes, tidal range, and current, temperature etc. Seismicity, volcanicity and other phenomena related to active tectonic margins (Zhang and Foufoula 1997).

Interaction with other human activities could be interpreted as the likely response of the local community to the project. It is essential to have the community support as there are several activities taking place in the sea. Some of these activities may directly prevent the installation, while others may impinge on the local socio-economy of the area (Vining and Muetze 2009). Hence, it is critical to analyse how the wave energy site will function harmoniously with other surrounding activities (Heru et al. 2008).

The information gathering stage is necessary for providing a clear picture of the project characteristics including information to consider as parameters for selecting wave sites. For a wave energy farm to be successful, it must be situated in a location with an energetic wave regime and the fundamental consideration of any device design is the construction of the device in a hostile environment. Table 2 presents the list of activities that may likely interact with a wave energy project.

The information presented in Table 2 is gathered from different literature sources and summarised as shown. This information on the activities that may likely interfere with the wave energy farm project will help decision-makers site wave energy facilities while considering other competing uses of the sea. The work in this thesis will provide planners with information that can be used to balance the harvesting of energy from waves with existing uses of marine and coastal ecosystems. The approach used for economic assessment of the wave energy facility usually involves the method which incorporates some information about potential impacts into a framework that can be used in parallel with a formal cost-benefit analysis.

Table 2: Activities That May Likely Interfere with The Wave Project

Serial/No.	Type of Activity
1	Oil & Gas extraction
2	Sand and Gravel extraction, Dredging
3	Fisheries/Aquaculture
4	Navigation routes/Military Activities
5	Submarine, telecoms/electric cables, sewage pipelines
6	Submarine Archaeology
7	Land scape and sea scape as public heritage
8	Sports and leisure use of the coastal area

1.4 Technical Components of Wave Energy Farm Projects

This refers to the main elements that should be considered in the bid to reduce the cost of energy generation using WEC technology. In this context, the key concept is innovation. Innovative cost reduction in this sense refers to all the relevant progress in innovative deployment and operation methods. This includes the radical changes in fundamental new energy capture concepts, design or methods to reduce cost (Hosna and Mohamed 2014). Some of the main elements that should be considered include structure & prime mover, installation, foundations & moorings, connection, control, Power Take Off (PTO) and Operations & Maintenance. An overview of the technical components that describes specific opportunities for innovative cost reduction within the different cost centres are highlighted in the following:

1. Structure & Prime Mover refers to the point of interaction between the resource and physical structure of the device which captures energy (e.g. the power-take-off equipment). Studies (García–Medina et al. 2014) mentioned that locations which tend to have higher wave energy potential are often located further from shore. This situation leads to increasing requirements for robustness and reliability (Brekken et al. 2013). This is the reason why developers and manufacturers of WECs are investigating different structural design that could lead to improving the yield of WECs (Vermaak and Kamper 2012).

Prime movers such as turbine blades are made of composite materials. Although the main structural element of the WEC device is steel, certain concepts are exploring other alternatives. This is discussed further in Chapter 3 critical review. In this context, using alternative materials such as concrete to build major components of the wave device could offer significant cost reduction potential in terms of reduced material and construction costs.

2. Installation refers to the strategy used to place the structure and device at the specified location for power generation. In this respect, the requirement for vessels and ancillary equipment needed to fully deploy WECs contributes to much of the cost of electricity generation (Dalgic et al. 2015). This is particularly due to the cost of hiring suitable vessels for the installation and O&M activities (Dalgic et al. 2014). If there is an innovative method in either the design or installation procedure which allows a lower cost vessel to be used, it will produce an impact on overall costs. There is scope for low-cost options that can cope with adverse weather conditions, such as drilling rigs or cable layers mounted on a Remotely Operated Vehicle (ROV) (SI OCEAN 2013).

Studies (Kaiser and Snyder 2012) acknowledged that the installation of floating wave devices is significantly cheaper than the installation of bottom-mounted devices. There is less potential for dramatic cost reduction in this area because much of the development has already been carried out by the offshore wind industry. However, there is a requirement to develop suitable configurations for connecting arrays. Studies (Sharkey et al. 2011) mentioned that subsea hubs that allow underwater electrical connection of several devices will make an important contribution to economies of scale for arrays

3. Foundations & Moorings refers to the method utilised (including permanent foundation constructions such as gravity bases or pile-pinned foundations, or could consist of moorings such as tight or slack moored systems) in securing the device to the seabed. One of the economies of scale available for multiple WEC device arrays is foundations or moorings shared between more than one device. The reason is that foundation costs are high. In the offshore oil and gas industry, design codes for mooring systems already exist, such as DNV OS-E301(2004), API RP-2SK (2005) and ISO 19901-7 (2005).

Figure 7 Illustrates how WECs are anchored to the seabed and moored by cables. This is applicable in order to use wave energy for electricity generation. Similar to other offshore structures moored on the sea floor, a typical WEC mooring system is likely to be composed of three parts: the mooring line, the connectors and the anchor. Studies (Pasternak *et al.*, 2010) mentioned that chain, wire rope, and synthetic fibre rope are the three main mooring line types that are used in offshore structures and could be used for WECs. Chains provide good catenary stiffness and are abrasion resistant. However, their restraining stiffness may not be appropriate for some WECs.

They can hamper the oscillation motion required to convert energy. Studies (Harris et al., 2004) suggested that synthetic ropes are advantageous because of their buoyancy property, which will reduce mooring weight influence during normal operation and are good candidates for deep-water applications. Anchors are the terminals that transfer the whole system forces to the seabed. The major requirements for a WEC mooring are to withstand the environmental and other loadings involved in keeping the device on the station. This is relevant to be sufficiently cost-effective so that the overall device economics remain viable.

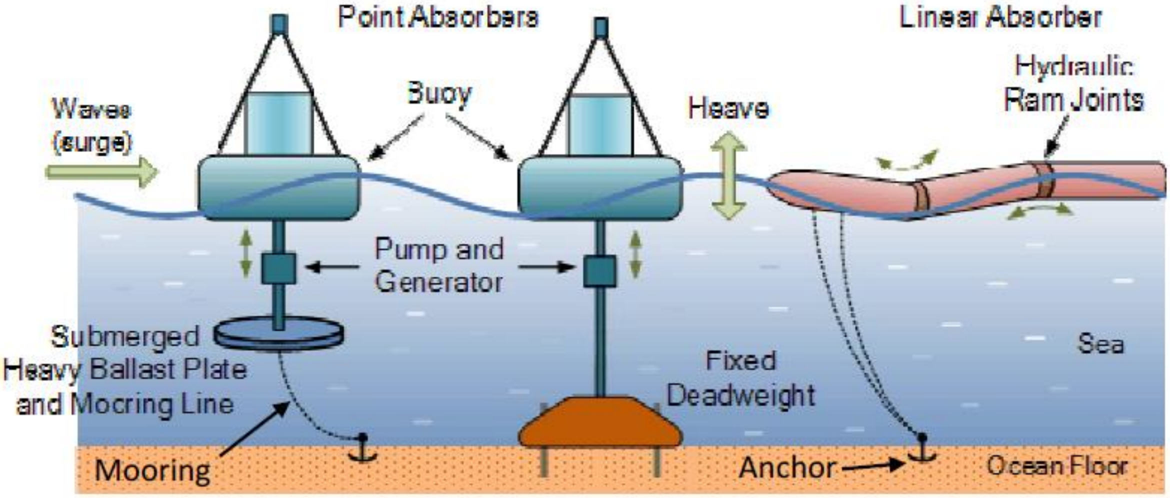


Figure 7: Wave energy converters mooring and anchor (Hosna and Mohamed, 2014)

Moorings for floating wave devices have less potential for cost reduction, although new (flexible) fibre materials could reduce weight and handling costs and decrease maintenance intervals (Harris et al. 2004). A guideline (DNV and Carbon Trust 2005) on applying the existing codes to the design and operation of WECs has been published by DNV and Carbon Trust. Nevertheless, the potential risk associated with mooring failure is lower for WECs, which are normally unmanned (Harris et al. 2004).

4. Connection refers to the power conditioning systems and transformers needed to export the generated electricity to the grid. This includes the cables and electrical infrastructure for connecting the power output from the device to the electricity network (O'Sullivan and Dalton 2009). This also includes the provision of a grid code compliant electrical output. The expansion of offshore wind is already providing a stimulus to develop solutions for offshore cabling and much of the learning from this industry will be transferrable to ocean energy. Development of subsea high voltage cables (both AC and DC) will also help to reduce costs.

5. Control in WEC devices involves incorporating systems and software that have the capability for independently adjusting certain parameters of the device to ensure favourable operation. WEC devices can be tuned to resonate better with a wider range of sea states (DTOcean 2014). In this context, control systems are utilised to optimise the performance of the device under a range of operating conditions. Continued development of control systems and software can provide greater opportunities for significant increases in yield with a minimal capital cost increase. By improving the way, the device interacts with the sea, an expected improvement in the yield can be achieved (Barret et al. 2008; Kramer et al. 2011).

6. Power Take Off (PTO) refers to how the mechanical energy extracted from the waves is converted into electrical energy. Several types of PTO exist including mechanical, hydraulic, or direct drive using permanent magnet generators (Rhinefrank, 2012). There is significant potential to optimise the configuration of PTO and structure of wave devices to increase yield, particularly in combination with control system improvements (Bahaj and Myers 2009). Hydraulic power take-off systems are commonly used but linear generators are also under investigation for use in wave devices (Le et al. 2009).

Other types of PTO also offer opportunities for improvement, for instance, the turbines in OWC devices are increasing in efficiency, improving the yield in recent devices compared to their predecessors. Figure 8 shows the different conversion stages for WECs. There is a variety of ways to extract power from waves. The mechanical interface is used to convert the slow rotational speed or reciprocating motion into a high-speed rotational motion for connection to a conventional rotary electrical generator. In this context, attention will be directed at the mechanism needed to convert wave energy into electricity as most building blocks in the generation system remain nearly the same after being transformed into the electrical form (Brekken *et al.*, 2010).

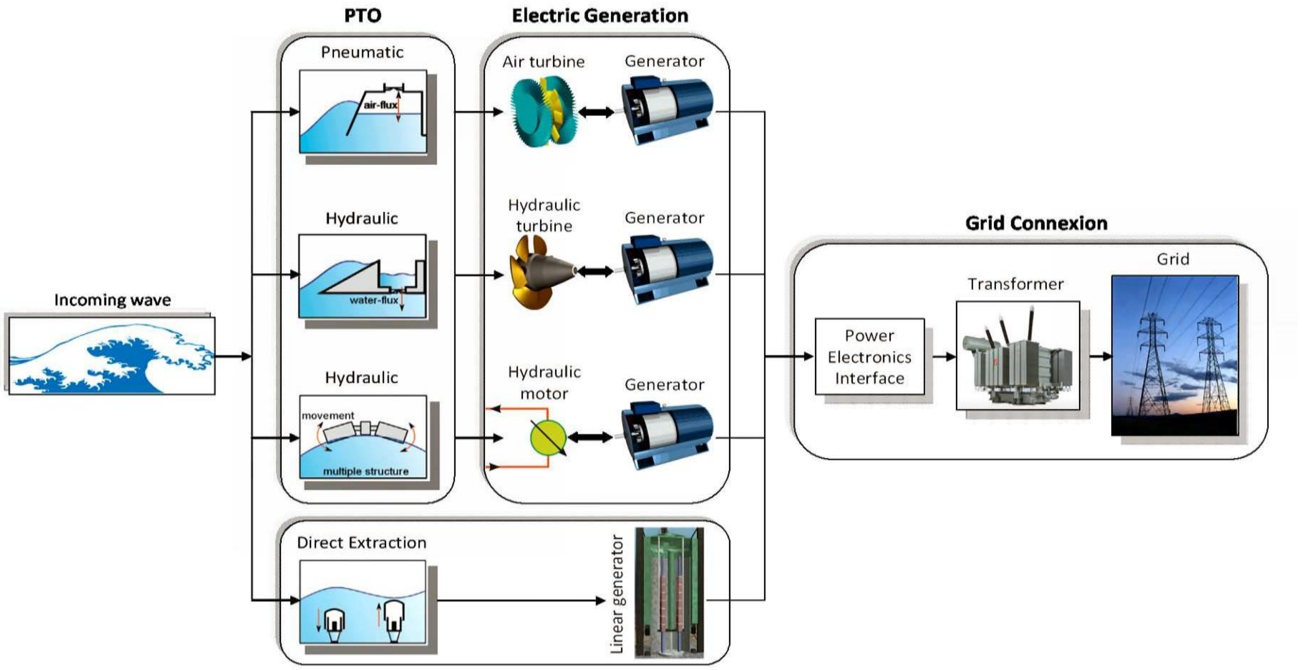


Figure 8: WEC Different Type of Conversions (Hosna and Mohamed, 2014)

7. Operations & Maintenance (O&M) refers to periodic repair and reconditioning work required to keep the WEC in continuous operation. This includes any physical maintenance of mechanical and electrical components within the device. Generally, the cost of offshore maintenance is more expensive when compared to on-shore. This due to the requirements for vessels to access the WEC. Thus, contributing to a significant proportion of the total maintenance cost (Rademakers et al. 2009). The key factors affecting O&M cost is the reliability and survivability of the device.

A key factor driving the O&M costs is the frequency of the WEC maintenance requirement. The proximity of the WEC farm to existing local ports and infrastructure will contribute to reducing the maintenance cost. Additional maintenance cost will be incurred if the WEC should be taken some distance to a port with suitable facilities for maintenance. This implies that O&M planning will also have to consider access to the WEC and retrieval. A possible solution could be providing designs of WEC that are simpler and easier to retrieve for maintenance.

For example, a coupling for a floating WEC device that allows a unit to be detached from its mooring quickly and towed to a sheltered maintenance base using a small boat. From the experiences of offshore wind farms, the O&M practices relevant to offshore WEC installations are related to corrosion problems and long-term stability of mooring systems based on suitable maintenance, control and operational strategies (Poore and Walford 2008). The cost of these O&M activities contributes substantially to the cost of energy production.

Experience from oil and gas industry confirms that some components of an offshore array may fail spontaneously and hence need immediate (Corrective) maintenance action; whereas other components may have to be maintained on a predetermined basis (Atkins et al. 1992). With respect to reducing maintenance cost, it will be a good practice to develop predictive condition monitoring using sensors on the device for early detection of potential faults. These illustrations form the basis for defining a strategy for developing the cost function with respect to specific O&M actions. The aim of O&M modelling is to access the exciting operation and maintenance methods which could be adapted in real applications of WECs.

1.5 Challenges of Wave Energy Generation Projects

Some of the complexities and challenges encountered in electricity generation projects arising from the choice of using the WECs to harness the wave power is often because there is very little or no experience in the operation of WEC technologies. The challenges for the deep offshore environment may include a significant increase in the cost of the technology and installation of the WEC device (Carbon Trust 2011). This implies that the depth at which deployment can take place is restricted by the technology and financial limitations.

Power production from offshore WECs is still considered to be very expensive because it suffers challenges such as more complicated foundations, longer electrical networks, installation and maintenance activities that may be dependent on vessels (Beels et al. 2011). In some cases, the operability of vessels and subsequently the accessibility of offshore WECs may be limited by harsher climate conditions. There is a vast potential for growth in the wave energy sector if the technical and economic challenges of wave energy capture are overcome. This situation has led to the development of protocols and guidelines for ocean energy device developers (EMEC 2010).

For WECs to survive the extreme load scenarios that may occur during storm conditions, WECs need to be over-engineered such that the ratio of working loads to extreme loads is higher compared to the expected average operating conditions. This presents a significant challenge for the wave energy industry in terms of demonstrating the survivability of a WEC. Some of the methods that have been adopted within the industry to deal with the challenges facing the wave energy sector include cost-reduction in installation, design modifications, and evolution of devices through the use of advanced materials (Allan et al. 2011; Beels et al. 2011). These examples are highlighted in the following:

In the case of Cost-Reduction in Installation, it is sometimes necessary to use seabed preparation techniques for certain device foundations (Lazakis et al. 2012). Seabed piling methods may be used to secure devices against unwanted movement. For example, Aquamarine Power designed a hinged flap that oscillates with the wave motion, in their OWSC design called Oyster (Henry et al. 2010). Technologies that require drilled piles for their foundation may have higher O&M cost because seabed operations such as piling require expensive vessel.

To reduce the costs of successive designs, modifications in the iteration process of future designs becomes necessary. Further iterations of the device may enable installation costs to reduce further by designing for a single monopole per device (DTOcean 2014). Reducing the number of piles required for the foundation could improve cost reduction because drilling operations for multiple devices could be performed in one vessel mobilisation. Thus, mitigating the need for multiple vessels and expensive cost overruns (Junginger et al. 2004).

For Design Modifications, materials such as Steel Reinforced Concrete (SRC) and Fibre Reinforced Polymer (FRP) are yet to prove their capability through a long-term operation and reliability testing with regards to their use in the construction of WECs. It is likely that there will be a phased transition into the use of these materials within future devices structural design (Harris et al. 2004; Previsic 2004). Studies (Previsic 2004) suggested that design modifications could be made to WECs to allow a more efficient power take off and greater device flexibility.

It is hoped that WECs will obtain additional reductions in the levelised cost of energy, as their developers continue to further research and progress on design optimisation (Allan et al. 2011). For certain device, optimum levels of energy extraction could be achieved by improving the control systems design without the need for new hardware. It is also envisaged that further cost improvements without affecting the performance of the device could be achieved by modifying the structural material from steel to concrete (Henry et al. 2010).

Devices evolution using advanced materials is a necessary part of the cost reduction process to bring the total levelized cost of energy to a level which competes with more mature sources of renewable energy such as wind. Typical first-generation technology will require substantial reductions in cost to attain a level of cost-competitiveness. The evolution could involve a radical overhaul of the design of a major component such as the mooring system (Gao et al. 2009). Alternatively, the evolution may take place in the form of a component change or upgrade; a sub-system change, but the overall design of the device would not be fundamentally altered.

Steel is used extensively in civil infrastructure and boat design applications. Majority of ocean energy converters are fabricated from steel. This is because steel is a metal that offers good and well-understood fatigue and stress limits. The use of steel has been proven in the marine environment, although in a very different application to ocean renewable energy. Some WEC developers are now investigating the use of Steel Reinforced Concrete or Fibre Reinforced Polymer (FRP) for certain components. For example, Pelamis was considering the use of concrete tubes in their next prototype (Yemm et al. 2012).

Aquamarine Power plans to use FRP in their next generation Oyster flap device (Henry et al. 2010). Designers of other wave devices are also considering the use of rubber or other flexible materials as the main structural component. The advantages of FRP over steel is due to its cost and weight savings. The disadvantages of FRP compared to steel is that the fatigue and stress limits are not yet well understood. In addition to the challenges of cost reduction and design modifications mention above, geotechnical constraints could hinder the development of wave energy projects in the nearshore environment.

Geotechnical constraints may refer to the limitations, either subsurface conditions, and materials used to determine the relevant physical/mechanical and chemical properties of WECs. This is relevant for monitoring site conditions and evaluating the stability of the device; assess risks posed by site conditions; design and structure foundations (Holtz et al. 1981). Geotechnical constraints normally result to reduction of the relative level of practical nearshore resource. Environmentally, WECs may take up a huge amount of space on top of the water which may interfere with natural habitats and migratory pathways.

Carbon trust (2011) emphasises that the key factors affecting the cost of energy in marine renewable energy systems are: performance, capital costs, O&M costs, and risks. The capital cost of marine renewable devices consists of several parts such as station-keeping, structural, energy conversion components, sub-assemblies and project costs (Andrawus et al. 2008). Capital costs are described in terms of cost centres, to allow comparisons by cost category. O&M costs can also be described by cost centres and vary by project size, location, and technology. Hence, further research is necessary to investigate areas of O&M cost reduction and to decide on appropriate locations for installation of the WECs.

1.6 Project Rationale

With the current global emphasis to reduce the over-dependence on burning fossil fuel which consequently releases anthropogenic emissions, it becomes necessary to consider other forms of renewable energy that will contribute to ``clean energy``, especially marine renewable energy resources. The reasons for conducting this research is to develop an integrated framework for the preliminary assessment of prospective locations for consideration of a wave energy farm. For electricity generation using a WEC technology, there has been no systematic development of a strategy which incorporates the resource assessment and O&M cost modelling for preliminary assessment of prospective locations for wave energy farm.

This study is motivated by the requirement for increasing research and development in wave energy devices; increased availability of the device and economic information. For the preliminary assessment of the WEC farm historical wave data for the location is analysed and applied to assess the wave power potential at the case study location. From the resource assessment point of view, it is important to ensure that the WEC to be installed should have the maximum efficiency to capture the wave energy from the sea states providing the bulk of the wave energy at the chosen location for deploying the WEC farm.

In this context, the wave energy resource potential for extraction at any location can be demonstrated. Using parameters such as the significant wave height and wave energy period in the historical wave data set the characteristics of the resource is investigated based on their frequency of occurrence and probability distribution in the dataset. The link between resource assessment model and the O&M model is illustrated in the flowchart of the integrated framework in Chapter 3 methodology and modelling. In relation to the O&M model described in the integrated framework, two intermediate outputs are obtained from the resource assessment model.

These intermediate outputs are related to the resource description in terms of the resource availability and accessibility of the WEC for the O&M activities. The accessibility factors link the resource assessment model to the O&M model for analysis of the O&M activities and cost estimates. In the integrated framework, the O&M case study result is based on the WEC farm attributes, O&M vessel accessibility and specific cost linked to the resource description output in the resource assessment model.

The O&M accessibility factors provide the information relevant to maximise the weather window during which the O&M activity can be performed safely. Hence, in the integrated framework, one of the key element suggested for minimising the O&M costs is maximising the weather window during which O&M activity is possible. If O&M activities can only be carried out in very favourable conditions, there is the probability that there will be delays in the project. This can contribute to additional O&M costs.

Analysis of weather conditions for each month can provide the information relevant to maximise the weather window during which the O&M activity can be performed safely. In this respect, the integrated framework uses the historical wave data for the selected location to further investigate the offshore accessibility factors for the O&M activities. In the integrated framework, analysis of the weather window is relevant to identify the suitable conditions when the O&M vessels can perform the O&M activities for the WEC farm. These aspects distinguish this study from other studies.

The WEC O&M financial consequences with respect to vessel operation are generally neglected in existing studies, thus contributing to the variation in the O&M cost estimates. Therefore, the contribution of this research to the field of knowledge and novelty of this thesis is the novel integrated framework because it considers within a single framework the methodology to investigate and evaluate the wave energy resource and operation and maintenance cost modelling for wave energy farm.

The feasibility of the O&M activities is assessed by identifying suitable maintenance strategies to account for the variation in the O&M cost estimates. The integrated framework developed is needed to manage change in the technical environment of the developing wave energy technology and the marine industry in general. This will help to provide answers to whether it will be worth investing time and capital resources towards deploying a wave energy farm.

1.7 Aim and Objectives

1.7.1 Thesis Aim

The main aim of the thesis is to develop and test an integrated framework for the resource assessment and operation and maintenance cost modelling for wave energy farm project, providing a decision-making support for investment options.

1.7.2 Specific Objectives

This thesis specific objectives includes the following:

1. Examination of different research work in the field and collecting relevant information available on wave energy resource, O&M studies, technology and economic data to develop the methodology for preliminary analysis of the data and to evaluate potential resource based on selected WEC.

2. Developing an integrated framework for the assessment of wave energy resource and O&M cost for maintenance activities of the WEC using existing theoretical models. Assessing the feasibility of deploying the WEC and O&M activities of the WEC.

3. Investigating the weather windows for O&M vessel operation using different scenarios and cost of O&M activities to account for variation in the cost of the O&M estimates.

4. Establishing the criteria for assessing the economic value of the wave energy farm project, together with the method that could be used for validating the proposed methodology and framework.

1.7.3 Specific Goals

The specific goal is to generate new knowledge through the development of an integrated approach for assessing the resource and O&M cost for maintenance activities of a WEC farm. This goal will provide an analysis routine (method) to analyze any chosen location for installing WECs. The goal of this research is to gain the relevant knowledge required in academics for teaching and training of future engineers in energy-related disciplines. To provide an intellectual lead in the pursuit of the low-carbon economy of the future.

1.8 Scope and Limitations of The Study

There is a need to define the limitations of this study and choosing these limitations provides the means to ensure consistency and clarity in the information presented. This thesis focuses on developing an integrated framework for wave energy resource assessment and modelling the O&M cost estimates of a WEC farm. The resource assessment method addresses the hydrodynamic modelling methods used to describe and evaluate the available and potentially extractable wave energy from the resource at any selected location. On the other hand, the O&M cost modelling is required to estimate the total O&M cost for operating the WEC farm.

The integrated framework provides the method and tools needed to identify and assess what makes up a marine energy device's capital and O&M costs. The intended or desired result will help to encourage the continuous exploitation of wave energy resources through the deployment of wave energy technologies in different coastal locations around the world. Firstly, it is important to mention that the WEC's movement is caused not only by the sea waves but by the internal water flow in the device.

The waves are affected by the WEC itself making the interaction rather complex. Secondly, the WEC has many variable parameters such as angles of the planes inside the WEC device, water mass, turbine placement as well as all spatial parameters defining length, breadth, and height of the different parts of the WEC device. These parameters could be determined when considering the different design concepts. The limitations applicable to this thesis include:

- The movements of WEC caused by the movements of the water inside the device are not considered. This limitation is posed by the complexity of this movement and because experience from WEC offers no such input when calculating the properties of the hull of the floating device in sea waves.

- The WEC and its performance are dependent on the size of its rated power matrix. The design of the WEC and its impact on the floating device hull design are not considered in the analysis of the energy generated from the sea waves.

1.9 Thesis Layout

Chapter 1 Introduction: This Chapter intends to demonstrate the topic of the present thesis and latest concerns regarding the choice of using WECs as an alternative source for electricity generation. Within this Chapter, an introduction and overview of the wave energy resource and potential are highlighted. This sets the stage for analysis of the main components of the resource assessment and O&M cost modelling.

An overview of the preliminary consideration for site selection and the relevant information on technical components of wave energy farm projects, together with challenges facing the development of wave energy generation projects are highlighted. Thereafter, the scope and limitations of this research are highlighted followed by an overview of the thesis outline and Chapter summary at the end.

Chapter 2 Critical Review: this Chapter presents a thorough critical review of wave energy resource assessment and O&M cost modelling through examination of different research work in the field. This is relevant to first identify the gaps in existing literature and secondly to try and bridge the gaps by identifying those technologies that could be developed further to address the problem surrounding the installation, deployment, O&M cost incurred in operating the wave energy plant. This will encourage the development and widespread use of WECs.

In addition, a background study on wave energy extraction focussing on developments in WEC technology and highlighting on advantages and disadvantages of some WEC technology is conducted. It is anticipated that electricity generation from ocean wave using WECs, will ultimately become competitive and perhaps become less expensive than other renewable energy sources.

Several aspects of ocean wave energy generation projects and WEC systems for harnessing the wave energy have also been reviewed to provide information that would enhance the implementation of WEC technologies. Hence, Chapter 3 provides the means for gathering the relevant available information on wave resource, technology, and economic data, to support the development of methodology and modelling in the integrated framework.

Chapter 3 Methodology and Modelling: This Chapter describes the approach used for developing the research methodology. It describes the step by step approach and illustrates how the research is structured. This is particularly important in terms of the details and information which are needed to achieve the research aim and objectives of developing a robust and reusable framework for resource assessment and O&M cost modelling in the proposed integrated framework.

To establish the process and implementation of the methodology, the main task will involve the characterisation of the wave field around a selected location of interest. This includes the process of initially investigating and evaluating the wave energy resource and determining the potential for the WEC to generate energy from the sea waves. In that respect, a well-defined combination of existing theoretical models/methods, are combined and applied to evaluate the wave energy resource.

The second section of this Chapter presents a description of the O&M cost model. The O&M model is developed for the WEC farm to assess the feasibility of deployment and O&M activities by investigating different O&M scenarios to account for variation in the O&M cost estimates. The integrated framework would help to establish the criteria that could be used for comparing and validating the proposed strategies to reduce the cost of O&M of WEC systems and to serve as a benchmark for comparing deployments of other types of marine renewables.

Chapter 4 Case Study Application of The Methodology: In this Chapter, the methodology and modelling in the proposed integrated framework are applied to a case study to illustrate the resource assessment and O&M modelling of a WEC farm project. The different step of the proposed methodology is illustrated in terms of defining the main attributes to analyse offshore wave conditions at the location of interest. Resource assessment for WEC systems involves both quantifications of the available power in the wave climate for conversion to electricity and characterization of the resource in terms of its variability and extreme conditions.

In this case wave dataset, which covers a period of 12 years is used for the analysis. The wave dataset is used to assess the seasonal and inter-annual variation in the wave power and subsequently establishing the wave power generation potential. This defines the resource assessment approach which is necessary for analysing the main parameters that are required for preliminary assessment of a selected location.

In addition, the O&M model is employed based on the information from the resource characterisation and description of the wave environment transformations for the location of interest. The relevant maintenance approach or combination of strategies are identified to evaluate the O&M cost estimates for maintenance of the WEC in the WEC farm. This will contribute to the development of an effective maintenance model for O&M of WEC systems. This will help to support the developers of WEC in achieving reduced downtime, optimised availability and maximised revenue.

Chapter 5 Resource Assessment Results and Discussion: In this Chapter, the findings and results of the resource assessment are presented and discussed. This includes the presentation of the results for the analysis of historical wave data (wind speed, wave height, and wave period). As an integrated framework, results of the environmental conditions in relation to weather windows for O&M vessel operations are also presented and discussed.

Chapter 6 O&M Modelling Results and Discussion: This Chapter demonstrates the results and discusses the key finding of the operational analysis and O&M vessel cost applicable to investigate variation in the O&M cost. The concept of net present value is discussed to analyse the economics of the WEC farm system. Results of the economic potential of the electricity producing plant are presented.

Chapter 7 Conclusion and Recommendation for Future Work: This Chapter presents the conclusion and summarises the novelty of the research. It summarises the work presented in this thesis and clearly identifies the main contributions. The contribution to theory and practice are highlighted together with concluding remarks and recommendation for future research.

1.10 Chapter Summary

A background information has been presented to set the pace for the work that is presented in this thesis. An overview of the preliminary considerations resource assessment and O&M cost modelling for assessment of prospective site for WEC farm has been presented. It is believed that a lack of understanding and quantification of the device behaviour is one of the main reasons for the delay in the development of the wave energy industry. The technical components of wave energy farm projects are also highlighted in order to facilitate a good understanding of the main elements contributing to cost reduction.

These help to form the basis for defining a strategy for developing the cost function with respect to specific O&M actions. The challenges of wave energy generation projects are in the form of variation in the O&M cost estimates and risks. The work done to addresses these challenges have been presented. Finally, the thesis layout explains what is covered in each section of the thesis. In the following section, the main aim and objectives of this thesis are clearly stated. Thereafter, a comprehensive literature review is conducted to identify the gaps, which are then addressed in the developed methodology and modelling of the integrated framework.

Chapter 2- Critical Review

2.1 Chapter Outline

This Chapter presents the review of the resource assessment and Operation and Maintenance (O&M) cost modelling for Wave Energy Converter (WEC) farm. The potential for WEC to extract energy from the resource using the different type of WEC technology is discussed. The main technologies, developments, and classification of the WECs are highlighted. For WECs to succeed they must extract the energy at low cost with practical O&M practices. The main aspects contributing to variation in the O&M cost estimates for WEC farm are discussed. The existing tools and models relevant to WEC O&M are reviewed and O&M transport using vessels for offshore WEC O&M activities is discussed. The focus is on the variation in the O&M cost estimates. However, supplementary information is presented in the integrated framework to support the life cycle assessment of the WEC farm project.

2.2 Review on Resource Assessment Methods for Wave Energy Farm

Wave energy resource assessment includes the hydrodynamic modelling efforts developed to help understand the behaviour of WECs operating in harsh offshore environmental conditions. This has contributed to support the generation of power through estimating the potential for the WEC to generate electric power from sea waves (Alves and Sarmento, 2007). In many locations worldwide in-situ measurements for ocean waves normally performed by small floating measurement buoy have been conducted (Iglesias et al., 2009). Extensive historical data sets are often available in industrialized nations and can be used to derive useful statistical parameters such as significant wave height, wave period, wind speed and wave direction from the buoys' accelerations for wave energy resource assessments (Iglesias and Carballo, 2011).

The significant wave height and wave energy period are two important parameters that directly influence the amount of wave power available in a resource (EMEC, 2009). The significant wave height and wave energy period of resulting waves will vary depending on the energy flux between the wind and the ocean surface (Dean and Dalrymple, 1984). One important issue that require more clarification based on the resource assessment methods in existing literature is related to the wave energy resource. There are two separate but closely related aspects of the wave energy resources (Carballo and Iglesias, 2012). For clarity in this thesis, the distinction between these two aspects of the wave energy resources are:

1. Wave power which is available at a location for a time including information about its variability on short timescales (hours to days). This can be assessed by making wave measurements at the position of interest (Carballo and Iglesias, 2012).
2. Wave power climate at a location: This includes the monthly, seasonal and annual statistics of wave power as well as a consideration of the variability of wave power on monthly, seasonal, annual and inter-annual timescales (EPRI, 2011). Experimental studies (Maganga et al., 2009) have been carried out to study the behaviour of marine energy converters capable of harnessing energy from the waves. Work has also been done to determine their flow characteristic (Germain et al., 2007).

Therefore, the first step in siting a wave energy conversion facility is to identify the area that is rich in wave power (Iglesias and Carballo, 2011). In principle, (Barstow et al., 2009) acknowledges that the assessment of the wave power climate can be accomplished by measurement. In practice, due to the difficulties and huge expenses required to maintain the wave measuring instruments over a long period, it becomes necessary to resort to other strategies such as using long-term wave modelling and other methods which use historical met-ocean data (Le et al., 2009).

The requirement for information about the resource before a long-term measured climatology can be assembled (García–Medina et al., 2014; Stopa et al., 2013) is also a constrain. For this reason the guidelines for development of wave energy projects and procedures to assess the wave energy resource at a given site was highlighted (Croll and P, 2009). Studies on wave energy resource assessment (Black and Veatch, 2004; Black and Veatch, 2005) emphasised that the theoretical wave energy resource refers to the theoretical maximum potentially extractable wave energy contained within the overall resource at the location of interest.

Furthermore, studies (Cruz et al., 2009) also highlighted the most important steps to follow for wave energy resource assessment. These steps are described and summarised below:

- In the Initial stage, a preliminary assessment of the wave energy resource is undertaken in the area of interest (Cruz et al., 2009). This can be done by using summary statistics derived from any suitable wave model. Generally, the validity of the result is confined to water of intermediate depth or deeper (EPRI, 2011).

- The Second stage involves an assessment of the inter-annual variability of wave power at the model site to ensure that the scheme is economically robust (Iglesias and Carballo, 2011). This assessment is performed by studying the inter-annual variability in the modelled data. It is recommended that the modelled data series is of adequate length.

- Thirdly, to ensure that wave conditions at the measurement site are not systematically different from those at the WECs site, assuming any of the different global wave models (e.g. UK Met Office model, the WAM Model etc.) grid points are used to perform the preliminary assessment. The next step is to transfer the modelled climate statistics from the global model grid point to the location of the WECs (González et al., 2007).

- Fourthly, assuming the modelling work confirms the suitability of the WECs site, the method for analysing the measured climate data and the algorithms required for interpreting the measurements to check the model results are developed (Yavuz et al., 2006). Finally, the method of analysing the resource assessment result is presented by way of interpreting the measurements and model results.

The site and facility-specific information can be used to evaluate how siting a WEC facility might influence existing coastal and marine uses (Cruz et al., 2009; Yavuz et al., 2006). Outcomes of the resource assessment will provide information on methods used to identify potential areas for siting WEC facilities to obtain greater energy production and cost benefits. Efforts on wave energy resource characterization for example, include analyses of measured buoy data and hind cast simulation data, directional spectra analysis (Lee and Kim, 2006).

To avoid the ambiguity and difficulty in comparing assessments results the International Electro Technical Commission (IEC) began Technical Specification (TS) (Whittaker and Folley, 2012). The Technical Specification on Wave Energy Characterization are often adopted for resource assessment. An overview of the Technical Specification (TS) project can be found in (Folley et al., 2012). In summary, it is necessary to provide a framework for presenting the variables which should be considered for preliminary analysis of the location of interest using historical wave data. The work presented in this thesis provides the methodology for establishing the criteria and for developing the integrated framework model for wave energy resource assessment and modelling the O&M cost for a WEC farm project. Supplementary information is presented in the integrated framework to support the assessment of CAPEX.

2.3 Developments on Wave Energy Extraction using WECs

This section discusses the developments in wave energy extraction using WECs based on findings from existing literature. It is common knowledge that the ocean contains a vast energy resource and there are several ways in which this energy can be harnessed. The energy contained within the waves manifests itself in the form of kinetic motion of water particles, with the energy imparted to the waves from the wind (Kinsman, 1965). Bedard et al., (2005) acknowledges that extracting energy from ocean waves for electric power generation could be a complex and challenging project. This is due to the fact that different prime-mover concepts developed for extracting useful energy from ocean waves needs to be considered (Kramer et al., 2011). Moreover, the mooring issues are also of importance and need to be considered.

The reason is because the location of a wave energy device will largely influence the type of mooring requirements as illustrated in Figure 9. In this context, significant civil engineering works will be required to integrate the device into a natural rock face or a man-made breakwater in the case of a typical shoreline device (Drew et al., 2009). The fundamental principle governing the design of WEC device often depends on the resource characteristics and the intended location of the device (Bergdahl and Martensson, 1995).

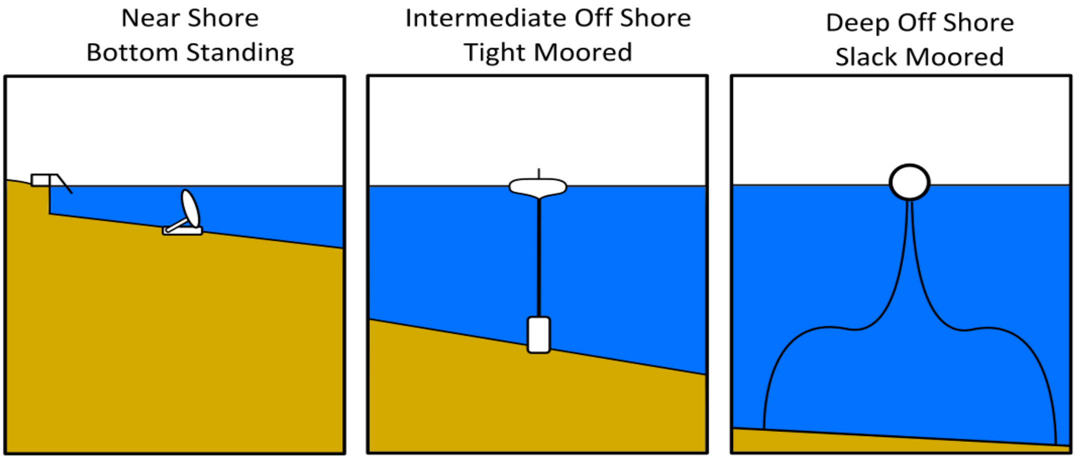


Figure 9: Mooring and Foundation Configurations for WECs Source: (SI OCEAN, 2013)

As illustrated in Figure 9, wave energy converters can be designed for operation in any specific water depth conditions, example: shallow water less than 20m, intermediate water 50 or deep water above 50m. As in all other floating structures, WECs need to be kept in position by station-keeping systems in order to realize its functionality and ensure its safety (Gao et al., 2009). According to the report (Johanning et al., 2006), the principal approach to design of WECs emphasises on survivability as the main concern for mooring system design.

WECs could be located nearshore, offshore and onshore. Near-shore device will rely on gravity mass or will rather employ either pinned pile foundations to hold the device in place (Gao et al., 2009). For devices located off shore, the mooring system may depend on the type and location of the structure and Power-Take-Off (PTO) system and may have the option of tight moorings or slack moorings to hold the device in place (Johanning et al., 2006; Gao et al., 2009; Bergdahl and Martensson, 1995). Mooring systems design issues and choices for wave energy converters has been presented in a review by Harris et al., (2004).

To establish wave energy as an important part of the global energy mix, several actions were taken during the last 10 years. These actions resulted in the establishment of wave energy test centres some in the UK (EMEC, WAVE HUB), Ireland and Portugal (EMEC, 2010). These facilities allowed developers to test prototypes under real sea conditions. But they are not real. They are simulated, resembling real and in some cases extreme and rare wave phenomena. Some of these developments included the Limpet plant on the island of Islay in Scotland (Henderson, 2006) and the OWC on the island of Pico, Portugal (Falcão, 2007).

As international interest continues to increase in the wave energy sector, development activity is also increasing. This is marked with the construction of a range of scale and full scale ocean energy test centres in Europe, USA and Canada (Mueller et al., 2010). There is also progress in plans for prospective new test centres in Asia (EMEC, 2012). Another important issue undermining the growth of the wave energy industry is identified as the lack of a single consistent and well documented source of information, which clearly defines the approach for wave energy characterization at a potential site (Beels et al., 2011).

Power production, device reliability, survivability, and the cost of energy are impacted by the sea state condition experienced by the WEC (Allan et al., 2011). For this reason, the development of a catalogue of wave characteristics at WEC test sites and potential deployment locations were supported by the U.S. Department of Energy’s (DOE) Marine and Hydrokinetic Energy (MHK) Program (Folley et al., 2012). This developmental initiative will allow WEC developers to compare and select test sites that will provide most suitable characteristics for their device and that which best meet their testing needs and objectives.

In the 1940s, only sporadic projects were seen: For example, Matsuda development of wave energy devices in Japan (Falcão, 2007). In the 1970s, the increase in the price of energy, because of the ’peak oil’ price, marked the development of the next stage in wave energy. From then major work was carried out at the time in several research institutes. For example, Salter (1974) provided experimental evidence, while Budal and Falnes (1980) provided the theoretical evidence that wave energy extraction from ocean waves was possible with high efficiencies.

Experimental work with the Salter duck (Salter, 1974) demonstrated by 2-D experiments that it was possible to reduce to zero the transmitted wave at a wave energy device. This meant that after passing through the wave energy device the wave would vanish. So, all the incident wave energy was absorbed or reflected from the devices. On the other hand, to satisfy the low-cost conditions, the use of devices within arrays is regarded as a good solution for cost reduction. This is because the devices share the structural support (either floating or fixed structures), the same grid connection and most of the switch gear. This permits “Economies of Scale”(Cruz et al., 2009).

The O&M are also optimised with arrays, as the devices are closer to each other. The proximity of the WECs within arrays in some cases improve power extraction (Budal and Falnes, 1980). Studies (González et al., 2007; Falcão, 2007) using different modelling techniques found for unrestricted WECs, that the power extracted by an array of WECs is larger than the power extracted by the same number of WECs within the array independently. The first studies used the point absorber approximation, where the devices are considered to have small dimensions (much smaller than the wavelength) and the scattered wave of the WECs is neglected in hydrodynamic interactions (Alves and Sarmento, 2007).

In other studies, (Thomas, 2008) used the plane wave approximation, where the radiated wave is reduced to a plane wave to calculate the forces on each device. With the increase in computational power the use of full diffraction and radiation models has become common practice (Alves and Sarmento, 2007). Panel codes are now used to obtain the hydrodynamic coefficients of the different array elements together with the respective interactions using the equations of motion, the power extraction for devices is obtained (Cruz, 2008). Having discussed the developments in wave energy extraction using WECs the next section identifies the different type of WEC and their classification.

2.4 Types of WEC and Their Classification

A critical review of the existing technology concepts within ocean energy device developers reveals that there is very little design consensus surrounding the design of wave energy technology. Studies on performance evaluation (Kramer et al., 2011) and experimental concepts of WECs (Yemm et al., 2012) show different WECs type that are on the prototype level and those that are being developed further to reach the commercial stage. The prototype level is needed to demonstrate working principles and proof efficiency as well as survivability.

Studies based on advances in the design of WEC (Whittaker and Folley, 2012) show that there are several areas in which a wave energy converter can be placed in order to harness the energy most efficiently. The evaluation and classification of the different types of WEC draws extensively on existing literature to explore the existing wave energy technologies across a variety of design types that are currently being developed and deployed. The importance of this current research and thesis is to help identify drivers for future technology developments and identify areas for future cost reduction.

There are devices with all the different combinations of power take-off mechanisms (e.g. hydraulic, linear generators, pulley connected to generators) and types of displacements (e.g. pitch, surge, heaving). Available figures show that there are over 250 numbers of device developers with original concepts. Approximately 157 of these device types including their developers name and country based are listed in Appendices 1. Further details of all the different developers can also be found on the EMEC website/wave energy converter arrays (EMEC, 2010).

Drew et al. (2009) presented a review on different types of WEC devices. Other studies (Allan et al., 2011; Carbon Trust, 2011) emphasised on cost effective energy extraction. The findings of these studies acknowledge that each WEC design type has different means of power production and each concept has its own perceived advantages and disadvantages. For clarity, consistency and to validate the information presented in this thesis, it is necessary to start by the classification of these devices. WECs are deigned to extract energy using the surge, heave or sway motions of the waves (or a combination of each). Table 3 illustrates the classification of WEC following the technique with which it is designed to extract energy.

Table 3: Classification of WEC Types (EMEC, 2009)

Device Type	Classification
Attenuators	A
Point Absorbers	B
Oscillating Wave Surge Converter (OWSC)	C
Oscillating Water Column (OWC)	D
Overtopping/Terminator	E
Submerged Pressure Differential	F
Bulge Wave	G
Rotating Mass	H
Others	I

The different type of WEC device and classification shown in Table 3 is related to their dimensions and orientation compared with the incident wave. Devices parallel to the incident wave are termed attenuators, normal to the incident waves, terminators, and relatively small dimensions point absorbers. Wave excitation force acts on part of the device, which will have a relative motion compared with other parts of the WEC (Sarmento et al., 1985). This relative motion can then be converted to useful energy in different ways (Falnes, 2002).

The descriptions on these wave-induced motions, linear and rotation around each axis (roll, pitch, and yaw) is presented in the Terms and Definitions section at the beginning of this thesis. WEC design are often categorised by the operating technique with which they use to convert the energy of the waves, e.g., point absorber, surface following, oscillating water column and overtopping etc. Some of the most prominent examples of wave energy converter technology designed to extract energy from the waves are described in the following:

Attenuator (A) in Table 3 refers to the WEC device type and classification of WECs which uses the energy within oncoming waves to induce an oscillatory motion between two (or more) adjacent structural components. The motion can be resisted by hydraulic rams which pump high pressure hydraulic fluid through a motor, or by a direct drive PTO system, to generate electricity (EMEC, 2010). Attenuator type WECs can be surface floating or fully submerged, the former is most common. Attenuators tend to yaw automatically to face the predominant wave direction.

Example of Attenuator is the Pelamis Wave Power (EMEC, 2009). The Pelamis concept initially developed and tested in Scotland was the first multi-unit wave farm to be built consisting of three units rated at 750KW each installed and connected to the grid in September 2008 in Aguçadoura, outside Portugal (EMEC, 2010). The Pelamis design is made up of individual tubular sections each linked to neighbouring segments by universal joints as shown in Figure 10 and Figure 11.

Figure 10: Pelamis Prototype Being Tested at EMEC Orkney (EMEC, 2010)

The machine was made up of connected sections which flex and bend as waves pass, and the motion is used to generate electricity (Max, 2009). Pelamis is a semi-submerged wave energy converter and it utilises the surface following technique. There are two Pelamis machines which have undergone grid-integrated testing at the European Marine Energy Centre in Orkney, UK (EMEC, 2010). Pelamis is designed with a self-referencing mechanism that allows the device to maintain a directional heading perpendicular to the oncoming wave direction.

Studies on design simulations and testing of a novel hydraulic power take off system of the Pelamis wave device (Henderson, 2006) mentioned that as a wave passes down the length of the device; motion is induced in each section. This follows the weathervane concept such that it can weathervane to face oncoming waves. Thereby, allowing the Pelamis device to enter a survival mode in which the WEC rides underneath extreme waves which would otherwise impart extreme forces. Pelamis can be moored in water depths exceeding 50m, and the first segment is moored causing the snake-like shape to align to the wave direction (EMEC, 2010).

Figure 11: Pelamis Wave Power (Max, 2009)

The waves cause the joints to bend and movement between neighbouring segments will be resisted by hydraulic rams. This resistance pump hydraulic fluid through pressure smoothing accumulators then on to a hydraulic motor linked to generators producing electricity (Yemm et al., 2012). Pelamis suffered some technical problems two months after its installation and the units had to be towed to shore. Although Pelamis claims to have solved the problem but their main investor Babcock & Brown, went into voluntary administration, causing the project to be halted until a new investor is found (Andrews et al., 2007).

Figure 12: Dexa Wave (Drew et al., 2009)

In addition, Dexa wave is another example of WEC classified as Attenuator (A) as shown in Figure 12. Dexa wave is a Danish wave energy device developer producing a hinged raft WEC where motion between the raft sections is resisted by hydraulic rams. In comparison to Pelamis, Dexa wave is in the early stages of development of a wave farm project on the island of Malta in the Mediterranean Sea. The device developer are Investigating alternative materials such as steel reinforced concrete for future devices (Drew et al., 2009).

Furthermore, Point Absorber (B) in Table 3 refers to device type and classification of point absorbing WECs. A point absorbing WEC is a complicated dynamical system. Compared to other technologies, they could potentially provide ample quantities of power in a relatively small device (Alves and Sarmento, 2007). This type of WEC is designed to use buoyant forces to induce a heaving motion of one body relative to a secondary fixed body (Alves and Sarmento, 2007). The fixed body may be moored to the sea bed or held in place by gravitational forces through a large foundation mass.

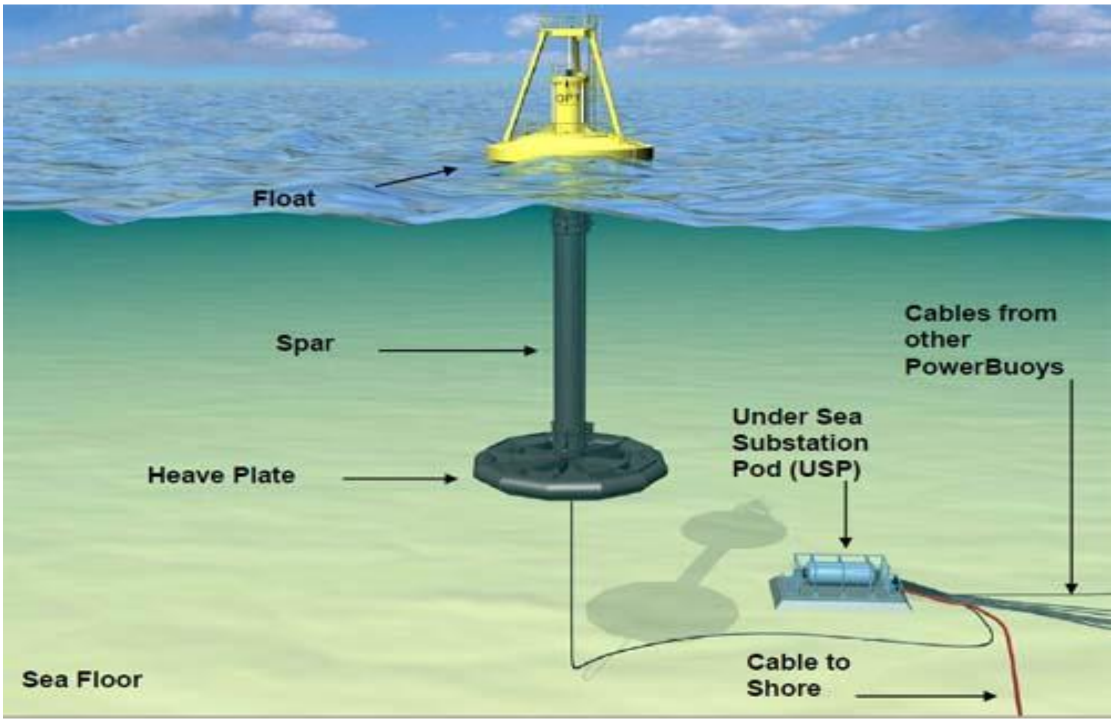


Figure 13: The General view of Turbine Connected to a Generator (Oceanenergy, 2016)

Figure 13 shows the general view of a turbine connected to a generator which produces electricity. The electricity is fed through the bottom of each buoy which is connected to an Underwater Substation Pod (USP). This USP was specifically patented by Ocean Power Technologies and can take up to ten PowerBuoy inputs (Oceanenergy, 2016). This USP significantly saves sea-bottom space limiting the amount of negative environmental impact that can take place on the seabed.

Point absorbers can receive incoming waves from any incident angle because they are non-directional devices (Falnes, 2002). This suggest that they can harness electricity from a single device at a certain point i.e. floating water buoys. In a study on hydrodynamic optimization of a heaving point absorber WEC (Alves and Sarmento, 2007) the authors mentioned that there are strategies and numerous designs for using these devices and mostly they all work in the similar manner. The operating principle is such that a semi-submerged buoy drives a Power Take-Off (PTO) device which acts as a linear or non-linear damper of the WEC system. Power conversion takes place in various forms depending on the conformation of the device.

Figure 14 shows the Ocean Power Technology (OPT*)* Power Buoy. This is an example of Point Absorber. This WEC device. is a semi-submerged floating device consisting of a toroidal float that moves with respect to an inertially stable spar structure tethered to the sea bed. The device is a self-reacting heaving buoy that floats on the surface of the ocean; slack moored in deep water. The floating buoy has two rods that are attached to piston- devices within a cylinder. The system is designed with a protective mechanism that can lock the structure and ceasing movement of the device when extreme waves are encountered, most especially in the event of storm waves.

Figure 14: Ocean Power Technologies (Oceanenergy, 2016)

Ocean water is pumped through a turbine and the bottom of the buoy due to the vertical motion which causes the piston inside the cylinder to rise and fall alongside the buoy due to the rising and falling of the ocean swells. The mechanical stroking motion of the buoy relative to the spar is converted to an electrical output via a sophisticated power take-off driving an electrical generator which produces electricity. To date, OPT have deployed the 150kW variant of the

Power Buoy in various wave climates. OPT were developing a 500kW Power Buoy device (EMEC, 2012). Figure 15 is an example of the sea based WEC device project.

Figure 15: Sea-Based WEC device Project (SI Ocean, 2012)

The Sea based WEC project is another example of a point absorber device that utilises a float on the surface of the water to move a linear direct-drive neodymium-iron-boron magnet generator. The generator is located within a tower on a sea bed foundation (SI Ocean, 2012). It is developed by a Swedish device developer developing a taut moored point absorber. The device is designed to have end-stops. This prevent the linear generator from exceeding the allowable travel. The sea bed mounted generators are anchored using a concrete gravity foundation. The dimensions of the foundation are designed to withstand the wave loading and installation can take place without requirement for seabed preparation (SI Ocean, 2012).

In addition, Oscillating Wave Surge Converter (OWSC) (C) in Table 3 refers to device type and classification of OWSC device. This is a novel shoreline or near-shore WEC. They are generally located in near-shore regions where the water particle motion becomes more ellipsoidal in shape (Thomas, 2008). As waves approach the shore, a reduction in water depth and drag from the sea bed results in an ellipsoidal wave particle motion. They are designed to use the surge motion of the waves to induce oscillating motions of a body in the horizontal direction (Tseng et al., 2000). OWSC are typically bottom mounted devices fixed directly to the sea bed. However, concept of floating OSWC devices are under development.

Figure 16 shows an example of Langlee Wave Power OWSC device. This is a floating steel structure as illustrated in Figure 16. The device can synchronise its movement with the passing wave motion caused by the forward and backward movement of its hinged "wings". The device is designed such that the wings can freely rotate through 360°. There is no end stop that could cause damage to the structure or water wings. The movement of the wings drives a hydraulic system to power electric generators. On-site maintenance would be required at specified periods for servicing the generator, anode replacement, mooring inspection, fatigue inspection, while major maintenance would require the device to be returned to base (Tseng et al., 2000).

Figure 16: Langlee Wave Power (Tseng et al., 2000)

Figure 17 shows the Aquamarine Power Oyster WEC device which is another example of OWSC. The device is a near-shore hydroelectric wave energy converter developed by Aquamarine Power (Aquamarine, 2010). It is designed for water depth between 10 to 15m, approximately 500m from the shore (Henry et al., 2010). A 315kW Oyster 1 proof-of-concept device has been operated at sea at the European Marine Energy Centre in northern Scotland between 2009 and 2011.The second-generation 800kW Oyster 800 began operation testing at sea in June 2012 when it produced first electrical power to the grid (EMEC, 2012).

Figure 17: Aquamarine Power Oyster (Aquamarine, 2010)

Experimental studies (Whittaker and Folley, 2012) conducted based on practical experience in the operation of the Oyster device agrees that nearshore OWSCs are serious contenders in the mix of wave power technologies. The authors explained that Oyster uses the resultant ellipsoidal wave particle motion that is generated as waves approach the shore to oscillate the buoyant hinged flap forwards and backwards with the wave surges. The main structure of the device consists of hydraulic PTO system, where high pressure water is pumped from the device to a shore based Pelton turbine and a buoyant bottom-hinged flap (Henry et al., 2010).

The oscillation is used to pump fresh water through a high-pressure pipeline to an onshore hydroelectric power plant. Double acting hydraulic cylinders allow both the forward and backward motion to pump. The pressurised water drives a Pelton wheel turbine connected to an electrical generator located on the shore. Multiple Oyster devices can be connected to a pipe manifold to allow the operation of a farm of devices requiring only a single onshore hydroelectric system. The first and second-generation Oyster devices were constructed from steel. The next-generation Oyster 801 is to be constructed from fibre-reinforced polymer (FRP) (Henry, et al., 2010). Maintenance strategy requires calm weather window for any offshore maintenance work. The device had to return to base for major maintenance work.

Furthermore, Oscillating Water Column (OWC) (D) in Table 3 refers to device type and classification of OWC device. OWCs are simple constructions that can be contained within a fixed structure at the shoreline. They are located near shore bottom as a bottom mounted structure contained within a man-made breakwater (Le et al., 2009). A report on wave generation by an oscillating surface-pressure and its application in wave-energy extraction (Sarmento et al., 1985) highlighted the operating principles of OWC devices. In operation, OWC uses a chamber that is part filled with water to drive air through a turbine.

The device acts as a large piston on the volume of air within the chamber. As waves rise within the OWC, the pressure in the chamber rises and air exhausted from the chamber drives the turbine. When the water level decreases the air flow reverses and air is drawn into the chamber, once again driving a turbine at the top of the column. The water column is constantly moving up and down as waves pass the OWC. This operation causes the compressed air to be driven through the turbine under pressure which in turn generates electricity (Sarmento et al., 1985).

As the wave recedes the opposite effect is experienced and air is sucked back into the OWC through the turbine continuing the electricity generation. An example of OWC: is Voith Hydro Wave-gen illustrated in Figure 18. This device developer has successfully completed two OWC projects, the LIMPET (Land Installed Marine Powered Energy Transformer) device and an OWC contained within a breakwater in Mutriku, Spain (Wright et al., 2003). LIMPET is a shoreline based OWC WEC device located on the island of Islay, on the west coast of Scotland. A breakwater was constructed in Mutriku, Basque county, Northern Spain, which incorporated a 300kW power generation system.

The WEC system of the Voith wave gen project shown in Figure 18 comprises of 16 individual OWC wave energy units contained within a 100m section of the breakwater. The design consists of Pneumatic PTO Wells turbine and induction generator. The mooring type is a shore-based structure. The maintenance Strategy is such that due to the location of the device, all maintenance and major repair works can be carried out on shore. A report on the status of ocean wave energy and future perspectives (Cruz, 2008) acknowledges that the breakwater was deemed necessary for additional protection to both fishing and recreational boats.

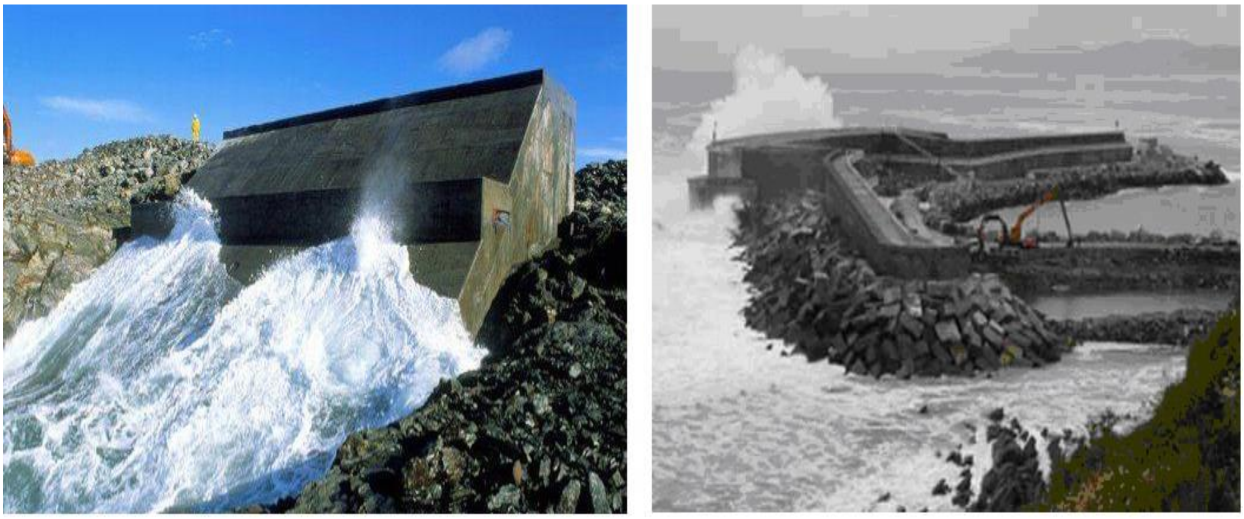


Figure 18: Voith Wave-gen (Wright et al., 2003)

Other studies on the theory behind the conversion of ocean wave energy (Thomas, 2008) agree that incorporating a wave energy generation plant into the breakwater can maximise the utility of the project. In addition, another example of a shoreline oscillating water column structure is WavEC Pico Plant. The WavEC has been responsible for the maintenance and operation of the plant since 2006. The goal of the project was to demonstrate the viability of OWC technology for production of electricity to a small grid (OceanEnergy, 2012).

The WavEC Pico Demonstrator OWC device is located on the Pico North Coast. The choice of installing the WavEC Pico Plant at the location was due to the presences of a suitable grid connecting point, suitable geographic conditions for this type of device, ease of access from local roads and suitable water depths in front of the WEC. In addition there is the availability of high energy levels at the chosen location (Le et al., 2009). Between 2007 and 2012, the Pico plant produced over 51MWh of electricity during 2730 hours of operation (EMEC, 2012).

Figure 19 shows an example of the WavEC Pico plant. The WavEC Pico plant is equipped with a horizontal-axis wells turbine-generator set and a guide vane stator installed on each side of the rotor. To avoid over pressure within the air chamber, a pressure relief valve controls the pressure, ensuring that the turbine does not stall. Due to the location of the device, all maintenance and major repair works can be carried out on shore.

Figure 19: WavEC Pico Plant Ocean Energy Limited (OceanEnergy, 2012)

Furthermore, Overtopping Terminator (E) in Table 3 refers to device type and classification of Overtopping device. An overtopping device is also known as a terminator device because of the way it absorbs or “terminates” all of the wave’s power (Bedard et al., 2005). The device could be described as a large floating reservoir capable of converting the wave energy into potential energy to generate electricity. Overtopping terminators are up to 390 meters wide and can hold between 1,500 and 14,000 cubic meters of water.

The reservoir is located at a height slightly above sea level to increase the amount of potential energy it contains. The reservoir is used as storage for the water which produces energy by flowing through a low-head hydraulic turbine. A review on wave energy technologies (Falcao, 2010) mentioned that the estimated average cost of building and installing one of this device was around $10 to $12 million. The device consists of ramps and reflectors extending off the end and turbines located at the bottom of the reservoir. The operation of the device is such that when waves first approach an overtopping terminator, they bump into its reflectors which are attached to the main body of the floating device.

These reflectors are angled outward to direct as much wave energy up to the device as possible (Bedard et al., 2005). This causes the waves to break across the device and the surge energy in the breakers allows water to be collected into the reservoir above the free water surface. A report (Gulli, 2005) explained that once the water is captured in the reservoir it is released back into the ocean via a turbine outlet located near the middle of the device. In general configurations of overtopping turbines are coupled to generators to produce energy.

The overtopping terminator is categorized as a wave capturer because in comparison to other wave energy devices that normally use the wave's kinetic energy to generate power, the terminator captures waves and takes advantage of their potential energy (Techet, 2005; Bedard et al., 2005). The Wave Dragon project is an example of overtopping type floating WEC. They are often located in water depths of more than 25 meters deep to take advantage of ocean waves with the highest amount of energy. As the reflectors gradually rise in height, it compresses the width. This action leads the water all the way up to the reservoir.

The ramps are placed in very shallow positions to cause the incoming waves to crash over into the reservoir, hence the name "overtopping" terminator. Figure 20 shows the Frontal view of Wave Dragon. The device is a 58m wide prototype weighing 237 tons with power output rated at 20kW deployed in 2003 off the coast of Denmark at Nissum. The structure comprises of a pressurized system of air chambers that allows the device height to be adjustable. This function also increases the amount of energy the device is capable of capturing with 16-20 turbines that spin as water is released from the reservoir (David., 2010).

Figure 20: Frontal View of Wave Dragon in Nissum (Drew et al., 2009)

The reservoir stores water at a height above the sea level and two reflector arms focus oncoming waves onto a ramp which directs some of the water from the oncoming waves up into the reservoir. Water in the reservoir is used to drive a hydroelectric turbine, making use of the pressure head between the water in the reservoir and the surrounding sea. The water passing through a hydroelectric turbine leaves the reservoir back to the sea through outlet holes in the bottom. In total, the Wave Dragon accumulated over 20,000 hours of operational experience between 2003 and 2009, with grid connection allowing generated electricity to be supplied to domestic homes (EPRI, 2011).

There are plans for a full-scale demonstration device to be deployed off the coast of Wales (EPRI, 2011). Some concerns about overtopping devices include the equipment’s cost, maintenance, and productivity. Studies (Whittaker and Folley, 2012) mentioned that the productivity aspect is not so much a concern anymore since these specific projects do not rely on wavelength, do not reflect energy, and harness close to 100%. However, money is also necessary to maintain terminators, especially the floating devices which are subject to high-energy waves in the open ocean. Furthermore, problems with the reflector arms have slowed development and it is unclear when a full-scale device will be built.

In addition to the device type and classification already described, Pressure Differential (F) in Table 3 refers to device type and classification of Pressure Differential WEC device. Studies (Drew, et al., 2009) mentioned that this type of device relies on oscillating hydrodynamic pressure caused by passing waves. They can be either floating or fully submerged WECs. Floating pressure differential devices could utilise the increased pressure due to passing waves to compress air through a turbine. Once the wave passes, the reduced pressure differential causes the body to return down to its starting position.

A review on wave energy technologies (Drew, et al., 2009) mentioned that the Submerged Pressure Differential devices work based on a pressure differential being created due to the movement of the waves. This suggest that submerged devices experience an induced motion as waves pass over the device creating a temporary vertical force on the body. Figure 21 show the Archimedes Wave Swing developed by AWS Ocean Energy. In the device, a pressure differential is created through the compression of air inside flexible membranes. This wave energy capture device can be considered a fully submerged point absorber (Drew, et al., 2009).

AWS Ocean Energy is developing a multi-cell array of flexible membrane absorbers. It is an example of Pressure Differential WEC device. The pressure differential induced within the device as the wave passes drives a fluid pump to create mechanical energy. The pressure differential is converted to pneumatic power by compressing air within a cell. The compressed air is used to drive an air turbine to produce electricity. A study on optimisation of wave energy extraction with the Archimedes Wave Swing (Valerio et al., 2007) mentioned that a typical device will be made up of 12 inter-connected cells, in order to allow air to flow between cells in anti-phase.

Figure 21: The Archimedes Wave Swing (AWS, 2010)

Figure 22 show the AWS Ocean Energy converter. The designed consist of an eccentric rotating mass connected to a direct drive permanent magnet generator as the PTO system. The modular design allows rapid removal and replacement of the flexible wave absorber cells. The full-scale device is anticipated to be more than 60m in diameter. The device will be slack moored in water depths of around 100m using standard mooring spreads (Valerio et al., 2007). The large structure provides an inherently stable platform allowing safe on-site maintenance for minor maintenance, the device can be returned to base for major maintenance.

Figure 22: AWS Ocean Energy (AWS, 2010)

Furthermore, Bulge Wave (G) in Table 3 refers to the device type and classification under Bulge WEC device. Bulge Wave is a novel concept for wave energy conversion developed by Bulge Wave Power. A report (Farley and Rainey, 2006) mentioned the main characteristic of the device and described the main features of the Anaconda wave energy converter. The device consists of a flexible rubber tube filled with water lying parallel to the wave direction. An example of a Bulge Wave device is the Anaconda wave energy converter shown in Figure 23. The device is moored to the seabed to allow it to orientate into oncoming waves.

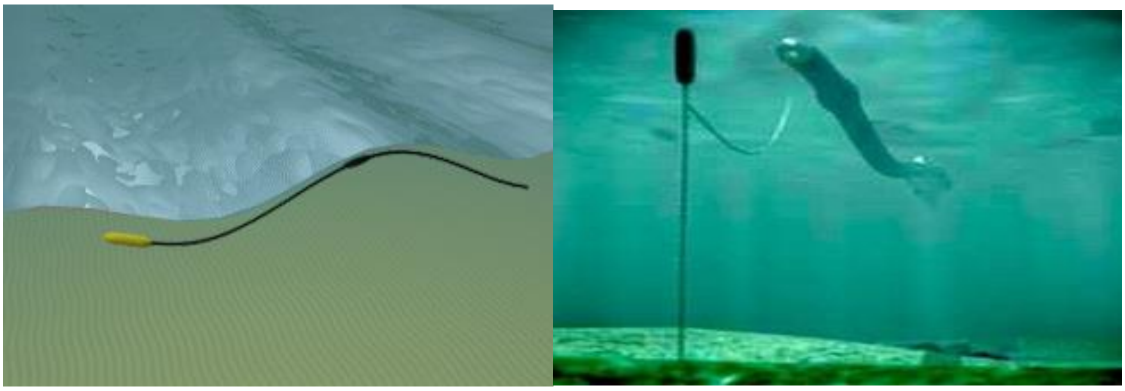


Figure 23: Artist's Impression of The Anaconda Wave Energy converter (Al-Salem et al., 2006)

The operation of the device is such that a differential pressure is created as the wave front passes over the device. This causes water contained within the flexible tube to be squeezed as the tube flexes compressing the water within, thus forming a bulge wave. This bulge wave travels along the device at a speed proportional to the wave velocity and the flexibility of the tube, gaining energy as the bulge grows. The energy in the compressed water can be used to drive a turbine located at the end of the tube (Maganga et al., 2009; Farley and Rainey, 2006).

In addition, Rotating Mass (H)in Table 3 refers to device type and classification of Rotating mass WEC device. Rotating mass device utilise the motion of the waves to cause pitch and roll to spin a rotating mass of a floating body (Chen and DelBalzo, 2013). Figure 24 shows an artist impression of a rotating mass device. The operation of the device is such that within the floating body an eccentric mass will be excited and will begin to rotate creating mechanical energy (Li et al., 2015). The rotation will drive an electrical generator contained within the device.

An example of a rotating mass device is the Penguin developed by Wello Oy, a Finnish company Founded in 2007 (Wello, 2013). The Penguin device shown in Figure 25 was fabricated in Riga, Latvia. The structure weighs approximately 220-tonne (excluding ballast) that is around 30 meters in length, and has a draft of seven metres. The design consists of an eccentric mass housed inside an asymmetrically shaped hull, designed to capture the rotational energy generated due to the rolls, heaves and pitches movements made with each passing wave.

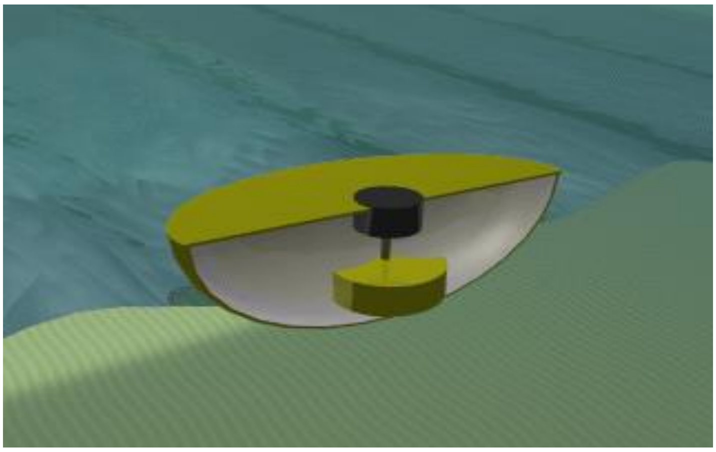


Figure 24: Rotating Mass (Chen and DelBalzo, 2013)

The revolutions of the spinning eccentric mass housed inside the hull are accelerated and maintained by these movements. These movements are used to drive the electric generator to produce electricity that can be exported via a subsea cable. The device has been undergoing testing at Lyness since arriving in Orkney in June 2011(EMEC, 2012). The device was first deployed at the Billia Croo wave test site in summer 2012 (Wello, 2013).

Figure 25: Wello Oy Penguin (Wello, 2013)

Finally, in Table 3 the device type and classification Other (I) refers to WEC Devices in the “Other” category. The reason is that they do not fit into any of the headings mentioned above. The devices in this category employ a novel or unconventional technique for extracting energy from the waves. Considering the different type of devices and their operation, device evolution is a fundamental pathway to the commercialisation of wave energy technology. This is particularly in the drive for WECs to reach cost-competitiveness with more mature forms of renewable energy technologies.

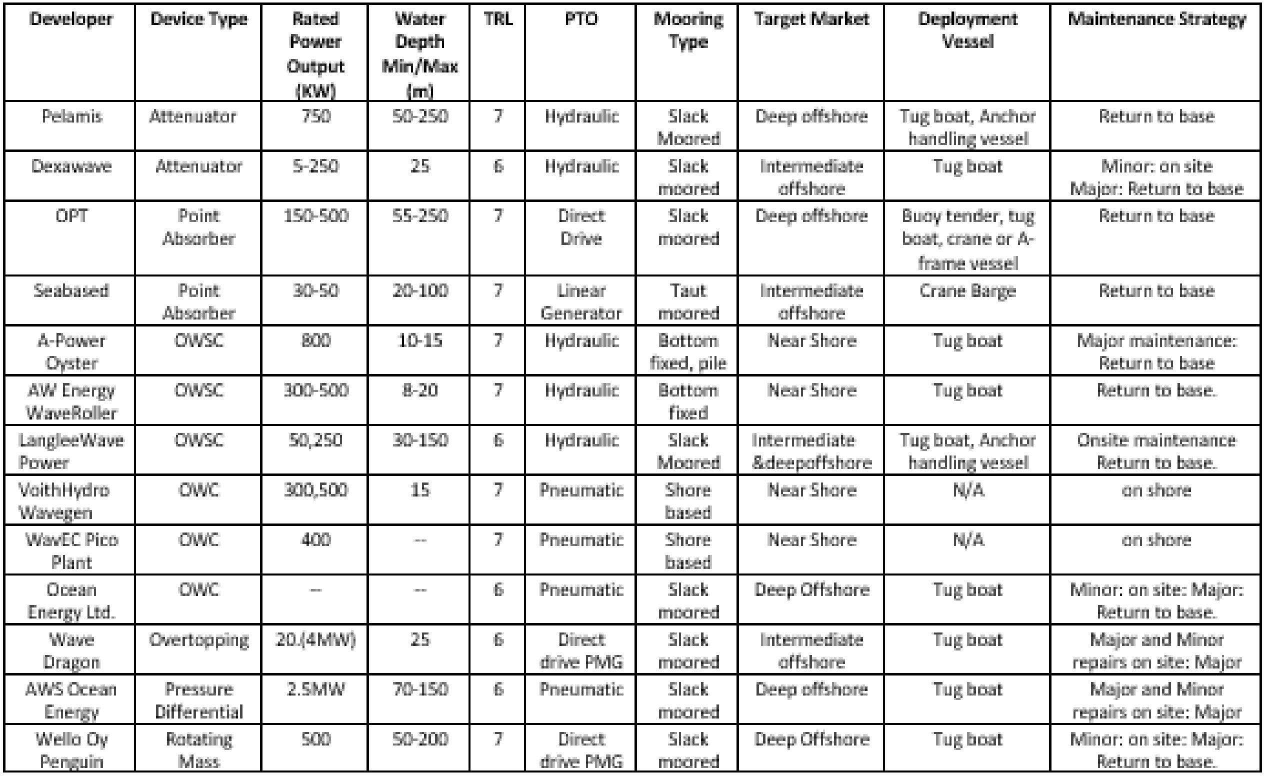
Without device evolution and subsequent cost reductions the market for wave energy will not develop. In this review, it is noticed that high prices are applicable to all renewable energy devices and hopefully with more time and better developments, appropriate funding will be available. WEC designs are quite different from WEC to WEC mainly due to differences in energy harvesting and subsequent conversion (Power Take-Off). However, studies (Bahaj, 2011) acknowledges that each design faces almost similar challenges.

Crucial for any design is the mooring which ensures a maintained position under both normal operating loads as well as extreme storm load conditions (Johanning et al., 2006). It should not exert excess tension loads on the electrical transmission cables and ensure the suitable safety distances between devices in multiple installations (Harris et al., 2004). A summary of the most relevant and up to date WEC converters is presented in a Table in 4. For each device developer, their rated power, operational water depth, power take off (PTO) mechanism, the type of mooring required and the target market for each device is presented.

Table 4 also provides information on the technology readiness level (TRL). The Technology Readiness Levels (TRLs) for wave energy projects provide a valuable metric of technology readiness and deliver useful guidance for the development process. In this context, the WEC devices listed in Table 4 have passed the first and second stages of applied and strategic research referring to TLR 1-4 (EMEC, 2009). WEC device developers in stage 3 are in the technology validation stage and this represents TLR 5-6.

Device developers such as Dexawave (Attenuator), Langlee Power (OWSC), Ocean Energy Ltd. (OWC), Wave Dragon (Overtopping) and AWS Ocean Energy (Pressure differential) are at TRL 6. This implies that they were at the stage of testing operational scaled models at sea including subsystem testing at large scale. On the other hand, developers and device type such as Pelamis (Attenuators), OPT, Seabased (Point Absorber), Oyster, AW Energy waveRoller (OWSC), WaVEC Pico Plant and Wello Oy Peguin (OWC) were at TRL 7.

Table 4: Summary of WEC Types and O&M Strategy (EMEC, 2009; Croll and P, 2009)



Developer	Device Type	Rated Power Output (KW)	Water Depth Min/Max (m)	TRL	PTO	Mooring Type	Target Market	Deployment Vessel	Maintenance Strategy
Pelamis	Attenuator	750	50-250	7	Hydraulic	Slack Moored	Deep offshore	Tug boat, Anchor handling vessel	Return to base
Dexawave	Attenuator	5-250	25	6	Hydraulic	Slack moored	Intermediate offshore	Tug boat	Minor: on site Major: Return to base
OPT	Point Absorber	150-500	55-250	7	Direct Drive	Slack moored	Deep offshore	Buoy tender, tug boat, crane or A-frame vessel	Return to base
Seabased	Point Absorber	30-50	20-100	7	Linear Generator	Taut moored	Intermediate offshore	Crane Barge	Return to base
A-Power Oyster	OWSC	800	10-15	7	Hydraulic	Bottom fixed, pile	Near Shore	Tug boat	Major maintenance: Return to base
AW Energy WaveRoller	OWSC	300-500	8-20	7	Hydraulic	Bottom fixed	Near Shore	Tug boat	Return to base.
LangleeWave Power	OWSC	50,250	30-150	6	Hydraulic	Slack Moored	Intermediate &deepoffshore	Tug boat, Anchor handling vessel	Onsite maintenance Return to base.
VoithHydro Wavegen	OWC	300,500	15	7	Pneumatic	Shore based	Near Shore	N/A	on shore
WavEC Pico Plant	OWC	400	--	7	Pneumatic	Shore based	Near Shore	N/A	on shore
Ocean Energy Ltd.	OWC	--	--	6	Pneumatic	Slack moored	Deep Offshore	Tug boat	Minor: on site: Major: Return to base.
Wave Dragon	Overtopping	20.(4MW)	25	6	Direct drive PMG	Slack moored	Intermediate offshore	Tug boat	Major and Minor repairs on site: Major
AWS Ocean Energy	Pressure Differential	2.5MW	70-150	6	Pneumatic	Slack moored	Deep offshore	Tug boat	Major and Minor repairs on site: Major
Wello Oy Penguin	Rotating Mass	500	50-200	7	Direct drive PMG	Slack moored	Deep Offshore	Tug boat	Minor: on site: Major: Return to base.

The TRL 7 implies that the developers and WEC device are at stage 4. In this case, full-scale prototype has been tested at sea. In addition, information on the type of deployment vessel and O&M strategy for the WEC O&M is also summarised in Table 4. In relation to the integrated frame work for the resource assessment and O&M cost modelling, the information is relevant because it gives an idea of the type of O&M strategy applicable for each device type and the vessel requirement. This information was gathered from existing literature and presented in the table form for consistency and clarity.

The assessment presented has identified the different WEC types. This can set the scene for the identification of technical improvements that can be considered for cost reduction in the O&M cost of the WEC farm. Studies (Cruz, 2008) mentioned that the areas of deep water that are suitable for wave device deployment are significantly larger than the areas available for near-shore device deployment. This may present opportunity to expand the market for deep water devices. The wave energy sector is at the cutting edge of engineering design with positive steps towards commercial viability now being demonstrated.

The characteristics of these devices play a critical role in quantifying the amount of energy that can be captured. Thus, different technologies for WEC devices have been proposed to capture the energy from waves. To deal with the uncertainty surrounding the O&M cost estimates for maintenance of the WEC device the review on the O&M theories and strategies relevant to WEC farm project is presented in the following section.

2.5 The Maintenance Theory and Strategies Relevant to WEC O&M

The maintenance theory: The main objectives of a maintenance task are primarily the deployment of minimum resources required to ensure that components perform their intended functions properly. The Classical theory of maintenance suggests that maintenance can either take the form of correction or prevention. This is to ensure the system reliability and to recover from breakdowns (Lazakis et al., 2012; Dinwoodie et al., 2013). This is the main theory behind the practice of maintenance operation.

When developing maintenance strategies for WECs, it is necessary to consider the location. The reason is WECs can be installed in different possible locations. WECs can be shore-based, fixed offshore and floating offshore structures (EMEC, 2009). The maintenance strategies for shore-based WECs are less dependent on weather conditions, mainly because they are accessible from shore (Tseng et al., 2000). On-site maintenance activities and repairs is required for fixed offshore WECs. In this case, experiences from offshore wind can be applied.

The maintenance of floating offshore structures is dependent on the weather conditions. In relation to O&M of WECs, the WEC can be disconnected and towed to a maintenance harbour for repair actions to be performed and returned afterwards. The repair actions can also be performed directly on-site. Detailed information about downtime influences of different WEC concepts can be found in (Wolfram, 2006). In summary, the maintenance activity is required to ensure the components continue to perform the functions for which they were designed (Lazakis et al., 2012).

Maintenance strategies: This is the process of selecting the optimum O&M strategy and is often a very complex task, particularly in the initial process of optimising WEC systems. An assessment of existing array level operation and maintenance strategies relevant to WEC farm projects is made through adopting the relevant experience gained from onshore and offshore wind industry. The reason for adopting these strategies is because the offshore wind technologies faces almost similar challenges when compared to the WEC technologies.

This is particularly true with respect to foundations, submersed electrical systems, personnel and vessel access to array devices, transport of materials, etc. (DTOcean, 2014). A review of specific O&M practices is important in this thesis to precisely evaluate the O&M strategies. This will equally provide the opportunity to define the O&M terminology and highlight relevant O&M practices for the WEC farm. Generally, different types of O&M strategies exist for WECs. Although different expressions may be used to describe the same O&M tasks.

According to Wiggelinkhuizen et al., (2008) O&M tasks can be classified under preventive maintenance and corrective maintenance. Maintenance can be performed after failure (corrective) or before a breakdown (preventive) occurs. Garg and Deshmukh, (2006) sub-classified O&M activities into preventive maintenance, condition-based maintenance, effectiveness centred maintenance, total productive maintenance, reliability centred maintenance, predictive maintenance, risk-based maintenance, computerised maintenance management systems, maintenance outsourcing and strategic maintenance.

Studies focusing on reducing the inspection and maintenance costs acknowledged that unscheduled downtime can be very costly assuming a device fails unexpectedly (Yan-ru and Hong-Shan, 2010). Higgins et al., (2008) described O&M approaches under three main sections: breakdown, corrective and preventive. O&M approaches was categorised by Pérez et al., (2010) as preventive, predictive, corrective (fault diagnosis), corrective (inspections) and proactive. Multiple O&M strategies can be applied to maintain WEC systems (Nielsen and Sorensen, 2011). Figure 26 show different maintenance (repair) strategies applicable to WECs.

The O&M practices in Figure 26 are elaborated to explain the key features and to demonstrate the main differences among these O&M practices. The main experiences which are critically reviewed are expected to be related to corrosion problems and long-term stability of mooring systems, although not explicitly mentioned but, rather discussed under the following:

Preventive maintenance: This strategy is also known as scheduled or time base (planned) maintenance. Preventive maintenance is performed with a certain time interval or based on a certain condition (critical level of directly or indirectly observed damage). Scheduled maintenance is based on a certain expected lifetime. For WECs typical examples for preventive maintenance may include lubrication, changing filters, check cooling systems or tightening bolts; repairing or replacing the components or parts before they fail. Depending on the type of device as discussed in previous sections of this thesis, maintenance could be performed at regular time intervals or as recommended by the equipment supplier regardless of condition.

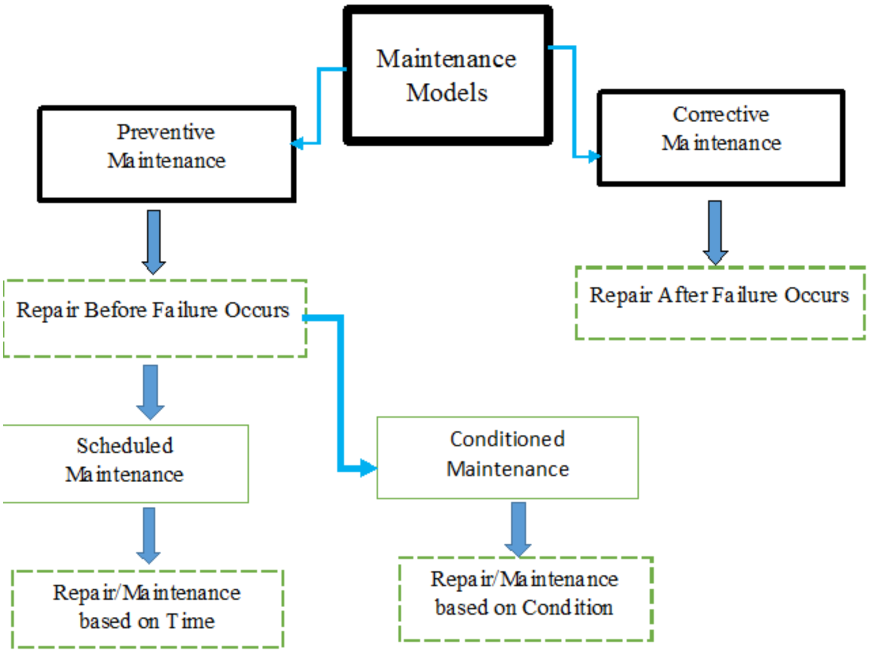


Figure 26: Different Maintenance (Repair) Strategies (Ambuhl1 et al., 2015)

One of the main disadvantages of the preventive maintenance practice is that it may lead to unnecessary repair cost. The reason is that in preventive maintenance the component is sometimes replaced before failure occurs. This is mainly because preventive maintenance requires periodic actions to reduce the probability of failure and prevent the degradation of equipment regardless of its condition at the time of inspection. Therefore, when applying preventive maintenance practice, the number of replaced components during a life time can be higher compared to other maintenance practices such as corrective maintenance.

Corrective maintenance: This refers to the unplanned O&M activity after a reported failure. This O&M strategy is also known as unscheduled or failure based maintenance (Ben-Daya et al., 2009). This could be applicable to WECs which require their maintenance operation to be performed onshore at the workshop. In that case, it will be suitably carried out when break down of the WEC occurs, or when faults are detected, or failures occur in any of the system components. However, it is important to minimise corrective maintenance.

According to (Higgins et al., 2008) corrective maintenance can cost four times more than the cost of the same repair when it is planned ahead. Since corrective maintenance is performed when a component has failed; corrective component replacements lead to irregular maintenance actions. In comparison to preventive replacement, the costs for corrective maintenance are associated with larger uncertainties than preventive maintenance. The reason is that preventive replacement tries to limit the downtime of the system but may, on the other hand, increase the number of performed maintenances or repairs.

The merit of corrective maintenance is that; it is the simplest strategy. The disadvantage is that it may lead to large costs due to cascaded failure effects, longer downtime, cost implications related to equipment, labour and logistics. This cascade effect may damage the main component which may lead to large repair or replacement costs. Therefore, the key to reduce the O&M costs is to minimising corrective maintenance.

Condition Based Monitoring (CBM): This maintenance strategy involves the continuous monitoring and inspection to detect incipient faults early, and to determine any necessary maintenance tasks ahead of failure. Conditioned monitoring maintenance is based on measuring damage. Due to the inherent demerits of either the preventive or corrective maintenance strategies, Condition Based Maintenance (CBM) techniques could be introduced as an alternative to mitigate against major component failure and system breakdown (Ambuhl et al., 2013).

A report on condition monitoring of wind turbines (García Márquez et al., 2012) defined Condition Monitoring (CM) as a tool commonly employed for the early detection of faults/failures so as to minimise downtime and maximize productivity. Campbell and Jardine, (2001) mentioned that the technique involves acquisition, processing, analysis and interpretation of data suitable for the selection of optimal maintenance actions. In a typical offshore WEC defects are bound to occur and in most cases, these may either be because of leaking and corrosion, which could possibly be detected by visual inspection.

García Márquez et al., (2012), suggested that discolouration of component surfaces may indicate slight temperature variations or deteriorating condition. The sound coming from the bearings can also indicate physical condition (Ben-Daya et al., 2009). Condition base maintenance is necessary based on the requirement of a more sophisticated approach to maintenance. This may be employed for typical failures such as cracking and roughness on the surfaces of the blades, electric short circuits in the generator, and overheating of the gearbox.

Risk based inspection: In the risk-based O&M approach both repair costs and lost income from no electricity production are considered in order to minimize the overall cost. Component failures and loss of electricity production may often happen during storm conditions where the device is not accessible. When a component fails, there are costs involved in replacing the component. The component failure influences the income because of the loss of harvested energy and the time in which the machine is out of use. Sørensen, (2009) suggested that the total resulting O&M costs can be minimized when considering risk-based O&M strategies.

2.6 Inspection and Maintenance Planning for WEC Farms

Inspection and maintenance planning for WEC farm projects could be based on the application of risk-based methods where information or experience from past inspections and monitoring results are considered. The theoretical background is described in Sørensen, (2009) for offshore wind turbines and can be transferred directly to WECs. One of the key metric used to demonstrate the added value of the extra O&M activity on the power production is the cost per unit energy production (O&M cost/MWh).

The offshore wind industry follows the strategy of increasing the number of installed megawatt per device in order to decrease O&M expenses per produced kilowatt hour (Sørensen, 2009). For a WEC farm an optimized maintenance strategy which considers the whole farm and not just a single device should be followed. The justification is that, the O&M expenses per produced kilowatt hour may decrease when increasing the installed capacity because many tasks associated with O&M of a single machine are the same, irrespective of its capacity.

Figure 27 shows a typical decision tree for optimal planning. Risk-based inspection (RBI) and maintenance planning depends on the initial design decisions, z, of the device. The initial design may include, e.g. design lifetime of the different components and whether the inspections are done offshore, or the device is tugged to a harbour for maintenance. The inspection plan depends on the decision parameters, e, which may change during the lifetime of the device due to increased knowledge (Bayesian updating) and decreased cost uncertainties.

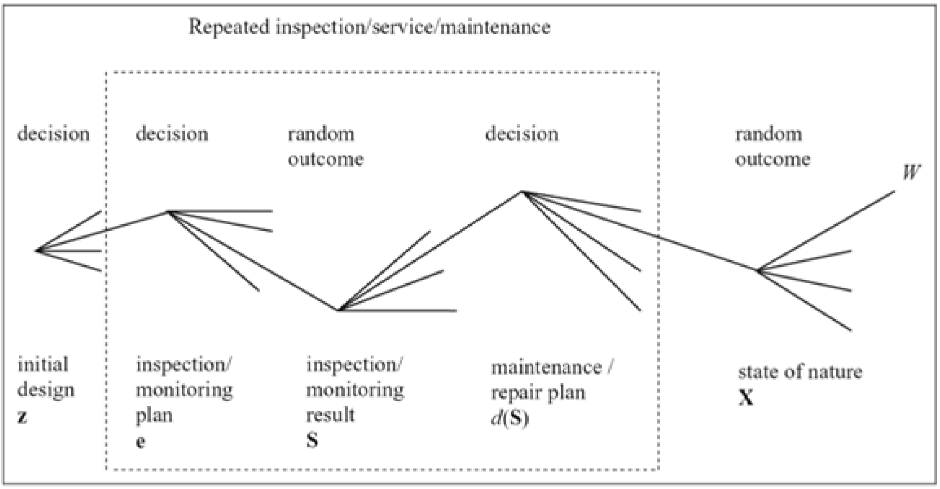


Figure 27: Decision Tree For Optimal Planning of Inspections and Maintenance (Sørensen, 2009)

The future decision parameters depend on the inspection or monitoring results, *S*. Based on the inspection or monitoring results, a maintenance or repair plan, *d(S)*, is developed. Together with the realization of uncertain parameters, *X*, a certain total gain minus costs, *W*, is calculated. Realizations of uncertain parameters include, for example, wind and wave climate and model uncertainties (Sørensen, 2009). The application of risk-based decision models for maintenance considerations requires that the condition of the different components considered can be described, e.g. with failure models where the uncertain parameters *X* are included.

2.7 Existing Tools and Models Relevant to WEC O&M

In the offshore environment, it is imperative to always minimise the level of risk involved in the handling/installation and O&M activities of ocean energy devices. Different O&M tools and models have been developed particularly for offshore wind to analyse and plan O&M activities. In this thesis, a review of these O&M tools and models are presented. With the focus of minimising the O&M cost of WEC farm, it is possible that the relevant tools could be adapted and applied for WEC O&M.

To estimate the O&M costs for the future 1-2-5-year life cycle of offshore wind farm projects, Energy Research Centre of the Netherlands developed a powerful tool, which can be a subsection of an O&M management system (Obdam et al., 2007; Rademakers et al., 2008; 2009). The ECN O&M Tool is generally considered to be the most comprehensive tool for analysing O&M costs and downtime (Ramakers et al., 2004; Curvers and Rademakers, 2004) and has received a validation statement from Germanischer Lioyd (Rademakers et al., 2011).

Sørensen, (2009) proposed a risk-based life cycle framework for the planning of O&M activities considering the deterioration and the future costs associated with inspection, monitoring, O&M, repair and failures of wind turbines through pre-posterior Bayesian decision theory. Garcia et al., (2006) developed the tool Intelligent System for Predictive Maintenance (SIMAP), which optimises the O&M schedule according to operational condition of the device considering the technical and economic conditions of the operators.

The problem with this tool is WEC farm operators may not have the expertise to interpret the signals since the application requires continuous data collection and diagnosis, which can sometimes be inefficient. In order to optimise the preventive maintenance costs Besnard et al. (2009) developed a model through examination of power production, preventive maintenance and corrective maintenance activities which can potentially create large cost savings.

O&M Cost Estimator developed by National Renewable Energy Laboratory and Global Energy Concepts could be applied for WEC O&M activities. This estimator includes a database that represents the values for device, site service and repair parts. This is relevant and could be applicable to O&M of WEC because the tool considers the typical costs associated with ongoing operations, including scheduled maintenance, unscheduled repairs, site management, and support personnel (Poore and Walford, 2008). Although, this tool was originally developed for on-shore wind farms; hence crucial aspects such as accessibility and vessel unavailability are not considered.

GL-Garrad Hassan developed O2M tool, which is based on work conducted by (Bossanyi and Strowbridge, 1992). The O2M tool takes the wave height values into account and performs time domain Monte-Carlo simulations (Philips et al., 2006). Studies on Risk assessment for installation and maintenance activities for ocean energy device (Lazakis et al., 2012) showed that O&M of offshore installations could either be examined qualitatively or quantitatively using a variety of well-known tools. Feuchtwang et al., (2012) proposed an event tree probabilistic delay model for four most likely situations concentrating on the relation between sea state and required repair time.

To minimise WEC O&M costs some suggested task include development of component reliability models, quantification of operation and O&M costs over time, evaluation of design standards and identification of high-risk components. In a report prepared by Sandia National Laboratories, (Walford, 2006) identified the costs of O&M as the aspects that contributes the most to the overall costs. The study also identified the possible approaches to reduce the O&M costs and additional actions, which should be considered in the future.

The need for understanding the offshore environment is highlighted in order to facilitate more reliable energy yield predictions, optimum designs and optimum strategies for operation and O&M (Kühn et al., 1999). Studies (Bussel and Bierbooms, 2003) suggested that the Dutch Offshore Wind Energy Convertor (DOWEC) project can possibly be adapted to calculate the total O&M costs; the achieved availability and the produced energy of the WEC farm. The reason is that in the DOWEC project a Monte-Carlo approach in which realistic maintenance actions are determined under random simulation of wind and wave conditions are implemented.

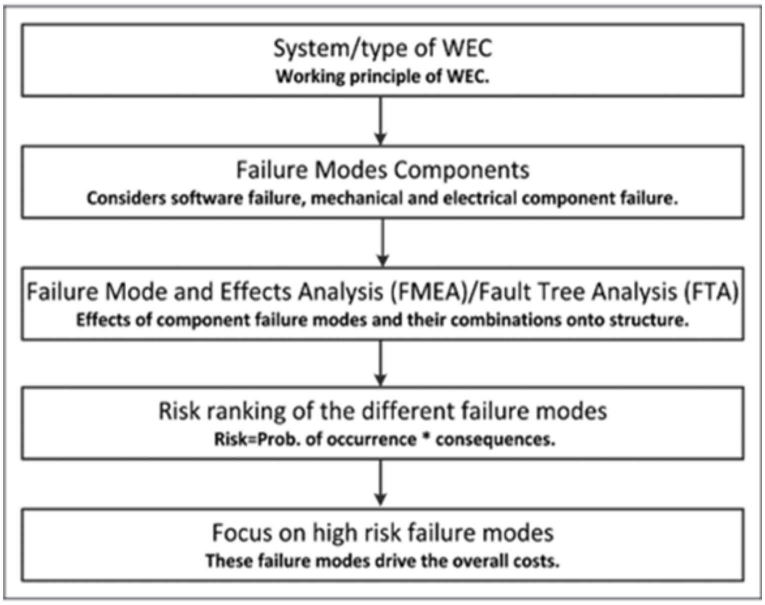


Figure 28: Flow Chart of Important Failure Modes of a WEC Concept (Ambuhl1 et al., 2015)

The applicability is to investigate random WEC failures, predefined maintenance crew deployment and given availability of maintenance equipment. In other studies (Pahlke, 2007) provided an overview of existing decision support systems and individual software tools in Power Project. The procedures to find the high-risk failure modes for optimal maintenance strategy of WECs (Ambuhl1 et al., 2015) was highlighted. It is suggested that before starting to plan the O&M activities, it is necessary to analyse the working principle and characteristic failures of mechanical or electrical components and control system in order to find the high-risk failure modes.

The procedure outlined in Figure 28 can be followed (Ambuhl et al., 2013). High-risk failure modes are of importance for defining the inspection plan and estimating the overall costs. Therefore, the working principle of the systems needs to be analysed by either a Failure Mode And Effect Analysis (FMEA) or a Fault Tree Analysis (FTA) (Thies et al., 2009).

2.8 WEC O&M Transport Means

Besides the influence of harsh environment conditions experienced in the offshore environment, one of the main issue associated with offshore O&M planning is particularly due to the dependency on vessels for transporting personnel and equipment required to perform maintenance activities (Dalgic et al., 2014). Vessels are floating structures which are utilised in environmental and site surveys, transportation and assembly of WEC components as well as planned and unplanned maintenance operations.

Several studies (Morgan et al., 2003; Krohn et al., 2009; Fingersh et al., 2006; Junginger et al., 2004) related to the design cost, including the economics of cost reduction for marine energy device and particularly for offshore wind energy have shown that vessels are particularly important, since the costs for vessels account for 50% of the total O&M costs. considering the objective of finding ways to reduce the uncertainty associated with high cost of O&M of WEC farms, it becomes relevant to consider the experience from these studies.

As obtainable in other marine renewable energy systems, designers and operators of WEC farms will require guidance in terms of procedures for design cost and economics of cost reduction to enable electricity generation from WECs more economically viable and competitive with other mature renewable energy sources. For WEC farm O&M, it is anticipated that performing maintenance operations at offshore locations will pose major challenges compared to performing the maintenance nearshore. The reason is that maintenance personnel, equipment and spare parts will need to be transported to and from offshore WEC farm by vessels.

The vessel requirement for performing the maintenance activities will contribute to a major part of the maintenance cost for operating the WEC farm. The computational experiments and optimization models proposed in relevant studies can provide guidance for WEC farm operators to investigate the methods to reduce cost of O&M vessels for WEC O&M activities. To reduce the cost of energy from WEC farms it is essential to keep the costs of the O&M vessel to a minimum by either keeping an optimal or near-optimal vessel fleet for this purpose. O&M vessels suitable for the WEC O&M activities are discussed in the following section.

2.8.1 Vessels Relevant for Offshore WEC O&M Activities

There are different types of vessels available in the market. Each of these vessels have their specific properties as well as benefits and drawbacks. For maintenance operations in offshore environment, the main functions of the vessels are to provide accommodation for ship crew and technical personnel, loading, transporting and assembling failed WEC components. For WEC farm O&M, the type of marine operation requiring vessels include: installation, repair, inspection and removal of the WEC.

Minor maintenance activities of WEC would require smaller vessel for transporting personnel for on-site inspections and repairs. These activities may include lubrication, sensor and hydraulic system repairs, electrical and electronic control system repairs. Major maintenance activities will require that the WEC be completely removed from the site and tugged to the on-shore maintenance facility in order to perform the repairs. In that case, equipment's and O&M vessel will be required for heavy lifting and towing the device to shore for repairs.

In this thesis, the O&M vessels are selected based on their capabilities to perform the required O&M task. Due to the higher charter rates, leg stabilised and heavy lifting vessels are not considered appropriate for WEC maintenance operations. The capabilities of these vessels are also above and beyond the scope of repairs. The most relevant types of O&M vessels applicable to WECs are highlighted and summarised in the following pages.

Crew Transfer Vessels (CTVs): These are vessels generally utilised for minor maintenance operations. For example: Mono-hull boats, small catamaran vessels and Small Water Plane Area Twin Hull (SWATH) vessels. They allow operators to keep the cost of minor maintenance operations at acceptable levels. Figure 29 shows a small work boat. Small workboats, can be used for offshore WEC O&M activities. The problem is that it may involve longer shuttling journey times resulting in considerable wasted productive time. Moreover, relatively small vessels pose a significant risk of capsizing in rough weather (Al-Salem et al., 2006).

Figure 29: Small Work Boat (WindWave, 2014)

Figure 30: Mono-Hull Crew Boat (WindWave, 2014)

Figure 30 is an example of a mono hull crew boat. As experienced for offshore wind farms, access for WEC O&M could be impacted by very poor weather tolerance, particularly in further offshore locations (Walker et al., 2013). Relatively smaller size vessels are more susceptible to challenging environment. Figure 31 show an example of a 35ft Catamaran Workboat. This type of vessel is relatively preferred compared to the very small work boat in Figure 29.

The expectations of operators and technicians are different; for example, the operators are more concerned with safety, transport time, fuel consumption and availability of vessels. The technicians are rather concerned about their safety, comfort, separation of cargo and basic catering services (Heinecke, 2010). Small Catamaran configurations shown in Figure 30 are often the preferred choice but operations are restricted to relatively low wave heights (1.5 metre). Experiences from offshore wind (Cameron, 2011) show that the operational wave height restriction limits the number of working days by 200, which can be increased to 310, if safe working wave height limit is improved to 3 metres.

Figure 31: 35ft Catamaran Workboat (WindWave, 2014)

The most distinctive characteristics of these vessels are high speed, small deck spaces, small crane capacities and safe access to WEC structures that will allow operators to take quick actions in case of urgent repairs. Figure 32 shows a Catamaran Workboat. These vessels are fast catamarans that work in the construction, operation and maintenance of offshore wind farms (WindWave, 2014). They can be used for WEC O&M activities because they have been designed to be safe and comfortable for the passengers on board and are regularly used in challenging environments.

Figure 32: Catamaran Workboat (WindWave, 2014)

Figure 33 show a Small Water-Plane Area Twin Hull (SWATH) vessels. They are generally utilised in minor maintenance operations, which allow operators to keep the cost of minor maintenance operations at optimum level. In addition, Tug Boats refers to small, but powerful boats that can be used to tow ships and barges. It is also used for pulling and pushing ships especially into harbours or up rivers. In this case, tugs can be used to help manoeuvre the device to the shore for maintenance repair.

Figure 33: Small Water Plane Area Twin Hull (SWATH) vessels (Incat Crowther, 2013)

Figure 34 show an example of a Tug Boat, they are highly manoeuvrable and powerful vessels. They can be used to manoeuvre the WEC device. In the integrated framework, a Tug Boat can be used to perform the O&M activities at the WEC farm and for towing the WEC to the maintenance base; in the case of maintenance activities that require the WEC device to be returned to the onshore maintenance facility. Following the review on O&M transportation for offshore renewable energy installations (Junginger et al., 2004; Fingersh et al., 2006; Krohn et al., 2009; Morgan et al., 2003), it is understood that offshore O&M activities are limited by the vessel operability. In this context, the O&M vessel operability is defined by the limiting significant wave height threshold.

Offshore Access Vessels (OAVs): This type of vessels may be used occasionally depending on the environmental and offshore weather conditions, particularly when there is a need for a much larger vessel than the conventional CTVs. This may be applicable particularly in the case when weather conditions restrict CTV access to WEC farm. Therefore, larger vessel such as the

OAVs will have better operational capabilities. OAVs in this context, only offers the choice of a much larger vessels (~50m).

Figure 34: Tugboat WOONA in Sydney Harbour (Travellers and Tinkers, 2013)

The advantages of OAVs over CTVs is their better operational capability and they are generally equipped with dynamic positioning systems. In rough weather when CTVs cannot operate, the use of OAVs may become suitable. The reason is that they are equipped with motion-compensating gangways installed for easy transfer of technicians on the WEC farm (Dai et al., 2013, O'Connor et al., 2013). Moreover, the cranes on these vessels provide ability to transfer medium weight components from vessels' deck directly to offshore WEC platforms.

The charter cost of these vessels is higher than CTVs and charter rates escalate quickly. This is a major concern particularly when targeted is cost reduction. Hence, OAVs are not considered as a feasible alternative. Table 5 presents a summary of vessels type with their pros and cons. Having considered the types of O&M vessels applicable to WEC O&M activities, the review on O&M vessel chartering and chartering scenarios is presented in the following sections.

Table 5: Characteristics of Vessels for WEC O&M Activities

Vessel type	Benefits	Drawbacks
Monohull	- Allow operators to keep the cost of minor maintenance operations at acceptable levels. - Reasonably lower charter rates - Very high speed (~ 30 knots) - High availability in the offshore market	- Longer shuttling journey times resulting in considerable wasted productive time. - Limited passenger space and cargo capacity - Limited facilities available, uncomfortable for passengers - Risk of capsizing in rough weather and limited safe access to WECs (H_s<1m)
Catamaran	- High speed (~ 20 knots) - Operational H_s=~1.8 m - Safe and comfortable for the passengers and safe access to WECs (H_s<1.5m) - High availability in the offshore market and are regularly used in challenging environments.	- Limited passenger (12 and more) and cargo capacity - Small deck spaces, and small crane capacities - Relatively higher charter rates
SWATH	- Allow operators to keep the cost of minor maintenance operations at optimum level. - Capacity of 12 to 60 passengers - High speed (~ 20 knots) - Operational H_s=~2.0 m - Safe access to WECs (H_s<1.8m) - Comfortable for passengers	- Limited cargo capacity - Low availability in the offshore renewable market - Relatively higher charter rates
Tug Boats	- Very flexible for unusual cargoes - Heavy lift capacity - Larger deck area/space - Relatively better stability characteristics	- Low availability due to offshore oil & gas industry - Slower mobilisation - Port entrance limitations due to size - Operations can be performed only in deep water
Offshore Access Vessels	- Better operational capability - Generally equipped with dynamic positioning systems - Ability to transfer medium weight components from vessels' deck directly to offshore WEC platforms - Larger deck area/space - Relatively better stability characteristics	- Charter cost is higher than CTVs and charter rates escalate quickly - Low availability due to offshore oil & gas industry - Slower mobilisation - Port entrance limitations due to size - Operations can be performed only in deep water

2.8.2 O&M Vessel Chartering

It is understood that the cost of vessels has the greatest potential to reduce the overall O&M expenditures. The reason is that O&M activities represent a significant share of the ongoing expenses during the lifecycle of the offshore WEC farm projects (Kaldellis and Kapsali, 2013). Therefore, an important requirement is being able to estimate the cost of vessel operation for offshore WEC O&M activities. There are some difficulties or factors which are known to negatively influence the process of estimating charter rates or gathering information required for estimating the vessel chartering cost. For example: lack of offshore wave data and confidentiality of available data.

It is essential to take these factors into consideration when considering the option of chartering a vessel to perform O&M activities. Although the development of WEC farm is still at the early stages, the decision process related to O&M vessel specification and chartering options could be considered to help investigated feasible alternatives for the O&M vessel requirement. However, O&M of WEC will require smaller vessel size particularly when the target is to decrease the cost of maintenance operations. The utilisation of smaller vessels may eventually lead to cost reductions in the vessel associated costs such as charter cost and crew cost.

There has been no detailed review of vessel chartering cost for O&M activities associated with WEC O&M. The experience is mainly adapted from offshore wind farm operations. Review of the literature related to offshore O&M activities is necessary to identify similar trends which could be applicable to WEC O&M. As experienced in offshore wind operations (Dalgic et al., 2015) acknowledged the fact that accurate cost estimation is required during operation. The need for offshore based estimation models, which utilise offshore-related data and offshore market specific circumstances was also emphasised.

The reason is because charter rates are determined by market. Majority of the models used for estimating the vessel charter rates, models the shipping industry instead of offshore marine renewable energy industry. For instance, Alizadeh and Talley, (2011), analysed tanker freight rates. Ko, (2010) applied a mixed-regime model to the dry bulk freight markets. Glen and Martin, (2004) surveyed spot market dry bulk and tanker charter rates. Kavussanos and Alizadeh-M, (2001) investigated the seasonality of spot, 1-year and 3-year time charter rates for dry bulk shipping.

Complementary studies conducted by Lazakis et al., (2013), and Dinwoodie et al., (2013) showed that the vessel costs contribute the largest percentage of costs which is the key component of overall costs to control. Detailed studies have also been conducted to established vessel charter rate estimation (Dalgic et al., 2014; Kaiser and Snyder, 2010; Kaiser and Snyder, 2012). This follows an examination of different database, including the shipping market charter rates for different types of vessels. In summary, it is understood that the offshore O&M vessel, market does not explicitly operate in the same way as the shipping vessel market, but there is a remarkable similarity between these vessels CAPEX and their charter rates.

This is because it presents a similar trend over similar trading/ chartering scenarios for specific chartering periods (Dalgic et al., 2014). Therefore, offshore WEC O&M vessels charter rate estimation can be established based on the relationship between the CAPEX of different vessels and associated charter rates for different periods. The relationship between the ships' CAPEX and 1-year charter rate could be established. The aim of considering vessel charter rates in this thesis is to assess the critical aspects that can significantly reduce overall costs of WEC O&M.

The O&M costs comprise of labour costs (technician costs), material costs (component cost), transportation costs (vessels and associated cost), fixed costs (port, bidding, etc.) and potential revenue loss. It is important to carefully plan the O&M activities because economic benefit from producing more energy by increasing the availability does not always lead to higher profits, since the increase in the total O&M costs may not be compensated (Santos et al., 2013). Generally, O&M vessels are chartered for a limited period instead of being purchased due to the associated initial capital investment.

2.8.3 O&M Vessel Chartering Scenarios

According to Pirrong, (1993), three common types of contractual arrangements in the maritime industry are Voyage charter, time charter and bareboat charter. O&M vessel charter agreements may vary depending on the specific circumstance. The O&M vessel chartering scenarios can be used to provide useful information that could provide more understanding of the vessel charter cost. For clear understanding of the O&M vessel chartering scenarios, these three types of contractual agreement are highlighted and summarised in the following sections.

1. Spot market or Voyage charter: In this case, the vessel owner is awarded a contract to carry a specific cargo with a specific vessel. The cost covers capital charges, daily running, and voyage costs. Spot market charter, is an alternative term for voyage charter. In this case, it is used to refer to vessel charter for one or a specified number of trips (voyages). Spot charter generally includes loading cost (i.e. an amount covering the operating cost of the insurer, as well as the chance that the insurer's losses for that period will be higher than anticipated) (Pirrong, 1993).

The spot market voyage charter in this thesis is used generally to describe the contractual agreement for chartering the vessel for an agreed upon total amount, in the event of specific O&M activities requiring specialised vessels. In this case voyage expenses, such as port, canal and fuel costs are paid by the owner of the vessel and not the charterer. If the time for the maintenance activity has already been predefined, such that the failure rates are not considered at random; then a specified time can be set for the selected vessel to arrive the WEC farm.

After all the O&M task are completed, the time for the vessel departure from the site is recorded. Assuming all the O&M tasks are completed within charter period, then total charter cost for vessel in that charter is estimated as: the vessel daily charter cost multiplied by the charter period of the single charter cost (Kaiser and Snyder, 2012; Pirrong, 1993). Assuming the vessel leaves the site after the agreed charter period is completed, demurrage is added to the total charter cost (Pirrong, 1993). In that case, the regular charter payment is continuously made until the vessel finally leaves the site.

The demurrage is paid between the final day of the agreed charter period and the day that the vessel finally leaves the site. The total charter cost for that charter in the spot charter agreement, is the regular charter cost, being equal to the daily charter rate multiplied by the charter period and the extension (Dalgic et al., 2014; Kavussanos and Alizadeh-M, 2001). Demurrage cost will be equal to the demurrage rate multiplied by the charter extension.

The summation of all the single charter costs is equal to the total charter cost of the vessel. Unplanned maintenance activities and circumstances that require instant access to WEC farms may require operators to hire vessels from the spot market for relatively short periods. In this context, short-term chartering is valuable for the WEC farms that have sequential maintenance activities in a specified period.

2. Time charter: This is also known as short term voyage charter, and refers to vessel charter for a fixed period at a set daily rate; instead of for a certain number of voyages or trips as in the case of spot market charter. Therefore, the time charter is an agreement between owner and charterer to hire all of ship for a specific period (e.g. daily, monthly or yearly) complete with crew for an agreed fee. The vessel owner pays the capital and operating expenses, whilst the charterer pays the voyage costs.

In this type of chartering option, the charterer charters the vessel for a set period. In this chartering strategy, the charterer can use the vessel for the O&M activities and equally direct the vessel to any desired location but the owner of the vessel retains possession of the vessel through its employment of the master and crew. Moreover, the voyage expenses such as port, canal and fuel costs are paid by the charterer and not the owner of the vessel (Alizadeh and Talley, 2011). Time charter generally does not include loading cost (i.e. an amount that is built in to the insurance cost) and unloading costs in the charter rate (Kaiser and Snyder, 2012).

Assuming the defined rate (base rate) is that updated each year, the selected O&M vessel charter cost could be estimated, by calculating the charter cost for each day of the charter period. For the fact that the vessel is always under a contract and extension will not be available, the demurrage cost for time charter is defined as zero. Therefore, total O&M vessel charter cost for time charter contract can be estimated as in the case of the annual O&M vessel cost being equal to the O&M vessel daily rate multiplied by 365 days in a year.

3. Bareboat charter or demise charter*:* This is also be known as long term charter strategy, having a minimum charter period of 1 year and maximum period of 20years. In this charter option, the vessel owner gives possession of the vessel to the charterer and the charterer hires its own master and crew. In this case, the charterer is responsible for daily running costs, voyage costs, O&M costs and expenses related to cargo handling and claiming (Alizadeh and Talley, 2011).

Bareboat chartering which provides more control on the costs elements, is a more feasible alternative for long-term operations. For short-term O&M activities, time charter or spot market voyage charter appear to be more practical due to the difficulty to arrange crew, provide provisions and complete administrative jobs for short term. Long term chartering requires advanced scheduling for the maintenance operations. In this case, the daily charter rate decreases; however, the financial risks due to low utilisation become more significant, since the vessel is chartered for a longer period based on the bareboat charter arrangement.

In this respect, the bareboat charterer hires out the vessel without crew or any operational responsibilities. It is important that the charterers have control of the crew and technicians. The general practice in shipping industry is to have a separate person/team, who is only responsible for the vessel management (Ko, 2010). This is because vessel crew or supplies are not included as part of the agreement; instead, the vessel charterer is responsible for employing the crew and the ensuring adequate provision of supplies for the vessel. It is the charterer's risk to charter the vessel for longer periods (Kavussanos and Alizadeh-M, 2001; Pirrong, 1993).

Kaiser and Snyder (2012) studied daily charter rates for offshore wind turbine vessels in 20-years charter period. The daily rates presented in their study, represent the average daily rates per vessel CAPEX for chartering a specific vessel over a period of 20 years. In this context, the management team takes the responsibility of arranging for the crew and ensuring that adequate supply and provisions are made available for the vessel and crew members.

2.8.4 The Sub-Charter Cost

The term ''sub-charter'' means "all types of charters or other contracts for the use of a vessel that are subordinate to a charter. In this thesis, sub-charter cost is used to describe the cost associated with all subordinate contract agreements that includes, but is not limited to, a voyage charter, a time charter, or a bareboat (demise) charter. In considering the sub-charter option, it is assumed that the sub-charter operations will not interfere with the O&M activities of the offshore WEC farm developer. However, sub-chartering means that the O&M vessel can be chartered to third parties to compensate the costs and increase the total revenue.

The sub-charter model uses the same charter rates as the spot market charter rates. When a vessel owner time charters his vessel to another party he does so with the expectation of making a profit out of the hire. To avoid any circumstance that may lead to insolvency and defaults on hire payment obligations during the time charter, the O&M vessel initially chartered from vessel owner with a time charter rate, could then be sub-chartered to the third parties with a spot market charter rate. When the O&M vessel is under a spot market (a voyage) charter agreement, the developer of the WEC farm or owner of the device may find that they may be obliged to pay more than they are expected to for the use of the vessel and carriage of their device or equipment.

In that case, the charterer can experience a negative cost if the benefits from using O&M are greater than its cost (Ambuhl1 et al., 2015; Dalgic et al., 2015). In this context, the sub-charter operations may be considered as a cost attribute, though the cost associated with them is reflected as negative cost, which basically decreases the total O&M cost (Dalgic et al., 2015). A negative cost may result from some combination of higher benefits and lower costs. It is all about understanding the type of O&M activities from their operational point of view and being able to measure the benefits each maintenance strategy would create and the cost reductions that may result.

2.8.5 The Bunker Fuel Cost

Fuel for marine use in engines and boilers are often divided into types and grades. The generic divisions of maritime fuel from lightest to heaviest include: Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Intermediate Fuel oil (IFO), Marine Fuel Oil (MFO) and Heavy Fuel Oil (HFO). Conventionally, fuel may be defined as a substance consumed by an engine or other device to produce energy or heat. Although, the general definition of bunker fuel is based on the two basic types of marine fuels i.e.- distillate and residual. A third type is a mixture of these two, commonly called "intermediate" (McLean and Biles, 2008).

Most ocean shipping contracts are called "voyage charters": this entails hiring a bit of space on a ship that is already going between two ports If the WEC farm operator hire the whole vessel based on a "time charter" agreement for a specified period, then he is liable for the fuel costs as a separate item. The amount of fuel consumption for a marine vessel depends on multiple factors. These include the vessel size, tonnage, loading condition, propulsion type (fuel oil,-stroke, medium speed diesel, dual-fuel, diesel-electric, all-electric, batteries, nuclear, etc.), speed, marine conditions, and the engine efficiency itself. Ships vary in their sizes and so does the fuel consumption.

Fuel consumption on board ship is measured by taking reading from flowmeters which are installed on the fuel oil line going to the engines. For marine operations and vessel transport, fuel additives such as: lubricants, engine coolants and maintenance related items which are consumed with fuel, by vessels to enhance engine performance are not normally considered to be fuel. However, these items may indirectly contribute to the total fuel cost estimate when evaluating the vessel consumption and logistics.

It is common practice for shipbuilders to define and supply the consumption rate of their ships, normally measured in metric tons per day. Some of the approximation used to define the consumption of heavy fuel oil, marine diesel, and lubricants have been applied in studies (McLean and Biles, 2008), to model and evaluate fuel consumption in different operational vessels. Fuel oil and lubricant consumption are measured when vessels are at sea. For simplicity and clarity, the modelling approach used in Chapter 3 methodology and modelling of this thesis, combines both the fuel oil and lubricant to determine fuel consumption and estimate of the total bunker fuel cost.

Depending on the size or type of O&M vessel and its engine/s, the standard fuel consumption rate is defined by the shipbuilder and expressed in litres consumed per hour of operation when running at a set speed. This consumption rate will not consider any factors which may increase fuel consumption (such as rough conditions or poor engine performance) and should only be used as a guide. Assuming a suitable O&M vessel is selected based on the capability of the vessel to perform the maintenance activities, diesel oil consumption can be measured during anchorage and when the vessel is not in operation.

To calculate the total bunker fuel cost for the vessel operations, the charter length is required to estimate the total fuel cost of the selected O&M vessel. It is also necessary to identify or rather define the type of maintenance activity that will be required. In the cost attributes section, the fuel consumption is defined for the vessel specification and the daily fuel consumption rates in operation. The number of days that the O&M vessel is utilised can be identified from the information recorded for operational time. Multiplication of the days in operation by the daily fuel consumption rates provides the total fuel consumption value attributed to the O&M vessel.

2.8.6 The OEM Cost

OEM (Original Equipment Manufacturer), refers to the act of a company using its own name to brand or customize an original product and offering its own warranty, support and licensing of the product. The term is a misnomer because OEMs are not the original manufacturers; it is only used to describe manufacturers who resell another company's product under their own name and branding. In the methodology and modelling of the proposed integrated framework described in Chapter 3, the maintenance action is considered based on the preventive and corrective maintenance of the generic components the WEC, mooring and cables.

The components which may serve as replacement spare parts are often manufactured by different companies, using customized designs based on specification of the WEC device developer or WEC farm operator. The cost of each component is defined in the cost specific attributes as described in Chapter 3 methodology and modelling of this thesis. These components may be replaced or overhauled on an annual basis depending on the O&M strategy. It is possible that any future increment due to the annual increment factor can be updated for each component in later calculations. This is because rates used for any present calculation and the cost of component may increase/decrease or remain at the same level. The total OEM cost is calculated from the summation of annual OEM costs.

2.9 Assessing the Economic Viability of WEC Farm

When attempting to assess the potential of the resource to provide energy suitable for commercial exploitation, it is not often straightforward to make comparison between two individual marine energy systems e.g. wave and wind energy despite their striking similarities. Stallard et al., (2009) mentioned that even for similar technologies, there is a considerable variation for unit electricity cost estimates. As illustrated in preceding sections, there are several types of WEC developed for extracting energy from the marine environment.

Valerio et al., (2007) observed that most experimental and prototype WEC technologies succeeded in the initial testing phases. However, only a few of these technologies have been put into use for electricity generation in the marine environment. This situation makes it difficult to independently assess the economic feasibility of deploying alternative technologies for commercial scale electricity generation in different parts of the world. Studies (Bedard et al., 2005; Previsic, 2004; Previsic et al., 2004) mentioned the approaches used for considering economic assessments for wave energy generation project. These approaches as summarised in this thesis may include:

- Economic assessment of a project
- Economic assessment of a technology.

For economic assessment of a project, it is recommended that the emphasis and priority should be on providing useful and credible information to conduct the economic assessment. Secondly, it is very important to identify the underlying process that affects cost and high risk cost areas (Stallard et al., 2009). In the case of economic assessment of a technology, it is important to understand factors that may affect the economic value of the technology because of continuous development and deployment. A report (Mueller et al., 2010) emphasised on the methods to identify the approach for economics assessment relevant for specific WEC projects.

In that study, relevant methods were identified in terms of preferred design options. This was particularly the case when the intention is to combine different technologies in a project to generate electricity for commercial purpose. This may further imply that a project may be evaluated to know the preferred combination of technology suitable for deployment in that site. Studies (Andrawus et al., 2008) had mentioned that the capital cost of a marine renewable device is made-up of several parts. In this context, the different parts may be defined as cost centres. Generally, the cost centres can be divided into station-keeping, structural, energy conversion components and sub-assemblies and project costs.

Figure 35 illustrate the capital cost breakdown for installation of a wave energy device as one single unit. It can be observed that the cost of installation of the single unit contributes the highest share. This is followed by the de-commissioning and transmission cost. In this case, transmission cost may refer to the cost associated with supply and distribution of the electricity generated from the WEC farm to the grid. This may include the cost of power conditioning systems, cables and transformers needed to export the generated electricity to the grid. The cost of the WEC device is also seen to contribute significantly to the capital cost breakdown. Other cost elements such as commissioning, mooring and insurance are relatively low.

For large installations or farm of devices, station-keeping might be considered under the project costs category. In this case, station-keeping may refer to the methods or systems such as the foundations and moorings utilised in securing the device to the sea bed. Since foundation costs are high, one of the economies of scale available for multiple WEC device arrays is foundations or mooring shared between more than one device. This implies that, the relationship between capital costs and O&M costs could be described in terms of cost centres (Allan et al., 2011). In this context, a cost centre refers to the different category of the individual cost attributes contributing to the total cost of the WEC farm project.

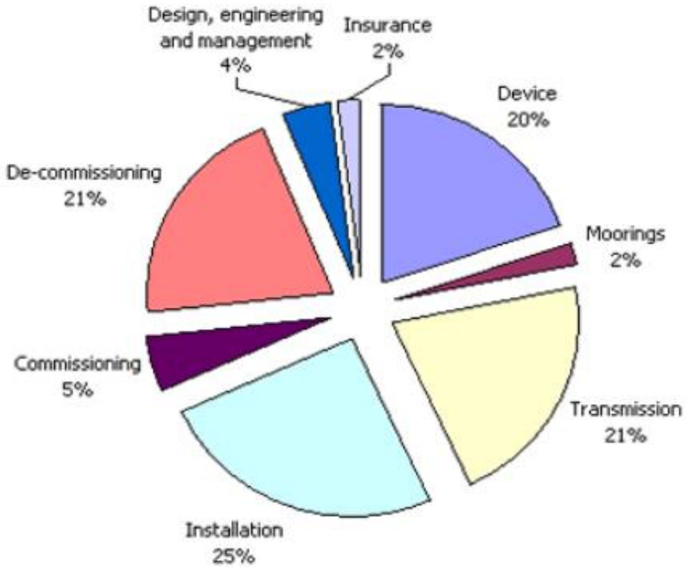


Figure 35: Capital cost breakdown for installation of a WEC as one single unit (Carbon Trust, 2013)

Figure 36 illustrates the capital cost breakdown for installation of a wave energy device in a wave farm of a certain size. In comparison to Figure 35 it can be observed that the component contributing to the highest share of the capital cost breakdown is the cost of the WEC device at 41%. Figure 36 suggests that there is prospect for cost reduction when multiple device installation is considered. This is demonstrated in the absolute reduction of the installation cost as well as the cost of transmission. There is also a reduction in de-commissioning cost suggesting that these can be further investigated for cost reduction in prospective projects.

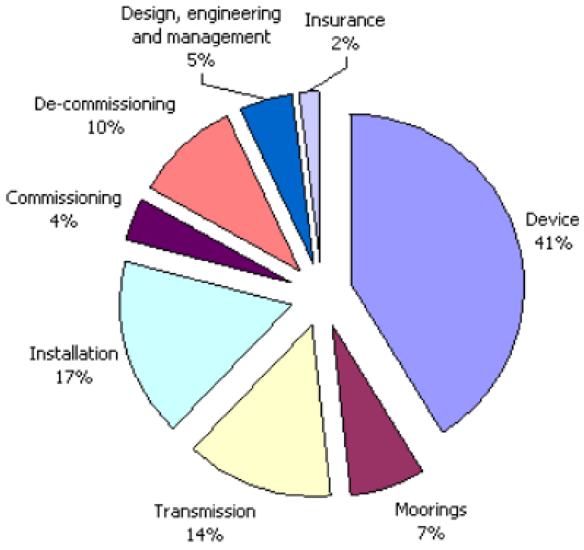


Figure 36: Capital cost breakdown for installation of a WEC in a wave farm (Carbon Trust, 2013)

In addition, cost components such as design, engineering and management, insurance and commissioning remain relatively low as in the case of installation of single unit of WEC device. This may suggest that there is not much potential for cost reduction in these areas. Benefits of economies of scale in this instance is relatively low. With respect to the offshore environment, a report on marine renewable energy systems (Carbon Trust, 2014) mentioned that the key factors affecting the cost of energy (COE) from WECs depends on: performance of the device (amount of produced electricity), capital costs, O&M costs and risks. Carbon Trust (2014) also reported that there is some overlap between structural and energy conversion components especially for wave energy devices, because the structure's geometry and size has a significant bearing on the device's ability to absorb power.

As observed in the case of capital costs, it may also be convenient to consider factors influencing WECs O&M costs in terms of cost centres. This will be of great benefit to cost analysis of wave energy farms. This is because during the design stages of WEC devices it is often necessary to provide more details for individual cost centres and how design decisions can affect CAPEX and OPEX (Beels et al., 2011). In Carbon Trust, (2005; 2011) it was mentioned that the O&M costs reach 57% of the OPEX for a specific WEC. In this case, OPEX may include all ongoing costs associated with fees such as royalty, community contributions and property taxes, required for the smooth operation of the WEC farm project.

The O&M cost is a part of the OPEX and in this case, refers to the cost directly incurred in the maintenance activities of the WEC device. This is to ensure that the WEC continues to produce electricity at optimum level. Figure 37 illustrates of O&M cost breakdown for a wave energy device installed as a single unit. It can be observed that the cost of planned maintenance accounts for the highest amount. This is followed by the cost of monitoring and insurance. In contrast to the capital cost breakdown, insurance is around 15%. However, the cost of licencing or certification is seen to contribute the smallest amount.

For maintenance of the wave energy device as a single unit it is observed that the cost of unplanned maintenance is relatively low at 14%. The lack of operational experience in the wave energy sector is identified as one problem experienced when attempting to quantify the profitability of a wave energy project. This situation is directly linked to the high level of variation in the operational costs and device availability estimates. The split of CAPEX between different cost centres varies considerably by project size. O&M costs can also be described by cost centres and vary by project size, location and technology. Annual average OPEX is a simplified description; OPEX will not stay the same in every year of a project.

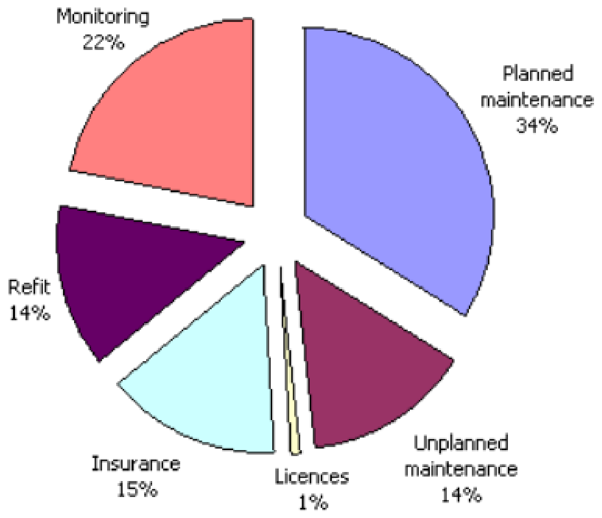


Figure 37: O&M cost breakdown for a wave energy device installed as a single unit (Carbon Trust, 2013)

Figure 38 illustrates the O&M breakdown of a wave farm of a certain size. It could be observed that as the farm size increases the cost of planned maintenance reduced compared to maintenance cost for single device. It is expected that the cost of unplanned maintenance would also increase as shown with the contribution of 28%. However, there may opportunities for cost reduction considering the size of the farm. There is a significant reduction in the cost of monitoring for multiple devices installed in a farm than for device installed as a single unit.

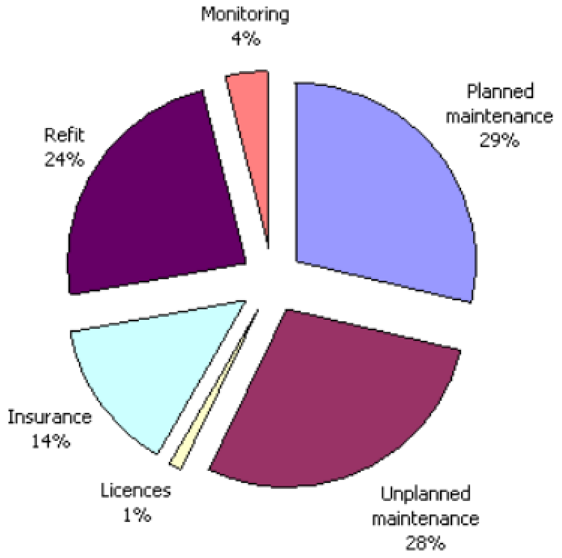


Figure 38: O&M cost breakdown for a wave farm of a certain size (Carbon Trust, 2013)

As in the case of the unplanned maintenance cost, there may be opportunities for cost reduction in refit depending on the farm size. As shown in Figure 38 refit contributes to 24% of the total cost breakdown compared to 14% in Figure 37. The cost centres shown are typical, including planned and unplanned maintenance, licences to be stationed and generate electricity at the location (often referred to as consents and permits), insurance, and ongoing monitoring activities. For this technology, a mid-life refit has been selected as a good compromise between maximising availability and minimising costs.

It can also be seen that about 1/7th of the total O&M costs are assigned to unplanned maintenance activities, which reflects a degree of uncertainty in the device's design for reliability. Inspection and maintenance costs are a significant contributor to the cost of energy for WECs. For these reasons, the impact on the maintenance strategies for offshore wave energy generation systems has been assessed based on variation and cost. It is evident that the global focus is now on accelerating development with the planning and testing of multiple wave energy devices constructed in arrays (e.g. array-scale projects).

These also are equally dependent on the ability to accelerate innovative technologies, develop supply chain dependencies and to establish the necessary fiscal and enabling policies to support long-term activity (Andrawus et al., 2008). It is understood that the development of marine renewable energy technologies requires huge investment in capital, and as the marine renewable energy sector continues to emerge, it presents new challenges, and also an abundance of opportunities in terms of developing a marine renewable energy sector that could lead to benefits (MarineRenewables, 2013) such as a new clean, sustainable resource to add to the energy mix, displacement of air emissions and greenhouse gases, job creation, trade, and economic growth.

2.9.1 Challenges of Investing in Marine Renewable Energy Systems

The cost of power generation from offshore wave farms is expensive compared to other source of renewable energy due to more complicated foundations, longer electrical networks, installation and maintenance activities that are dependent on vessels. The costs of the WEC technology and lack of capital to develop technologies and projects have also been identified as factors influencing development of the marine renewable energy sector. In addition, prototype developments taking longer than expected and uncertainties around devices interaction with the environment are also some of the challenges.

A report (Cradden et al., 2013) identified the challenges as extreme wind and wave conditions capable of limiting the operability of the vessels needed to access offshore facility. Other challenges include minimal collaboration as devices/projects are developed in isolation and suffer from lack of pooled ideas (Bedard et al., 2005). Moreover, track record is not yet well developed for utility acceptance. The marine renewable energy sector must overcome these risks and challenges in order to advance to a mature industry.

Although these challenges may be unique to regions, it is common knowledge that many of them span globally. Studies (Bedard, 2009) agrees that these challenges could also create opportunities to develop solutions to issues affecting the global industry. Atkins et al., (1992) acknowledged the requirement for new tools, enabling technologies and systems for high-flow environments. Over the past decade a significant amount of work has been done to address many of these challenges and risks (Bedard et al., 2005; Bedard, 2006), but new questions and complexities have emerged as the industry looks to develop array-scale projects (Cruz et al., 2009).

2.9.2 Factors Affecting WEC O&M Cost

Raventos, et al (2010) identified O&M costs for WEC to consist of material costs, labour costs, access vessels & lifting vessels costs, and revenue losses. In this thesis, the main factors deemed to have an influence on the O&M costs of wave farm projects are discussed in terms component reliability, environmental factors, farm specification, and other factors. Kraemer, et al (2011) acknowledge that the cost of O&M activities represents a significant contributor to the total expenses of the farm, during the lifetime of offshore WEC farm.

The lifetime of the device will significantly affect O&M costs, because older equipment requires more attention, also O&M costs incurred in the years furthest in the future are the most highly discounted. The factors which may be responsible for the increased cost of maintenance operations is due to the rough environmental conditions, shorter weather windows and more importantly, the requirement of specialised vessels to carry out the maintenance activities.

2.10 Review of O&M Cost for WEC Farms

The energy generated from marine renewable source is considered very low when compared to the set targets (DoE et al., 2013), notwithstanding the significant investment that has already been made. For economic and productivity reasons, it is often necessary to provide more details for individual cost centres during the preliminary design stages of WEC farm systems. In this thesis, an attempt is made to evaluate the potential for WEC farm to generate useful energy at the selected location. In addition, O&M cost estimates for operating a WEC farm is described.

The general guidelines for assessing the economic value of WEC farm project has been provided based on the review of relevant literature. The objective is to develop the methodology and modelling in the integrated framework for resource assessment and O&M cost modelling. This will help to deal with problems surrounding the variations in the O&M cost estimates and factors such as capital cost and operating cost associated with large scale commercial deployments of WEC farm projects. This will be of benefit to potential investors and policy makers concerned with the problems of decision making for future energy generation.

A report based on experience of wind turbines (Gellatly, 2013) confirmed that O&M is considered as a significant contributor to the Levelised Cost of Energy (LCOE) and this may also be applicable to WECs. It is therefore, necessary to review the methodologies, approaches, practices or procedures involved in the O&M processes relevant for wave energy generation projects. This will help to achieve part of the research objective which is to consider what makes up a marine energy device's capital costs, OPEX and O&M costs, as well as opportunities to reduce it.

2.11 Gaps in The Existing Literature

Electricity generation using WECs is still at the early stages of development and testing. The review of the existing technology and concepts within ocean energy device developers reveals that there is very little design consensus surrounding the design of WEC. One important issue undermining the growth of the wave energy industry is identified as the lack of a single consistent and well documented source of information which clearly defines the approach for preliminary assessment of the wave energy resource at a potential site.

Secondly, the ambiguity and difficulty in comparing assessments results are some of the issues found in the existing literature for example (Barstow, et al., 2009, Carballo, & Iglesias, 2012). To avoid this problem, it is necessary to provide a framework for presenting the variables which are relevant for estimating the wave resource for preliminary analysis of the selected location. Furthermore, the issues relating to offshore access for WEC O&M activities is considered. These aspects are not included in existing feasibility studies for WEC farm project. That is why it is necessary to considered vessel specific attributes as they influence the cost of O&M activities.

In addition, most of the information and models found in existing literature are not applicable to offshore WECs. The theoretical information presented in the literature are often not applicable to real cases due to limited information on operations and unavailability of failure data to support he O&M strategies. Moreover, the influence of the O&M vessel transport cost on the O&M activities of WECs are often not considered in existing methods for preliminary assessment. This brings about the variations surrounding the WEC O&M cost estimates.

For WECs to succeed they must harvest the wave energy at considerably low cost with feasible O&M practices. There is therefore the need for an integrated framework for resource assessment and modelling the O&M cost estimates for preliminary assessment of any selected location for deployment of a WEC farm. In this context, offshore WEC O&M transport means is considered within the offshore project life cycle. The importance of this review to this thesis is to identify drivers for future technology developments and identify areas for future cost reduction.

2.12 Chapter Summary

In this Chapter, the review of the existing literature is presented. This starts with an overview of the resource assessment methods and introduction to energy extraction using WEC. Subsequently, the review on classification and different types of WEC was presented to identify key technological concepts. The type of WEC device is an essential component in the evaluation process where the objective is to efficiently harvest wave energy under different wave conditions by location. To succeed, WECs should be optimized to effectively extract wave energy under most wave conditions.

The WEC must extract a considerable amount of energy at low initial capital cost with practical O&M. In that case the review on existing tools, maintenance theory and O&M strategies relevant to WEC farm O&M is presented. The major gaps identified include the variations in the O&M cost estimates for the WEC farm operations. This relates to the requirement of vessels to carry out the O&M activities. The review is narrowed down to vessels relevant for offshore WEC O&M activities and vessel chartering options. The critical review helps to provides better understanding about the characteristics of wave energy resource and the resource characterisation play a critical role in quantifying the amount of energy that can be captured.

The O&M aspect can potentially create impact in reducing the variations surrounding O&M cost estimates for WEC farm operations. The reason is that the O&M modelling aspect in the integrated framework applies O&M vessels relevant for offshore WEC farm O&M activities. In this case, ideal O&M vessel charter rates are applied to analyse the O&M cost estimates for WEC farm project. By identifying the gaps in the existing studies, the integrated framework resource assessment and O&M Cost modelling for offshore WEC farm is proposed and presented in Chapter 3 methodology and modelling.

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Chapter 3 Methodology and Modelling

3.1 Chapter Outline

This Chapter presents and discusses the integrated framework for resource assessment and Operation and Maintenance (O&M) cost modelling proposed in this thesis. A critical review of existing methods on wave energy resource and O&M cost modelling for WEC farm projects has been presented in Chapter 2. To achieve the research aim and objectives as described in Chapter 1 and to bring alternative solutions to the issues identified in Chapter 2, an intergraded framework is proposed in this methodology. This framework is used to assess the wave energy resource and the O&M cost estimates of a WEC farm. The Chapter is outlined as follows: the introductory information related to the development of the proposed methodology is provided in Section 3.2.

Section 3.3 identifies and defines the main Resource Assessment (RA) input and the O&M input is defined in Section 3.4. In Section 3.5 a detailed description of the resource assessment model is presented and the theoretical background for the analysis used to demonstrate the assumptions and parameters required for assessing the wave energy resource throughout the methodology is also presented. Section 3.6 describes how the main input requirements for assessing the OPEX and modelling the O&M cost associated with the WEC farm project are analysed. In addition, the relationship between different cost attributes and input of the project CAPEX are described and the financial indicators are defined in Section 3.6. The assumptions of the developed model are presented in Section 3.7. As a conclusion, the summary of this chapter is presented in Section 3.8.

3.2 Development of The Proposed Methodology

In this section, the procedure followed to develop the proposed structure of the integrated framework for assessing the wave energy resource and O&M cost estimates for a WEC farm are described. The reason for an integrated framework on resource assessment and O&M cost modelling for a WEC farm project is to provide a basis for investigating the issues surrounding variation in the resource and productivity estimates of any selected location for deployment of a WEC farm. The integrated framework will also help reduce the variation surrounding the high operational cost associated with the O&M activities of the WEC farm project. Moreover, behind every resource assessment, there is the possibility of installing a WEC device to harness the wave energy at the potential location.

The WEC must be able to harvest the wave energy with practical O&M activities and ideal cost. Therefore, the information on the potential wave energy resource and that which can be theoretically extracted using a WEC; together with practical O&M strategies at the selected location is relevant to support the continuous generation of power from the WEC. This will help to encourage and support the development of electricity generation using WEC technology. The O&M aspect has been identified as a major contributor to the cost of operating the electricity generation project using WEC technology as discussed in Chapter 2 critical review.

The gap identified in the literature of existing methods include the inability of these methods to account for the O&M planning activities as well as the O&M cost for running the WEC farm. These aspects are some of the main issues surrounding the variation and significant cost estimates associated with the WEC O&M. This is particularly true in terms of planning and logistics required for maintenance activities involved in daily operations of the WEC farm project. In the methodology and modelling approach of this proposed integrated framework, the combined input of the resource assessment and O&M modelling are considered and analysed within a single framework. Hence in the methodology and modelling performed, the major five components of the integrated framework addressed are the following:

1) Resource Assessment Model: this provides the basis and information applicable to initially describe/ assess the wave energy resource for any elected location using the integrated framework.
2) O&M Model: this is applicable to evaluate the major contributors to the O&M cost of the WEC farm.
3) Project OPEX Analysis: this describes the main elements that are analysed to investigate the variation in the O&M cost estimates.
4) Project CAPEX Estimation: this is applicable to define/estimate the total initial cost of the WEC and other associated costs that may influence the overall cost of the project.
5) Financial indicators: this describes the information relevant to establish the suitability and economic viability of the WEC farm project to support investment decisions.

Figure 39 shows the flowchart of the Integrated Framework. There are two main input sections namely RA input and O&M input shown in the thick black blocks on the left of Figure 39. These two main input blocks provide information for the analysis of the Resource Assessment model and O&M model blocks shown as the thick black blocks in the centre of Figure 39. The main output of the Resource Assessment block is the Resource Description block. The output of the Resource Description provides information which is later used as input in the O&M model. The main output of the O&M model is the Total Maintenance Cost block.

As an integrated framework, the RA input block also provides information to investigate the marine operational environment with respect to the O&M model. This is particularly relevant in terms of defining the wave farm attributes for the case study location. The arrows present the flow of information between the input and output blocks. In this case, the thin arrows depict the flow of information related to the input. The thick arrows depict the information related to the output. The blocks with the dotted lines in the centre of Figure 39 represents Intermediate input/information relevant to illustrate the case study application and OPEX in relation to the O&M modelling.

The intermediate input/information such as the hourly sea state and weather windows are the output of the resource description block based on the resource assessment model. This is applicable to initially assess the offshore wave/climate condition at an offshore location and to describe the marine operation environment for O&M vessel operations. The O&M strategy block and Vessel charter rate block provide specific output information for the O&M model in the integrated framework. The project OPEX analysis and CAPEX blocks shown in Figure 39 represents the main cost elements considered in the integrated framework to investigate the variation in the O&M cost estimates and total initial cost of the WEC farm project.

The financial indicator block represents the different components/information required to demonstrate the economic value of the WEC farm project. The decision block helps to highlight the results and discussion of the resource assessment and O&M modelling based on the findings of the integrated framework model developed in this thesis. The decision block attempts to synthesize the information in the framework by investigating and evaluating the main components that have been identified as factors hindering the deployment of wave energy farm using WEC technology.

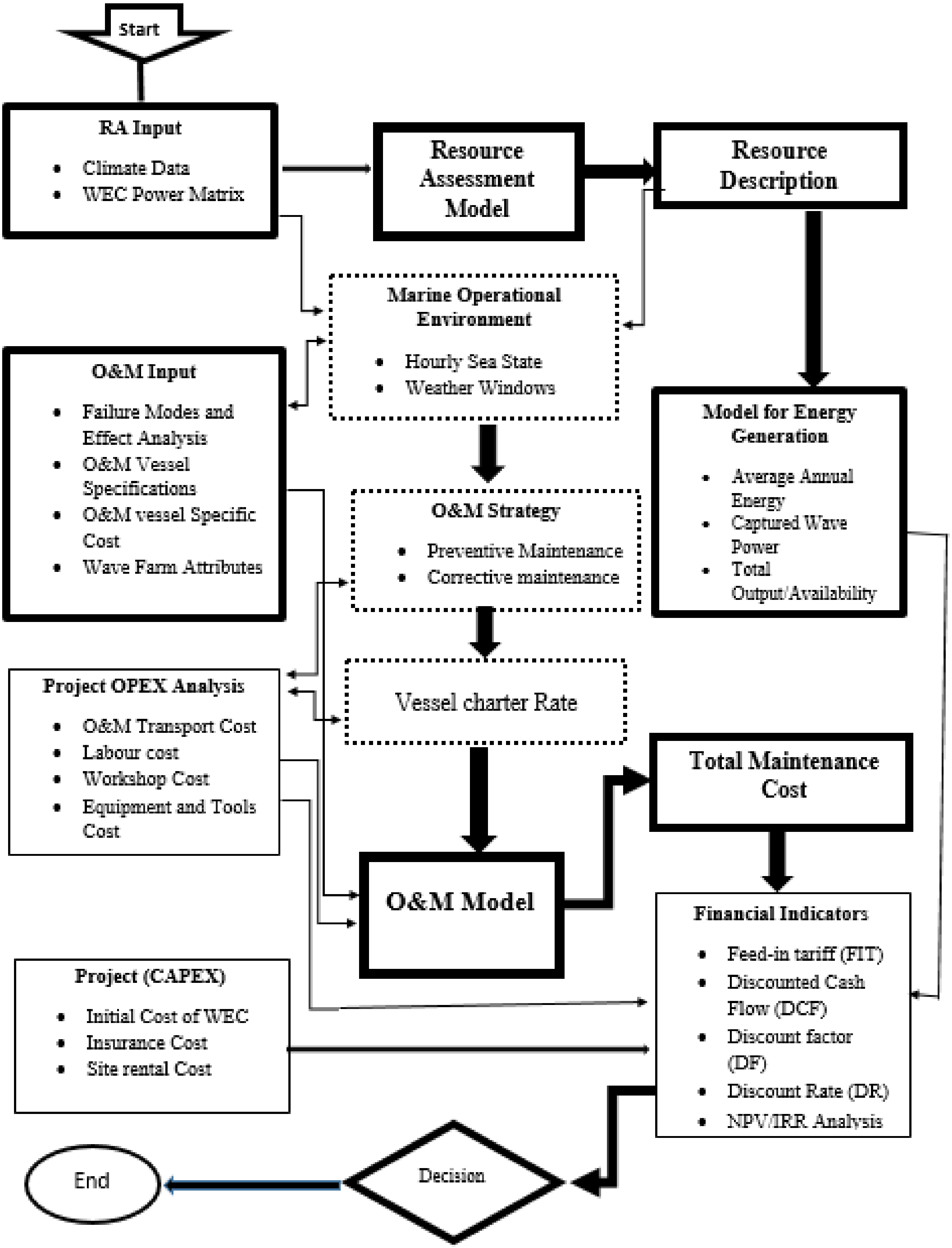


Figure 39: Flowchart of the Integrated Framework for Resource Assessment and O&M Modelling

The proposed methodology brings together in a single framework the method for preliminary assessment of the wave energy resource and a model to estimate the O&M cost of a WEC farm in any selected location. This can illustrate the benefits and drawbacks as well as potential improvement opportunities to reduce the O&M costs and increase the competitiveness of the industry. As an integrated analysis model, the integrated framework firstly analyses the input of the resource assessment model. This is to evaluate whether the conditions at the prospective site are ideal or within certain acceptable limits. The ideal or acceptable limits are defined based on the observations from findings during the review of existing literature on wave energy resource (Barstow et al., 2009; Black and Veatch, 2004) and characterisation (EMEC, 2009; Lenee-Bluhm et al., 2011). In the next section, the Resource Assessment (RA) input is described.

3.3 Resource Assessment (RA) Input

The aim of this section is to explain how the main input parameters (e.g., climate data, farm attributes, O&M vessel specification, WEC/power matrix and FMEA) in this integrated framework for resource assessment and O&M costs modelling are analysed. In this context, the input required to develop the proposed methodology and modelling is initially described.

3.3.1 Climate Data

In this thesis, the climate data refers to the standard oceanographic measurement description and units of historical wave data. In the methodology and modelling developed in this integrated framework, the climate data describes the initial input requirement and information needed to assess the suitability of a prospective WEC farm site. To assess the offshore wave condition, the first step is to define the wave climate at the offshore location. In this thesis, the climate data is also referred to as historical wave dataset. The historical wave dataset consists of different variable parameters such as the wind speed, significant wave height, and wave period. These parameters are relevant for performing the preliminary wave data analysis.

In the context of the proposed resource assessment methodology, the historical wave data input is used to describe the initial wave condition in the selected location. As mentioned earlier, the ideal wave conditions are defined based on findings from existing literature on wave energy resource assessment and characterisation. For example, the report (WaterTechnology, 2004) acknowledged that if the significant wave height is too low (e.g. lower than 1 m), the energy output will be low, while the operation cost is not low.

The reason is because the output of the device is dependent on the availability of the resource (García–Medina et al., 2014; Lenee-Bluhm et al., 2011), whereas the O&M is to ensure that the WEC device is available to generate the wave energy from the resources (Wolfram, 2006; Santos et al., 2013). However, when the significant wave height is too high (e.g. higher than 6 m), there is the tendency for the WEC to have a significant reliability issue (Wolfram, 2006; van Bussel and Zaaijer, 2003). The reason is that higher significant wave height value may impose a high load on the WEC system and this may cause the WEC device to fail.

Therefore, in the developed integrated framework for resource assessment and O&M cost modelling, it is assumed that the minimum and maximum significant wave height should be around 1m and 6m respectively. This is an ideal range for the offshore wave condition to maximise the productivity and economic benefits of the WEC farm (Teillant et al., 2012). The application of the historical wave data for resource description, together with the analysis of operational activities for estimating the O&M cost are discussed with more details in Chapter 4 case study application of the methodology.

If the wave condition at the selected location is acceptable, following the results of the preliminary analysis of the historical wave data, then the assessment proceeds to the next stage. In this respect, the resource characterisation and description, being an output of the resource assessment model provide information as the input of hourly sea state and weather window to the O&M model for the WEC farm O&M planning activities. The marine operational environment builds on the hourly sea states record and depends on the information of the weather window.

The novelty of this methodology and modelling procedure developed in this integrated framework is demonstrated in the application of the historical wave data at different stages in this thesis. Firstly, using a combination of the wave parameters to characterise the resource in terms of the resource assessment method and secondly to perform the vessel operability analysis for the O&M planning activities. These parameters in the historical wave data are regarded as the major environmental constraints. They are required to describe the resource assessment model as well as the O&M model, particularly with respect to O&M activity because very strong winds and high wave heights can create issues in the operations.

3.3.2 WEC Power Matrix

The WEC power matrix refers to the characteristic power production input as well as the device specification input. In this methodology and modelling, the WEC power matrix is used to describe the technical production performance of the device. The power matrix lists the energy production rates of the WEC for different sea state parameters in the form of a table or matrix. As applicable in engineering analysis of devices, the information relating to the device specification, reliability and performance are classified under the device characteristics.

In this context, the WEC design specification provides explicit information about the characteristics of the WEC. Studies (Previsic, 2004; Previsic et al., 2004) have shown that the ability of a WEC device to capture wave energy can be expressed by wave energy absorption performance that is available from WEC device manufacturers. In this integrated framework, the resource assessment model is employed to generate the hourly wave power production over the lifetime of the farm. By combining the power matrix of any selected device, the captured wave power and total energy output due to availability can be established.

3.4 O&M Input

This section defines the main input of the O&M model in the integrated framework. As an integrated framework, other factors that may contribute indirectly to the total O&M cost estimate are also evaluated by analysing other associated costs such as the initial cost of the WEC, insurance and site rental. These associated costs are considered for the purpose of clarity to distinguish between OPEX and CAPEX of the WEC farm. Therefore, depending on the type of O&M strategy, the different cost components of the OPEX block is analysed based on the O&M vessel specific cost input to evaluate the total O&M cost.

3.4.1 Failure Modes and Effect Analysis (FMEA)

In this methodology and modelling, the O&M activity is defined based on a Failure Modes and Effect Analysis (FMEA) table an example of which is shown in Table 6. The FMEA table provides information relating to the component name or type, the probability of failure for the specific component, the consequences of failure, cost of parts, the man-hours of repair or labour cost and the location of repair for a generic WEC device. In this case, the probability of failure is not Hs specific. The reason is that the FMEA table used to illustrate the example does not refer to any specific WEC device.

The labour hours can be a function of the significant wave height. The reason is that if the significant wave height criteria defined for the O&M vessel utilisation is not within the acceptable limit, this may cause a delay in the maintenance activities. Consequently, the maintenance activity may be suspended until favourable conditions are met. In this respect, factors affecting the cost of maintenance activities include the number of WECs, the magnitude of labour-hours per WEC device that is needed to perform a maintenance operation and transport cost.

The FMEA table is defined as an input in the integrated framework to support the wave farm attributes. This is necessary because the reliability of each subcomponent of the WEC is specified under an FMEA table which lists the likelihood of failure of each component of the WEC. The different component and input in the FMEA table are adapted from existing literature because failure information for specific WEC are scarce and not readily available. It is important to mention that the information presented in Table 6 do not represent a specific WEC concept. The reason is that they were determined using information relative to other industries, for example, offshore wind, oil, and gas (Teillant et al., 2012).

Table 6: Failure Modes and Effect Analysis Table (Teillant et al., 2012).

Component-Name	Quantity-In design	Probability-of failure (Per year)	Consequence-of failure (% Power loss)	Cost of-parts (£)	Man hours-of Repair (Hours)	Repair-location
Hull structure	2	0.0066	100	50000	72	Onshore
Bearing pads	12	0.002	100	2000	10	Onshore
Motor	1	0.005	100	25000	48	Onshore
Dynamic riser	1	0.00125	50	10000	20	On-site
Mooring line	4	0.0013	100	20000	100	On-site
Generic component	120	0.005	100	2500	12	On-site

On the other hand, depending on the specific WEC device, the information presented in Table 6 can be a function of the water depth and current. However, WEC specific failure rates of components can be estimated directly from experiments (Johanning et al., 2011) or can be adapted from failure rate data from relevant industries based on so-called adjustment factors (Thies et al., 2012) or using Bayesian statistics (Thies et al., 2009). The FMEA and input of the wave farm attribute provide information for O&M model. The information is applied to illustrate the example of breakdown events to demonstrate the O&M strategy described for the WEC farm O&M.

Based on an initially defined wave farm attribute, the maintenance activities contributing to the OPEX, namely: the on-site inspection/service, or the preventive and the corrective maintenance activities are then analysed. It is assumed that within a life cycle period of 25 years for a WEC farm, scheduled on-site visits to the WECs will be undertaken for on-site inspection or preventive maintenance activities. More detailed information on the FMEA table and how it is used to demonstrate the O&M strategy for the WEC farm is presented in Chapter 4 case study application of the methodology.

3.4.2 O&M Vessel Specifications

The requirement for vessels to perform O&M activities in the WEC farm has been identified as the main contributor to the cost of operating the WEC farm project. This is also the reason for the variation in the O&M cost estimate. The O&M cost modelling makes use of published data from offshore ship and service industries, to capture information relevant to the day price of vessel hire and the purchase cost of support vessels. Therefore, the O&M vessel specification is defined as an initial input in this integrated framework to assess the feasibility of employing vessels for O&M activities in the WEC farm project.

When assessing the costs of installation, maintenance and removal activities for a WEC, the type of vessel required and the duration of the operations are the main drivers (Stallard et al., 2010). In this respect, the cost of employing the O&M vessel is accounted for in the preliminary assessment of the WEC farm project. This represents a novelty in the integrated framework because, both the resource assessment and O&M cost input are considered in a single framework. This addresses the issues relating to the suitability of the selected location in terms of the productivity and economic feasibility.

Using the combined input of the resource assessment and O&M cost model, the wave energy resource is assessed, together with the offshore accessibility factors for the marine operational environment. Nevertheless, the main purpose of O&M vessel specifications input in this thesis is to simulate the operational cost in the case of chartering the O&M vessel for WEC O&M activities. In developing this methodology, the O&M vessel specification is defined in a more generic context; so that the methodology can be adapted for any type of maintenance activity that may require a vessel for its operation.

Several types of vessels capable of performing different types of maintenance activities have been identified and discussed in Section 2.8 of Chapter 2 critical review. The O&M activities of WEC will require smaller vessels. These for example, may include, small crew boats, Crew Transfer Vessels (CTV) (mono-hull or catamaran configurations) and tugboats. In the integrated framework, the output of the resource assessment model is used to pre-define the marine operational environment in terms of the weather window for O&M vessel operation.

To ensure safe access of the O&M vessel during operation, the limiting significant wave height threshold defined for the weather window in the case study location should not be exceeded. If the weather window is not within the O&M vessel operability limit, the O&M activity requiring the vessel is advised to be suspended until suitable conditions are met. Moreover, during extreme storm conditions, the O&M vessel cannot sail, or perform any maintenance activity due to high risk of sinking and capsizing. In this case, the vessel must be kept in the specified port.

3.4.3 O&M vessel Specific Cost

O&M vessel specific cost input is required to evaluate vessel charter cost and agreement. This is necessary for the O&M transport and logistics planning. The cost of chartering a vessel for O&M activities is a major contributor to the total O&M cost. Studies for offshore wind farms O&M (Morgan et al., 2003; Junginger et al., 2004), show that O&M vessels makeup to 73% of the total O&M cost. These studies proved that the development and study of new O&M vessels are important for the O&M transport requirement for offshore renewable energy installations. Table 7 presents the generic input parameters for O&M vessel charter agreement.

The information refers to the O&M vessel chartering specific cost input. This is applicable to illustrate the type of details required to analyse the O&M vessels main cost input as it affects operational cost. From these input total charter cost, total fuel cost, total staff cost, total O&M cost, total dry-dock cost, and total fixed cost are calculated. There are different types of charter agreements and the costs associated with O&M vessels are directly dependent on the charter agreement. This has been explained in detail in Section 2.8.2 and Section 2.8.3 in Chapter 2 critical review. In this methodology and modelling, the emphasis on vessel charter scenario is focused on identifying major factors that influence the operational cost and as such, establishing the criteria required to analyse them.

Table 7: O&M Vessel Time Charter Cost Input (Lazakis et al., 2013; Dalgic et al., 2015)

Input Name	Type	Unit
Charter rate	Charter cost	£/day
Crew cost	Staff cost	£/person
O&M technician cost	Staff cost	£/person
Management team cost	Staff cost	£/person
Fuel Cost	Fuel cost	£/ton
Annual increase	Annual Increase	%

Assuming the vessel is chartered from the spot market, the criteria for analysing O&M vessel specific cost is shown in Table 8. Nevertheless, it is understood that accurate charter rate datasets are required to calculate the charter cost of O&M vessels. The method followed to model the O&M vessels cost is presented based on relevant chartering options and corresponding charter rates for O&M vessels employed in the shipping market. Table 8 suggest that winter/summer charter rate can be different even for the same area of operation depending on the availability of the O&M vessel during the period.

In this context, an estimation process for daily charter rates associated with the vessels for major maintenance operations is described following experiences adapted from offshore wind turbine O&M charter rate modelling (Lazakis et al., 2013; Dalgic et al., 2015). This approach will allow WEC farm operators to plan their maintenance strategies by considering the share of vessels’ costs in the overall maintenance costs (Dinwoodie et al., 2013). From the charterer or operator point of view, accurate estimations towards better planning are important in the offshore WEC O&M activities. This will also assist in evaluating different chartering options, which account for the major amount of the maintenance budgets.

Table 8: O&M Vessel Spot Market Cost (Lazakis et al., 2013; Dalgic et al., 2015)

Input Name	Type	Unit
Winter charter rate	Charter cost	£/day
Summer charter rate	Charter cost	£/day
Winter demurrage	Charter cost	%
Summer demurrage	Charter cost	%
Annual increase	Charter cost	%
Mobilisation cost	Mobilisation cost	£
Annual increase	Mobilisation cost	%

3.4.4 Wave farm Attributes

In the developed methodology and modelling, the wave farm attribute is initially defined as an input in the resource assessment model. This is relevant to illustrate the initial WEC farm attributes and offshore condition in relation to the O&M model. The input of the wave farm attributes is the information related to the WEC farm characteristics such as WEC device type, power matrix, number of WECs, wave data and weather conditions. The output of the wave farm attribute block is the input of the O&M strategy. The purpose of wave farm attribute block is to transform their inputs into outputs. For example, the Initial wave data input and material reliability data are transformed from discrete formats (the input) to continued probability functions (the output) or from the time domain to frequency domain.

The wave farm attributes also provide information on different type of services input related to the WEC farm. For example, productivity, unit material/equipment cost, facility availability and O&M vessel specification for assessment of the transportation cost. In this case, the labour performance (productivity), unit material/equipment cost, facility availability and O&M vessel specification are not included in the CAPEX. In this case, they are classified under the operating cost in the O&M model.

3.5 Resource Assessment Model

This section provides a description of the theory behind the dynamics of sea waves and the introduction to the analysis of the motions of floating bodies in sea waves. This will help to form the basis upon which the discussions and calculations for the resource assessment are considered in the methodology and modelling framework proposed in this thesis. Studies on wave energy resource assessment (Barstow et al., 2009) have been conducted to support the theory of motions of floating bodies in sea waves. The dynamics of sea waves and their interaction with oscillating systems (Bahaj and Myers, 2009) has also been investigated.

As could be observed in the existing literature on resource assessment and the dynamics of sea waves, a detailed resource assessment involves the energy description at a location of interest. This is based on the analysis of wave spectra parameters produced from a simulated hind cast (Dallman and Neary, 2014). The main spectral parameters for characterization of wave energy resources are the significant wave Height H_s, spectral peak period T_p, mean direction (θ), and wave power level P (i.e., the flux of energy per unit length of wave crest) (Falnes, 2002).

Figure 40 is used to illustrate the resources assessment model decomposed from the methodology and modelling in this integrated framework proposed in this thesis. In this methodology, the parameters used for the resource assessment model are wind speed, significant wave height and wave energy period. The significant wave height and wave energy period are the two most important parameters required to evaluate the energy available in the wave resource. The reason is that the significant wave height and wave energy period are the two well-defined parameters that are consistent in existing studies on resource assessment.

One of the main issues and gaps identified in the existing literature on resource assessment is the ambiguity and difficulty in comparing the resource assessment results. The cause of this problem is because too many variables that are not well defined and consistent with well-established methods are used to describe the resource. To avoid the problem of ambiguity and to ensure clarity in the results of the resource assessment, the significant wave height and wave energy period are used since they are deemed to be well defined in existing studies (Barstow et al., 2009, Bahaj and Myers, 2009) and consistent.

The wind speed is applicable to describe the duration of the weather window for WEC O&M activities in the marine operational environment. The wind speed variable is also a well-defined parameter that is consistently based on the review of the existing literature. The marine operational environment builds on the information of the hourly sea state defined by the wind speed, significant wave height and peak wave energy period. In this respect, the significant wave height and wind speed parameter are applied to define the maximum/minimum criteria of the weather window threshold for the O&M activities using vessels.

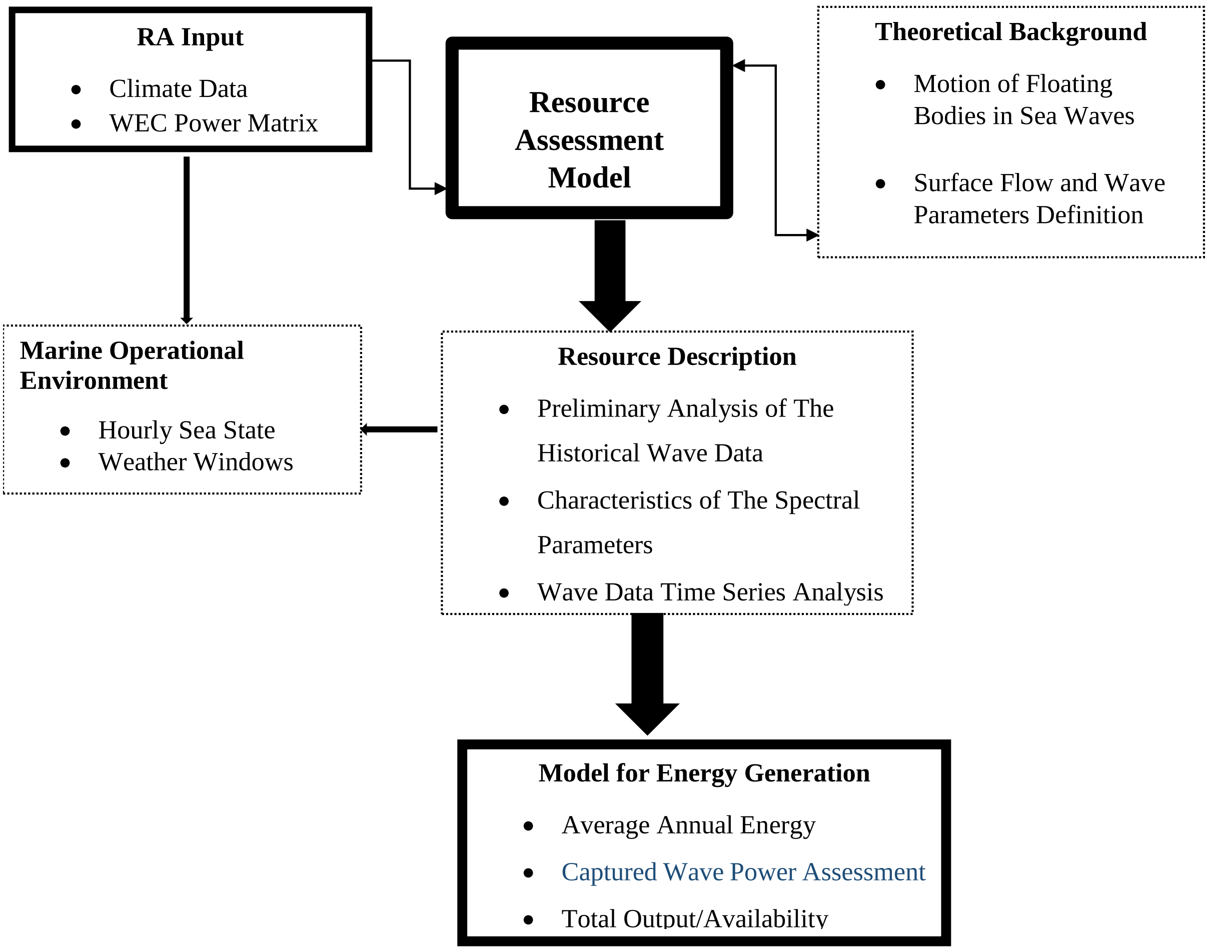


Figure 40: Resources Assessment Model

In this context, the duration of the weather window can be defined as a period where quantities such as H_s, T_p, and wind speed, remain at levels which permit a given set of marine operations to be performed safely (Chen et al., 2008). The existing studies on wave energy resource assessment (García–Medina et al., 2014; Lenee-Bluhm et al., 2011; Folley et al., 2012), has been useful to critically examine the relevant parameters for the wave energy resource description at a location of interest.

Operators or designers of the WEC farm would normally resort to modelling the WEC farm system (García–Medina et al., 2014; Folley et al., 2012) to obtain information on energy output, because it is not practical to conduct experiments of building and operating a large WEC farm to estimate unit cost. In this respect, the next section begins with a description of the theoretical background starting with an introduction to the motion of floating bodies in sea waves.

3.5.1 Theoretical Background

3.5.1.1 Motion of Floating Bodies in Sea Waves

As can be found in existing literature of fluid dynamics (Abbott et al., 1989), a rigid floating body has six motional degrees of freedom, which could be denoted as $V_1, V_2, \dots V_6$: three of these refers to the translational motion, i.e., in the x- y- and z-directions, while the other refers to three rotational motion around each of the axes as depicted in Figure 41. The equation of motion of a floating body can be represented using the formula:

$$M\ddot{V} = F$$ *Equation 1*

Where:
M : is a 6 × 6 mass matrices,
$\ddot{V}$: the positions of the vector in the six degrees of freedom, differentiated twice in time in the equation forming the body acceleration.
F: the forces vector and moments acting on the body.
The forces F, acting on the body can be split accordingly (Bahaj and Myers, 2009) into:

$$F = F_e + F_r + F_{rs}$$ *Equation 2*

Where:
F_e: the wave-excited forces
F_r: denotes the hydrodynamic reaction forces from the water and
F_{rs}:the reaction forces from the mooring system.

For the system of forces, the hydrodynamic reaction force can be expressed as:

$$F_r = -A_r\ddot{V} - B_r\dot{V} - C_rV \qquad \text{Equation 3}$$

Where:

$\mathrm{A_r}$: a 6 × 6 matrix containing hydrodynamic mass or added mass.

$\mathrm{B_r}$: a 6 × 6 matrix containing hydrodynamic damping coefficients and

$\mathrm{C_r}$: a 6 × 6 matrix containing the hydrostatic stiffness.

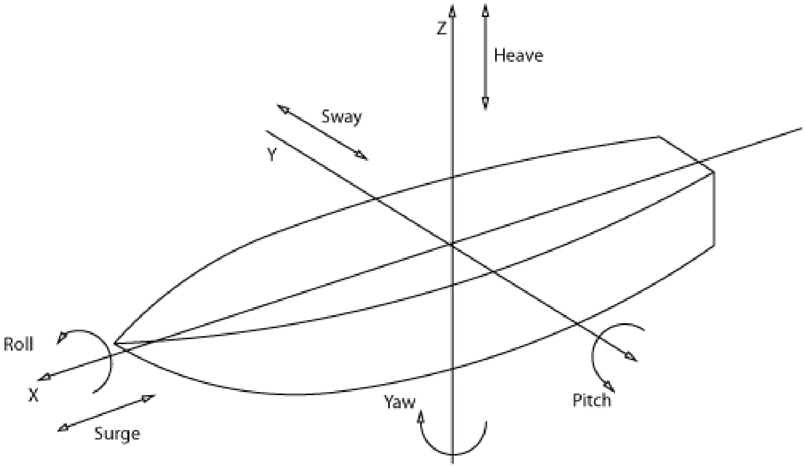


Figure 41: A Floating Body’s Motion and Degrees of Freedom (IMU,2015)

Combining Equations (1), (2) and (3) we obtain the expression in Equation 4 which should be solved when investigating the movement of floating structures in sea waves.

$$(M + A_r)\ddot{V} + B_r\dot{V} - C_rV = F_e + F_{rs} \qquad \text{Equation 4}$$

It is important to note that the matrix form of Equation 4 produces six different differential equations which could individually be solved using different techniques for each.

3.5.1.2 Surface Flow and Wave Parameter Definition

In the proposed resource assessment methodology and modelling in the integrated framework, the surface flow parameters for the selected wave energy site is described following the theory developed by Airy in 1845. This theory often referred to as linear wave theory. In studies of wind wave generation and propagation on ocean surface (Kinsman, 1965), the application of linear wave theory is demonstrated for waves propagating on the ocean surface. The linear wave theory is adapted from existing is applicable to define the wave parameters and the phenomena of the ocean surface flow.

In line with the objective of eliminating the ambiguity in the parameters used in describing the resource assessment in this integrated framework, the linear wave theory is deemed to be a well-defined theory which provides information to discuss the theoretical background of ocean waves and the surface flow parameters. Moreover, this theory is consistent in providing an ideal approximation of wave characteristics for a wide range of wave parameters observed in relevant studies (Kinsman, 1965; Le et al., 2009a; Falnes, 2002).

Linear wave theory is a branch of fluid dynamics which describes the linearized propagation of any gravity wave in any homogeneous fluid. The linear theory represents pure oscillatory waves. With respect to wave energy resource assessment, water waves are considered oscillatory or nearly oscillatory if the motion described by the water particles in circular orbits that are closed or nearly closed for each wave period (Holmes and Barrett, 2007). In this context, it is important in this thesis to differentiate between two types of surface waves.

The two types of surface waves are seas and swells. Seas refer to short-period waves still being created by winds. Seas are short-crested and irregular waves with periods within 3- to 25- sec range. Swells refer to waves that have moved out of the (selected location) generating area. Generally, swells are more regular waves with well-defined long crests (i.e., they have well defined and distinctly separated crests) and relatively long periods (Sakhare and Deo, 2009). Moreover, seas usually have shorter periods and lengths; their surface appears much more disturbed than swells.

The growth of wind-generated oceanic waves is not indefinite; meaning that, the point when waves stop growing is termed a fully developed sea condition. At that point, wind energy is imparted to the water leading to the growth of waves. Dean and Dalrymple (1991) suggested that a more complete theoretical description of waves may be obtained as the sum of many successive approximations, where each additional term in the series is a correction to preceding terms. The action of ocean waves is a major factor in coastal engineering design.

In shallow water of depth d< 20m, the properties of waves change; particularly the height and their direction of travel, which must be included in design calculations (Holmes et al., 2007). It should be noted that the waves are propagating in the direction of the positive x-axis. However, there are limitations to the applicability of linear theory. The theory is useful provided the assumptions made in developing this theory are not grossly violated. Dean and Dalrymple (1991), mentioned that the assumptions made in developing the linear wave theory are:

1. The fluid is homogeneous and incompressible; therefore, the density ρ is constant.
2. Surface tension can be neglected.
3. Coriolis effect due to the earth's rotation can be neglected.
4. The pressure at the free surface is uniform and constant.
5. The fluid is ideal or inviscid (lacks viscosity).
6. The wave being considered does not interact with any other water motions. The flow is irrotational so that water particles do not rotate (only normal forces are important and shearing forces are negligible).
7. The bed is a horizontal, fixed, impermeable boundary, which implies that the vertical velocity at the bed is zero.
8. The wave amplitude is small and the waveform is invariant in time and space.
9. Waves are plane or long-crested (two-dimensional).

For the description of the water surface and sea waves, these assumptions seem to work (Dean and Dalrymple, 1984). The information presented in this theoretical background is useful in terms of providing a background understanding of the hydrodynamic relationship between wave energy conversion and electricity generation using WEC technology. Nevertheless, wave theories are approximations to reality. They may describe some phenomena well under certain conditions that satisfy the assumptions made in their derivation.

The problem often encountered is that they may fail to describe other phenomena that violate those assumptions. For this reason, care must be taken to ensure that the wave phenomenon of interest is ideally described by the theory adopted. With respect to the wave parameter definition, a progressive wave may be represented by the variables x (spatial) and t (temporal) or by their combination (phase), defined as:

$$\theta = kx - \omega \qquad \text{Equation 5}$$

Where:

θ: the phase angle representing the combined phase of k and ω. The values of θ vary between 0 and 2π.

k: the wave number (k = 2π/L) (radians/m) (L: is Wavelength Length).

ω: is the angular or radian frequency. (ω = 2π/T) (radians/s) (T: is Time).

The θ-representation is used in this Chapter because it is a simple and compact notation. The phase above is arbitrary. Thus, a phase angle of θ_0 could be added in all expressions for $\theta = \omega t - kx$. Figure 42 is used to illustrate the parameters that define a simple, progressive wave as it passes a fixed point in the ocean. A simple periodic wave of permanent form propagating over a horizontal bottom may be completely characterized by the wave Height H, Wavelength L and water Depth d.

In Figure 42, the highest point of the wave is the crest and the lowest point is the trough. For linear or small-amplitude waves, the height of the crest above the Still-Water Level (SWL) and the distance of the trough below the SWL are each equal to the wave amplitude α.

$$\alpha = \frac{H}{2}\ (m) \qquad \text{Equation 6}$$

Where:

H: is the wave Height. The time interval between the passage of two successive wave crests or troughs at a given point in the wave period T.

The wavelength L is the horizontal distance between two identical points on two successive wave crests or two successive wave troughs. Other wave parameters include the phase velocity or wave celerity C:

$$C = \frac{L}{T} = \frac{\omega}{k} \qquad \text{Equation 7}$$

The wave steepness ε:

$$\varepsilon = \frac{H}{L} \qquad \textit{Equation 8}$$

The relative depth d/L, and the relative wave height H/d are the most common parameters encountered in coastal engineering practice (Dean and Dalrymple, 1984). In addition, wave motion can be defined in terms of dimensionless parameters H/L, H/d, and d/L; these are often used in practice. Linear waves as well as finite-amplitude waves may be described by specifying two dimensionless parameters, the wave steepness: ε= H/L and the relative water depth d/L. The relative depth determines whether waves are dispersive or nondispersive and whether the celerity, length, and height are influenced by water depth.

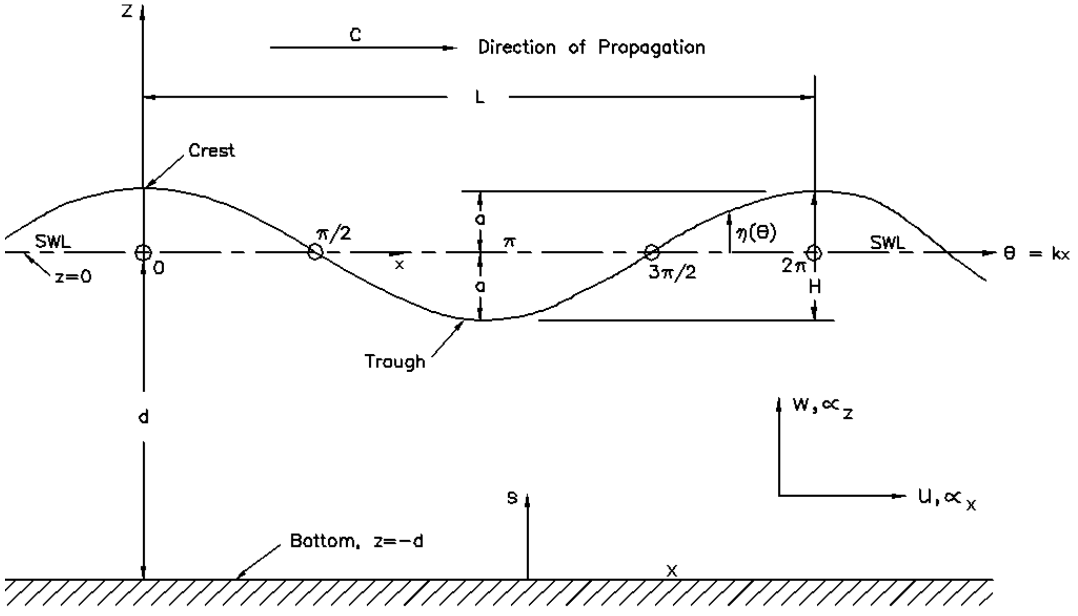


Figure 42: Definition of terms - sinusoidal, progressive wave. Source: (Dean and Dalrymple, 1984)

Wave steepness is a measure of how large a wave is relative to its height and whether the linear wave assumption is valid. Large values of the wave steepness suggest that the small-amplitude assumption may be questionable. A third dimensionless parameter, which may be used to replace either the wave steepness or relative water depth, may be defined as the ratio of wave steepness to relative water depth.

3.5.2 Resource Description

This section provides information on the theories and existing spectral models applicable in describing the wave energy resource. In this context, the methods for theoretical descriptions of a typical energy distribution and how the spectral parameters are derived from the wave spectrum is described using different wave energy spectral models. Initially, the method used in the preliminary analysis of the historical wave data is described. This is followed by description of the spectral models used to characterise and evaluate the wave energy resource.

Various properties about the sea state can be found from the wave spectrum. In designing offshore structures, it is often necessary to know the biggest waves produced by a given wind speed. This is because the sea often shows a seemingly random pattern of waves with different wave heights and frequencies which are super positioned. Different spectral models have been used to identify the properties of the wave train and how it transmits energy through the water. Some examples adopted from existing literature are used to form the basis for analysing the wave environment in for the resource assessment modelling developed in this framework.

3.5.2.1 Preliminary Analysis of The Historical Wave Data

In the preliminary analysis of the historical wave dataset, the first task is to find out any potential problems with the dataset and as such acquire more information from the data. However, for the statistical analysis of the historical wave dataset, it is assumed that the dataset should follow a normal distribution. For defining either the discrete or continuous functions of the random variables in the historical wave dataset, the theory of the probability distribution function is applied. In the case of discrete probability function, the random variables take on a finite number of values (i.e., there is no infinite value). In the case of a continuous probability function, the random variable (number) takes on an infinite number of values.

In addition, when a random variable takes on an infinite number of values the probability is equal to zero and the whole area under the curve must be equal to 1. The distribution function $D(x)$, also called the Cumulative Distribution Function (CDF), describes the probability that a variate X takes on a value less than or equal to a number x. The distribution function is sometimes also denoted $F(x)$ (Evans et al., 2000). Associated with a continuous random variable is the Probability Density Function (PDF). The probability function $P(x)$ of a continuous distribution is defined as the derivative of the (CDF) $D(x)$, given by the relationship in the formula:

$$D'(x) = P[P(x)]_{-\infty}^{x} = P(x) - P(-\infty) = P(x)$$ *Equation 9*

Equation 9 illustrates the relationship between the distribution function and a continuous probability density function *P(x)* The integration process is used to find the area under the curve. Thus, for a PDF the sum of the area must be equal to 1. In this context, the continuous random variables (X) are quantities whose values range over an interval of numbers. On the other hand, a variate is a generalization of the concept of a random variable that is defined without reference to a probabilistic experiment. It is defined as the set of all random variables that obey a given probabilistic law. Therefore, *P(x)* (when it exists), is simply the derivative of the distribution function.

$$P(x) = D'(x)$$ *Equation 10*

Similarly, the relationship between the distribution function and a discrete probability *P(x)* can be described using the formula:

$$D(x) = P(X \leq x) = \sum_{X \leq x} P(x)$$ *Equation 11*

3.5.2.2 Characteristics of The Spectral Parameters

An essential part of the development process for any proposed WEC farm is the resource description of the site. This involves the method for identifying the properties of the wave. The wave energy spectrum provides the means for describing the spectra parameters Generally, wave spectral models are presented in the form:

$$S(\omega) = \alpha\omega^{-p}\exp(-\beta\omega^{-q})$$ *Equation 12*

Where:
$S(\omega)$: refers to the wave energy spectrum
α: the wave amplitude or intensity of the Spectra
β : the shape factor
p: the peak factor
q: the quantity related to the wave frequency

Related to the wave spectrum is a series of characteristic numbers called the spectral moments. The spectral moment is just the variance of the surface. These numbers, when denoted are defined as: m_n, where n = (0,1,…n^{th}); with n^{th} being the n^{th} component of the spectral moment. This practice makes the n^{th} moment relationship useful in terms of quantifying or obtaining the properties of the wave (EPRI, 2011; Barstow et al., 2009). The zeroth moment (n=0, m_n=m_0) or the variance of the wave elevation is defined as the area under the spectral curve. The n^{th} moment relationship could be described and evaluated using the formula:

$$m_n = \int_0^{\infty} \omega^n \, S(\omega) d\omega \qquad \textit{Equation 13}$$

Where:

m_n: The m_n: The mean wave frequency $\overline{\omega}$ is the ratio of the first moment to the zeroth moment as shown in Equation14:

$$\overline{\omega} = \frac{m_1}{m_0}; \bar{T} = \frac{2\pi}{\overline{\omega}} \qquad \textit{Equation 14}$$

The zero-crossing frequency ω_z is the square root of the ratio of the second moment $m_2$to the zeroth moment m_0 as shown in Equation 15:

$$\omega_z = \sqrt{\frac{m_2}{m_0}} \qquad \textit{Equation 15}$$

The spectral peak frequency is the frequency for which $S(\omega)$ attains its maximum. It can be obtained by differentiating $S(\omega)$ with respect to ω and equating the result to zero i.e.:

$$\frac{dS(\omega)}{\omega} = \alpha\omega^{-p} \times q\beta\omega^{-q-1} \exp[-\beta\omega^{-q}] - \ p\alpha\omega^{-p-1} \exp[-\beta\omega^{-q}] = 0$$

$$\alpha{\omega_0}^{-p} \times q\beta{\omega_0}^{-q}{\omega_0}^{-1} \exp[-\beta{\omega_0}^{-q}] = p\alpha{\omega_0}^{-p}{\omega_0}^{-1} \exp[-\beta{\omega_0}^{-q}]$$

$${\omega_0}^{-q} = \frac{p/q}{\beta} \qquad \textit{Equation 16}$$

Equation 16 is the spectral peak or modal wave frequency ω_0. It could be rewritten as:

$$\omega_0 = (\frac{\beta}{p/q})^{1/q}; \beta = \frac{p/q}{\omega_0{}^{-q}}; \frac{p/q}{\beta\omega_0{}^{-q}} = 1; \beta\omega_0{}^{-q} = p/q$$ *Equation 17*

Substituting: $U = \beta\omega^{-q}$; in Equation12. In the general spectral model, we have that:

$$du = -q\beta\omega^{-q-1}d\omega; d\omega = -\frac{du}{q\beta\omega^{-q-1}}; \omega = \left(\frac{B}{u}\right)^{1/q}; \omega^n = \left(\frac{\beta}{u}\right)^{n/q}; \text{ and}$$

$$\omega^{-p} = (\frac{\beta}{u})^{-p/q}; \omega^{q+1} = (\frac{\beta}{u})^{(q+1)/q};$$

Therefore,

$$m_n = \int_{\infty}^{0} \left(\frac{\beta}{u}\right)^{n/q} \alpha \left(\frac{\beta}{u}\right)^{p/q} \exp(-u) \left(-\frac{du}{qB\omega^{-q-1}}\right) = \int_{\infty}^{0} \left(\frac{\beta}{u}\right)^{n/q} \alpha \left(\frac{\beta}{u}\right)^{p/q} \omega^{q+1} \exp(-u) \frac{du}{q\beta}$$

$$= \int_{0}^{\infty} \left(\frac{\beta}{u}\right)^{n/q} A \left(\frac{\beta}{u}\right)^{-p/q} \left(\frac{\beta}{u}\right)^{(q+1)/q} \exp(-u) \frac{du}{q\beta} = \frac{\alpha}{q\beta} \int_{0}^{\infty} \left(\frac{\beta}{u}\right)^{\frac{q+1+n-p}{q}} \exp(-u)du$$

$$m_n = \left(\frac{\alpha}{q\beta}\right) \beta^{\frac{q+1+n-p}{q}} \int_0^\infty U^{-\left(\frac{q+1+n-p}{q}\right)} \exp(-U)du$$ *Equation 18*

3.5.2.2.1 Neumann Spectrum

This is the first analytical spectral model that was used for engineering design purpose. It was developed in 1953 by Neumann and it is expressed in terms of wind speed, based on the following relationships:

$$S(\omega) = \alpha\omega^{-6} \exp\left[-\beta(\frac{\omega U}{g})^{-2}\right] = \alpha\omega^{-6} \exp\left[-2(\frac{\omega U}{g})^{-2}\right]$$ *Equation 19*

Given that:

$$\beta = 2\left(\frac{U}{g}\right)^{-2}; U = U_{10}\left(\frac{y}{10}\right)^{1/7}$$ *Equation 20*

Where:

y: refers to the vertical distance in meters above the average sea level commonly taken as 19.5m. Assuming:

$$\frac{dS(\omega)}{d\omega} = 0 \text{ at } \omega = \omega_0; \frac{dS(\omega)}{d\omega} = \alpha\omega^{-6} \times 2\beta\omega^{-3}\exp[-\beta\omega^{-2}] - 6\alpha\omega^{-7} \times \exp[-\beta\omega^{-2}] = 0$$

$$\alpha{\omega_0}^{-6} \times 2\beta{\omega_0}^{-3}\exp[-\beta{\omega_0}^{-2}] = 6\alpha{\omega_0}^{-7} \times \exp[-\beta\omega^{-2}]$$

$$\omega_0 = \left(\frac{\beta}{3}\right)^{1/2} \qquad \textit{Equation 21}$$

Alternatively, using Equation 17 given as: $\omega_0 = (\frac{\beta}{p/q})^{1/q}; \beta = \frac{p/q}{{\omega_0}^{-q}}; \frac{p/q}{\beta{\omega_0}^{-q}} = 1; \beta{\omega_0}^{-q} = p/q;$ in the general form we have that:

$${\omega_0}^{-q} = \frac{p/q}{\beta}; p = 6; q = 2;\ {\omega_0}^{-2} = \frac{3}{\beta};\ \omega_0 = (\beta/3)^{1/2} = \sqrt{\frac{2}{3}} \times \frac{g}{U}\ 0.8165\,\frac{g}{U}$$

$$\beta = 3{\omega_0}^2 \qquad \textit{Equation 22}$$

Substituting equation 22 in Equation 19, we obtain:

$$S(\omega) = \alpha\omega^{-6}\exp\left[-3(\frac{\omega}{\omega_0})^{-2}\right] \qquad \textit{Equation 23}$$

Recalling the general definition of the n^{th} moment, given in Equation 13; and comparing with Equation 18. Substituting:

$$U = \beta\omega^{-2};\ du = -2\beta\omega^{-3}d\omega;\ \omega = (\frac{B}{U})^{1/2};\ \omega^n = (\frac{B}{U})^{n/2};\ \omega^{-3}(\frac{B}{U})^{-3/2};\ \omega^{-3}d\omega = -\frac{du}{2B}$$

The zeroth moment (m_0) is obtained by calculating the area under the spectral curve so that:

$$m_n = \int_0^\infty \left(\frac{\beta}{U}\right)^{n/2} \alpha \left(\frac{\beta}{U}\right)^{-3/2} \exp[-U]\frac{du}{2\beta} = \frac{\alpha\beta^{\frac{(n-5)}{2}}}{2}\int_0^\infty U^{(3-n)/2}\exp[-U]du \qquad \textit{Equation 24}$$

Therefore:

$$m_0 = \frac{AB^{-5/2}}{2} \times \frac{3\pi^{1/2}}{4};\ \ m_1 = \frac{AB^{-2}}{2}; m_2 = \frac{AB^{-3/2}}{2} \times \frac{\pi^{1/2}}{2}; m_4 = \frac{AB^{-1/2}}{2} \times \pi^{1/2} = \frac{A}{2}\sqrt{\frac{\pi}{B}} \qquad \textit{Equation 25}$$

From Equation 25 α can be obtained as:

$$\alpha = \frac{8\beta^{5/2}m_0}{3\pi^{1/2}} = \frac{8(3\omega_0{}^2)^{5/2}(H_s{}^2/16)}{3\pi^{1/2}} = 1.466H_s{}^2\omega_0{}^5 \qquad \textit{Equation 26}$$

where:

H_S: is the significant wave height.

The Neumann Spectral model can be rewritten by substituting α and β in Equation 19 with $1.466H_s{}^2\omega_0{}^5$ and $3\omega_0{}^2$respectively. Therefore:

$$S(\omega) = 1.466H_s{}^2\omega_0{}^5\omega^{-6}\exp[-3\left(\frac{\omega}{\omega_0}\right)^{-2}] \qquad \textit{Equation 27}$$

Where:

H_S and $\omega\ _0$are given in terms of the wind speed, U.

3.5.2.2.2 Pierson-Moskowitz Spectrum

The most common relationships used in representing sea states all over the world is that originally proposed by Pierson-Moskowitz (P-M spectrum) in 1964 (Massel, 1996). The P-M model assumes that as wind blows steadily over a large area of the sea for a long period, it will eventually come to the state when the waves will reach a point of equilibrium with the wind. This state is often described as a fully developed sea (Pierson et al., 1964). P-M spectrum is one of the simplest descriptions for a typical energy distribution. It is found to be useful for representing severe storms and waves in offshore structural designs. In relation to wave energy resource assessment, spectral parameters derive from the wave spectrum follow the relationship between energy distribution and wind is given as:

$$S_{PM}(\omega) = A\omega^{-5}\exp[-B(\omega)^{-4}] = \alpha g^2\omega^{-5}\exp\left[-\beta(\frac{\omega U}{g})^{-4}\right] \qquad \textit{Equation 28}$$

Where:

$A = \alpha g^2$; $B = 0.74(\frac{\omega U}{g})^{-4}$; $\omega_0 = g/U_{19.5}$

$S_{PM}(\omega)$: the Pierson-Moskowitz Spectrum,

$\alpha = 8.1 \times 10^{-3}$: a numerical constant that controls the intensity of the Spectra,

$\beta = 0.74$: a numerical constant that controls the shape factor,

$\omega = 2\pi f$: f, is the frequency in Hertz,

g: gravitational acceleration(m/s),

$U_{19.5}$: the wind speed at a height of 19.5m above the sea surface (m/s).

The Spectral distribution of the P-M Spectrum is given in terms of wind speed. Both A and B were related to the wind speed 19.5m above the mean sea surface. A drag coefficient of 1.3 × 10^{-3} is often assumed in the literature sources, so that the frequency of the peak of the P-M spectra defined by a spectral peak frequency(ω_p) given by the formula:

$$S_{PM}(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\beta \left(\frac{\omega_p}{\omega}\right)^4\right] \quad \textit{Equation 29}$$

This is calculated by solving:

$$\frac{dS(\omega)}{d\omega} = 0\text{; For } \omega_p \text{ to obtain: } \omega_p = 0.877\, g/u_{19.5}$$

Where:

ω_p): peak wave frequency = $0.877g/\pi U_{19.5}$

$\alpha = 0.0081$: a numerical constant that controls the intensity of the Spectra,

$\beta = 1.25$: a numerical constant that controls the shape factor,

$\omega = 2\pi f$: f, is the frequency in Hertz.

P-M spectrum can be represented in terms of spectral peak period,ω_0, based on the assumption that:

$$\frac{dS(\omega)}{d\omega} = 0 \text{ at } \omega = \omega_0\text{; } \frac{dS(\omega)}{d\omega} = A\omega^{-5} \times 4B\omega^{-5}\exp[-B\omega^{-4}] - 5A\omega^{-6} \times \exp[-B\omega^{-4}] = 0$$

$$A\omega_0{}^{-5} \times 4B\omega_0{}^{-5}\exp[-B\omega_0{}^{-4}] = 5A\omega_0{}^{-6} \times \exp[-B\omega^{-4}]$$

$$\omega_0 = \left(\frac{B}{1.25}\right)^{1/4} \quad \textit{Equation 30}$$

As discussed in previous sections, the spectral peak or modal wave frequency ω_0 given in Equation17 could be applied to rewrite Equation 30. Given that:

$$\omega_0 = (\frac{B}{p/q})^{\frac{1}{q}}; B = \frac{p/q}{{\omega_0}^{-q}}; p = 5; q = 4;\ \omega_0 = (\frac{B}{5/4})^{\frac{1}{4}}; B = \frac{5/4}{{\omega_0}^{-4}} = \frac{1.25}{{\omega_0}^{-4}} \qquad \textit{Equation 31}$$

Therefore:

$$\mathrm{S}(\omega) = \mathrm{A}\omega^{-5} \exp[-1.25(\frac{\omega}{\omega_0})^{-4}] \qquad \textit{Equation 32}$$

$$\mathrm{B} = 1.25{\omega_0}^4 = 0.74(\frac{\mathrm{u}}{\mathrm{g}})^{-4}; {\omega_0}^{-4} = \frac{0.74}{1.25}(\frac{\mathrm{u}}{\mathrm{g}})^{-4}; \omega_0 = 0.877(\frac{\mathrm{g}}{\mathrm{u}}) \qquad \textit{Equation 33}$$

Similarly, recalling the general definition of the n^{th} moment, applied to describe and evaluate the n^{th} moment relationship given in Equation 13 and comparing with Equation 29. It follows that, substituting:

$$\mathrm{U} = \mathrm{B}\omega^{-4}; \mathrm{du} = -4\mathrm{B}\omega^{-5}\mathrm{d}\omega; \omega = (\frac{\mathrm{B}}{\mathrm{u}})^{1/4}; \omega^{\mathrm{n}} = (\frac{\mathrm{B}}{\mathrm{u}})^{\mathrm{n}/4}; \omega^{-5} = (\frac{\mathrm{B}}{\mathrm{u}})^{-5/4}; \omega^{-5}\mathrm{d}\omega = \frac{\mathrm{du}}{4\mathrm{B}}$$

$$m_n = -\int_{u=\infty}^{u=0} \left(\frac{B}{u}\right)^{n/4} A\, exp[-u]\frac{du}{4B};\ m_n = \int_0^\infty \left(\frac{B}{u}\right)^{n/4} \frac{A}{4B} exp[-u]du \qquad \textit{Equation 34}$$

$$m_n = \frac{AB^{(\frac{n-4}{4})}}{4}\int_0^\infty U^{-n/4}\, exp[-U]\, du \qquad \textit{Equation 35}$$

$$m_0 = \frac{AB^{-1}}{4} = \frac{A}{4B};\ m_1 = \frac{AB^{-3/4}}{4} \times r\frac{3}{4} = \frac{AB^{-3/4}}{4} \times 1.2254 \qquad \textit{Equation 36}$$

$$\mathrm{m}_2 = \frac{\mathrm{AB}^{-1/2}}{4} \times \pi^{1/2} = \frac{\mathrm{A}}{4}\sqrt{\frac{\pi}{\mathrm{B}}};\ \mathrm{m}_4 = \frac{\mathrm{A}}{4} \times \infty = \infty \qquad \textit{Equation 37}$$

The zeroth moment can equally be expressed in terms of the root mean square water surface elevation, σ; using the following relationships:

$$\mathrm{m}_0 = \sigma^2 = \frac{\mathrm{A}}{4\mathrm{B}} = \frac{\alpha \mathrm{g}^2}{4\times(5/4){\omega_0}^4};\ \sigma = \sqrt{\mathrm{m}_0} = \sqrt{\frac{\alpha}{5}} \times \frac{\mathrm{g}}{{\omega_0}^2} \qquad \textit{Equation 38}$$

In this case, the significant wave-height is calculated from the integral of S (ω) to obtain:

$$(\xi)^2 = \int_0^{\infty} S(\omega)d\omega = 2.74 \times 10^{-3}\frac{(U_{19.5})^4}{g^2}$$ *Equation 39*

Where:

$(\xi)^2$: the significant wave amplitude

g: gravitational acceleration (m/s)

$U_{19.5}$: the wind speed at 19.5m above the sea surface (m/s).

Significant wave amplitude (ξ_s) is given by:

$$\xi_s = 2\sigma = \sqrt{\frac{\alpha}{5}} \times \frac{2g}{{\omega_0}^2}$$ *Equation 40*

Where:

σ : the variance i.e. the root mean square water surface elevation,

g: gravitational acceleration (m/s),

ω_0: the spectral peak or modal wave frequency (radians/s)

It follows that the significant wave height H_s is given by:

$$H_s = 4\sigma = \sqrt{\frac{\alpha}{5}} \times \frac{4g}{{\omega_0}^2} = 0.161\frac{g}{{\omega_0}^2}$$ *Equation 41*

$$\omega_0 = \sqrt{\frac{0.161g}{H_s}}$$ *Equation 42*

The significant wave-height calculated from the Pierson-Moskowitz spectrum is:

$$H_{\frac{1}{3}} = 0.21\frac{(u_{19.5})^2}{g} \approx 0.22\frac{(u_{10})^2}{g}$$ *Equation 43*

Where:

g: gravitational acceleration (m/s),

$U_{19.5}$: the wind speed at 19.5m above the sea surface (m/s)

U_{10}: the wind speed at 10m above the sea surface (m/s).

The spectral significant wave height, H_{m0} (m); derived from the wave spectrum is commonly expressed as:

`

$$H_s \approx \sqrt{2H_{rms}} == H_{m0} = 4\sqrt{m_0}$$ *Equation 44*

The square root of the variance of the surface is the standard deviation of the surface. The standard deviation is a common measure for the variations about the mean and it is consistent in the approximation for the surface height variations. For historical reasons, it has become a standard to denote four times the standard deviation the significant wave height (Techet, 2005). The mean period (T_m) for a broad spectrum is estimated using the formula:

$$T_m \approx 2\pi \frac{m_0}{m_1} \quad \text{Equation 45}$$

Where:

m_0: the zeroth moment of the variance spectrum

m_1: first moment of the variance spectrum.

For a narrower spectrum, it is estimated as:

$$T_m \approx 2\pi \sqrt{\frac{m_0}{m_2}} \quad \text{Equation 46}$$

Where:

m_2: second moment of the variance spectrum.

It is worth emplacing that several other quantities can be calculated through the spectral moments. This is usually done directly at the buoy or weather station performing the wave measurements. With respect to the resource assessment model developed in this framework, the energy period, T_e(s) is calculated using the formula:

$$T_e = \frac{m_{-1}}{m_0} \quad \text{Equation 47}$$

Where:

$m_{-1}$and m_0: are the minus (first) and 0th moments of the wave spectrum. m_{-1} is defined as: $m_{-1} = \sum_{i=1}^{n} \frac{S(f_i)}{f_i} \Delta f_i$.

The mean energy period, T_e(s) is widely used to describe the sea state and is more robust than the peak period (due to a high sensitivity to spectral shape). The PM spectra defined by the significant wave height (H_s) and the peak wave period (T_p) is given by the formula:

$$S_{PM}(\omega) = 5\pi^4 \frac{H_s^2}{T_p^4} \cdot \frac{1}{\omega^5} \exp\left[-\frac{20\pi^4}{T_p^4} \cdot \frac{1}{\omega^4}\right]$$ *Equation 48*

Where;

ω: 2πf : f, is the frequency in Hertz.

H_s: significant wave height (m)

T_p: peak wave period (s)

The PM spectra defined by the significant wave height (H_s) and zero crossing period (T_z) is given by the formula:

$$S_{PM}(\omega) = 4\pi^3 \frac{H_s^2}{T_z^4} \cdot \frac{1}{\omega^5} \exp\left[-\frac{16\pi^3}{T_z^4} \cdot \frac{1}{\omega^4}\right]$$ *Equation 49*

Where:

ω: 2πf: f, is the frequency in Hertz

H_s: significant ant wave height (m)

T_z: peak wave period (s)

The mean wave direction θ_m(°) is given as:

$$\theta_m = \int_0^{2\pi} \int_0^{\infty} \theta S(f, \theta)\, df d\theta$$ *Equation 50*

Where:

$m_{-1}$and m_0: are the minus (first) and 0th moments of the wave spectrum, respectively, it has been already defined in previous pages.

$S(f, \theta)$: the spectral energy density ($m^2 H_z{}^{-1}$), which represents the energy distribution as a function of the frequency, f (Hz), and direction, θ(°).

The spectral width, is used to characterize the spreading of energy along the wave spectrum. It is calculated using the formula:

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}{}^2} - 1}$$ *Equation 51*

Where:

ϵ: is the spectral bandwidth parameter.

since the P-M spectrum is broad banded, it follows that as:

$$\mathrm{m}_4 \to \infty;\ \epsilon^2 = 1 - \frac{\mathrm{m}_2{}^2}{\mathrm{m}_0\mathrm{m}_4} \to 1$$ *Equation 52*

3.5.2.2.3 Bret-Schneider Spectrum

The Bret Schneider spectral model was obtained because of modifying the P-M spectrum (Lee and Kim, 2006). The model assumes that the spectrum is narrow-banded and the individual wave height and period follow the Rayleigh distribution (Holmes, 2001; Techet, 2005). The formula for the Bret Schneider (one-sided) ocean wave spectrum is:

$$S(\omega) = A\omega^{-5}\exp[-B\omega^{-4}]$$ *Equation 53*

Where:

B: 67.5% of $\omega_s{}^4$

A: $4\mathrm{Bm}_0$

ω: the modal (most likely) wave frequency.

The significant wave heights obtained from the modified P-M spectrum were smaller than those observed; so, it was then necessary to adjust B in spectral model to 67.5% of the original B; Equating B to $0.675\omega_s{}^4$ thus, giving rise to the new spectrum presented in Equation 53 (Techet, 2005). Therefore:

$$B = 0.675\omega_s{}^{-4}; A = 4(0.675\omega_s{}^{-4})\frac{H_s{}^2}{16} = 0.1688\omega_s{}^4 H_s{}^2$$ *Equation 54*

The spectrum (Equation 53) is derived for a fully-developed sea, but may also be acceptable for partially developed sea states. In such cases:

Significant wave frequency:

$$\omega_s = \frac{2\pi}{T_s}$$ *Equation 55*

Significant wave period:

$$T_s = 0.857T_0$$ *Equation 56*

Where:

$$T_0 = \frac{2\pi}{\omega_0};\ \omega_0 = (\frac{B}{1.25})^{1/4}$$ *Equation 57*

Studies (Hasselmann, 1974; Holmes et al., 2007) have shown that the significant wave period obtained from both P-M and Bret Schneider spectra are equivalent.

3.5.2.2.4 JONSWAP Spectrum

Hasselmann et al. (1973) also modified the Pierson-Moskowitz spectrum by multiplying it by adding the peak enhancement term. These adjustments were necessary due to the need for expressing the spectrum in terms of wave height and period, during the joint North Sea wave project (JONSWAP) (Hasselmann et al., 1973). This resulted to a peak-enhanced Pierson-Moskowitz spectrum. The JONSWAP spectrum is defined in terms of frequency (f) given by the formula:

$$S(\omega) = \frac{155}{{T_1}^4} {H_s}^2 \omega^{-5} \exp\left[-\frac{944}{{T_1}^4}\omega^{-4}\right] (3.3)^{\gamma}$$ *Equation 58*

Where:

γ: the peak-enhancement factor, having a default value of 3.3.

The effect of which is to increase the peak of the Pierson-Moskowitz spectrum (Hasselmann et al., 1973). Given that:

$$\gamma = \exp\left[-\frac{1}{2}\left(\frac{\omega-\omega_0}{\tau\omega_0}\right)^2\right] = \exp\left[-\frac{1}{2}\left(\frac{0.191\omega T_1 - 1}{\tau}\right)^2\right]$$ *Equation 59*

And the shape parameter:

$$\tau = 0.07;\ \omega \leq\ \omega_0\ and\ 0.09;\ \omega > \omega_0$$ *Equation 60*

Such that:

$$\omega_0 = \frac{5.24}{T_1};\ T_0 = 1.199T_1 = 1.287T_z$$ *Equation 61*

Alternatively:

$$S(f) = \beta {H_{\frac{1}{3}}}^2 {f_p}^4 f^{-5} \exp\left[-1.25(f_p f^{-1})^4\right] \gamma^{\exp[-{f_p}^{-1} f - 1^2/2\xi^2]}$$ *Equation 62*

Where:

$$\beta = \frac{0:0624}{0:23 + 0:0336\gamma - 0.185(1.9+\gamma)^{-1}}(1.094 - 0.01915\ In\gamma) \qquad \text{Equation 63}$$

And:

$$\xi = 0.07, f \le f_p; 0.09, f > f_p, \qquad \text{Equation 64}$$

This spectrum was later recommended by the 7th International Towing Tank Conference, ITTC, for limited fetch (Hasselmann, 1974).

3.5.2.2.5 ITTC Spectrum

The International Towing Tank Conference (ITTC, 1966, 1969, and 1972) modified the P-M Spectrum in terms of the significant wave height Hs and zero crossing frequency ωz given by the following formulas:

$$S(\omega) = A_1\omega^{-5}\exp[-B_1\omega^{-4}] \qquad \text{Equation 65}$$

$$A_1 = \alpha g^2;\ \alpha = \frac{0.0081}{k^4};\ B_1 = \frac{A_1}{4m_0} = 4A_1{H_2}^{-2} = \frac{4\alpha g^2}{{H_s}^{-2}} \qquad \text{Equation 66}$$

$$\sigma = \sqrt{m_0} = H_s/4 \qquad \text{Equation 67}$$

$$\omega_z = \sqrt{\frac{m_2}{m_0}} \qquad \text{Equation 68}$$

Following from Equation15 in the general form:

$$\omega_z = (\pi B_1)^{1/4} = \left(\frac{4\pi\alpha g^2}{{H_s}^2}\right)^{1/4} = \left(\frac{4\pi\times 0.0081g^2}{16\sigma^2k^4}\right)^{1/4} = \frac{0.2824(\frac{g}{\sigma})^{1/2}}{k} \qquad \text{Equation 69}$$

$$k = \frac{\left(\frac{g}{\sigma}\right)^{1/2}}{3.54\omega_z} \qquad \text{Equation 70}$$

$$A_1 = \alpha g^2\frac{0.0081}{k^4}g^2 = \frac{124}{{T_z}^4}{H_s}^2 \qquad \text{Equation 71}$$

$$B_1 = \frac{A_1}{4m_0} = 4A_1 {H_s}^{-2} \frac{496}{{T_z}^4}$$ *Equation 72*

Therefore, rewriting equation 59 in terms of significant wave height and zero crossing period we have:

$$S(\omega) = \frac{124}{{T_z}^4} {H_s}^2 \omega^{-5} \exp[-\frac{496}{{T_z}^4} \omega^{-4}]$$

Equation 73

Figure 43 illustrates the example of commonly used wave spectra using the wave energy density and frequency for certain sea stste. In addition to the short-term wave statistics presented above, long term sea state statistics are often given as a joint frequency table of the significant wave height and the wave energy period. From the long and short term, statistical distributions it is possible to find the extreme values expected in the operating life of a WEC. A WEC designer can find the most extreme sea states (extreme values of $H_{1/3}$ and T_1) from the joint frequency table, and from the wave spectrum the designer can find the most likely highest wave elevation in the most extreme sea states.

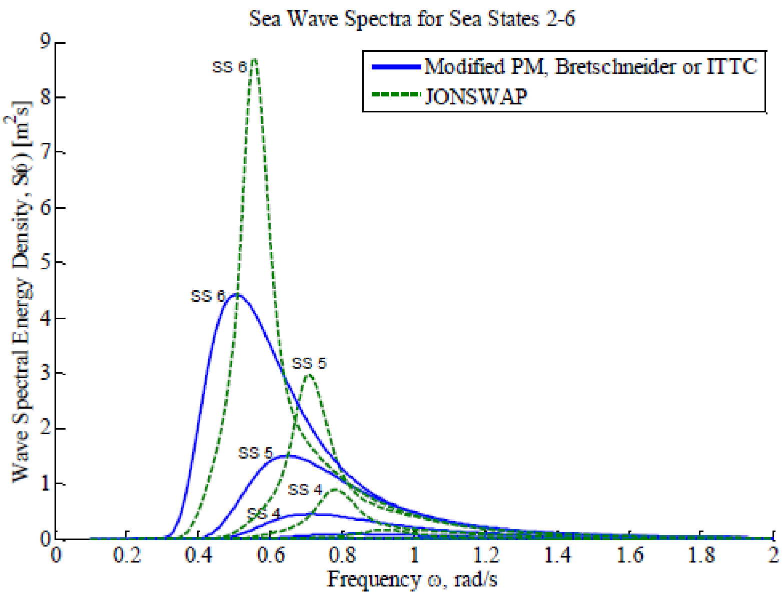


Figure 43: Examples of commonly used Wave Spectra plotted for Sea States 2-6 (Lee and Kim, 2006)

3.5.2.3 Wave Data Time Series Analysis

In the preliminary analysis of the wave data, a model relationship is used to describe the ocean flow surface for the of wave properties using the linear theory defined in previous sections. The probabilistic model can also be used to provide the basis of determining design wave conditions. In this methodology, wave energy resource description and distribution makes use of wave frequency tables (scatter Tables) showing certain combinations of the significant wave height and wave energy periods based on the preliminary analysis of the historical wave data for the selected site.

The reason is well defined and consistent parameters, such as the significant wave height, $\mathrm{H_s}$, and wave energy period, $\mathrm{T_p}$, an be applied to describe the sea state. For systems such as WECs which respond dynamically, more information on the significant waves heights associated with different wave energy periods is needed (García–Medina et al., 2014). It is in this context that the time series analysis used in this resource assessment model is applied to initially described the surface e flow parameters for preliminary analysis of the wave data. Assuming (x, y) are Cartesian co-ordinates with y = 0 at the still water level (positive upwards). The vertical coordinate (y), may be expressed as:

$$y = \eta(x, t) \qquad \textit{Equation 74}$$

Where:

x: the horizontal x-axis

t: time

η:the free water surface.

The mean elevation of the ocean surface is:$\mathrm{y} = 0$, while the impermeable bottom is at:
$\mathrm{y} = -\mathrm{d}$.

The reason for this is because, in the Cartesian coordinate (x, y) the still water which represents the surface is denoted by the positive upward force, whereas the impermeable bottom is normally denoted by the negative downward force in relation to the depth. The boundary conditions used to obtain a solution for wave motion are linearized, that is, applied at y = 0 not on the free water surface, y = η, hence the term Linear wave theory. It is important to also mention that a wave is a travelling disturbance. Therefore, an oscillating wave is a sine wave that that has a travelling disturbance sinusoidal pattern as can be seen in the general wave equation used in physics. A single sinusoidal wave travelling in the x-direction, can be defined in terms of its period and height:

$$\eta(x,t) = \alpha.\sin\left(kx - \omega t + \theta\right) = \frac{H}{2}\sin 2\pi\left(\frac{x}{L} - \frac{t}{T} + \theta\right) \qquad \textit{Equation 75}$$

Where:

α: the wave amplitude = H/2 (m)

k: the wave number = 2π/L (radians/m)

ω: the wave frequency = 2π/T (radians/s) [f is also used for wave frequency = 1/T (Hz)]

θ: is a phase angle.

The Energy (E) per unit surface area for a linear wave is:

$$E = \frac{\rho g \alpha^2}{2} \qquad \textit{Equation 76}$$

Where:

ρ : water density

g : acceleration due to gravity

a : wave amplitude

The wave can be defined by its height, H and its period, T, or by α^2, proportional to its energy and ω its frequency. A two-dimensional random sea, (all waves travelling in the x-direction) can be considered as the summation of many individual linear waves:

$$\eta(x,t) = \sum_{n=1}^{n=\infty} \alpha_n.\sin(k_n x - \omega_n t + \theta_n) \qquad \textit{Equation 77}$$

The assumption is that $\theta_n$are independent and uniformly distributed between zero and 2π.

3.5.3 Model for Energy Generation

In order to determine the theoretical energy that could be extracted from the ocean wave at an offshore location, a simple model is defined for the wave energy generation. In this case, it is assumed that the motion of the sea waves could be represented by the waveform given in terms of a simple harmonic motion with the formula:

$$y = \beta sin\frac{2\pi}{ƛ}(vt - x)$$ *Equation 78*

Where:

β: sea wave amplitude (m)

v: wave propagation velocity (m/s)

ƛ: wave length (m)

t: wave cycle time (s)

Given that:

v_p: is the particle velocity and $\frac{dy}{dt}$ is the infinitesimal increment in y, with respect to time t.

v_p: can be determined by differentiating Equation 78 with respect to time, so that:

$$v_p = \frac{dy}{dt}$$ *Equation 79*

Where:

$\frac{dy}{dt}$ is derived following:

$$\frac{dy}{dt} = \frac{2\pi\beta v}{ƛ} cos\frac{2\pi}{ƛ}(vt - x)$$ *Equation 80*

Work done (W) per unit volume of a displacement of dy is given by:

$$W = Fd = (ma)d = md\left(\frac{d^2y}{dt^2}\right)$$ *Equation 81*

Where:

W: denotes the work done by the system during the whole of the reversible process.

F: Force

d: displacement

m: mass

a: acceleration

$\frac{d^2y}{dt^2}$: denotes an infinitesimal increment of work done by the system, transferring energy to the surroundings. So, that:

$$W = \int \rho \left[\frac{4\pi^2\beta v^2}{\lambda^2}\sin\frac{2\pi}{\lambda}(vt - x)\right] dy$$ *Equation 82*

Work done at a distance y; i.e.: - 0 → y:

$$W = \int_0^y \rho \left[\frac{4\pi^2\beta v^2}{\lambda^2} \sin\frac{2\pi}{\lambda}(vt - x)\right] dy$$ Equation 83

Where:
ρ: the density of sea water.

The total wave energy of a wave system is defined as the sum of all components of the kinetic and potential energy of the wave system. This is described in the following section.

3.5.3.1 Average Annual Energy and Wave Power Assessment

This section describes the approach followed to evaluate the wave energy at the selected location in the resource assessment model in the integrated framework. It is recommended that annual and seasonal values be reported. Efforts geared towards developing the methodology for wave energy resource assessment are critical for developing knowledge of the physical conditions experienced by WEC devices and arrays. In this context, the objective of using cheap and freely available data that is consistent and reliable for preliminary assessment of the resource is achieved.

This will be of benefit to developing countries where there is scarcity and often unavailability of reliable data to provide information for resource assessment. Particularly in terms of cost reduction. Consequently, developers of WEC device and WEC farm operators can gather useful and reliable information for assessment of possible wave energy sites. However, the total energy (E) generated by the wave system of regular progressive wave is the sum of its kinetic energy (E_k)and potential energy(E_p). The kinetic energy is that part of the total energy due to water particle velocities associated with wave motion. It is the energy contained in the water mass from the free water surface to the bottom of the sea. The kinetic energy per unit length of wave crest for a wave defined with the linear theory can be found from the formula:

$$E_k = \frac{1}{2}\rho \int_{-\infty}^{0} \left[\frac{2\pi}{T} \; \alpha e^{kz}\right]^2 dz = \frac{1}{2}\rho\omega^2\alpha^2 \frac{1}{2k} = \frac{1}{4}\rho g\alpha^2$$ Equation 84

The part above the mean water level cannot be included in first order calculations and is thus not included in the integral. The potential energy is that part of the energy resulting from part of the fluid mass being above the trough: the wave crest. To evaluate the wave energy system, it is possible to calculate the potential energy by integrating over one wavelength which is calculated as the deformation work needed to give form to the wave. The potential energy per unit length of wave crest for a linear wave is given by the formula:

$$E_p = \frac{1}{\lambda}\int_0^{\lambda} \rho g \xi \frac{\xi}{2} dx = \frac{1}{4}\rho g \alpha^2 \qquad \text{Equation 85}$$

Where:
ρ: the fluid density
g: gravitational acceleration
α: the amplitude= $H/2$
ξ: the significant wave amplitude
λ: wave length

Based on the Airy theory, if the potential energy is determined relative to Still Water Surface (SWL), and all waves are propagated in the same direction, potential and kinetic energy components are equal, and the total wave energy in one wavelength per unit crest width is given by the formula:

$$E = E_p + E_k = \frac{1}{2}\rho g \alpha^2 \qquad \text{Equation 86}$$

Where subscripts k and p refer to kinetic and potential energies.

This is the energy per unit surface area for a linear wave, which turns out to be equal to the potential energy. The potential energy is due to wave height and kinetic energy is due to motion of water particles. As the wave progresses, it transfers energy from point to point in its direction. This proves that the energy of a wave is proportional to the square of the amplitude of the wave. The unit for the energy in this case is given as Joule per meter square (J/m^2). Furthermore, the specific energy or wave energy density (E_d), is the total average wave energy per unit surface area, given by the formula:

$$E_d = \frac{\rho g}{16} {H_s}^2 C_g \qquad \text{Equation 87}$$

Where:

E_d: is the wave power per metre of wave front corresponding to the class representative of each wave bin; the unit given as (kWm^{-1}).

ρ: is the seawater density(Kgm^{-3})

g:is the gravitational acceleration(ms^{-2})

$\mathrm{H_s}^2$: significant wave height (m)

Cg: is the group velocity (ms^{-1})

In engineering practice, a more common way to describe the energy in a wave system is the power per meter wave front (Cruz, 2008). This is also known as the wave energy flux. It is defined as the rate at which energy is transmitted in the direction of wave propagation across a vertical plan perpendicular to the direction of wave advance and extending down the entire depth (Alves and Sarmento, 2007). A report (Water Technology, 2004) confirms that the rate at which energy is transmitted in each direction of travel is relative to the wave height and group velocity expressed as wave power (P) by the equation:

$$P = E_d C_g$$

Equation 88

Where:

E_d: Wave Energy density,

$\mathrm{C_g}$: Wave group velocity.

Equation 88 proves that the total wave energy is the sum of the kinetic and potential energy components of the wave system given as E_d being wave energy density. The wave power is therefore defined as the potential available wave energy flux per unit width of wave crest. Therefore, the corresponding equation for direction of maximum directionally resolved wave power becomes:

For deep water:

$$P = \frac{\rho\, g\, H_s^2}{16}\,\frac{gT}{4\pi}$$

Equation 89

For shallow water:

$$P = \frac{\rho\, g\, H_s^2}{16} \frac{gT}{4\pi} \sqrt{gd}$$ *Equation 90*

The power of ocean waves is expressed in kW per meter wave crest front. An energy balance for a region through which waves are passing will reveal that, for steady state, the amount of energy entering the region will equal the amount leaving the region provided no energy is added or removed (Kinsman, 1965). Assuming linear theory holds, the average energy flux per unit wave crest width transmitted across a vertical plane perpendicular to the direction of wave advance is calculated by vertically integrating the work done per unit time at level y (being the vertical coordinate) (Le et al., 2009b). After the integration, the wave energy flux (energy transport) becomes:

$$\bar{\bar{J}} = \frac{1}{4}\rho g \alpha^2 = \frac{\omega}{k} = \frac{C}{2}E = C_g E$$ *Equation 91*

Where:

E: total energy generated by the wave system($\mathrm{kWm^{-1}}$).

$\bar{\bar{J}}$: the wave energy flux (energy transport)

g: acceleration due to gravity($\mathrm{ms^{-2}}$)

$\mathrm{C_g}$:the group velocity($\mathrm{m^{-2}}$)

k: wave number ($\mathrm{m^{-1}}$)

c: wave speed ($\mathrm{m/s}$)

ρ: the density of sea water($\mathrm{Kgm^{-3}}$)

Equation 91 implies that the wave energy travels across the ocean with speed equal to that of the group velocity. Note also that α is the wave amplitude as opposed to the wave Height, which is denoted as H, referring to the distance measured between the crest and the trough of the wave, making it twice the size of the wave amplitude. Rewriting Equation 91 with the wave Height the formula for the power per meter wave front becomes:

$$\bar{\bar{J}} = \frac{1}{32\pi}\rho g^2 T H^2$$ *Equation 92*

Where: the unit for J is W/m.

Therefore, the omnidirectional wave power, J which indicates the resource available, is the sum of the contributions to energy flux from each of the components of the wave spectrum:

$$J = \sum_i \rho g C_{g,i} S_i \Delta f_i \qquad \textit{Equation 93}$$

Where:
ρ: the density of sea water
g: acceleration due to gravity
$C_{g,i}$: the group velocity
S_i: the variance density, and
Δf_i: the frequency bin width at each discrete frequency index i

Dean and Dalrymple (1991) mentioned that the group velocity C_g, being the second component of the wave power train is largely dependent on the wave period and water depth. The group velocity can be calculated following linear wave theory expressed using the formula:

$$C_g = \frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)\left(\frac{gT}{2\pi}\tanh(kh)\right), \qquad \textit{Equation 94}$$

Where:
h: local water depth (d)(m)
k: wave number (m^{-1})
T: peak wave period(s)
g:gravitational acceleration (m/s)
$\mathrm{g\,T}/2\pi \tanh(2\pi \mathrm{h}/\mathrm{k}) = \mathrm{c}$: wave speed (m/s).

In deep and shallow waters, the equation for C_g can be simplified following Equation 95 and Equation 96 given below:

For deep water:

$$C_g = \frac{gT}{4\pi} \qquad \textit{Equation 95}$$

For shallow water:

$$C_g = \sqrt{gd} \qquad \textit{Equation 96}$$

3.5.3.2 Total Annual Energy Output Due to Availability

Determining the total annual energy is an important requirement in the process of estimating total cost of operating the WEC farm. This is one of the main benefits of the integrated framework for resource assessment and O&M modelling. For the preliminary assessment of the resource in deep water offshore conditions, the annual power per unit width of wave crest, which can also be referred to as the incident wave power ((J) in kilowatts per meter of wave energy device width, or kW/m) is estimated for a given measurement associated with each sea state using parameters ($\mathrm{H_s}$), and ($\mathrm{T_p}$). The incident wave power is estimated using the formula:

$$J = 0.42 \times (H_s)^2 \times T_p \qquad \textit{Equation 97}$$

Where: 0.42 is a multiplier (or fixed conversion factor) (Bedard, 2006) suitable for a well-represented two parameter Bret Schneider spectrum and it is exact for any sea state (EPRI, 2011).

To determine the necessary values of T_p from the datasets, it is common practice to employ fixed conversion factors based on a theoretical spectral shape such as Bret-Schneider or JONSWAP spectrums (Hasselmann et al., 1973). The reason is because these models are deemed as representative of the dominant local wave conditions. Although, depending on the exact shape of the wave spectrum; relative amounts of energy in sea and swell components, the multiplier value may range from 0.3 to 0.5 (Bedard, 2006; EPRI, 2011). Therefore, based on the values of (Hs) and ($\mathrm{T_p}$) for each measurement, the dataset could be sorted into the appropriate sea state bin.

The availability of the offshore wind farm is a well-known measure that show the power productivity of the offshore wind farm. In this methodology, the power-based availability is calculated. In previous sections the model for energy generation was described. The theoretical energy that could be extracted from the ocean wave at an offshore location was described as the total energy per unit volume Equation 86, which refers to the total sum of the kinetic and potential energy of the wave system. This is equivalent to theoretical energy that could be extracted from the wave resource.

The definition of the theoretical energy is as that of the wave energy density (E_d). Following Equations 89, 90 and 97, which represents the proportion of the annual power production to the theoretical power production, it follows that the total annual energy output due to availability may be obtained using formula:

$$Availability = \frac{Power\ Production}{Theoretical\ Power\ Production} \qquad \text{Equation 98}$$

Model predictions are especially useful when *in situ* measurements are not available for sufficiently long periods of time. In this thesis, an attempt is made to analyse the potential of wave energy extraction from specific sites by typically choosing a suitable source of primary data. Verification is through comparing the results of the simulations with sites where data are available. In the next section, the main input for investigating the O&M cost modelling in the integrated framework is described.

3.6 Operation and Maintenance Model

This section explains how the main input required for modelling the WEC farm O&M cost is analysed. In the O&M cost modelling the relationships between the main elements that contribute to total OPEX cost are analysed. To determine the Cost of Energy (CoE) from a WEC farm, it is necessary to understand the main attributes that make up the total operational cost of the WEC farm. In this case. the method followed to evaluate OPEX cost associated with the WEC farm is described based on a detailed analysis of the preventive and corrective maintenance attributes. Figure 44 illustrate the flowchart of the O&M modelling approach.

In the O&M modelling approach illustrated in the flowchart of Figure 44, the O&M input block is shown to ensure consistency in the integrated framework. A detailed explanation of the Resource Assessment input and O&M input in the integrated framework has been presented in Section 3.3 and Section 3.4 respectively. In this case the information in the marine operational environment block is an output of the Resource Assessment model based on the resources description as explained in previous pages.

The novelty of this modelling procedure developed in this framework, is that apart from modelling the relationships between the main factors directly contributing to the variation in the operational cost through the OPEX analysis, the integrated approach also considers other specific input of the project total initial cost and associated fees. This is necessary to investigate their influence on the total cost of the WEC farm and to distinguish between the O&M cost. In the end, the financial indicators are applied to assess the economic value of the WEC project.

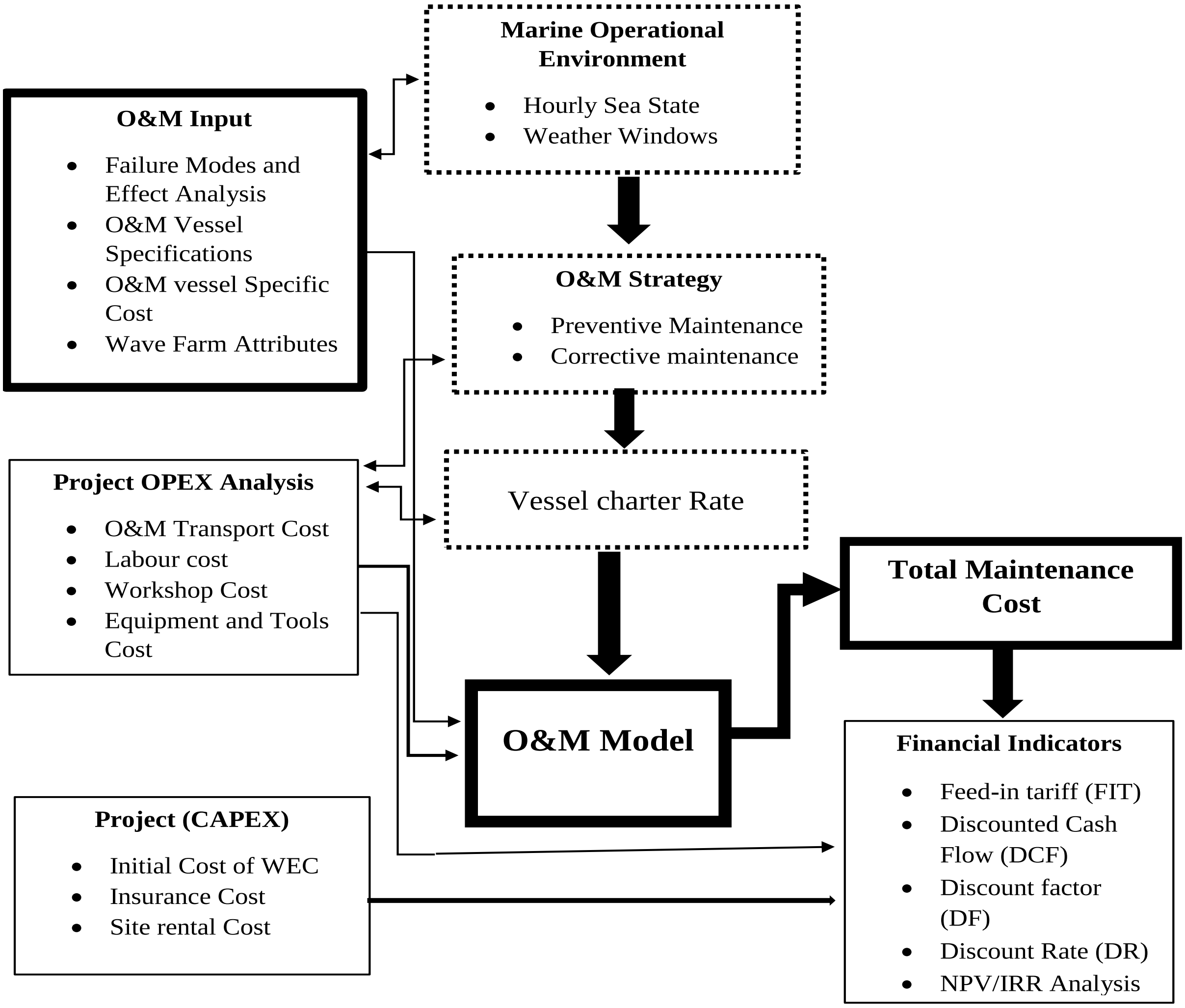


Figure 44: The O&M Modelling Approach

The methodology and modelling approach developed in this integrated framework will contribute to providing a holistic approach to investigate the variation in the O&M cost estimates. This is achieved by examining the O&M input parameters influencing the cost elements. Figure 45 illustrates the O&M model decomposed from the integrated framework for Resource Assessment and O&M cost modelling. In this case the output of the climate data input defined in the Resource Assessment model is introduce as a combined input to describe the wave farm attributes to investigate the marine operational environment in the O&M model.

Figure 45 shows the operational environment assessment tool. A detailed explanation of the different elements in the operational environment assessment tool is presented. This is the procedure for analysing the operational cost based on the O&M modelling in the integrated framework. The main contributors to the Total Maintenance Cost are the transport cost, labour cost, workshop cost, vessel charter cost and equipment /tools cost. Maintenance costs are computed separately for preventive and corrective maintenance activities with initial input from the wave farm attributes.

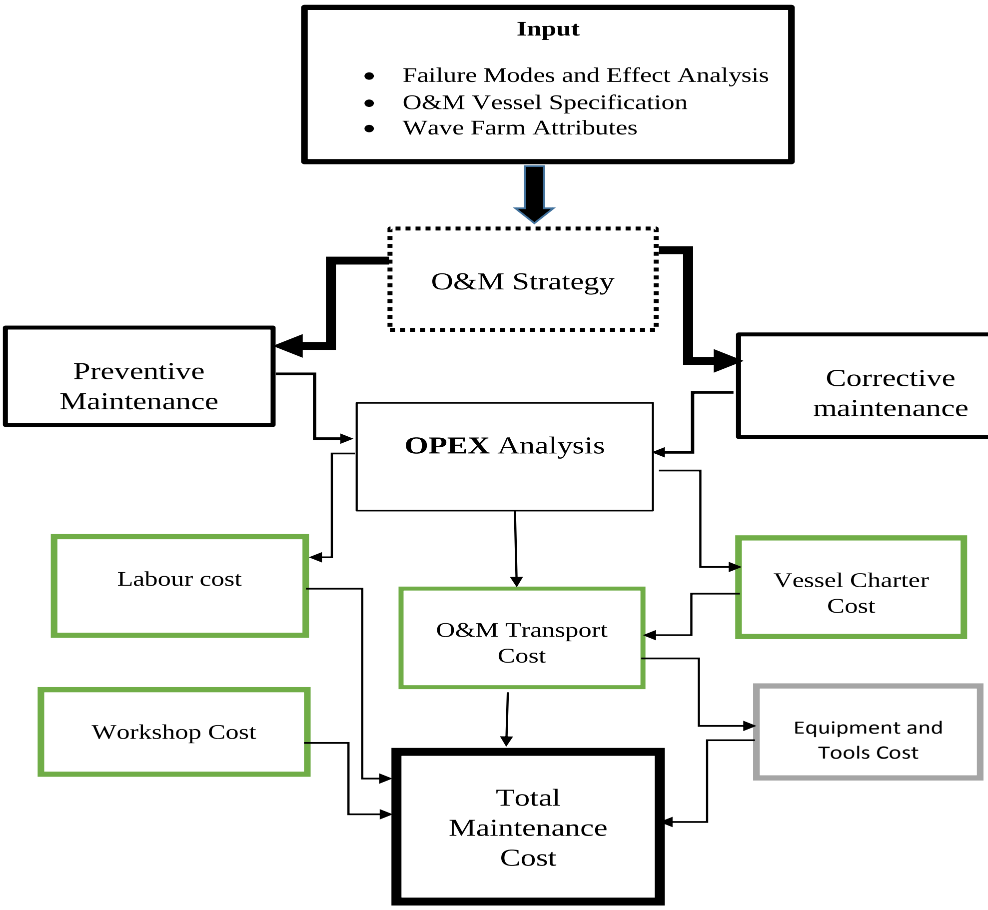


Figure 45: Operational Environment Assessment Tool Decomposition

The operational characteristics of the WEC are presented in Chapter 4 case study application of the methodology to illustrate the O&M modelling performed. In the end, different operational scenarios, associated with the cost of preventive and corrective maintenance actions are used to demonstrate the main findings in Chapter 6 results and discussions. As with any type of marine energy converter, the deployment, installation and activation of WECs induces a cost related to the actual O&M activities of the device. How the different cost attributes are estimated is explained in the following sub sections.

To ensure consistency in the structure of the presentation and framework developed in this thesis, in Figure 45 the combined input is shown in the input block. As mentioned in previous pages a detailed explanation of the Resource Assessment input and O&M input in the integrated framework has been presented in Section 3.3 and Section 3.4 respectively. The specific details for the FMEA table, O&M vessel specification and wave farm attributes has also been presented in subsections 3.4.1, 3.4.2 and 3.4.4 respectively. This is applicable to illustrate the method for assessing the operational environment in the integrated framework proposed in this thesis.

In the following sections, the elements of the operational environment assessment tool are described in detail. This is relevant for clarity and to understand the different parameters used to evaluate the O&M cost. This is followed by description the main attributes of the preventive and corrective maintenance cost model. Subsequently, the procedure for OPEX analysis is described based on different components contributing to the total maintenance cost and how they are estimated.

3.6.1 O&M Strategy

Having considered the RA input and O&M input in the flowchart of the integrated framework in Figure 39 as presented in previous pages, the combined input is also illustrated in Figure 44. Following the flow chart in Figure 45, this present section explains the O&M strategy. When deploying commercial devices which often are placed further offshore, O&M becomes an important cost driver for CoE for WECs (Bedard et al., 2005; Besnard et al., 2009). For this reason, the methodology and modelling approach develop for the integrated framework considers the maintenance strategies applicable to O&M of a typical WEC device to investigate the O&M cost estimate. The repair or maintenance activities of the WEC could be performed onsite or onshore in the maintenance workshop. The relevant O&M strategies include:

- Preventive Maintenance – Planned-Overhaul Replacement (Major/Minor)
- Corrective unscheduled Maintenance- Unplanned or Failure based Replacement

In this thesis, the methodology for estimating O&M cost of the WEC farm is carried out considering several attributes of major features for preventive and corrective maintenance. This include the identification of the transportation, labour, workshop and equipment/tools cost associated with these types of maintenance activities. All the different components are estimated for different operational scenarios as well as for the maintenance of a single device per day. In the end, the O&M cost per device is estimated as well as the cost per multiple WECs per day. The following sections describes the method for estimating the O&M cost.

3.6.1.1 Preventive Maintenance Cost

In this section, the various attributes of the planned or preventive maintenance cost are examined to provide the basis for estimating the total operational cost associated with the preventive maintenance activities. Generally, this involves the procedure for estimating the cost of both the onsite routine servicing and inspection for repair or replacement maintenance actions of the WEC at the WEC farm. Replacement maintenance entails fixing an existing or pending failure on one or more devices (Gulli, 2005).

Major replace activities such as overhauling will require the WEC to be taken temporarily off-line, thus entailing indirect costs of lost power (Black and Veatch, 2004). The major cost attribute associated with this O&M strategy include the transportation, labour, workshop and equipment cost. The study (Lazakis et al., 2013) demonstrated that these components can be estimated using formula:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq} \qquad \textit{Equation 99}$$

Where:

C_{pm}: preventive maintenance cost (£)

C_{trans}: transportation cost (£)

C_{lab}: labour cost (£)

C_{work}: workshop cost (£)

C_{eq}: equipment cost (£)

The repair or replacement maintenance cost for a WEC device in any specified year is calculated as the sum of the transportation, labour, workshop and material/equipment cost for that period. In this respect, the annual replacement cost is estimated based on the sum of the repair or replacement cost for each individual year, averaged over the entire project life. Hence the annual replacement costs over the entire project life can be estimated obtained using the formula:

$$ARC = \frac{\sum(Total\ replacement\ cost)}{Project\ years} \qquad \textit{Equation 100}$$

Where: ARC is the annual replacement cost.

It is important to note that the major factors affecting the components cost of replacement maintenance are failure rates, including the replacement cost for broken components and WEC downtime. However, the parameters for calculating the preventive and corrective maintenance activities are the same, the only difference is in the name.

3.6.1.2 Corrective Maintenance Cost

As in the process of estimating the preventive maintenance cost model, the corrective or unscheduled maintenance actions follows the same way and uses the same parameters as the preventive maintenance action. In this respect, the corrective maintenance cost is calculated using the formula:

$$C_{cm} = C_{trans} + C_{lab} + C_{work} + C_{eq} \qquad \textit{Equation 101}$$

Where:

C_{cm}: Corrective/unscheduled maintenance cost (£)
C_{trans}: Transportation cost (£)
C_{lab}: Labour cost (£)
C_{work}: Workshop cost (£)
C_{eq}: Equipment cost (£)

Comparing Equations 99 and 101, the parameters used for estimating the corrective maintenance cost is the same as that for the preventive maintenance strategy. Nevertheless, there are certain differences particularly when it involves estimating the failure rate and consequently the downtime caused by unexpected failures of different components. The unexpected failures of the different components of the WEC need to be considered. this will involve investigating the individual failure rate of each component affecting the annual availability of the WEC device.

The information on relating to failure rate for WECs are scarce and not readily available. The reason is that of WECs is still at its early stages of development with testing of prototypes and in some cases, full scale devices. The methodology and modelling employs a more general approach to investigate the failure rate so that it can be applied to any type of WEC when the information of failure rate is available. This is applicable to the O&M strategy described in this integrated framework. In this context, a valid alternative is suggested in relevant studies on O&M modelling (Lazakis et al., 2013).

This alternative involves the process of using actual failure rates from other related fields of research and application in the renewables sector (e.g. wind turbines, other renewable energy devices) adjusted to the subject case study by employing certain adjustment factor. In this case, two factors are relevant for the analysis of the failure rate. The first factor f_1, is for the naval underwater environment. The second factor f_2 is for the data uncertainty origination (e.g. data compiled from various sources such as research papers and other project reports) (Lazakis et al., 2013). The calculation of the failure rate for component can be performed using formula:

$$\lambda_n = \lambda_{orig} \times f_1 \times f_2 \qquad \textit{Equation 102}$$

Where:

λ_n: failure rate for n component

λ_{orig}: original failure rate

f_1: adjustment factor for naval underwater environment (Value 6.30)

f_2: adjustment factor for data uncertainty origination (1.10 +-10%)

Combining the individual failure rates for each device component, the overall device failure rate is estimated (Lazakis et al., 2013). Availability of a system is typically measured as a factor of its reliability (Wolfram, 2006). Studies (Walford, 2006) acknowledges that as reliability increases, so does availability. Moreover, availability of a system or device may also be increased by the strategy of focusing on increasing testability, diagnostics and maintainability (van Bussel and Zaaijer, 2003; Ambuhl et al., 2013).

Maintenance can be challenging but is extremely important for the safety of the equipment and its surrounding. Therefore, the availability is an important metric used to assess the performance of repairable systems, accounting for both the reliability and maintainability properties of a component or system. The device availability $\mathrm{A_d}$, is calculated by using the exponential distribution to provide the operational period during which the device may operate free of failures. That is:

$$A_d = 1 - e^{\lambda t} \qquad \textit{Equation 103}$$

Where:

$\mathrm{A_d}$: Device availability per year (%)

λ : Overall device failure rate

t: Time for which availability is accounted for

The reason for using the exponential distribution is due to the assumption that most reliability engineering problems can be modelled well by the exponential distribution. In a search for simplicity and solutions that can easily be understood, derived and communicated, many practitioners have embraced simple equations derived from the underlying assumption of an exponential distribution for reliability prediction and system reliability analyses. The exponential distribution models the behaviour of units that fail at a constant rate, regardless of the accumulated age.

In this context, the estimation of the overall annual availability of the device will enable the determination of the time that the vessels and equipment for the unexpected maintenance tasks will be needed as well (Lazakis et al., 2013). However, cost attributes which make up the operational expenditure cost of WEC farm have been highlighted. On-site maintenance would be required at specified periods for service or replacement, mooring inspection, fatigue inspection, while major maintenance would require the device to be returned to base. In the following section, a detailed description of how these cost components are estimated is presented. This will provide a clearer understanding of how the total O&M cost is derived.

3.6.2 OPEX Analysis

In this section, the major contributors to the total O&M cost are defined following the flow chart in Figure 45. It is expected that during the life span of the WEC farm, several scheduled and unscheduled maintenance activities would be performed in order to keep the WEC operational and to sustain the power generation.

3.6.2.1 O&M Transport Cost

For O&M of WEC small crew boats or a Crew Transfer Vessel (CTV) can be used to transport equipment and personnel to and from the WEC farm for O&M activities. Moreover, when the need arises the whole device can be towed to a maintenance harbour using a tug boat. For a proper assessment of the OPEX cost for running a WEC farm, it is relevant to first identify the main elements that contribute to the transportation cost. The different O&M vessels suitable for WEC farm O&M activities have been discussed in Chapter 2 critical review to support the development of this integrated framework for resource assessment and O&M cost modelling.

It is anticipated that the vessels with the ability to perform the O&M activities more efficiently in harsh conditions and with better structural condition would have higher daily charter costs (Dalgic et al., 2014). O&M actions on offshore WEC or near-shore WEC can be performed either offshore or onshore. Focusing on offshore maintenance actions, it becomes necessary to hire a boat (e.g. tug boat, small crew boats or CTVs), to access the WEC. Onshore O&M actions are mainly of importance for floating WECs. In that case the device is disconnected and towed to the maintenance harbour (Bussel and Bierbooms, 2003).

Onshore maintenance of WECs will require that the device be towed to a harbour where the maintenance actions can be performed. Therefore, the O&M vessel should be selected based on its capabilities and suitability for the operational environment in terms of carrying out the maintenance activity at the WEC farm. In this framework, a general approach is followed to describe the cost associated with WEC O&M transport. The reason is to make the integrated framework adaptable for assessment of any marine renewable energy converter.

In this respect, the cost associated with the O&M transport is considered as an outcome of two attributes. The difference between both attributes and the justification for it is that: in the first case, O&M vessel can be chartered, and in the second case, the O&M vessel can either be purchased out rightly as brand new vessels or built newly (new built). Assuming the first option is selected, then the O&M vessel will have an associated charter cost. In the instance when two maintenance vessels are required, then the associated vessel charter cost can be the combination of vessel 1 charter cost ($\mathrm{C_{vc1}}$) and vessel 2 charter cost ($\mathrm{C_{vc2}}$) calculated using the formula:

$$C_{trans} = C_{vc1} + C_{vc2}$$ *Equation 104*

Where:

$\mathrm{C_{trans}}$: transportation cost (£)

$\mathrm{C_{vc1}}$: vessel 1 charter cost (£)

$\mathrm{C_{vc2}}$: vessel 2 charter cost (£)

In this framework, O&M transport cost is considered for identifying the main attributes that contribute to the total O&M transportation cost. Assuming the second case is considered, then the new-built vessel will have an associated initial capital cost. In this respect, the associated cost is calculated using formula:

$$C_{trans} = C_{nb}$$ *Equation 105*

Where:

$\mathrm{C_{trans}}$: transportation cost (£)

$\mathrm{C_{nb}}$: vessel new built-capital cost (£)

The O&M strategy is applicable to help in achieving the objective of investigating the variation in the O&M cost estimates for maintenance activities of the WEC farm project. In this respect, the O&M cost modelling is used to examine the main attributes contributing the total O&M cost based on either the preventive or corrective O&M strategy. Since the components of the transport cost have been described, it is necessary to establish the criteria for estimating the daily charter cost for the vessels used in the O&M activities.

3.6.2.2 Estimation of the vessel charter cost

This section presents the method used for estimating the cost associated with vessel chartering. In this integrated framework two different types of vessels categories may be required for the O&M transport and logistics planning. These vessels are categorised as Small Vessel 1; being a small but suitable vessel for transporting of personnel to and from the WEC farm for on-site maintenance activities. The second is categorised as Big Vessel 2; being a big suitable for either towing the WEC and transporting the equipment and personnel for maintenance activities

There are different chartering option depending on the cost and suitability any vessel alternative may be selected. Studies (Dalgic et al., 2014; Lazakis et al., 2013b) mentioned that the charter option and the defined daily rate are closely connected to the total charter cost of the selected vessel. O&M vessel chartering options are described in Section 2.8.2 in Chapter 2 critical review. In this methodology, a more general approach is followed to ensure consistency in the information presented. Therefore, the cost associated with chartering one vessel is calculated using formula:

$$C_{vc_1} = T_1 \times R_1 \times (1 + f_{ves}) + C_f \qquad \textit{Equation 106}$$

Where:

C_{vc_1}: Vessel 1 charter cost (£)

T_1: time vessel 1 is chartered (hours)

R_1: daily rate for vessel 1 (£/day)

f_{ves}: vessel contingency factor for delays due to weather conditions (%)

C_f: annual Cost of fuel

Furthermore, the time that the maintenance vessel 1 is hired is equal to:

$$T_1 = T_{wf1} + T_{wf2} + T_{wf3} + T_{insp} \qquad \textit{Equation 107}$$

Where:

T_1: time that the maintenance vessel 1 is chartered

T_{wf1}: time to WEC farm (hours)

T_{wf2}: time in WEC farm (hours)

T_{wf3}: time to detach/attach one WEC (hours)

T_{insp}: inspection time per WEC

On the other hand, time to the WEC farm is equal to:

$$T_{wf1} = \left[2 \times \frac{Dist1}{(V_{sp1} \times 1.852)}\right] \times (1 + f_{ves}) \qquad \text{Equation 108}$$

Where:

Dist1: distance to the WEC farm (km)

V_{sp1}: vessel speed to reach WEC farm (knots)

f_{ves}: vessel contingency factor for delays due to weather conditions (%)

Furthermore, time in the WEC farm is equal to:

$$T_{wf2} = Dist2 + \left[2 \times \frac{Dist1}{(V_{sp2} \times 1.852)}\right] \times (1 + f_{ves}) \qquad \text{Equation 109}$$

Where:

Dist2: distance in the WEC farm (km)

V_{sp2}: vessel speed in the WEC farm (knots)

In addition, the time to detach the old WEC and attach the new WEC in place is calculated as:

$$T_{wf3} = (T_{rov} + T_{other}) \times (1 + \ f_{ves}) \qquad \text{Equation 110}$$

Where:

T_{rov}: time to mobilise/demobilise (ROV) from vessel (hours)

T_{other}: time other than ROV-bring WEC on board vessel (hours)

Following the procedure for estimating the transport cost as described above, the inspection time (T_{insp}) may vary depending on the time of the initial examination of the WEC. In this case, it may be considered on an hourly basis per device. In addition to the attributes of the O&M vessel cost already described, other cost specific attributes associated with the O&M

vessel cost are the fuel cost and crew cost. The method followed to estimate these additional cost specific attributes is described herein. In order to perform the preventive maintenance tasks based on the requirement for a single vessel, the cost of fuel needed can be estimated following:

$$C_f = D_{fc} \times D_{sea} \times P_{fuel} \times N_{main} \times Oil_{corf} \qquad \textit{Equation 111}$$

Where:

C_f: the cost of fuel needed

D_{fc}: daily fuel consumption (tons of fuel)

D_{sea}: days at sea

Pr_{fuel}: price of fuel (£/ton)

N_{main}: number of main engines (constant)

Oil_{corf}: lube & diesel oil correction factor set as 1.15 (constant)

On the other hand, the daily fuel consumption (D_{fc}), is estimated following:

$$D_{fc} = EP_{max} \times SF_{oc} \times F_{mean} \times 10^{-6} \times 24 \qquad \textit{Equation 112}$$

Where:

EP_{max}: engine power max (KW)

SF_{OC}: specific fuel oil consumption (gr/KW*h)

F_{mean}: (%) of main power output

In furtherance to the cost attributes described above, it is also relevant to estimate the cost of the crew that will be employed on board the O&M vessel. There is also labour cost associated with the vessel operation regardless of any charter strategy implemented. Assuming the vessel is chartered or purchased, the crew cost and vessel management fees will be applicable. However, with respect to vessel chartering and operation; staff cost refers to the cost associated with the vessel staff i.e. members of the vessel crew directly responsible for providing support and assistance to the technicians on board the vessel.

Assuming the vessel is charted on the spot market, the total cost of man hours will include the cost of the crew and technicians. In this respect the method followed to estimate the maintenance vessel crew cost is given using formula:

$$C_{crew} = \sum_{n}^{i=1} \mathrm{C}_{\mathrm{crew}_{\mathrm{i}}} = \mathrm{C}_{\mathrm{crew}_1} + \mathrm{C}_{\mathrm{crew}_2} + \cdots \mathrm{C}_{\mathrm{crew}_{\mathrm{n}}}$$ *Equation 113*

Where:

$\sum_{\mathrm{n}}^{\mathrm{i=1}} \mathrm{C}_{\mathrm{crew}_{\mathrm{i}}}$: cumulative crew cost (£)

$\mathrm{C}_{\mathrm{crew}_{\mathrm{i}}}$: the cost of each crew member employed on board the vessel (£)

Note that the cost of each crew member is estimated per number of crew needed on board the vessel employed, multiplied by a factor of two because the crew members employed on board any vessels are working on an on-off rota throughout the year. The vessel crew is assumed to be provided by the vessel owner and all the vessel staff costs are independent from the vessel utilisation. The total crew cost for the selected vessel is estimated based on agreed hourly rates. The reason is because, if the vessel is managed by the vessel owner, it is assumed that the charterer has no responsibility after the vessel leaves the site.

On the other hand, assuming a second maintenance vessel is required to work in tandem with the first maintenance vessel, the method for estimating the cost is given using the formula:

$$C_{vc2} = T_2 \times R_2 \times f_{ves}$$ *Equation 114*

Where:

$\mathrm{C}_{\mathrm{vc2}}$: vessel 2 charter cost (£)

T_2: time vessel 2 is chartered (days)

R_2: daily rate for vessel 2 (£)

$\mathrm{f}_{\mathrm{ves}}$: vessel contingency factor for delays due to weather conditions (%)

As in the case of the first maintenance vessel 1 charter, the time second maintenance that vessel 2 is chartered follows the same method as described above to estimate the cost. At this point it is necessary to describe other cost components mentioned earlier such as the labour, workshop and equipment/tools cost in the following sections.

3.6.2.3 Estimation of The Labour Cost

The labour cost refers to the cost for man hours, including cost of technicians or personnel responsible for performing the on-site inspections and maintenance/repair work. An hourly rate is used to estimate the cost of technicians or personnel required for performing the maintenance work. It is required that the owner of the vessel employs or contract the services of specialised maintenance technicians due to the high complexity and technicality of the O&M activities. In this respect, the labour cost can be estimated following:

$$\mathrm{C_{lab}} = \mathrm{N_{tech}} \times \mathrm{Tw_{ves}} \times \mathrm{T_{wt}} \times \mathrm{R_{ves}} \qquad \textit{Equation 115}$$

Where:

$\mathrm{C_{lab}}$: labour cost (£)

$\mathrm{N_{tech}}$: number of technicians (on board the vessel)

$\mathrm{Tw_{ves}}$: time working/vessel operation time (hours per day)

$\mathrm{T_{wt}}$: total working time (days)

$\mathrm{R_{ves}}$: rate/hour on vessel (£/hour)

Note that $\mathrm{T_{wt}}$, is the total working time spent for repairing all the devices in the WEC farm (which may be equal to the time (in days) that the maintenance vessel 1 is chartered ($\mathrm{T_{wt}} = \mathrm{T_1}$).

3.6.2.4 Estimation of The Workshop Cost

On top of the above, the Workshop cost ($\mathrm{C_{work}}$) is given by:

$$\mathrm{C_{work}} = \mathrm{Cw_{lab}} + \mathrm{C_{sp}} \qquad \textit{Equation 116}$$

Where:

$\mathrm{C_{work}}$: workshop cost (£)

$\mathrm{Cw_{lab}}$: workshop labour cost (£)

$\mathrm{C_{sp}}$: spare parts cost (£)

In addition to the above, the workshop labour cost ($\mathrm{Cw_{lab}}$) is specified following:

$$\mathrm{Cw_{lab}} = \mathrm{N_{tech}} \times \mathrm{T_w} \times \mathrm{T_{wt}} \times \mathrm{R_w} \qquad \textit{Equation 117}$$

Where:

$\mathrm{Cw_{lab}}$: workshop labour cost (£)

$\mathrm{N_{tech}}$: number of technicians (at the workshop)

$\mathrm{T_w}$: workshop working /operation time (hours)

$\mathrm{T_{wt}}$: total working time (days/year)

$\mathrm{R_w}$: workshop rate/hour (£)

Furthermore, the workshop spare parts cost ($\mathrm{C_{sp}}$) is given by:

$$C_{sp} = \sum_{n}^{i=1} \mathrm{C_{sp_i}} = \mathrm{C_{sp_1}} + \mathrm{C_{sp_2}} + \cdots \mathrm{C_{sp_n}} \qquad \textit{Equation 118}$$

Where:

$\sum_{\mathrm{n}}^{\mathrm{i=1}} \mathrm{C_{sp_i}}$: cumulative spare parts cost (£)

$\mathrm{C_{sp_1}}$: the cost of each spare part used for the device (£)

3.6.2.5 Estimation of The Equipment and Tools Cost

The cost of equipment and tools ($\mathrm{C_{eq}}$) needed to perform the preventive maintenance tasks is given by:

$$\mathrm{C_{eq}} = \mathrm{C_{rov_1}} + \mathrm{C_{rov_2}} + \mathrm{C_{other}} \qquad \textit{Equation 119}$$

Where:

$\mathrm{C_{eq}}$: equipment cost (£)

$\mathrm{C_{rov_1}}$: cost for using ROV 1-inspection ROV (£)

$\mathrm{C_{rov_2}}$: cost for using ROV 2-working ROV (£)

$\mathrm{C_{other}}$: other equipment cost including tools (£)

In this case, the cost for employing ROV 1 and ROV 2 are calculated as shown next:

$$\mathrm{C_{rov_1}} = \mathrm{T_{rov_1}} \times \mathrm{f_{rov_1}} \times \mathrm{R_{rov_1}} \qquad \textit{Equation 120}$$

Where:

$\mathrm{T_{rov_1}}$: time ROV 1 is working, equal to vessel 1 operation time (days /year)

f_{rov_1}: contingency factor for not using ROV 1 due to weather conditions

R_{rov_1}: rate/day for ROV 1 (£)

Similarly, the cost for employing ROV 2 (working ROV) is provided by the following formula:

$$C_{rov_2} = T_{rov_2} \times f_{rov_2} \times R_{rov_2}$$ *Equation 121*

Where:

T_{rov_2}: time ROV 2 is working, equal to vessel 1 operation time (days /year)

f_{rov_2}: contingency factor for not using ROV 2 due to weather conditions

R_{rov_2}: rate/day for ROV 2 (£)

The cost for any other equipment/tools that will be used on board the vessel for the service and maintenance operations of the WEC farm is specified by:

$$C_{other} = \sum_{n}^{i=1} C_{other_i} = C_{other_i} + C_{other_2} \dots + C_{other_n}$$ *Equation 122*

Where:

$\sum_{n}^{i=1} C_{other_i}$: cumulative cost for any other equipment/tools used on board the maintenance vessel (£)

C_{other_i}: the cost for any other equipment/tools used on board the maintenance vessel (£)

3.6.3 Total Maintenance Cost

In the previous sections the OPEX analysis have been used to describe how the different cost components are estimated. However, the O&M cost is driven by the Total maintenance cost (T_{mc}), which is derived as the summation of the preventive and corrective maintenance costs using the formula:

$$T_{mc} = C_{Pm} + C_{cm}$$ *Equation 123*

Where:

T_{mc}: Total maintenance cost (£)

C_{Pm}: Preventive maintenance cost (£)

C_{cm}: Corrective maintenance cost (£)

Furthermore. when the entire WEC farm project is considered, $\mathrm{T_{mc}}$ should be maximised for the WEC farm and not just for a single device alone. In this respect, other attributes relating to the overall WEC farm project need to be estimated. For example, when considering preventive maintenance these other attributes may include: the preventive maintenance cost per device ($\mathrm{C_{pm1}}$), preventive maintenance cost per MW (gross: $\mathrm{C_{pm2}}$, and net: $\mathrm{C_{pm3}}$,) and the preventive maintenance cost per kW hr ($\mathrm{C_{pm4}}$).

The method followed to determine these attributes are described in the following section. Estimating the preventive maintenance cost per device $\mathrm{C_{pm1}}$, is determined using the formula:

$$\mathrm{C_{pm1}} = \frac{\mathrm{C_{pm}}}{\mathrm{N_{WEC}}} \qquad \textit{Equation 124}$$

Where:

$\mathrm{C_{pm1}}$: preventive maintenance cost per device

$\mathrm{C_{pm}}$: preventive maintenance cost (£)

$\mathrm{N_{WEC}}$: number of devices used in the WEC farm project

The preventive maintenance cost per MW (gross) $\mathrm{C_{pm2}}$,refers to the cost of the total amount of electric power generated by the WEC during the given period. This can be estimated using the formula:

$$\mathrm{C_{pm2}} = \frac{\mathrm{C_{pm}}}{\mathrm{Cap_{wec_{gr}}}} \qquad \textit{Equation 125}$$

Where:

$\mathrm{C_{pm2}}$: preventive maintenance cost per MW (gross)

$\mathrm{C_{pm}}$: preventive maintenance cost (£)

$\mathrm{Cap_{wec_{gr}}}$: gross capacity of WEC farm

It follows that:

$$\mathrm{Cap_{wec_{gr}}} = \mathrm{Cap_{Sgr}} \times \mathrm{N_{WEC}} \qquad \textit{Equation 126}$$

Where:

$\mathrm{Cap}_{\mathrm{Sgr}}$: single device output capacity gross (MW)

In addition to the above, the preventive maintenance cost per MW (net) $\mathrm{C}_{\mathrm{pm3}}$, is estimated using the formula:

$$\mathrm{C}_{\mathrm{pm3}} = \frac{\mathrm{C}_{\mathrm{pm}}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}} \qquad \textit{Equation 127}$$

Where:

$\mathrm{C}_{\mathrm{pm3}}$: preventive maintenance cost per MW (net)

C_{pm}: preventive maintenance cost (£)

$\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}$: net capacity of WEC farm

It follows that:

$$\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}} = \mathrm{Cap}_{\mathrm{S}_{\mathrm{net}}} \times \mathrm{Cap}_{\mathrm{wec}_{\mathrm{gr}}} \qquad \textit{Equation 128}$$

Where:

$\mathrm{Cap}_{\mathrm{S}_{\mathrm{net}}}$: single device output capacity net (MW)

$$\mathrm{Cap}_{\mathrm{S}_{\mathrm{net}}} = \mathrm{Cap}_{\mathrm{Sgr}} \times \mathrm{f}_{\mathrm{cap}} \times \mathrm{f}_{\mathrm{p}} \qquad \textit{Equation 129}$$

Where:

$\mathrm{Cap}_{\mathrm{Sgr}}$: single device output capacity gross (MW)

$\mathrm{f}_{\mathrm{cap}}$: capacity factor (%)

f_{p}: power generation availability (%)

Furthermore, the preventive maintenance cost per (kwh) ($\mathrm{C}_{\mathrm{pm4}}$, is estimated using the formula:

$$\mathrm{C}_{\mathrm{pm4}} = \frac{\mathrm{C}_{\mathrm{pm}} \times 10^{2}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{T}}} \times 10^{6}} \qquad \textit{Equation 130}$$

Where:

$\mathrm{C_{pm4}}$: preventive maintenance cost per kwh

$\mathrm{C_{pm}}$: preventive maintenance cost (£)

$\mathrm{Cap_{WEC_T}}$: total WEC fam net capacity (output) (MW/hr/year)

Furthermore:

$$\mathrm{Cap_{WEC_T}} = \mathrm{Cap_{WEC_{net}}} \times N_{WEC} \qquad \textit{Equation 131}$$

The sane process is followed to estimate the corrective maintenance cost per device ($\mathrm{C_{cm1}}$), corrective maintenance cost per MW gross ($\mathrm{C_{cm2}}$) and net ($\mathrm{C_{cm3}}$) and the corrective maintenance cost per kwh ($\mathrm{C_{cm4}}$). The equations described above are the same. The only difference is using the corrective maintenance cost in the place of the preventive maintenance cost respectively. Having examined the cost parameters for estimating the total maintenance cost for a combination of input of the farm attributes in terms of the preventive and corrective maintenance sequence, the next section examines the elements that may contribute to WEC farm project total initial cost and describes the method to evaluate the associated cost.

3.6.4 Project (CAPEX)

In the methodology and modelling developed in this integrated framework, the project capital cost is identified in the flowchart of Figure 39. This is applicable to illustrate other cost components such as the initial cost of the WEC, insurance cost and site rental cost. The reason is that these cost elements are associated cost that can contribute to the overall cost of WEC farm project. Therefore, they are examined in this integrated framework to differentiate between the O&M cost, project capital cost and associated fees in the O&M modelling approach illustrated in Figure 44.

3.6.4.1 • Initial cost of WEC

As described in Figure 44 illustrating the O&M modelling approach in the integrated framework, the initial cost of WEC refers to the cost of purchasing a single unit of the WEC device. In relation to the project capital cost, this refers to the Total Initial Cost (TIC) incurred in purchasing the WEC device and constructing the WEC farm. The TIC is relevant in this framework because it provides the information relating to other associated cost which are not directly related to the O&M cost estimates, but are necessary to investigate other cost elements contributing to the total WEC farm project cost. This is relevant for analysis of annual cash flow to assess the economic value of the WEC farm project.

The total cost of the WEC farm is calculated as the sum of the capital cost, which represents the initial cost of purchasing the WEC (IC_{WEC}), the O&M cost and associated fees. In this respect, the main cost elements contributing to the total WEC farm cost are analysed. A report (Sharkey et al., 2011) suggested that the CAPEX could be quantified as either dry or wet CAPEX. In this context, the dry CAPEX quantification addresses the costs associated with manufacturing cost components. The wet CAPEX quantification considers the grid connection costs. This is estimated using electrical inter-array network.

The life time capital cost ($\mathrm{Life}_{\mathrm{Cap}}$) of a WEC farm is a related to the dry CAPEX if it only considers the initial capital cost of buying or manufacturing the WEC device (Carbon Trust, 2011). On the other hand, the wet CAPEX estimates the grid connection costs. For example, the cable cost for electricity transmission, the distance from the WEC farm to the local grid connection including the cost of installation and decommissioning the cable (Beels et al., 2011). In this respect, the life time capital cost ($\mathrm{Life}_{\mathrm{Cap}}$) of a WEC farm, is estimated by multiplying the unit capital cost of the WEC device, which is the sum of the cost of purchasing one WEC device, including the installation and decommissioning the WEC, with the total number of WECs in the farm as follows:

$$Life_{cap} = \sum_{wec} \sum_{y} IC_{wec_y} = N \times Unit_{cap} \qquad \textit{Equation 132}$$

Where

N: the total number of WECs in the farm.

$\mathrm{Unit}_{\mathrm{Cap}}$: the unit capital cost of the component.

$\sum_{\mathrm{wec}} \sum_{\mathrm{y}} \mathrm{IC}_{\mathrm{wec}_{\mathrm{y}}}$: the sum of the cost of purchasing one WEC device in the year, y.

The unit capital cost ($\mathrm{Unit}_{\mathrm{Cap}}$) is given as:

$Unit_{cap} = IC_{wec} + D_{offhsore} \times Cable_{unit}$ *Equation 133*

Where:

$\mathrm{IC_{wec}}$: the initial capital cost of one WEC device including the cost of manufacturing, installing, and decommissioning.

$\mathrm{D_{offshore}}$:` the offshore distance from the farm to the local grid connection,

$\mathrm{cable_{unit}}$: the unit cable cost which is the sum of the per meter cost of manufacturing, installing, and decommissioning a cable.

3.6.4.2 Insurance

The insurance cost as described in Figure 44 illustrating the O&M modelling approach in the framework is linked to the project CAPEX model because it represents the cost associated with the WEC farm initial cost. This aspect is considered to assess the impact of insurance on the net present value of a project. Insurance rates are selected according to the specific project requirement and calculated by multiplying the rates with the Total initial cost (TIC) or project CAPEX using the formula:

$Insurance = TIC \times Insurance\,\%$ *Equation 134*

Where:

TIC: the total cost incurred in purchasing the WEC and constructing the farm

Insurance %: is the percentage rate chosen for insurance.

3.6.4.3 Site rental

In addition to the insurance cost, the site rental is considered as an associated cost in relation to the project CAPEX or TIC. Associated fees may include the costs of permitting, licensing, and certification. Studies (Dalton and Gallachóir, 2010) mentioned that the permitting fee is dependent on the number of WEC device in the farm. On the other hand, the licensing and certification are not (Fingersh et al., 2006). The permitting cost are highly dependent on the policy of the regulatory agencies (Fingersh et al., 2006; Li et al., 2010). Site rental is often calculated based on the rental cost of offshore generating stations (O’Sullivan and Dalton, 2009; Dalton and Gallachóir, 2010) using the formula:

$$Site\ Rent = Gross\ Revenue\ \times Rent\ \%$$ *Equation 135*

Where:

Rent%: is the percentage rate chosen for Rent.

In this methodology, fees are assumed to be a one-off cost as in the case of capital cost. The integrated framework developed in this research seeks to include a quantification of the costs associated with all the relevant phases that contributes to variation in the WEC farm cost estimates. The TIC of the WEC device is considered based on the estimated manufacturing cost available in existing literature. In the end, a financial indicator which employs discounted cash-flow techniques to produce selected economic indicators are also illustrated.

3.6.5 Financial Indicators

As described in Figure 44 illustrating the O&M modelling approach in the integrated framework, to help achieve the objective of establishing the criteria for assessing the economic value of the WEC farm project, the financial indicator block is incorporated to the methodology and modelling in this integrated framework work. This aspect also represents part of the novelty and contribution of this research methodology to knowledge. In this integrated framework, the financial indicator block is employed as a tool for assessing the economic value of the electricity generation project using WEC technology. This tool is necessary to support investment decisions in the development of wave farms and in the development of wave energy converter (WEC) technology.

A financial indicator may be defined as a piece of economic data employed by analysts to make financial calculations. This is used to interpret current or future investment possibilities or to judge the overall health of a project. The economic assessment of a project is subject to the established financial and political policies governing the local market where the project is undertaken. The financial indicators can be anything the investor chooses. Specific pieces of data released by government and non-profit organizations have become widely acceptable (Dalton and Gallachóir, 2010; O’Connor et al., 2013). In this integrated framework, the financial indicator block employs discounted cash-flow techniques to produce selected economic indicators.

The indicators which it can produce include: Net Present Value (NPV), Internal Rate of Return (IRR). In this respect, the main financial input required to illustrate the economics of the WEC farm in O&M cost modelling is described. By doing so, the costs occurring at each phase of the project lifecycle can be estimated. The main financial input considered include: Feed-in tariff (FIT), Discount Factor (DF), Discount Rate (DR), Net Present Value (NPV) and Internal Rate of Return (IRR). The method used in analysing the financial calculations to illustrate the economic viability of the wave energy farm is discussed in the following section.

3.6.5.1 Feed-In Tariff (FIT)

In the case of offshore renewable energy, financial indicators may include traditional financial assumptions such as: tax rates, Renewable Energy Feed-in-Tariff (REFIT) and Renewables Obligation Certificate (ROC), used in alignment with financial practice of the wave energy project (Dalton et al., 2012). In the UK, the ROC is issued to eligible operators supplying electricity to the national territory with green power for each MWh they produce (Allan et al., 2011). In this integrated framework, the Feed-in-Tariff (FIT) is one of the financial assumptions used to assess the economic value of the electricity generation project.

A study (Sijm, 2002) defined Feed-in tariff (FIT) as the regulatory minimum guaranteed price per kWh that an electricity utility company should pay to a private independent producer of renewable power fed into the grid. Grid sales are a credit and are added to other negative cost values for each year. Grid sales are product of two variables such as: the electricity tariff rate from the utility company and the total annual energy output, being the total energy produced each year.

3.6.5.2 Discounted Cash Flow (DCF)

Discounted Cash Flow (DCF) may be defined as a valuation method used to estimate the attractiveness of an investment opportunity. The DCF technique tries to calculate the present value of a project based on projections of how much money it is going to make in the future. In DCF analysis, future free cash flow projections are employed based on their discounted values. This is applied to investigate the amount of money that would circulate within the project with respect to the CAPEX, OPEX, and revenue. A discount rate is applied to arrive at a present value estimate which is used to evaluate the potential for investment. In cost considerations, the discounted present values, C_0, are always important and it is given as (Henderson, 2008):

$$C_0 = \frac{C}{(1+r)^T} \qquad \text{Equation 136}$$

Where:

C_0: the discounted present values

C: is the real cost

T: is the time in years when the cost occurs

r: is the annual real rate of interest

3.6.5.3 Discount Factor (DF)

The discount factor (DF), may be defined as the percentage rate required to calculate the present value of a future cash flow. A discount factor can be thought of as a conversion factor for calculating the time value of money. The principle of calculating time value of money is built on the idea that funds placed in a secure investment earn interest over time. In relation to the discount factor is the compounding principle which states that if a certain amount of money is invested in the present value, the future value will increase over a time.

In this methodology, the DF is used to convert all cost and benefits associated with the WEC farm project life cycle into present monetary values. The idea is to investigate whether the investment potential is secure. The future value of the amount invested can be converted to the equivalent present value by multiplying the future value by the discount factor. The discount factor is calculated using the discount rate and can be defined using the formula (Henderson, 2008):

$$DF = \frac{1}{(1+DR)^n} \qquad \text{Equation 137}$$

Where:

n: the length of payback time

DR: the discount rate i.e. an interest rate commensurate with perceived risk used to translate future payments or receipts to present cash value.

3.6.5.4 Discount Rate (DR)

The discount rate accounts for the time value of money. This is based on the principle that the value of the currency today is worth more than the value of that same currency tomorrow. The reason is that the currency today has the capacity to earn interest in future. The Discount Rate, DR%, used in the discount factor formulas is the effective rate per period. It employs the same basis for the period (annual or monthly) as used for the number of periods, n. If the nominal interest rate (rate per annum or rate per year) is known, the discount rate can be calculated using the formula:

$$DR = \left(1 + \frac{r}{k}\right)^{\frac{k}{p}} - 1$$ *Equation 138*

where
r: nominal annual interest rate
k: number of compounding periods per year
p: number of periods per year corresponding to the basis for n

In addition, the discount factor for multiple device is calculated based on a cumulative factorial reduction in price (Dalton et al., 2012). Device manufacturers provide some form of discount to encourage multiple purchases. This makes cost of purchasing multiple devices cheaper than buying a singular device (Allan et al., 2011). The sum of the discounted costs is obtained using the formula:

$$Total\ ICwec = \sum_{1}^{n} P_n \times ICwec_n$$ *Equation 139*

Where:
$\mathrm{ICwec_n}$: the Initial cost of the WEC per device (£)
n: cumulative total of number of devices representing the sum of the discounted cost,
P: percentage reduction used in (initial cost) costing for WEC, derived using formula:

$$P = N^{in(bdf)/in(2)}$$ *Equation 140*

Where:

N : the number of WEC components,

$'\mathrm{bdf}'$: the bulk discount factors.

3.6.5.5 NPV and IRR Analysis

For a WEC farm project to be commercially attractive it must be technically feasible as well as economically viable. Studies (Stallard et al., 2009; Callaghan, 2006) acknowledged the use of well-established methods such as the Present Value (PV) approach for assessing the economic performance of wave energy conversion projects. Net Present Value (NPV) may be defined as the difference between the Present Value (PV) of cash inflows and the Present Value (PV) of cash outflows given using formula as:

$$NPV = PV(Income) - PV(Expenses) \qquad \text{Equation 141}$$

The NPV analysis considers a breakdown of the capital cost of components, installation cost, O&M costs and the electricity revenue generated across a life-time (Y) of the WEC farm project. For a specified time (T) of the WEC farm project, the NPV model uses the PV approach to calculate the Levellised Cost of Energy (LCoE) (O'Connor et al., 2013; Dalton et al., 2012) using the formula:

$$LCoE = \frac{PV(CAPEX)+PV(OPEX)}{PV(EP)} \qquad \text{Equation 142}$$

Where:

EP: the energy production in kWh

The PV of a Cash Flow (CF) (O'Connor et al., 2013). is estimated as:

$$PV(CF) = \sum_{T=T_0}^{Y} \frac{CF(T)}{\left(1+\frac{DR}{100}\right)^{T}} \qquad \text{Equation 143}$$

Where:

T_0: the first non-zero value year of the cash-flow CF.

To analyse the viability or profitability of the project considering the associated costs; the NPV is obtained by adding all the discounted cash flows over the lifetime as using the formula (O'Connor et al., 2013):

$$NPV(CF) = \sum_{T=0}^{Y} \frac{FCF(T)}{\left(1+\frac{DR}{100}\right)^{T}} = \sum_{T=0}^{Y} DCF(T)$$ *Equation 144*

A positive NPV indicates that the earnings generated by a project in present value of the specified currency, exceeds the anticipated costs (also in present specified currency). Therefore, the project is deemed to be viable and profitable. Generally, an investment with a positive NPV will be a profitable one and one with a negative NPV will result in a net loss. This concept is the basis for the Net Present Value Rule, which dictates that the only investments that should be made are those with positive NPV values. In addition, the IRR is a parameter or measure of calculating rate of return on an investment.

The IRR may be defined as the percentage which corresponds to the discount rate used in capital budgeting that makes the NPV of all cash flows from a project equal to zero. Capital budgeting specifically refers to the planning process used to determine whether long term investment in the project are worth the funding of cash through the firm's capitalization structure (Cheremushkin, 2010).The IRR is used to assess the lifetime cash inflow and outflow to determine whether the potential return generated measure up to the standard set in the investment appraisal. It is often necessary to evaluate and determine the potential expenses. This is because a prospective WEC farm project would attract huge capital investment.

As mention in the review, the OPEX includes all cost associated with O&M, insurance, utility charges and rent, and as such Annual cash flow (ACF) is calculated as the sum of the revenue in TIC and OPEX. It is derived from the equation (Teillant et al., 2012; O'Connor et al., 2013):

$$ACF = -TIC - OpEx + revenue(FIT)$$

Equation 145

ACF- being the sum of the revenue in, TIC and OPEX. Where OPEX includes O/M, insurance, utility charges and rent.

The expenditures may include building new plants or investing in long term assets. Generally, the IRR is commonly used along with the NPV to assess the desirability of a project (Cheremushkin, 2010). This suggest that the higher the IRR is above the discount rate a project is expected to have, the more desirable it is to undertake the project (Feibel et al., 2003).The term internal refers to the fact that its calculation does not incorporate environmental factors (e.g., the interest rate or inflation). With financial indicators growth, can be identified in several ways (e.g. Profitability, Revenue, Return on Investment (RoI) and Cash Flow.

3.7 Assumptions of The Developed Methodology and Modelling

As applicable with any research, certain assumptions are made to enable the implementation of the research study. On the other hand, the research could also have some limitations. For more clarification, it becomes necessary to explain these aspects to the reader. Thus, the limitations and assumptions applicable to this research thesis are described in the following:

1. For statistical analysis of the historical wave data, it is assumed that the data set should fit to a normal distribution. In this respect, the historical wave data set is analysed to check if the data is normal or follows a normal distribution.
2. The WEC and its performance are dependent on the size of WEC. The WEC hardware is assumed to be fixed over the device lifetime so WEC efficiency will not increase over time. Electrical energy output is adjusted for WEC downtime resulting from failure and off-line maintenance.
3. Climate is assumed to be uniform between offshore WEC farm and O&M port.
4. It is assumed that the selected O&M vessel is capable enough to perform all the specified major O&M activities in terms of crane capacity and operational water depth. Maintenance vessel performance is also assumed to be perfect so that there are no additional costs due to vessel failure.
5. Maintenance tasks are classified as either preventive or corrective maintenance, condition-based maintenance is not considered directly as it is assumed to fall under the replacement maintenance failure rate.
6. Labour and materials discounts are function of the farm plan (size, distance etc.). For example, the larger the farm size, the cheaper the unit cost of material.

7. When a maintenance team is initially assigned to a WEC, the priority is finalising the preventive or corrective maintenance task as soon as possible. When the maintenance tasks are completed, same technician team continues to do scheduled maintenance (if required) within the WEC farm.
8. It is assumed that the major repairs cannot be suspended after repair activity is started; therefore, the O&M vessel can only start the O&M activity, if there is no expected storm during repair period.
9. In the case of siting or developing a WEC farm for producing electricity, it is assumed that the WEC farm developers or operators may require a building which would serve as a maintenance base or workshop for device that need to be removed from site and maintained onshore in a more suitable environment (Beels et al., 2011); they may also require vessels with specialized equipment for lifting and transporting the device to and from the offshore WEC farm location (Dalgic et al., 2015; Lazakis et al., 2013).

3.8 Chapter Summary

The methodology and modelling in the integrated framework presented in this thesis is unique and novel in the sense that it provides a within a single framework, a comprehensive and robust methodology for preliminary assessment of the wave resource and the O&M cost modelling of a WEC farm using the device characteristics. In addition, the integrated framework provides the means for assessing the economic value of the WEC farm project. A detailed description of the relationships between all the factors contributing to the total O&M cost of a WEC farm has been presented.

This contributes to achieving the objective of developing an integrated framework for assessment of wave energy resource and O&M cost for maintenance activities of the WEC using existing theoretical models. The integrated framework provides a consistent approach to investigate the sensitivity of all the factors associated with the choice of using the WEC as an alternative source for electricity generation. In addition, it is shown that capital cost and the fees are deterministic and fixed values, whereas the O&M cost of an offshore structure is uncertain and variable because of the unexpected factors such as weather and sea states which may lead to uncertain O&M needs.

In the analyses of planned and unplanned maintenance events for the WEC farm project, an estimation process for daily charter rates associated with suitable vessel for the O&M activities has been described. The annual O&M cost per unit energy depends upon preventive maintenance cost, corrective maintenance cost, and annual energy produced. In the following chapter, the case study application of the methodology is carried out. This is relevant to validate the structure of the methodology and modelling in this integrated framework and to demonstrate the accuracy of the analysis results.

Chapter 4-Case Study Application of the Methodology

4.1 Chapter Outline

This Chapter describes the relevant information required to illustrate the case study of the proposed integrated framework to validate the methodology and modelling in Chapter 3. It is not practical to conduct experiments to estimate unit cost by building and operating a large scale WEC farm in order to obtain information on energy output and total O&M cost. For this reason, designers of WECs or operators of the WEC farm would normally resort to modelling the WEC farm system to obtain desired information.

In this respect, the case study of the resource assessment is described in Section 4.2. Subsequently, information related to the resource assessment output is presented in Section 4.3. The attributes for analysing the OPEX and O&M cost estimates for operating the WEC farm are described in Section 4.4. In Section 4.5 the main financial indicators are described to illustrate the economic value of the WEC farm project. A Chapter summary is presented in Section 4.6 to summarise the Chapter.

4.2 Resource Assessment Case Study

To select a suitable site for commercial installations of a WEC farm project, it is important to have an informed and accurate characterization of the wave energy resource in the selected location. In this respect, a case study example of the resource assessment method in the proposed integrated framework described in Chapter 3 methodology and modelling is applied to validate the analysis performed in this thesis. The main input considered in the case study of the resource assessment method include: historical wave data from the location, WEC device and Power Matrix. The resource assessment method starts with preliminary analysis of the wave data input for the selected location.

4.2.1 Project Location

Historical wave data for the location of interest should be acquired to perform the analysis. Most meteorological institutes charge a fee for making wave data available, whereas some provide it for free. In this case, free data was searched for and obtained through the National Oceanic and Atmospheric Administration's, National Data Buoy Centre (NDBC). The sea characteristic measurements utilized were obtained as Standard Meteorological Data. The wave data time series with hourly frequency was measured from a wave directional buoy over a period of 12 years.

The wave data is in the form of historical observations collected from an offshore directional Wave Rider Buoy, located at a point of coordinates: 21.671 N 158.117 W (21°40'14" N 158°7'2" W); Water depth: 200 m. Station 51201 - Waimea Bay, Hawaii, HI. Figure 46. Shows the map of Station 51201 - Waimea Bay. Waimea Bay is in Haleiwa on the North Shore of O'ahu in the Hawaiian Islands at the mouth of the Waimea River.

Figure 46: Map of Station 51201 - Waimea Bay, Hawaii (BuoyAlarm, 2016)

Studies on economic assessment of marine renewable energy schemes (Stallard et al., 2009) suggested that suitable locations for siting commercial renewable energy projects should have access to nearby infrastructure such as maintenance harbour, existing grid connection and a good road network in the local area. This will help to support the development of the project. The location has existing infrastructure such as "the historic Rainbow Bridge over the Anahulu River which marks the northern entrance to old Haleiwa town.

The location has two nearby beach parks surrounding the small boat harbour located in Waialua Bay. Haleiwa Beach Park located to the north and Haleiwa Alii Beach Park located to the south. There are also small shops, eateries and many galleries. Based on the Chapter 2 critical review and relevant studies on preliminary consideration for site selection (Cruz et al., 2009), this location is deemed to exhibits the relevant characteristics of a suitable location. Figure 47 shows the map of the location in Honolulu County and the state of Hawaii. For the raw data to be presented as scatter plots of hours which illustrate the distribution of wave conditions at the selected location, the raw data obtained need to be subjected to some form of data processing.

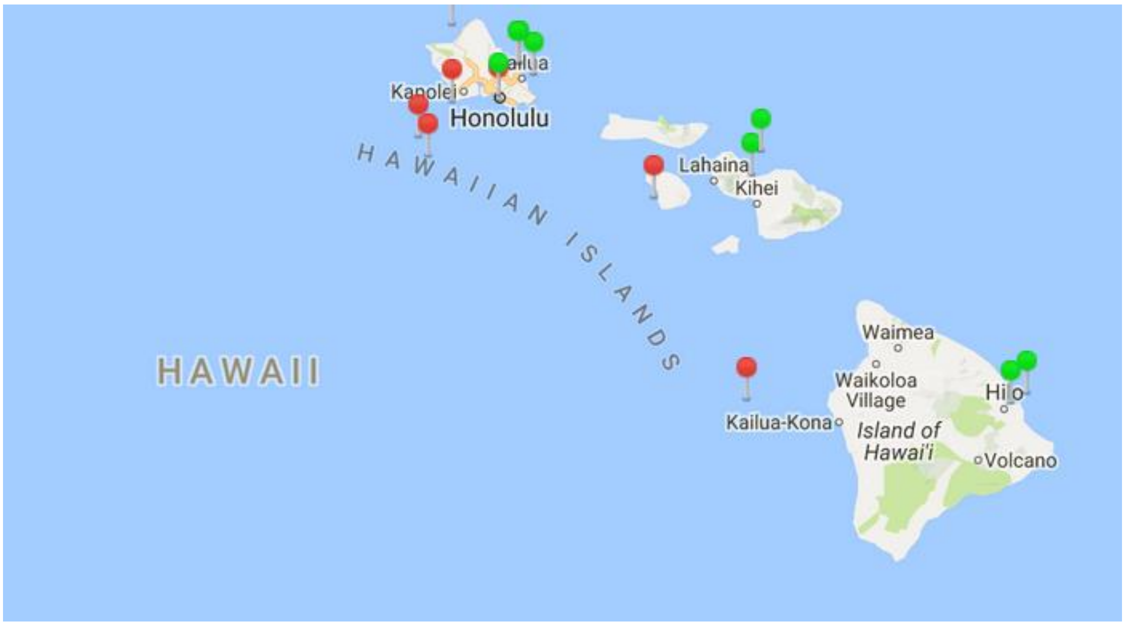
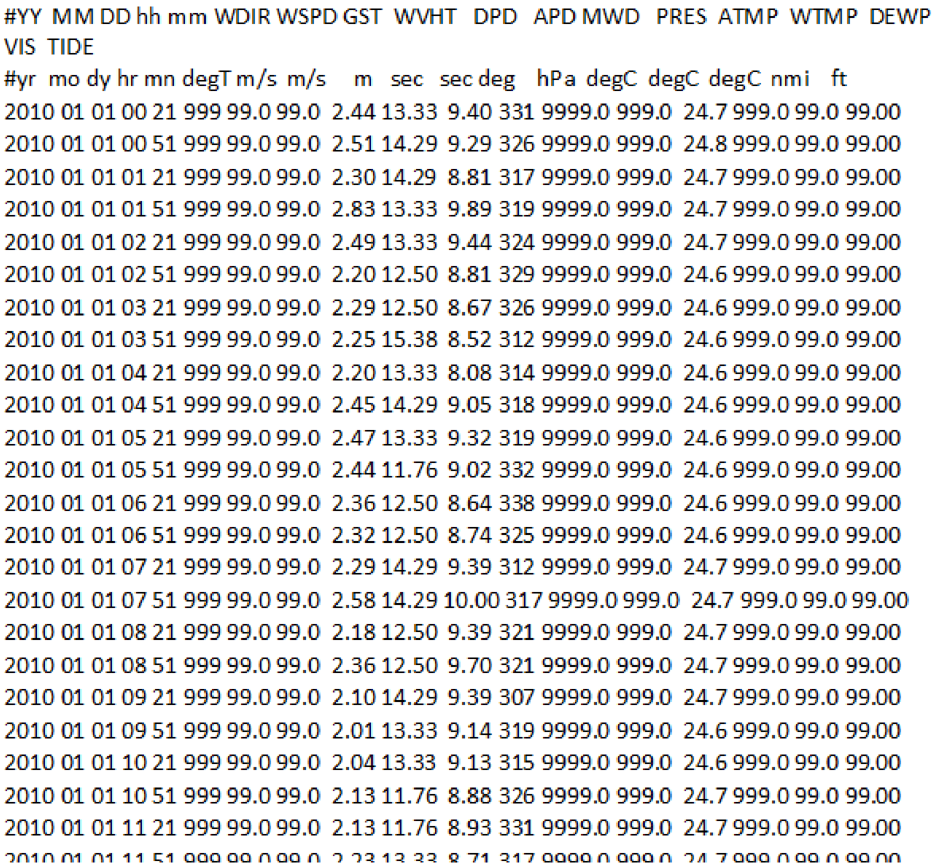


Figure 47: Location in Honolulu County and the state of Hawaii (BuoyAlarm, 2016)

4.2.2 Wave Data Processing

The historical wave data files that have gone through post-processing analysis represent the data sent to the National Data Buoy Centre (NDBC) archive centres (NDBC, 2016). The wave data formats are generally the same for all stations. It is observed from the raw data files that missing data (measurements) in the historical wave data files are denoted by a variable number of 9's or 999.0 99.0 depending on the data type. This variable numbers represent the outliers. The raw data are originally retrieved as text files and must undergo pre- processing for it to be used in the analysis.

Figure 48 shows an example of a section extracted from the wave data sample in 2010. The table in Figure 48 is presented intentionally to show how the numbers are bunched together. The full dataset includes all the measurement made in a certain year, month, day, hours, and minutes for each of the wave parameters. The dataset comprises 169,828 data points recorded from the period January 2005 to December 2016, covering a period of 12 years. The dataset consists of different variable parameters such as the wind speed (WSPD), significant wave height(WHT) and dominant wave period (DPD).



```
#YY  MM DD hh mm WDIR WSPD GST  WVHT  DPD  APD MWD  PRES  ATMP  WTMP  DEWP
VIS  TIDE
#yr  mo dy hr mn degT m/s  m/s    m   sec  sec deg   hPa  degC  degC degC  nmi   ft
2010 01 01 00 21 999 99.0 99.0  2.44 13.33  9.40 331 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 00 51 999 99.0 99.0  2.51 14.29  9.29 326 9999.0 999.0  24.8 999.0 99.0 99.00
2010 01 01 01 21 999 99.0 99.0  2.30 14.29  8.81 317 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 01 51 999 99.0 99.0  2.83 13.33  9.89 319 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 02 21 999 99.0 99.0  2.49 13.33  9.44 324 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 02 51 999 99.0 99.0  2.20 12.50  8.81 329 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 03 21 999 99.0 99.0  2.29 12.50  8.67 326 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 03 51 999 99.0 99.0  2.25 15.38  8.52 312 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 04 21 999 99.0 99.0  2.20 13.33  8.08 314 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 04 51 999 99.0 99.0  2.45 14.29  9.05 318 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 05 21 999 99.0 99.0  2.47 13.33  9.32 319 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 05 51 999 99.0 99.0  2.44 11.76  9.02 332 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 06 21 999 99.0 99.0  2.36 12.50  8.64 338 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 06 51 999 99.0 99.0  2.32 12.50  8.74 325 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 07 21 999 99.0 99.0  2.29 14.29  9.39 312 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 07 51 999 99.0 99.0  2.58 14.29 10.00 317 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 08 21 999 99.0 99.0  2.18 12.50  9.39 321 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 08 51 999 99.0 99.0  2.36 12.50  9.70 321 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 09 21 999 99.0 99.0  2.10 14.29  9.39 307 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 09 51 999 99.0 99.0  2.01 13.33  9.14 319 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 10 21 999 99.0 99.0  2.04 13.33  9.13 315 9999.0 999.0  24.6 999.0 99.0 99.00
2010 01 01 10 51 999 99.0 99.0  2.13 11.76  8.88 326 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 11 21 999 99.0 99.0  2.13 11.76  8.93 331 9999.0 999.0  24.7 999.0 99.0 99.00
2010 01 01 11 51 999 99.0 99.0  2.23 13.33  8.71 317 9999.0 999.0  24.7 999.0 99.0 99.00
```

Figure 48: Sample of the raw wave data for 2010’

The first column denoted as YY refers to the year which in this example is 2010. This is followed by other elements abbreviated as MM, DD, hh and mm, referring to the month day, hour and minutes respectively. Definition of other elements included in the raw data file of the historical wave dataset is provided in Appendices 2 description of wave data measurement and units. The wave data is an important requirement for the resource description or characterisation. It is relevant to describe how the energy is distributed and the monthly occurrence of each sea state bin.

The information provided through analysing the wave data and theoretical energy available, is useful in terms of helping to decide where the WEC device could be placed to yield maximum benefits. The mean monthly power available at the WEC site are generated by synthesising the information defined in the historical wave data. The information about the intra annual variability of the resource can also be ascertained from the wave data analysis. For clarity,

Table 9 shows an example of a section extracted from the wave data sample in 2010. In this case, only the relevant parameters are extracted to excel and put in table for clarity.

The wave readings contain raw sea surface elevation time series at a sampling frequency of 1.28 Hz, with an hourly frequency. In this case study, the wave data initially undergoes preliminary processing to eliminate the outliers. The wave data processing is relevant to eliminate the unwanted parameters and outliers as illustrated in Table 9. This makes the information in the historical wave dataset to be easily readable. The pre-possessing of the wave data also ensures that the missing data denoted by the variables 9 or 999, representing the outliers are eliminated. After the pre-processing the generic characteristic of the wave data sets is preserved.

The preliminary analysis of the wave data is then performed to generate the frequency distribution and probability of occurrence of the sea state parameters. The wave dataset is required to perform the analysis. Subsequently, the wave data set is presented to illustrate the characteristics of the wave distribution and weather window required for modelling O&M activities. The wave data set selected for this case study application is a good representation of the offshore wave environment for this research.

The reason is that it offers the benefits of being a wide series data consisting of good and bad weather years. This is particularly useful when demonstrating the intra annual variability of the resource. Moreover, studies (Heru et al., 2008; Lenee-Bluhm et al., 2011) acknowledged that the wave dataset is also important for the analysis of seasonal (monthly) variations in the climate parameters. In the first step of investigating the case study location the in the resource assessment model, the pre-processing of the historical wave data involves examining the basic parameters contained in the historical wave data set.

In the end, a statistical summary which includes relevant parameters such as the hourly wind speed, significant wave height and wave period observations for the entire period of 12 years (2005-2016) in the historical wave dataset is used to describe the sea state. This can provide a source of useful information for easy reference when the need arises.

Table 9: Example of A Section Extracted from The Wave Data Sample In 2010

'YYYY'	'MM'	'DD'	'hh'	'mm'	'WSPD'	WHT'	DPD'	APD'	'MWD'
2010	1	1	0	21	0	2.44	13.33	9.4	331
2010	1	1	0	51	0	2.51	14.29	9.29	326
2010	1	1	1	21	0	2.3	14.29	8.81	317
2010	1	1	1	51	0	2.83	13.33	9.89	319
2010	1	1	2	21	0	2.49	13.33	9.44	324
2010	1	1	2	51	0	2.2	12.5	8.81	329
2010	1	1	3	21	0	2.29	12.5	8.67	326
2010	1	1	3	51	0	2.25	15.38	8.52	312
2010	1	1	4	21	0	2.2	13.33	8.08	314
2010	1	1	4	51	0	2.45	14.29	9.05	318
2010	1	1	5	21	0	2.47	13.33	9.32	319
2010	1	1	5	51	0	2.44	11.76	9.02	332
2010	1	1	6	21	0	2.36	12.5	8.64	338
2010	1	1	6	51	0	2.32	12.5	8.74	325
2010	1	1	7	21	0	2.29	14.29	9.39	312
2010	1	1	7	51	0	2.58	14.29	10	317
2010	1	1	8	21	0	2.18	12.5	9.39	321
2010	1	1	8	51	0	2.36	12.5	9.7	321
2010	1	1	9	21	0	2.1	14.29	9.39	307
2010	1	1	9	51	0	2.01	13.33	9.14	319
2010	1	1	10	21	0	2.04	13.33	9.13	315
2010	1	1	10	51	0	2.13	11.76	8.88	326
2010	1	1	11	21	0	2.13	11.76	8.93	331
2010	1	1	11	51	0	2.23	13.33	8.71	317
2010	1	1	12	21	0	2.32	11.76	8.58	325
2010	1	1	12	51	0	2.25	12.5	8.02	319
2010	1	1	13	21	0	2.21	11.11	8.13	333
2010	1	1	13	51	0	2.38	11.76	8.21	328
2010	1	1	14	21	0	2.21	11.76	7.83	322
2010	1	1	14	51	0	2.05	11.76	7.69	328
2010	1	1	15	21	0	2.21	11.11	7.91	318
2010	1	1	15	51	0	2.17	11.11	7.94	329
2010	1	1	16	21	0	2.06	11.76	7.67	335
2010	1	1	16	51	0	2.02	11.76	7.24	331
2010	1	1	17	21	0	2.22	11.76	7.9	333
2010	1	1	17	51	0	2.23	11.76	7.35	331
2010	1	1	18	21	0	2.24	11.11	7.43	335
2010	1	1	18	51	0	2.28	11.11	7.38	332
2010	1	1	19	21	0	2.16	11.11	7.2	333
2010	1	1	19	51	0	2.16	11.11	7.21	345
2010	1	1	20	21	0	2.12	11.11	7.33	336
2010	1	1	20	51	0	2.06	11.11	7.63	331
2010	1	1	21	21	0	1.94	11.11	7.8	346
2010	1	1	22	21	0	1.98	11.11	7.88	343

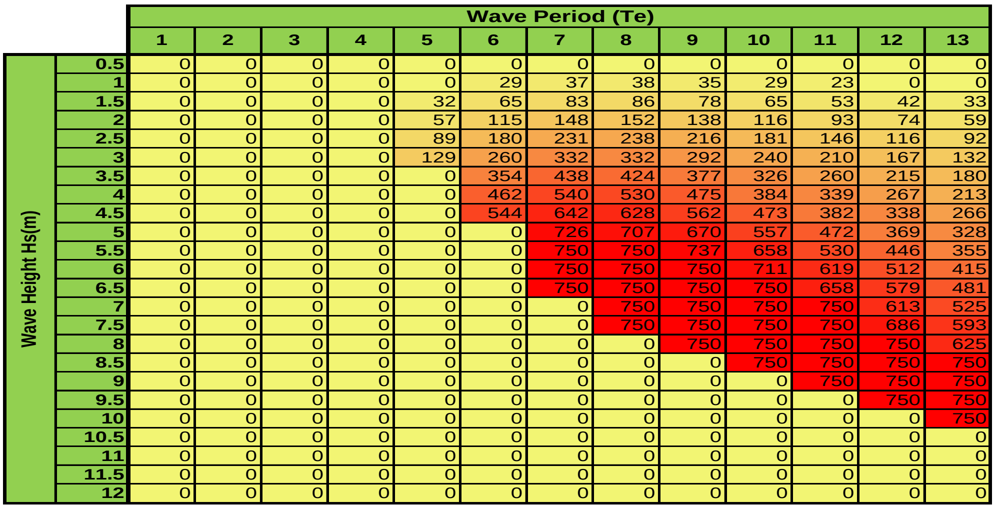
4.2.3 WEC Device Characteristics and WEC Power Matrix

To assess the feasibility study of WEC farm project, the power matrix of a selected device is adapted from literature for the analysis of power production and O&M cost estimates. The reason is because the resource assessment and O&M for any wave energy project or location is site specific. Hence different devices would have different power production depending on the power rating. The O&M of the devices will also be different depending on the location either offshore or onshore.

In Chapter 2 critical review, existing WEC technologies that have been proposed to capture the energy from waves have been discussed. Example include: Pelamis wave power (EMEC, 2010; Yemm et al., 2012), Energetech-OWC (Previsic, 2004). The choice of WEC is an essential component in efficiently capturing wave energy under different wave conditions by location. The characteristics of these devices also play a critical role in quantifying the amount of energy that can be captured (Bedard et al., 2005).

Studies (Bahaj, 2011; Dunnett and Wallace, 2009) mentioned that the power production input of WEC devices is often defined in terms of the electricity price (£/KWh) and annual increase (%). The device selected for the case study example is the Pelamis P1 first prototype. This WEC device is 120m long, 3.5m in diameter. The power rating is 750KW and weighed 700 ton (Pelamis, 2007). The Pelamis power matrix (Pelamis, 2007) presented in Table 10 where the power peaks at 750KW for a number of sea states.

Table 10: Power matrix for the Pelamis WEC (Values in KW) (Pelamis, 2007)



		Wave Period (Te)												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Wave Height Hs(m)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	29	37	38	35	29	23	0	0
	1.5	0	0	0	0	32	65	83	86	78	65	53	42	33
	2	0	0	0	0	57	115	148	152	138	116	93	74	59
	2.5	0	0	0	0	89	180	231	238	216	181	146	116	92
	3	0	0	0	0	129	260	332	332	292	240	210	167	132
	3.5	0	0	0	0	0	354	438	424	377	326	260	215	180
	4	0	0	0	0	0	462	540	530	475	384	339	267	213
	4.5	0	0	0	0	0	544	642	628	562	473	382	338	266
	5	0	0	0	0	0	0	726	707	670	557	472	369	328
	5.5	0	0	0	0	0	0	750	750	737	658	530	446	355
	6	0	0	0	0	0	0	750	750	750	711	619	512	415
	6.5	0	0	0	0	0	0	750	750	750	750	658	579	481
	7	0	0	0	0	0	0	0	750	750	750	750	613	525
	7.5	0	0	0	0	0	0	0	750	750	750	750	686	593
	8	0	0	0	0	0	0	0	0	750	750	750	750	625
	8.5	0	0	0	0	0	0	0	0	0	750	750	750	750
	9	0	0	0	0	0	0	0	0	0	0	750	750	750
	9.5	0	0	0	0	0	0	0	0	0	0	0	750	750
	10	0	0	0	0	0	0	0	0	0	0	0	0	750
	10.5	0	0	0	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0	0	0	0	0
	11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	0	0	0	0

The reason for selecting the Pelamis WEC and power matrix in this thesis is simply because it is the only WEC to date that has a published power performance matrix available in public domain. It is also the only device which has provided some preliminary initial cost estimates, which were used in the EPRI study (Previsic, 2004). Studies (Previsic, 2004; Previsic et al., 2004) have showed that the ability of a WEC device to capture wave energy can be expressed by wave energy absorption performance. The absorption performance parameter is available from WEC device manufacturers.

The reliability of the Pelamis power matrix has never been fully verified since it was first published in 2003 and unfortunately there has been no update of the matrix. There have also been no revised initial costs estimates for the Pelamis device, nor has the company volunteered to provide up to date costs. Therefore, the Pelamis device, its power matrix and costings are only used in the context of a case study. This is to provide a platform methodology to examine the thesis research aims. The power of a WEC is often dependent on the significant wave height (H_s), and the wave energy period ((T_e) (Carballo and Iglesias, 2012).

The theoretical peak power for the Pelamis device is 750KW for most of the representative number of the sea states. Some WEC devices have the ability to optimize their performance in response to site-specific conditions (Previsic et al., 2004). The yellow cells on the bottom left corner in the scatter plot of the power matrix in Table 10 correspond to sea-states beyond the theoretical maximum wave steepness (1/7) hence are very unlikely to occur in deep water conditions of depth up to 50m (Falnes, 2002; US and Army Corps, 2002).

For extreme sea-states with $H_s$larger than 12m and/or T_e13s, the power rating of the device is approximated to the nearest cell defined in Table 10. For each hour the energy production is given by multiplying the cell corresponding to the couple (H_s, T_e) defining the sea state in the power matrix (Beels et al., 2011; Gotthardsson, 2011).

4.3 Resource Assessment Output

In this case study, the resource assessment model is employed to generate the hourly wave power production over the lifetime of the farm. This is done by combining the power matrix, the availability and the wave measurements. The WECS power matrix and the wave scatter diagram provide an efficient representation that allows a device's wave energy conversion performance to be estimated for a given site's wave conditions. The total annual energy output for the year was estimated by multiplying each cell point of the scatter plot of hours with the corresponding cell of a WEC power matrix.

4.3.1 Resource Characterisation

The ocean surface and wave resource is often characterised based on the probability distribution and occurrence given by two parameters such as a significant wave height H_s and wave energy period T_p. These two parameters are normally called the sea state (Carballo and Iglesias, 2012). In this thesis, a probability distribution is described as a function of the wave energy sea state bin. The wave energy bin is defined as a bi-variate interval of significant wave height H_s and peak energy period T_p. In this respect, each of the sea states in the dataset is assigned to the corresponding wave bin, so that their contribution to the total offshore energy resource can be investigated.

The wave energy is assessed following a typical offshore wave condition considered based on the JONSWAP spectrum. This sea state was defined as the ocean boundary condition (Hasselmann et al., 1973; Evans et al., 2000). Studies (Lee and Kim, 2006) mentioned that most cases of offshore waves in nature are growing wind waves. The JONSWAP spectrum considered is adequate for growing wind waves in deep water. Spectral models such as the Pierson–Moskowitz are more suited in the case of fully developed seas (Hasselmann, 1974).

4.3.2 Analysis of The Basic Parameters

The initial step followed in the resource assessment method involves a preliminary analysis of the basic parameters contained in the historical wave dataset. In this case, the relevant parameters include the hourly wind speed, significant wave height and wave period observations for the period of 12 years (2005-2016). Table 11 show a statistical summary of the historical wave dataset used to describe the sea state. Presenting the data in this form make it useful for easy reference when the need arises.

Table 11: Maximum, Minimum, Mean and Standard Deviation of The Annual Datasets

Wind Speed Values(m/s)					Significant Wave Height-Hs (m)				Wave Period- Tp (seconds)			
Year	Max	Min	Mean	Stdv	Max	Min	Mean	Stdv	Max	Min	Mean	Stdv
2005	19.8	0	7.4	3.7	5	0.3	1.6	0.7	22	3	10.4	3.3
2006	22.1	0	6.5	3.3	5	0.3	1.6	0.7	25	3	10.7	2.8
2007	27.8	0	7.4	3.9	6.2	0.4	1.6	0.7	22	4	10.4	2.8
2008	24.0	0	6.5	3.2	6.1	0	1.5	0.6	22	0	10.4	2.9
2009	22.3	0	6.2	3.5	6.4	0	1.7	0.8	22	0	10.9	3
2010	28.3	0	6.9	3.3	5.9	0	1.6	0.7	22	0	10.4	3
2011	25.6	0	6.7	3.1	5.1	0	1.6	0.6	22	0	10.7	3
2012	28.8	0	6.4	3.2	6.3	0	1.6	0.7	22	0	10.5	3
2013	22.7	0	6.7	3.2	6.1	0	1.6	0.7	25	3.7	10.8	3.2
2014	21.3	0	6.7	3.3	7.4	0	1.7	0.9	22	3.5	11	2.9
2015	28.0	0	6.9	3.2	4.9	0	1.7	0.7	22	3.2	10.6	2.8
2016	22.3	0	7.5	3.5	8.4	0	1.9	0.9	22	4	10.3	3

From the preliminary analysis of the historical wave data, it could be observed that these parameters occur simultaneously in real sea conditions. For this reason, a table containing the summarised statistical description of the dataset for the case study location is relevant for reference purposes. Subsequently, this table summarising the maximum, minimum, mean and standard deviation of the annual dataset will be used for the analysis of the wave power. Further details of initial statistical description of the historical wave data is provided in Appendices 3.

4.3.3 Scatter Plot of Hourly Sea States

Scatter plot of hours is used to illustrate occurrence of significant wave heights and wave energy periods. Results of wave data analysis are normally presented as scatter diagram showing the occurrence of the significant wave height and wave energy period (WaterTechnology, 2004). This is necessary to reduce the uncertainty in the results for resource assessment. The output from the wave data analysis are then applied in terms of calculating the theoretical energy available in the resource, the intra annual variability of the resource and analysis of power that could be generated by the WEC (Cornett, 2008).

Table 12 shows the yearly occurrence in hours for values of each sea state bin. There are 17 bins in number. The characteristics of these bins includes hourly sea states of each of the selected interval. This employs a 1-hour interval for model result spanning over a period of 12 years. Table 12 is an example of the yearly occurrence in hours for bin values or intervals starting from 0.5m to 8.5m for each sea state bin. In this case, the long-term historical wave dataset is used to investigate the number of hours that each sea state occurs over a given period. A sea state table for the case study location is prepared from the historical wave dataset.

Table 12: Yearly Occurrence in Hours for Bin Values of Each Sea State

Bin..Hs (m)	Yr1	Yr2	Yr3	Yr4	Yr5	Yr6	Yr7	Yr8	Yr9	Yr10	Yr11	Yr12	Total
1….0.5	30	124	51	3	5	1	0	0	0	6	0	8	228
2….1.0	1408	1741	1559	367	345	334	304	288	385	380	276	193	7580
3….1.5	2992	2745	3323	622	648	631	689	711	551	549	699	605	12028
4….2.0	1787	2097	1745	424	427	341	393	390	351	329	397	386	9067
5….2.5	1002	1141	762	253	206	21	195	191	161	232	236	189	3668
6….3.0	565	447	312	196	89	95	89	106	107	149	130	141	2426
7….3.5	77	183	178	88	52	56	34	26	53	60	61	88	1100
8….4.0	157	28	77	24	28	19	5	22	30	43	20	44	555
9….4.5	53	28	26	17	16	7	2	7	4	19	12	18	231
10...5.0	41	14	17	8	9	4	2	1	3	6	3	13	121
11...5.5	14	0	8	7	6	4	0	5	1	0	0	10	55
12….6.0	0	0	3	0	0	0	0	0	3	3	0	2	11
13….6.5	0	0	0	0	0	0	0	0	0	0	0	0	0
14….7.0	0	0	0	0	0	0	0	0	0	0	0	0	0
15….7.5	0	0	0	0	0	0	0	0	0	0	0	0	0
16….8.0	0	0	0	0	0	0	0	0	0	0	0	1	1
17….8.5	0	0	0	0	0	0	0	0	0	0	0	1	1

Table 12, shows the number of hours each value of the significant wave height in the selected bin occurs in a year over the 12 years period. The analysis was performed using the data analysis tool 'COUNTIF' in excel. An explanation of how the table was generated is provided in the following. For example, considering Year 4; first the values of the significant wave height are sorted into different bins ranging from 0.5m to 8.5m. The sea state bin refers to the selected interval used to define the limit of the range of values (e.g. from 0.5m to 1m, 1m to 1.5m up to 8.5m).

The interval is selected based on the observed minimum and maximum values in the preliminary analysis of the raw data summarised in Table 11 above. It can be observed that the highest value of the significant wave height in the entire period of dataset is 8.4m. For this reason, the highest value in the range is set as 8.5m. The value of 0.5m is selected as the start of the interval. Studies (Thomas, 2008) mentioned that below the value of 0.5m the contribution is not significant. After selecting and setting up the bin limit, the excel function is then applied to each row and column to generate occurrence of each of the parameters in the range according to their corresponding values.

The process is repeated for the total number of years in the historical wave dataset. In Table 12, it can be observed that the significant wave height parameter contributing the most to the wave energy resource is Hs=1.5m. It has the highest value of 3,323 occurring in year 3 and with a total occurrence of 12,028. This is followed by Hs=2m, with its highest occurrence of 2,097, in the year 2 and with total value of 9,067. It can also be observed that high significant wave height values around 6.0m to 8.5m will not have a significant contribution to the wave energy resource because their occurrence is very low and in most cases the occurrence is zero.

4.3.4 Contribution of Energy Bin to The Wave Energy Resource

Having examined the occurrence of each bin value of the significant wave height and determined its relative frequency of occurrence in hours per year, the annual wave energy contribution associated with the sea state bin can be estimated. From the preliminary analysis, it is observed that the wave heights and periods occur simultaneously in real sea conditions. For this reason, wave frequency table containing data summarised for the location is relevant to show the contribution of combinations of the wave motions of $\mathrm{H_s}$and $\mathrm{T_p}$, to the resource.

Referring to Table 11 of the summarised descriptive statistics of the annual distribution of the basic parameters; the maximum value of the wave energy period is 22 seconds, while the minimum is zero. The information on the maximum and minimum values of the significant wave height and wave energy period parameter is used to define and set up the bin limit for the bivariate distribution of the significant wave height (H_s) and peak wave period (T_p). The peak wave period (T_p), is the inverse of the frequency at which the wave spectrum has its maximum value for the measured sea state in the dataset.

For the preliminary assessment of the resource in deep water offshore conditions, Table 13 illustrates the contribution of each wave energy bin associated with the sea state parameters ($\mathrm{H_s}$ and $\mathrm{T_p}$) to the wave energy resource. Table 13 is relevant to illustrate the wave power (P_a) per unit width of wave crest. This can also be referred to as the incident wave power (J) in Kilowatts per meter (KW/m) of wave energy device width, estimated for a given combination of (H_s and T_p) in the dataset. The wave power is obtained by multiplying each value of (H_s) in the column with the corresponding row of (T_p).

Table 13: Contribution of Energy Bin to The Wave Energy Resource

		Wave Period (Tp) seconds										
Bin	Hs(m)	3	5	7	9	11	13	15	17	19	21	23
1	0.5	0.3	0.5	0.7	0.9	1.2	1.4	1.6	1.8	2.0	2.2	2.4
2	1	1.3	2.1	2.9	3.8	4.6	5.5	6.3	7.1	8.0	8.8	9.7
3	1.5	2.8	4.7	6.6	8.5	10.4	12.3	14.2	16.1	18.0	19.8	21.7
4	2	5.0	8.4	11.8	15.1	18.5	21.8	25.2	28.6	31.9	35.3	38.6
5	2.5	7.9	13.1	18.4	23.6	28.9	34.1	39.4	44.6	49.9	55.1	60.4
6	3	11.3	18.9	26.5	34.0	41.6	49.1	56.7	64.3	71.8	79.4	86.9
7	3.5	15.4	25.7	36.0	46.3	56.6	66.9	77.2	87.5	97.8	108.0	118.3
8	4	20.2	33.6	47.0	60.5	73.9	87.4	100.8	114.2	127.7	141.1	154.6
9	4.5	25.5	42.5	59.5	76.5	93.6	110.6	127.6	144.6	161.6	178.6	195.6
10	5	31.5	52.5	73.5	94.5	115.5	136.5	157.5	178.5	199.5	220.5	241.5
11	5.5	38.1	63.5	88.9	114.3	139.8	165.2	190.6	216.0	241.4	266.8	292.2
12	6	45.4	75.6	105.8	136.1	166.3	196.6	226.8	257.0	287.3	317.5	347.8
13	6.5	53.2	88.7	124.2	159.7	195.2	230.7	266.2	301.7	337.2	372.6	408.1
14	7	61.7	102.9	144.1	185.2	226.4	267.5	308.7	349.9	391.0	432.2	473.3
15	7.5	70.9	118.1	165.4	212.6	259.9	307.1	354.4	401.6	448.9	496.1	543.4
16	8	80.6	134.4	188.2	241.9	295.7	349.4	403.2	457.0	510.7	564.5	618.2
17	8.5	91.0	151.7	212.4	273.1	333.8	394.5	455.2	515.9	576.6	637.2	697.9

The energy associated with each wave field can be obtained from its wave power and its probability of occurrence in an average year based on the characterisation of the offshore wave resource. One important criterion that should be considered is that the WEC to be installed should have maximum efficiency for the sea states providing the bulk of the energy. In this context, the sea state providing the bulk of the energy in terms of the significant wave height are $H_s =$1.5m and $H_s = 2.0m$ as illustrated in Table 12 above.

Studies (Iglesias et al., 2009; Carballo and Iglesias, 2012) acknowledged that to evaluate the available resource, the sea state parameters can be sorted into bins corresponding to the bivariate distribution for intervals of H_s and T_p. The available resource is calculated based on the distribution of sea state parameters with a view to determining the theoretical power output of the WEC when placed in the location. In this case study example, the dominant sea states are selected as the spectra specification based on results in the preliminary analysis of the dataset. This is used to determine the available wave resource and the potential wave power.

As mentioned in previous pages, Table 12 is used to illustrate a sea state table prepared from the historical wave dataset for the case study location. It shows the yearly occurrence in hours for values of each sea state bin. In this case, the number of hours each significant wave height value occurs in any selected bin is demonstrated for the 12 years period. From the preliminary analysis, it is observed that the wave heights and periods occur simultaneously in real sea conditions. In this context, the information presented in Table 12, 13 and 14 are linked to describe the bivariate distribution of the significant wave height (H_s) and peak wave period (T_p).

4.3.5 Average Annual Energy

The wave energy resource available at the WEC site is assessed using the frequency of occurrence approach. This approach is particularly useful for describing the occurrence of each sea state. In this context, a wave system is represented as the sum of large number of elementary component wave bins with different frequencies and random phases. The total annual contribution of each energy wave bin (sea state bin) (MWhm^{-1}) to the annual resource is often expressed as a percentage of the total annual energy in an average year (Carballo and Iglesias, 2012). The occurrence is expressed in hours or as a percentage of time in an average year.

Based on the results of the preliminary analysis of the historical wave dataset presented in Table 12, it is assumed that the WEC is operational at wave heights ranging between 0.5m and 8.5m. In this case a model of the wave fields is generated from the wave dataset. The significant wave height, wave energy period and wave power is obtained from each wave field. The energy associated with each wave field is obtained from its wave power and its probability of occurrence of the significant wave height and wave energy period in an average year following the characterisation of the offshore wave resource.

In the context of wave energy resource assessment, the wave data is the main input requirement. The relevant mean and peak wave periods for these significant wave heights were chosen from the wave dataset. A total of ten wave spectra characterised energy period is used in the analysis. Table 14 illustrates the spectral specification selected to evaluate the amount of wave energy that the WEC would capture in these scenarios. The spectral name S1 to S10 are used in this thesis for simplicity to describe and differentiate each energy bin used in the analysis of wave power.

Mean wave length in Table 14 was calculated from the relationship between the angular wave number (k)and (ω) the angular frequency, then solving for λ to obtain the simplified dispersion relation as discussed in Chapter 3 methodology and modelling. The sea state is the condition of the ocean surface considered as a stochastic field and characterised by the wave spectrum. The wave energy spectrum is an example of the energy bin containing the information of the sea state with respect the significant wave height and wave energy period.

Table 14: Specifications of Spectra Parameters

Spectrum	H_s(m)	$T_e(s)$	$\lambda_{(e)}$(m)	$T_p(s)$	$\lambda_{(p)}$(m)
S1	0.5	3.4	17.8	4.5	62.4
S2	1.0	4.5	31.2	5.4	89.8
S3	1.5	5.1	40.0	6.2	118.4
S4	2.0	6.1	57.3	7.2	159.7
S5	2.5	6.4	63.1	7.5	173.3
S6	3.5	6.5	65.1	8.4	217.4
S7	4.5	7.2	79.8	8.7	233.2
S8	5.0	7.5	86.6	9.1	255.2
S9	6.0	8.1	101.1	10.1	314.4
S10	8.0	8.4	108.7	10.5	339.8

In Table 14 H_s, T_e and T_p. are not calculated because they are examples of the wave fields obtained directly from the historical wave dataset. They are applicable to illustrate the sea state parameters sorted into bins corresponding to the bivariate distribution for intervals of H_s, $T_e$and T_p. The significant wave height, wave energy period and wave power is obtained from each wave field based on the characteristics of the resource as illustrated in Table 13.

Having specified the spectral parameters as illustrated in Table 14, the available wave energy and wave power output in the case study location can be investigated. In the resource assessment method, the total available wave energy in the resource is calculated from each of the defined spectral parameter using the data from the case study location. According to the linear wave theory the total energy available in the waves is composed of potential and kinetic energy (McCormick, 1973).

Table 15 illustrates the example of energy available in the waves and wave power output calculated using historical wave dataset from case study location. Considering the wave energy spectrum S1 in Table 15, the total energy available in the waves is assessed by application of

Equation 88 as discussed in Section 3.5.3.1 in Chapter 3 methodology and modelling. The total annual energy is estimated from the number of occurrences of each bin divided by the total occurrence of all the data points in the specified year, multiplied by the energy available in the waves.

Table 15: Energy available in waves and Wave Power Calculated with Wave Data From Case Study Site

Wave Energy Spectrum	H_s(m)	Energy Available in Waves (J/m^2)	Annual Energy J/m^2	Annual Energy (%)	Wave Power (KW/m)
S1	0.5	1256.91	7.95	0.63	0.47
S2	1.0	5027.63	972.34	19.34	2.27
S3	1.5	11312.16	4663.23	41.22	5.86
S4	2.0	20110.50	4353.41	21.65	12.10
S5	2.5	31422.66	2970.36	9.45	19.69
S6	3.5	61588.41	1359.97	2.21	43.22
S7	4.5	101809.41	328.38	0.32	73.99
S8	5.0	125690.63	265.07	0.21	95.55
S9	6.0	180994.50	67.36	0.04	152.71
S10	8.0	321768.00	0.00	0.00	282.24

In this context, considering year 3 in Table 12 showing the yearly occurrence of each sea state bin, the occurrence of S1 is 51 hours. The annual energy for wave spectrum S1 is estimated by dividing the total occurrence (51) by the total annual occurrence in the entire population in the specified year 3 given as 8061 hours. This is then multiplied by the total energy available in the waves. The result becomes the annual energy for selected spectrum S1. The same method is used to assess the energy available in the waves and total annual energy based on the values of (H_s and T_p) that have been sorted into the appropriate sea state bin.

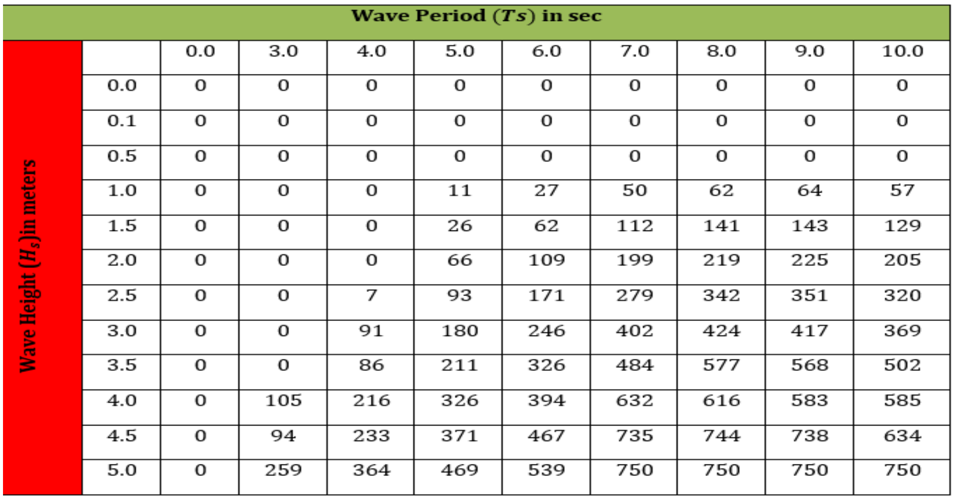
The number of occurrences in each bin is divided by the total number of occurrence in the entire period and the result is the percentage of time that a given sea state bin occurs when multiplied by 8,766 hours in an average year. Thus, providing the number of hours that each sea state occurs. In Table 15 it can be observed that the annual energy contribution of wave spectrum S10 is zero. The reason is that the occurrence of wave bin S10 is zero for the selected year.

The percentage occurrence is calculated for each energy bin to illustrate the proportion of the of the total annual energy that is available in the wave bin for spectrum S1 in year 3. This is obtained by dividing the total annual energy by the energy available in the waves and multiplying by 100%. In addition, the incident wave power ((J) in kilowatts per meter of wave energy device width, or kW/m) is estimated for a given period associated with each sea state using parameters (H_s and T_p). the wave power output represents the energy that could be captured from the wave energy resource employing a WEC device.

4.3.6 Captured Wave Energy

Studies (Bedard, 2006; EPRI, 2011) confirmed that multiplying the number of hours that each sea state occurs by the incident wave power density (KW/m) for that bin yields the wave energy contribution (kWh/m) of that bin. Summing the wave energy contribution across all bins and dividing by the number of hours in a year yields the annual average incident wave power at the reference location. The annual captured wave energy (kWh/yr.) per WEC device is calculated by summing up all the captured wave energy in each sea state bin.

Table 16: Wave energy absorption performance (kW) in each sea state bin for Pelamis (Previsic, 2004)



		Wave Period (Ts) in sec								
Wave Height (H_s)in meters		0.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	0.0	0	0	0	0	0	0	0	0	0
	0.1	0	0	0	0	0	0	0	0	0
	0.5	0	0	0	0	0	0	0	0	0
	1.0	0	0	0	11	27	50	62	64	57
	1.5	0	0	0	26	62	112	141	143	129
	2.0	0	0	0	66	109	199	219	225	205
	2.5	0	0	7	93	171	279	342	351	320
	3.0	0	0	91	180	246	402	424	417	369
	3.5	0	0	86	211	326	484	577	568	502
	4.0	0	105	216	326	394	632	616	583	585
	4.5	0	94	233	371	467	735	744	738	634
	5.0	0	259	364	469	539	750	750	750	750

The captured wave energy (kWh/year) represents the amount of electricity that can be produced from a WEC when placed in the case study location. The different types of WEC device employed in extracting energy from the waves was discussed in Chapter 2 critical review. Based on the review, wave energy absorption performance for which there is public information is illustrated in Table 16. Captured wave energy for each sea state bin is calculated by multiplying each cell in the table of annual occurrence of hours in Table 12 by each corresponding cell of the wave energy absorption performance in Table 16 (Previsic, 2004).

The wave energy that could be extracted from any selected location can be estimated as a function of sea states and the wave energy absorption performance of the WEC device (Previsic et al., 2004). For WEC devices sufficient data is not always readily available for performance prediction on generated power as a function of sea state. This situation makes it rather difficult to establish a "baseline" performance against which industry improvements can be benchmarked. The situation is more difficult when different underlying assumptions and model test methods have been used to generate the power production estimates (EPRI, 2011).

4.3.7 Vessel Accessibility Weather Windows

The historical wave data is used to model the marine operational environment. The wave input data is used to determine the weather windows suitable for marine operations. Maintenance actions and O&M costs for offshore structures strongly depend on the weather conditions which define the accessibility of the devices. Boats and Vessels are used for transporting crew and their equipment. Studies (Cradden et al., 2013; O'Connor et al., 2013) on weather windows analyses have been performed to quantify the levels of access to marine renewables for O&M planning activities. In offshore engineering, a weather window may be defined as a period where quantities such as $\mathrm{H_s, T_p, wind\ speed}$, remain at levels which permit a given set of marine operations to be performed safely.

In this context, the weather window needs to be specified in terms of the number of occurrences, the durations and starting time of for each working shift (Graham, 1982). This is required for the planning of the O&M activities of the WEC farm. Efforts geared towards developing the methodology for wave energy resource assessment are critical for developing knowledge of the physical conditions experienced by WEC devices and arrays. As an integrated framework, the case study approach to investigate the variation in the O&M cost estimates is presented in the following section.

4.4 Application of Operational Expenditure (OPEX) Modelling

In this section, a case study application of the operational expenditure modelling is presented. The lack of operational experience has often been considered as one of the problem undermining the development of wave farms using the WEC technology. Assessment and calculation of OPEX has been an important study area for wind farms (Morthorst, 2003). Studies on vessel chartering for offshore O&M activities of wind farms (Dalgic et al., 2014) acknowledged that there are two major types of O&M vessels; the vessels for the minor maintenance activities and the vessels for the major maintenance activities.

In this case study, the O&M vessel requirement illustrates the vessel specification or attributes of the O&M vessel required for the offshore WEC farm O&M activities. To illustrate the methodology and O&M modelling developed in the integrated framework; first the vessel specification is considered and defined based on the specific type of O&M activity for the repair or deployment of a WEC farm at the case study location. Therefore, the O&M scenarios considered are:

- Preventive Maintenance – Overhaul Replacement (Major repair/ Minor repair)
- Corrective unscheduled Maintenance- Failure based Replacement (Major/Minor repair)

The applicability of the O&M vessel such as Crew Transfer Vessels (CTVs) and tug boats, which in this case are classified as Small vessel 1 or Offshore Support Vessels(OSVs), in this case classified as Big Vessel 2 depends on the underlying weather condition during the time that the O&M vessel is required. This implies that either Small Vessel 1 or Big Vessel 2 can be employed to perform the O&M activities at the WEC farm. In this context, the Big Vessel 2 will only be required when access by smaller vessels in the category of Small Vessel 1 is limited due to the significant wave height threshold.

The choice of employing the Big Vessel 2 will be considered based on the cost and benefits. This is applicable particularly due to the objective of finding ways to reduce the O&M cost. In this respect, specific cost attributes in relation to the O&M cost is applied to investigate the most cost-effective approach to allocate O&M resources such as: Crew Transfer Vessels (CTVs) or tug boats and O&M technicians required for each maintenance activity. In this regard, the case study is illustrated to validate the proposed methodology and modelling proposed in the integrated framework.

4.4.1 Wave Farm Attributes

For economic assessment and O&M cost modelling of the WEC farm, the initial input of the WEC farm attribute is considered. Table 17 shows a summary of initial input of the wave farm attributes. In this case the main information required are the input relating to the WEC device specific characteristics and power output, including the number of devices in the WEC farm. It is important to mention that the information presented in Table 17 for the initial wave farm attributes is used only as an example to illustrate the case study in the integrated framework.

The information is gathered from relevant literature of studies in the field and presented in the form shown for clarity.

Table 17: A summary of the wave farm attributes

Farm Attributes	Value
Pelamis gross output capacity/ device	0.75MW
Number of devices operating (N_{dev})	60
Depth of Pelamis P1 device	50 m
Pelamis P1 O&M Access limit	$\mathrm{H_s} = 2\mathrm{m}$
Capacity factor (f_{cap})	40%
Power generation availability (f_p)	98%

The information in Table 17 defines the initial input of the WEC farm. The Pelamis gross power output capacity refers to the total power output of the device without considering any intermediate reduction or loses because of power generation or transmission. The Pelamis gross power output is adapted from existing literature (EMEC, 2010). On the other hand, the net capacity factor may be defined as the ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same amount of time (RERL, 2008).

The capacity factor is defined for any electricity producing installation, i.e. a fuel consuming power plant or one using renewable energy. For renewable energy, such as solar power, wind power and electricity generation using WEC, the main reason for reduced capacity factor is generally the availability of the energy source (EMEC, 2009). The plant may be capable of producing electricity, but its "fuel" (wind, sunlight or water wave) may not be available. The availability of the wave energy resource was estimated for the case study location.

The results which are presented in Chapter 5 resource assessment results and discussion show that the availability of the resource on a monthly time scale throughout the year is around 98%. The Pelamis P1 O&M access limit refers to the maximum significant wave height threshold required for safe O&M activities of the WEC device. The results of the accessibility for different significant wave height weather windows are also demonstrated in Chapter 5 resource assessment results and discussion.

4.4.2 O&M Vessel Specification

In addition to the initial wave farm attributes, the O&M Vessel Specification input is defined for the WEC farm O&M activities. A critical review on O&M vessel chartering agreement has been presented in Section 2.8.2 and Section 2.8.3, in Chapter 2 critical review. The relevant input required for calculating the criteria for O&M vessel transport cost is summarised in Table 18. As illustrated in Table 18 the O&M vessel specification and cost input defines the type of input and the unit in relation to the type of vessel that will be required to carry out the O&M activities of the WEC at the WEC farm.

Table 18: O&M vessel specification input

Input Name	Type	Unit
Number of O&M technicians	Operational Cost	£/person
Number of Vessel Crew	Cost	£/person
Daily fuel consumption in operation	Cost	tons
Daily fuel consumption in port	Cost	tons
Climate conditions	Survival	- -

In this respect, the O&M technicians refers to the personnel directly responsible for performing the repair or maintenance activity on the WEC. The number of technicians may vary depending on the WEC farm size and operational requirements. The vessel crew refers to the vessel staff such as the captain, engineer and deck crew. These personnel are responsible for the vessel operation and services. The vessel crew is a cost input and the amount for each crew member vary per the category and rank of the personnel. The input of the wave farm attributes is relevant for the analysis of the O&M cost estimates and to define the scenario that is used to demonstrate the results of the O&M cost presented in Chapter 6 O&M Modelling results and discussion.

4.4.3 Estimating Cost of Preventive O&M Strategy

O&M activities involving repair of WECs could be performed on site or onshore. Depending on the type of maintenance strategy the onsite maintenance can be for minor repairs and visual inspection. The onshore maintenance can be for the major repairs or overhaul. In that case the WEC will be towed to the onshore maintenance facility for the repair to be performed (Bussel and Bierbooms, 2003). The types of failure and man hours required to perform the maintenance activities as shown in the FMEA table together with the initial input of the wave farm attributes, provides the relevant information for the WEC farm O&M cost model.

For a WEC farm project life cycle of 25 years, it is assumed that scheduled on-site visits to the WECs will be undertaken for on-site inspection or preventive maintenance activities. Moreover, it is assumed that some components (e.g. hull structure, bearing pads and motor) of the WEC device will need to be maintained in an onshore maintenance facility (Ambuhi et al., 2015). For either onsite or onshore maintenance, a vessel will be required for the onsite maintenance activities and to tow the WEC device to the onshore maintenance facility.

Based on the initially defined wave farm attribute, the maintenance activities contributing to the OPEX, namely: the on-site inspection/service, or onshore maintenance/repair action for the preventive O&M strategy is analysed. Depending on the type of maintenance strategy employed, the annual maintenance cost is calculated based on the sum of all the maintenance cost averaged over the entire project life. A project life cycle of 25 years is assumed in this case study example to illustrate the O&M cost for the preventive maintenance strategy. This is because a project life cycle of 25 years is deemed within this thesis to be an ideal time to justify in terms of recovering the huge financial investment that will be required.

Furthermore, it is expected that on-site visits to the WECs will be undertaken to perform on-site inspection or preventive maintenance activities for the generic components such as: the mooring lines and dynamic risers. For the preventive maintenance or major repairs of components such as the hull structure, motor and bearing pads; that need to be performed onshore, a suitable vessel will be required to tow the WEC to the onshore maintenance facility. Table 19, is used to illustrate the combined input of the WEC farm specific attributes and O&M cost components relevant for analysis of O&M cost, in the case of estimating the cost of preventive maintenance actions.

As shown in Table 19, a cost value is allocated to each input parameter. This is relevant to validate the methodology and modelling in Chapter 3, developed for the integrated framework on resource assessment and O&M modelling. For that reason, the WEC farm attributes and O&M cost components together with the day rates of suitable O&M vessels for WEC farm operations, the cost of the crew employed on the maintenance vessels and technicians to perform the maintenance actions are illustrated. A detailed explanation of Table 17 is provided to clarify how these aspects are modelled. In this case, the daily charter rates for Small Vessel 1 is estimated as £5,000. These vessels are smaller O&M vessels such as: tug boats and CTVs.

Table 19: Wave Farm Attributes and O&M Specific Cost Attributes

Total Transportation Cost	Value
Charter rate/day Small Vessel 1	£5,000
Charter rate/day Big Vessel 2	£19,000
Vessel new building cost	£1,500,000
Crew cost (1) Captain	£18,000-30,000/person
Crew cost (2) Engineer	£15,000-27,000/person
Crew Cost (3) Deck Crew	£15,000- 20,000/person
Distance to the WEC Farm	100 km
Distance in the WEC farm	2 km
Vessel Speed	20 knots
Vessel Speed in the WEC farm	5 knots
Contingency factor bad weather	20 %
Engine power max	2,000 kw
% of max speed	80
Specific Fuel Oil Consumption (SFOC)	175(gr/kw*h)
Number of days at sea	10
Price of fuel	363 (£/MT)
Number of main engines	1
Lubricants & Diesel oil correction factor	1.15
ROV Mob/demob time	0.5 hrs
Time other than ROV (bring WEC on board)	0.5 hrs
Inspection time per device	2 hrs

In addition, the daily charter rate of a “Big Vessel 2 such as: Offshore Support Vessels (OSVs) is estimated as £19,000. The “Big Vessel 2 is capable of performing the maintenance operations in challenging environment due to high significant wave height or bad weather condition. The daily charter rates are obtained from existing literature applicable to O&M of marine renewable devices. The cost of the O&M vessel captain, and deck crew vary depending on experience and the size of the vessel.

The values presented in Table 19 illustrates the average annual cost. For example, the annual cost of the skipper or captain of a Small Vessel 1 is around £18,000, while the annual cost of the captain for a Big Vessel 2 is around £30,000. However, cost associated with vessel crew and technician cost are also considered as average values. The reason is because salary range for vessel crew and technician varies per the rank and experience of the crew member. The number of crew/ technician associated with each cost category is also specified and this can vary depending on the size of the O&M vessel.

Therefore, to calculate the total cost for each category, the average cost is multiplied by the corresponding number specified in that category. Moreover, the O&M vessel specification and specific attributes such as engine power max, percentage of maximum speed, Specific Fuel Oil Consumption (FOC), number of main engines, lubricants & diesel oil correction factor can also vary depending on the type of vessel. For example, the number of main engines could be 1 for smaller vessels or 2 for bigger vessels. The values in Table 19 are adapted from relevant studies on O&M vessel modelling and equipment cost (Lazakis et al., 2013).

These crew costs and the specific O&M vessel attributes adapted from literature are ideal values for the category of vessels in relation to O&M activities of renewable energy devices. The price of fuel is based on the current market value of marine diesel per metric ton available in public domain. Prices internationally are usually quoted in United States Dollars (USD). The values in Table 19 were converted based on the prevailing foreign exchange rates. The type of equipment needed for the replacement maintenance affects both the equipment cost and the transportation cost. The labour, equipment and transportation costs are proportional to the required maintenance time. The vessel operation cost is determined by vessel speed and offshore farm distance.

4.4.4 Estimating Cost of Corrective O&M Strategy

Similarly, the cost of the corrective O&M strategy is analysed based on the input of the FMEA and the initial WEC farm attributes. In the following sections, how the O&M strategy is applied to investigate the cost of O&M action for repair of the WEC components is illustrated. As described in Section 3.6.1.2 in Chapter 3 methodology and modelling, for estimating the O&M cost of corrective or unplanned maintenance activities, the main attributes are the same for all different sub-cost elements (transportation, labour, workshop and equipment/tools). However, there is an additional feature regarding the failure rates of the various components of the WEC.

In the case of a typical WEC device failure rate adjustment factors of the generic components can be adapted. Generally, the failure rate parameters could be identified based on the specific turbine components and failure types. The distribution can be defined based on an initial input value. Nevertheless, there would be an additional cost for the O&M vessel required to perform the corrective maintenance action. The reason for this additional cost is due to the unexpected timing and in most cases unavailability of the O&M vessel. In the methodology and modelling developed in the integrated framework, the O&M activity is defined based on a generic Failure Modes and Effect Analysis (FMEA) table.

As mention earlier, the FMEA table is used to present the generic failure rate for different components and their probability of failure. In this respect the O&M modelling is applicable to investigate the OPEX with the objective of evaluating the cost of the O&M activities based on either the preventive or corrective maintenance. The O&M strategy identifies the type of maintenance activity that is performed. The influences of the different parameters for example, failure rate, inspection time and cost of the corrective maintenance action are evaluated for the overall costs and the number of repairs needed during its lifetime.

In this respect, access and availability with respect to weather windows and impact on energy output on the wave farm operations are demonstrated. In the end, the outcome of each maintenance activity based on the O&M strategy used to illustrate the case study example is presented in Chapter 6 O&M modelling results and discussion. Factors affecting the cost of maintenance action include the number of WECs, the magnitude of labour-hours per WEC device that are needed to perform a maintenance operation and transport cost. To reduce operational cost, it is suggested that on-site maintenance for minor repairs and inspection be performed using smaller O&M CTVs.

4.4.5. Total Initial Cost (TIC)

In this case study, the main elements contributing to annual cash flow are illustrated. This is relevant to demonstrate the Total Initial Cost (TIC) of the WEC farm project. As mentioned in the methodology and modelling presented in Chapter 3, the TIC represents the total cost incurred in purchasing the WEC device and constructing the farm. Table 21 Shows the main elements contributing to the WEC farm cost and represents the parameters used to evaluate other aspects of initial cost of the WEC farm project as a percentage of the Initial Cost of the WEC ($\mathrm{IC_{WEC}}$). Previsic, (2004) estimated the costs of WEC infrastructure by calculating TIC as a percentage of the initial cost of WEC ($\mathrm{IC_{WEC}}$).

This estimate has since been the bench mark for many wave energy CAPEX and OPEX assessments. The accurate prediction of energy cost of a WEC farm is important to the justification of planning and constructing such a farm project. In this thesis, capital cost is analysed based on the initial cost estimates of Pelamis device in 2011. In studies (Dalton et al., 2012), the price of steel is used as the multiplying factor to evaluate the initial cost of WEC ($\mathrm{IC}_{\mathrm{WEC}}$) and total project initial cost (TIC). This is because the Pelamis power matrix also used the prices of steel as a multiplying factor.

Table 20: Costs of WEC farm calculated as a percentage of IC_WEC, based on (Previsic, 2004)

WEC Parameter	% of $\mathrm{IC}_{\mathrm{WEC}}$
Replacement Costs	90%
Management Fees	10% of total TIC
Mooring	10%
Cabling	10%
Grid Connection	5%
Decommissioning Fees	5%
Spare parts	2%
GHG Investigations	0.05%

An amount of £1,600,000 is used for the $\mathrm{IC}_{\mathrm{WEC}}$, This amount includes all the cost associated with the device internal components and cost of steel sections. Table 22 presents an example of $\mathrm{IC}_{\mathrm{WEC}}$ and the Total Initial Cost (TIC), for a 0.75MW, 45 MW and 75MW WEC farm project. The $\mathrm{IC}_{\mathrm{WEC}}$ of the Pelamis adapted from literature was obtained from the 2004 EPRI report in California (Previsic, 2004). To illustrate the economic value of the WEC farm, the Annual Cash Flow (ACF) of a WEC farm is estimated for the different project category. In this case, the TIC only considers the initial capital cost of the WEC device.

Table 21: Example of the specific project size and cost used for the O&M cost calculation

Project Capacity	Cost/KW		N_{dev}	Size
0.75MW Farm	$\mathrm{IC}_{\mathrm{WEC}}$ TIC	£3,440/KW £6,400/KW	1	Small
45MW Farm	$\mathrm{IC}_{\mathrm{WEC}}$ TIC	£2,000/KW £3,680/KW	60	Medium
75MW Farm	$\mathrm{IC}_{\mathrm{WEC}}$ TIC	£1,280/KW £2,000/KW	100	Large

4.4.6 Site Rental

Site rental is calculated based on the rental cost of offshore generating stations or as a percentage of gross revenue (O'Connor et al., 2013; Dalton et al., 2011). An Irish governments paper on offshore generating station costs (Irish Government, 2000) quotes commercial rents of €3,800/MW per. year. This is based on the nominal output of each turbine rating of 1MW or a percentage of gross revenue (2-2.5%) being paid as rental over the site sought. It is anticipated that the wave energy site rental costs will be similar to offshore wind rental costs. A group of offshore engineering experts (Fingersh et al., 2006) assumed that the permitting fee is around 37 times the capacity of the generator.

A similar approach for estimating the permitting fee is used as an example to illustrate the site rental cost. The reason is that these fees are highly site dependent. In that case, it was assumed that the siting and permitting fees for operating a 100MW farm is round £3.7M (Fingersh et al., 2006). Table 23 illustrates the input values relevant for analysis of the WEC project. In relation to the integrated framework for resource assessment and O&M modelling, the O&M model input can be used in the initial planning phases to assess the financial risk and to estimate the total operational cost for running the WEC farm project, as well as estimating the future O&M cost for operating WEC array units.

Table 22: A summary of Input values for the project. (O'Connor et al., 2013; Dalton et al., 2010)

Parameter	Value
Borrowing or Interest rate	7.5 %
Inflation Rate	3 %
Project Years	25
Feed in Tariff	0.35 /Kwh
Bulk Purchase Discount Factor (bdf)	0.9
Insurance Rate	3 %
Pelamis O&M Rate	3 %

4.5 Financial Indicators

The financial indicators have been described in Chapter 3 methodology and modelling in the integrated framework. The financial indicators are relevant for assessing the economic viability of the WEC farm project. The assessment is focused on WEC farm profitability and makes use of detailed operational simulations. In this case, the procedure is illustrated following an assessment of the impact of OPEX on Net Present Value (NPV) and Internal Rate of Return (IRR) based on the O&M cost modelling. The main financial input considered in this case include: Feed-in tariff (FIT), Discount Factor (DF), Discount Rate (DR), Discounted Pay-Back Period (DPBP), Net Present Value (NPV) and Internal Rate of Return (IRR).

4.5.1 Feed-In Tariff (FIT)

Grid sales are a credit and are added to other negative cost values for each year (O'Connor et al., 2013). Dalton et al (2010) recommended a FIT of £0.30/KWh which was estimated in their report to produce a positive financial return and internal rate of return (IRR) for an Irish wave farm. The revenue based on a corporate tax rate of 12.5% and a feed-in tariff of £0.22/KWh, was implied (O'Sullivan and Dalton, 2009). Feed in tariffs may need to be higher particularly in situations when staggered installation over a 10-year period is considered. In such cases, Dalton et al., (2011) recommended a FIT of £0.35/KWh.

4.5.2 Calculating the Discount Factor (DF) and Discount Rate (DR)

For the assessment of CAPEX and OPEX of a wave energy project it is necessary to make some cash flow assumptions. One of such assumption is that the rate of inflation is the same for all costs. Studies on operational expenditure cost for wave energy projects (Dalton et al., 2011) applied a general inflation rate of 3% to assess the economic value of the WEC farm. The assumption is logical when calculating the discount rate of the wave energy project given that the discount rate (DR) is the interest rate commensurate with perceived risk used to convert future payments or receipts (within a project lifetime) to present cash value.

The discount factor is calculated using the discount rate and the discount rate is a function of the borrowing rate and inflation rate. Therefore, by defining the discount rate based on the assumption of constant cash values, inflation is factored out of the economic analysis during the project lifetime (Dalton et al., 2011). In that case, all costs become translated real costs. Studies (Dalton et al., 2011) suggested that a discount rate of 10%, in the range for wave and tidal energy projects as recommended by Carbon Trust (Callaghan, 2006) can be applied.

4.6 Chapter Summary

In this case study related to a novel integrated framework which considers the wave energy resource assessment methodology and O&M cost modelling has been presented. Within the framework, the method followed to establish the economic value of the wave project is also identified. In the resource assessment method, access and availability with respect to weather windows at the case study location is illustrated and the impact on energy output and wave farm operations is quantified. The modelling approach used to develop the algorithms required to generate estimates of operational costs and device availability for the operational simulation is illustrated.

The case study has been applied to consider the cost associated with the maintenance strategies for preventive and corrective maintenance events for the WEC farm. The operational simulations have been developed expressly to generate the O&M costs estimates; device availability which reflect device characteristics and chosen O&M strategy. O&M vessel for the offshore WEC farm is assessed through analyses of environmental conditions, vessel specification and suitability of the vessel to perform the required maintenance operation.

Chapter 5-Resource Assessment Results and Discussion

5.1 Chapter Outline

This Chapter demonstrates the results and discusses the key finding of this study, having described the integrated framework for resource assessment and O&M cost modelling in Chapter 3 methodology and modelling and the case study illustrated in Chapter 4. Section 5.2 presents the results of the preliminary analysis based on investigation of the historical wave dataset. This is followed by results of the wave data time series analysis and frequency of occurrence in Section 5.3 and in Section 5.4 results of annual averages are presented.

Section 5.5 presents the variations and seasonality of the data and in Section 5.6 the results of investigation of the wave power and productivity assessment are demonstrated. Thereafter, results of the offshore accessibility factors are discussed in Section 5.7. The Chapter summary is presented in Section 5.8 to conclude the results and discussion of the resource assessment.

5.2 The Preliminary Analysis

The preliminary analysis of the historical wave dataset illustrated in Chapter 4 case study application of the methodology, is to achieve the objective of finding out any potential problem with the historical wave dataset. In the process, more detailed information can be acquired from the dataset. For example, some problems that may be observed together with the information that may be acquired could be described in relation to such cases where the data have excess skew: which means that the data may be lopsided. Moreover, the data may have excess kurtosis (very fat tails) or the data may be bi-modal (i.e. having two humps).

In some cases, the data may follow a distribution other than the normal distribution; as there are many other types of distribution that the data set can follow. These examples mentioned are some of the useful information that could be obtained in the preliminary data analysis. In this respect, the underlying assumptions of the historical wave dataset and distribution are investigated and described to validate the methodology and modelling. The results of the initial statistical description in the preliminary analysis is summarised and presented in the form of a table for each of the selected parameters in the historical wave dataset.

The wave power climate is illustrated using the wave dataset measured over a period of 12 years for the case study location. In Table 23, the maximum, minimum, mean and standard deviation values for each year in the historical wave dataset is presented for the variables of the wind speed values. These values are later used to illustrate the probability distribution of the variable of the wind speed in the historical wave data set. The main significance of presenting the data in this thesis is to describe or characterise the distribution.

Table 23: Maximum, Minimum, Mean and Standard Deviation of Wind Speed Values

Wind Speed Values(m/s)				
Year	Max	Min	Mean	Stdv
2005	19.8	0	7.4	3.7
2006	22.1	0	6.5	3.3
2007	27.8	0	7.4	3.9
2008	24.0	0	6.5	3.2
2009	22.3	0	6.2	3.5
2010	28.3	0	6.9	3.3
2011	25.6	0	6.7	3.1
2012	28.8	0	6.4	3.2
2013	22.7	0	6.7	3.2
2014	21.3	0	6.7	3.3
2015	28.0	0	6.9	3.2
2016	22.3	0	7.5	3.5

In the initial statistical description for the wind speed values as presented in Table 24, this thesis attempts to find out the highest values or extreme conditions. It could be observed that the year with the strongest wind speed occurred in 2007, having the value of 27.8m/s, while the minimum value is zero. The mean and standard deviation value is required to calculate the probability distribution of the wind speed values. In this case the mean values range between 6.2 to 7.5 and the standard deviation is between 3.1 and 3.7 as illustrated in Table 24.

In this thesis, the normal distribution is applicable to describe the random variables of the historical wave dataset for the case study location. Generally, the random variables are either continuous (infinite) or discrete (finite). In this context, a Probability Density Function (PDF), is applied to describe the behaviour of the continuous random variable if it should be measured.

On the other hand, a Probability Mass Functions (PMF) can be used to describe the behaviour of the discrete random variable if it should be counted. Associated with either the PDF or PMF is the Cumulative Distribution Function (CDF).

The CDF describes the probability that a variate X takes on a value less than or equal to a number (x) in a range or interval. It is important to mention that all distributions perform the same function: to characterize the behaviour of the random variable. In this context, it is a matter of two-different perspective which can be taken about the distribution. Thus, the first perspective is either if the distribution is discrete or continuous. The second perspective is the type of questions asked or type of information (sort) to find out from the distribution.

The method followed in the preliminary analysis requires that the variable values of the selected parameter are first sorted into bins. In this context, the bin values represent the values of the selected interval within a specified range. In the case of the wind speed values, the bin values started from zero (the minimum value), with intervals of 0.5m/s, up to the maximum value of 28m/s in order to account for all the values within the selected range. This is applicable because, theoretically the PDF associated with a continuous random variable requires an interval since it draws from an infinite number of possibilities in the distribution.

Figure 49 shows the plot of a standard normal distribution (bell curve), used to illustrate the result of the probability distribution of the random variables of the wind speed values in 2005. In this case, the line in the graph indicates the continuous distribution because it characterises the continuous random variable. The y-axis represents absolute values of the probability density function, while the x-axis the wind speed values (m/s). In this case assuming any point is picked from the distribution, the significance of Figure 49 is to demonstrate that the value picked does not refer to that point alone. The reason is that there are an infinite number of values along that continuous distribution.

Thus, a probability density question is asked from the distribution. Theoretically, if the random variable should be measured, it is continuous and it draws from an infinite number of possibilities. Therefore, in the following sections for the results presented, the main difference between the distribution function as applicable in this thesis is the question asked with respect to either a density or a cumulative question. Assuming a local point on the x-axis of the distribution is specified, for example 8m/s; what this imply is that, it will not be proper to say that (*x*) is equal to 8m/s because it is continuous.

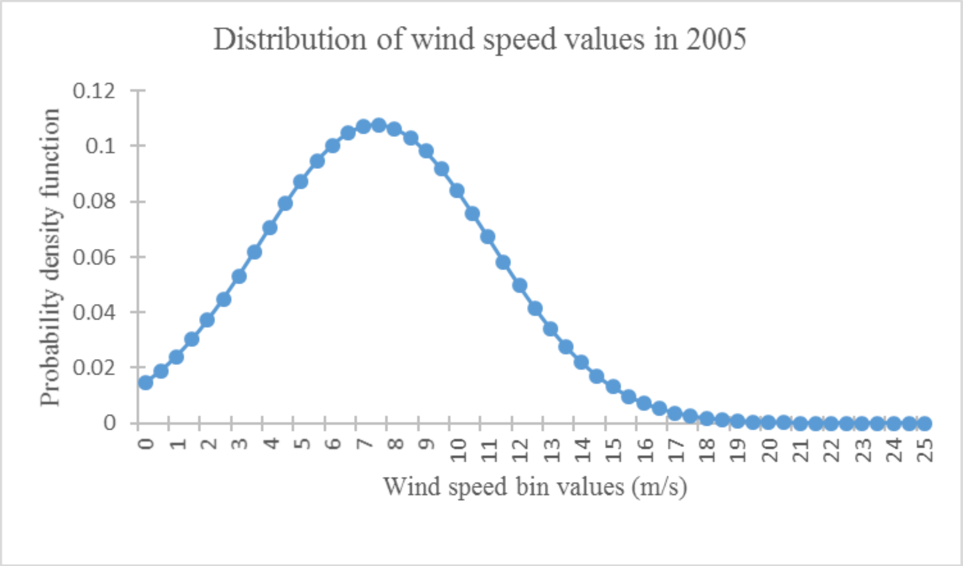


Figure 49: Probability Distribution of Wind Speed Values in 2005

In this context, the conventional question will be to ask what the probability is, for that random variable to fall in between two values (e.g. 7.5 and 8.1). In this case, it becomes a density question because the density question asks what the probability is for the random variable being approximately equal to 8m/s, but technically, referring to an interval. This idea provides the information about the continuous random variable with respect to the probability density function. The value 8m/s is used as an example in this discussion, to ask the probability density question in a manner such as: what is the probability that the random variable (*x*) will lie in between two values that is approximately equal to 8m/s. In Figure 49 the answer in is 0.1.

In that case the answer is the probability density function which gives the local probability of an approximate outcome of the random variable. Similarly, Figure 50 is used to illustrate the probability distribution of the wind speed values for other selected years in the historical wave dataset. As in Figure 49, the y-axis represents absolute values of the PDF, which gives the probability that the continuous random variable in the distribution of any of the selected year is approximately equal to some value within the selected interval on the x-axis. The x-axis represents the selected interval and range of the wind speed bin values.

As could be observed in Figure 50 the distribution tends to be the same as each other. Thus, presenting a similar pattern for every year in the entire period of the historical wave dataset. One of the reason for the similarity is because there is not much difference in terms of the spread of the mean and standard deviation of the variables (Evans et al., 2000). The reason for selecting the odd number years is to ensure consistency in the presentation of the results in this section. Since the first year in the dataset is 2005, it is ideal to start with the first year.

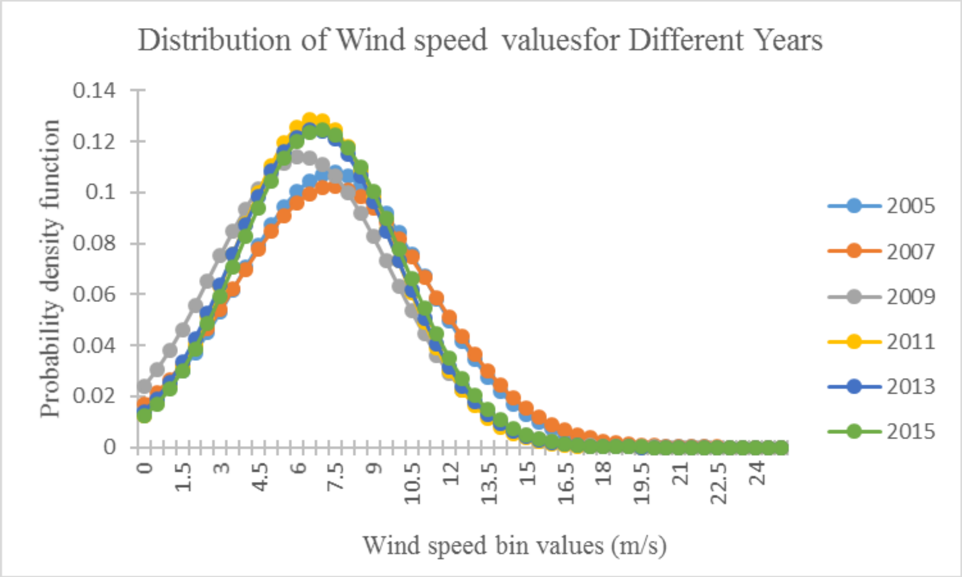


Figure 50: Probability Distribution of Wind Speed Values for Different Years

In contrast to the PDF, the PMF associated with a continuous random variable draws from finite number of possibilities in the distribution. This implies that the distribution of PMF can be counted. As with the PDF, it can also be used to specify a local point on the x-axis to provide the information which gives the probability that a discrete random variable is exactly equal to a specific value in the range. At this point, it is important to emphasize that the standard normal distribution (bell curve) has a total area (probability) equal to 1 and it is also symmetrical about the mean. Therefore, in the analysis of the probability function, all the values of the function must be non-negative and should sum up to 1 (Johnson et al., 1993).

In a sense, the PDF is measured and can be used to specify a local point on the x-axis. This will provide the information on the probability of an approximate outcome of the random variable. In this context, the PDF used to ask the " approximately equal to" question. This is applicable for only positive values of the random variable (i.e. values on the right-hand side of the mean) (Evans et al., 2000). Assuming the average wind speed values are obtained for each year in the case study location; the probability mass function can be used to find out the amount of probability mass lying over the specified value in the range. For instance, at wind speed values of 8m/s, the amount of probability mass lying over the value is equal to 0.1.

The probability of the maximum wind speed value in 2005 lying within the range of 17m/s is approximately equal to 0.0037 when a density question is asked. Similarly, the probability mass of the minimum wind speed value for the year 2005 lying in the range of 2m/s is exactly equal 0.037 when the mass function is considered. The PMF functions exist for either scalar or multivariate random variables whose domain is discrete (Stewart, 2011).

As mentioned earlier, associated with either the PDF or PMF distribution is the CDF. In this respect, the CDF is used to ask a cumulative question (i.e. a “less than" question). Hence, the CDF is applicable to describe the probability that a normally distributed random variable in a continuous distribution, is less than or equal to some value of the random variable in the selected interval. The significance of Figure 51 is to illustrate the distribution of the cumulative function for variables of the wind speed values in year 2005. In Figure 51 the y-axis illustrates absolute value of the CDF, while the x-axis is the bin values of the wind speed intervals.

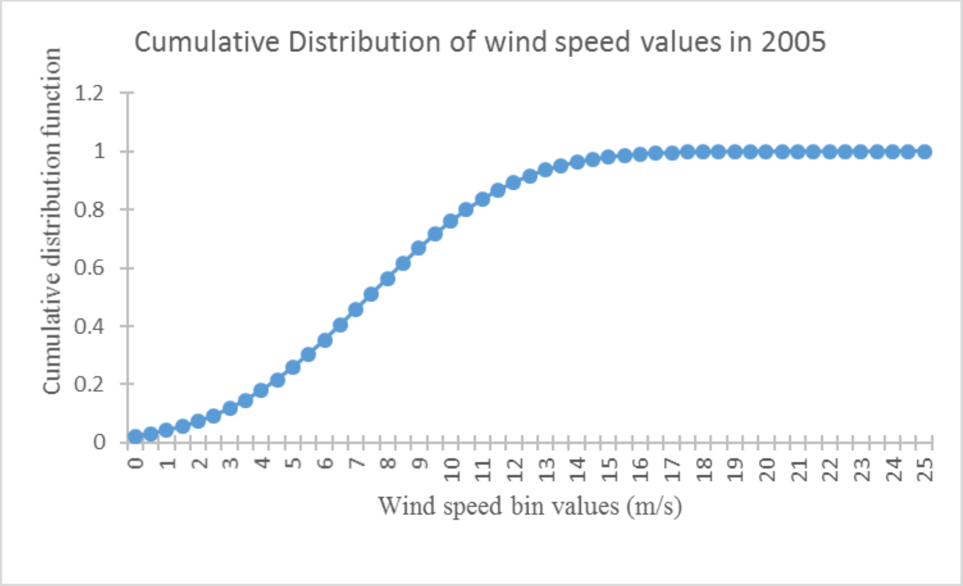


Figure 51: Cumulative Distribution of Wind Speed Values in 2005

The blue line depicts the cumulative distribution function which provides the information that the probability of the random variable is less than or equal to the local point specified on the x-axis. This is the only difference when comparing between the graphs presented in Figure 49 and Figure 51. In Figure 51, the probability is the total area to the left of the density function curve as a percentage of the area under the curve. For example, picking any point such as 8m/s from the graph in Figure 51, the blue line characterises the area under the curve to the left.

Therefore, the probability will be approximately equal to or less than some variable, in this case 0.56, which is approximately equal to or less than 56%. Hence, the blue line of curve in the graph in Figure 51 rises to right and it asymptotic to100%. This is because as it moves out to the right, the probability of picking any value such as 18m/s is 0.99, which is less than or approximately equal to 99%. This is almost the whole area which is close to 100%. This example illustrates the cumulative distribution function.

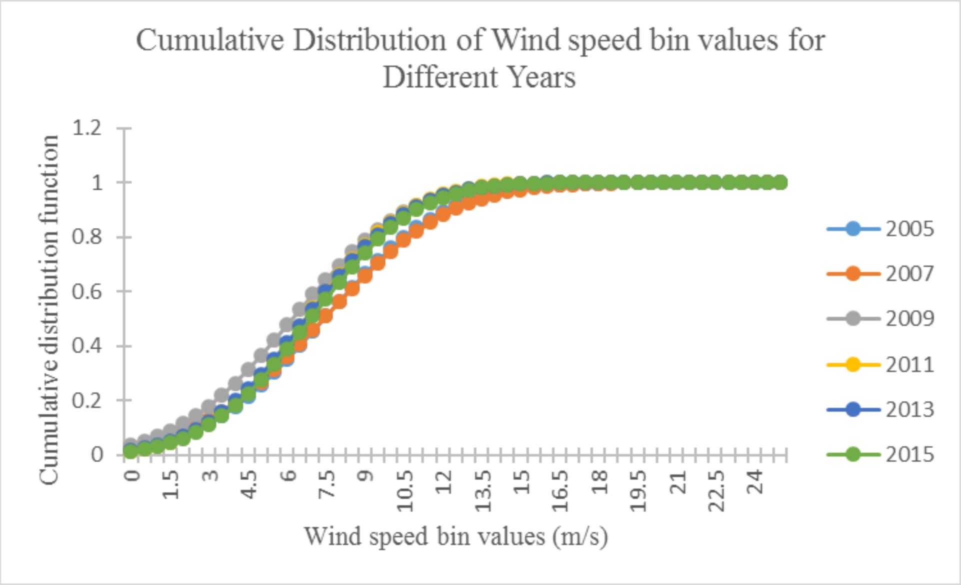


Figure 52: Cumulative Distribution of Wind Speed Values for Selected Years

The difference or key point is that instead of an approximately equal to value, the distribution is used to find a less than or equal to value. In addition, the importance of Figure 52 is to illustrate the cumulative distribution for variables of the wind speed values for different years based on the preliminary analysis of the historical wave dataset. In Figure 52, the observation is that all the different years have and maintain the same generic characteristic in the dataset. The result demonstrates consistency in the historical wave dataset used. These results suggest that the wind speed dataset does not to have any adverse variation.

In this case, the continuous random variables (*x*) are those quantities whose values range over an interval of numbers and associated with these continuous random variables (*x*) is a probability density function *F(x)* (Evans et al., 2000). In addition to the preliminary analysis of the wind speed values, the values of the significant wave height and wave energy period were also analysed. This is to find out the underlying assumption of the data distribution and if the values in the dataset fits to a normal distribution. The results of the initial statistical description of the significant wave height variables in the historical wave dataset are summarised and presented in Table 24.

Similarly, Table 24 presents the maximum, minimum, mean and standard deviation values of the significant wave height measurement for each year in the dataset. The maximum value is 8.4m and this value occurred in the year 2016. The minimum value recorded is zero for almost all years. Moreover, the mean is in the range of 1.5 and 1.9; while the standard deviation range between 0.6 and 0.9. These values are used to plot the graph of the probability distribution. This is significant to describe the distribution of the significant wave height variables in the historical wave dataset.

Table 24: Maximum, Minimum, Mean and Standard Deviation of Significant Wave Height Values

Significant Wave Height-Hs (m)				
Year	Max	Min	Mean	Stdv
2005	5	0.3	1.6	0.7
2006	5	0.3	1.6	0.7
2007	6.2	0.4	1.6	0.7
2008	6.1	0	1.5	0.6
2009	6.4	0	1.7	0.8
2010	5.9	0	1.6	0.7
2011	5.1	0	1.6	0.6
2012	6.3	0	1.6	0.7
2013	6.1	0	1.6	0.7
2014	7.4	0	1.7	0.9
2015	4.9	0	1.7	0.7
2016	8.4	0	1.9	0.9

As in the case of the initial statistical description for the wind speed values, this analysis intends to find out the highest values or extreme conditions that may be present in measurement of the significant wave height values. The importance of Figure 53 is to demonstrate the result of the probability distribution of significant wave height values in 2005. In Figure 53, the line in the graph indicates the continuous distribution function and it characterises the continuous distribution of the significant wave height variable.

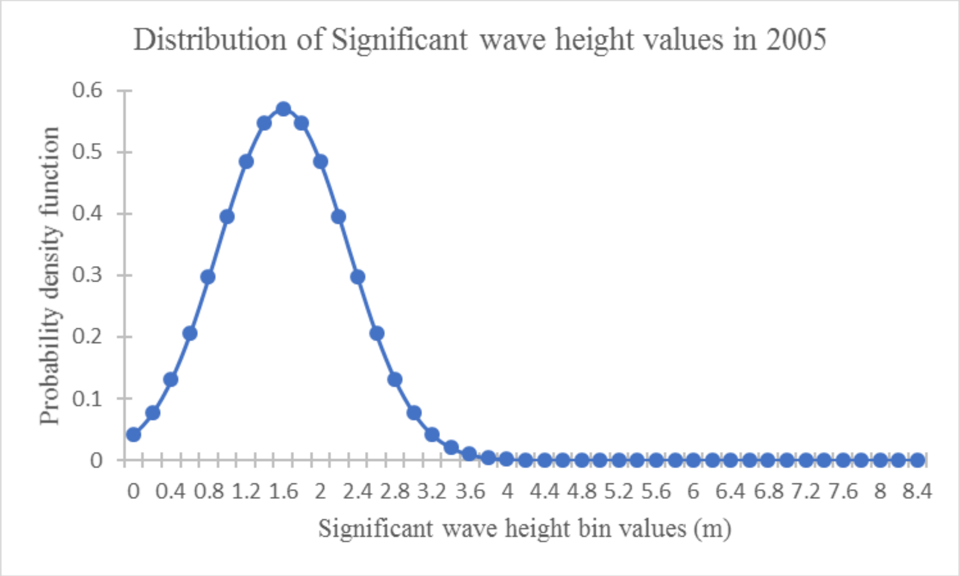


Figure 53: Probability Distribution of Significant Wave Height Values in 2005

In this case, the y-axis represents the absolute values of the probability density function of the continuous distribution. The x-axis represents the bin values of the selected intervals of the significant wave height variables. Assuming any point such as 2m is picked on the x-axis. Considering that there is an infinite number of possibilities in the distribution. Since, it is continuous and draws from an infinite number of possibilities; it is possible to find out the probability that the random variable will fall in between two values (e.g. 1.5 and 2.1), if a density question is asked.

In this context, it is proper to ask what the probability is for the random variable (*x*) to be approximately equal to 2m, technically referring to the interval (1.5 and 2.1). The value 2m is used to illustrate the example in the discussion of the significant wave height variables. Thus, the probability that the random variable (*x*) will lie in between two values that is approximately equal to 2m is approximately equal to 0.48. This is the probability density function, which gives the local probability of an approximate outcome of any variable of the significant wave height value in the distribution.

Similarly, Figure 54 is used to illustrate the probability distribution of the significant wave height values for other selected years in the historical wave dataset. In this case, the y-axis represents the PDF, which provides the information on the local probability of an approximate outcome of any variable of the significant wave height value in the distribution. The x-axis represents the bin intervals and values for the range. As could be observed in Figure 54; the distribution tends to be the same as each other for every year in the entire period of the historical wave dataset.

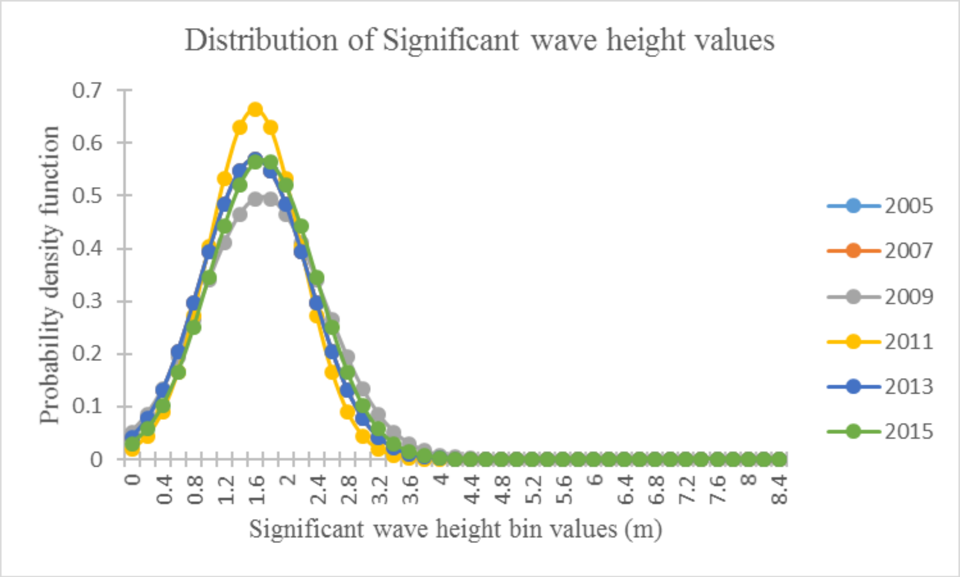


Figure 54: Probability Distribution of Significant Wave Height Values for Different Years

The reason is because there is not much difference in terms of the spread of the mean and standard deviation of the variables. Following the same procedure as in the analysis of the wind speed values, the significant wave height values were initially sorted into corresponding bins which represents the interval for the values of the significant wave height variable in the range. In this case, the bin values started from zero (the minimum value), with intervals of 0.1m up the maximum value of 8.5m in order to account for all the values in the range.

As mentioned earlier, technically density questions require an interval because the PDF draws from an infinite number of possibility. Therefore, an " approximately equal to" question is applicable to specify any local point on the x-axis. This will provide the information on the probability of an approximate outcome of the selected variable. For example, in Table 24 of the maximum and minimum values of significant wave height values for each year; the maximum significant wave height value in 2007 is 6.2m.

In this case, the amount of probability mass lying within 6.2m is approximately equal to a density of 0. On the other hand, the probability of the mass value lying within the interval of 0.4m being minimum value recorded in 2007 is approximately equal to a density of 0.13. The same method is used to evaluate the probability function of other years in Figure 54. The results indicate that the amount of probability mass lying between the interval 1.5m to 2m is approximately equal to a density of 0.48, with the highest value of approximately equal to 0.53 in 2011.

In addition, the significance of Figure 55 is to illustrate the distribution of the cumulative function for variables of the significant wave height values in year 2005. As in previous discussions on the CDF, a cumulative question (i.e. a “less than" question) is asked to evaluate the probability that the normally distributed significant wave height variable in the continuous distribution is less than or equal to the value of the random variable in the selected interval. In Figure 55, the y-axis represents the cumulative distribution function in absolute values. The x-axis represents specified bin intervals of the significant wave height values.

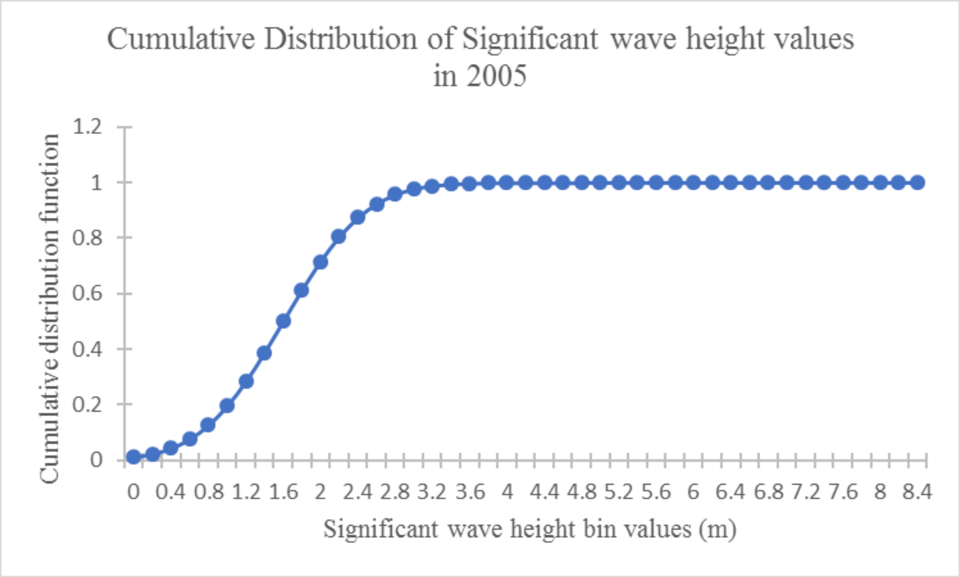


Figure 55: Cumulative Distribution of Significant Wave Height Values in 2005.

The blue line in indicates the cumulative distribution function which provides the information that the probability of the significant wave height variable in the selected year of the distribution is less than or equal to the local point specified on the x-axis. Therefore, the probability is the total area to the left of the density curve as a percentage of the area under the curve. For example, picking any point such as 3m from the graph in Figure 55, the blue line characterises the area under the curve to the left of 3m. Therefore, the probability will be approximately equal to or less than some value, in this case 0.96, which is approximately equal to or less than 96%.

As can be seen in Figure 55, the blue line in the distribution rises to right and it is asymptotic to 100%. As the curve approaches, the probability of picking a value such as 4m is 0.99, which is almost the entire area approximately equally to or less than 100%. Furthermore, Figure 56 is applicable to illustrate the cumulative distribution for variables of the significant wave height values for selected years based on the preliminary analysis of the historical wave dataset. The y-axis shows the values of the cumulative distribution function in absolute values; while the x-axis represents the specified bin intervals of the significant wave height values.

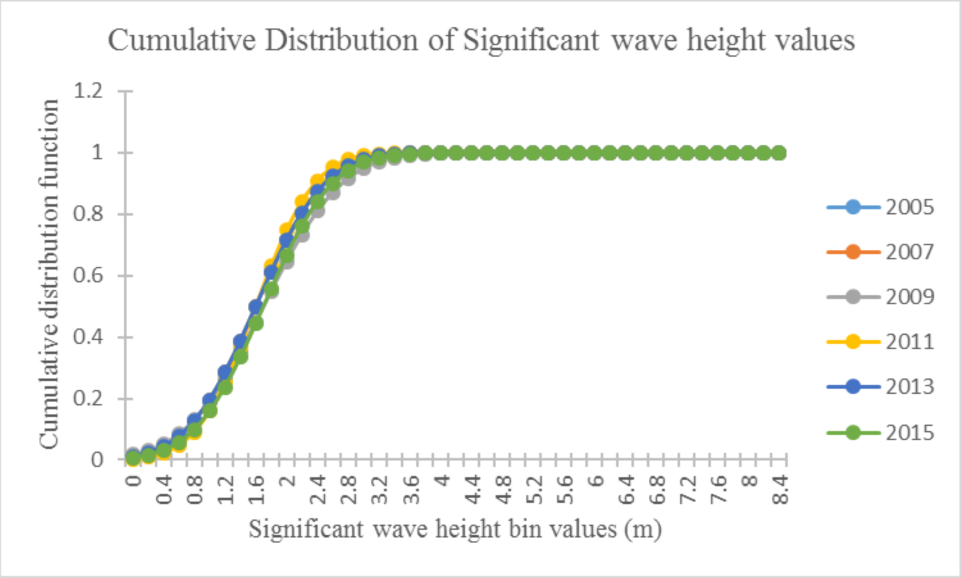


Figure 56: Cumulative Distribution of Significant Wave Height Values for Different Years

It could be observed that all the curves have and maintain the same generic characteristic. This illustrate consistency in the historical wave dataset. The results do not show any adverse variation in the dataset. However, the PDF gives the exact value of the probability distribution based on the integral of the area under the curve. In this context, the important thing is to calculate the probability that the random variable (x) is in between two numbers. This implies that integrating over the PDF, the interval between any two specified values turn to be the limit of integration. Hence, the PDF assumes that the data is distributed the same as the population it came from(Abramowitz and Stegun, 1972; Stewart, 2011).

In addition, the wave energy period values were also considered in the preliminary analysis. As in the analysis of other parameters, the importance of this is to help find out the underlying assumption of the data distribution and to also check if the values in the dataset fits to a normal distribution. In Table 25, the maximum, minimum, mean and standard deviation values of the wave energy period for each year in the historical wave dataset are presented. In Table 25 it is observed that the maximum values for the wave period measurement follow a similar trend with exception of year 2006 and 2013 having similar maximum values of 25 seconds.

Table 25: Maximum, Minimum, Mean and Standard Deviation of The Wave Energy Period Values

Wave Period- Tp (seconds)

Year	Max	Min	Mean	Stdv
2005	22	3	10.4	3.3
2006	25	3	10.7	2.8
2007	22	4	10.4	2.8
2008	22	0	10.4	2.9
2009	22	0	10.9	3
2010	22	0	10.4	3
2011	22	0	10.7	3
2012	22	0	10.5	3
2013	25	3.7	10.8	3.2
2014	22	3.5	11	2.9
2015	22	3.2	10.6	2.8
2016	22	4	10.3	3

The minimum value for the wave period ranges between zero for some yeas to 4 for others. The calculated mean values range between 10.3 to 11 seconds, while the standard deviation range between 2.8 to 3.3 seconds. Following the same procedure as described for the analysis of the wind speed and significant wave height values, the mean and standard deviation values of the wave energy period variables are used to investigate the probability distribution of the wave energy period values. Figure 57 is used to illustrate the result of the probability distribution of the wave energy period values in 2005.

As observed in the distributions of the wind speed and significant wave height variables in 2005, the bell curve in the graph of Figure 57 is significant to illustrate the continuous distribution which characterises the distribution of the wave period variables. In this case, the y-axis represents absolute values of the probability density function; while the x-axis represents intervals of the wave energy bin value with units of measurement in seconds. Assuming any point on the x-axis (e.g. 10sec) is picked from the distribution; an interval is required to define the density function considering that there is an infinite number of possibilities in the distribution.

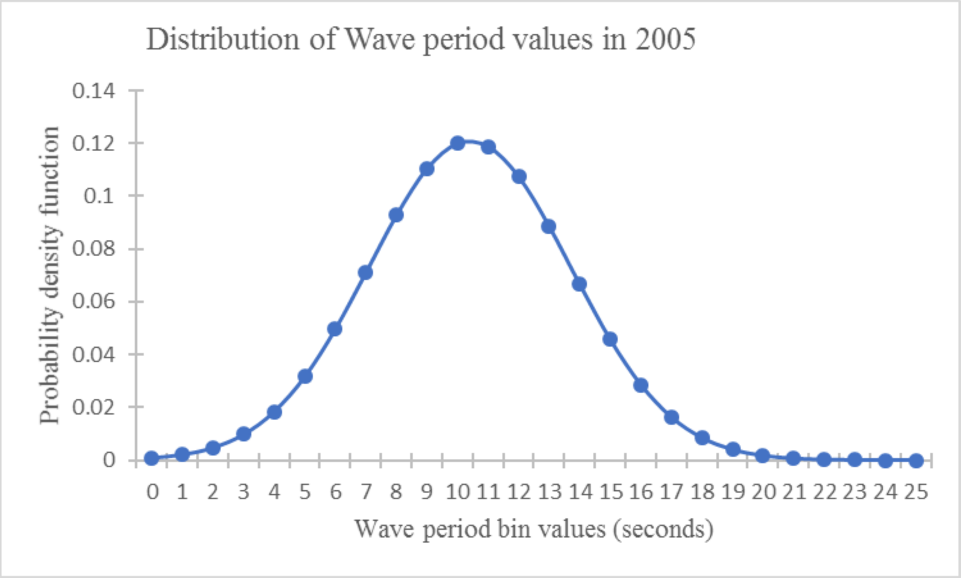


Figure 57: Probability Distribution of Wave Energy Period Values in 2005

In this context, if a density question is asked, the selected variable (x) is not exactly equal to 10 seconds because it is infinite and continuous. In that case, it is assumed the probability of having the value 10 seconds will fall in between two values (e.g. 9.5 and 10.1). This implies that the probability of picking the random variable (x) from the interval (9.5 to 10.1) is approximately equal to 10 seconds. Furthermore, the probability that the random variable (x) will fall in between two values that is approximately equal to 10 seconds is 0.12, which is approximately 12%. This is the probability density function which gives the local probability of an approximate outcome of any value of the wave energy period variable in the distribution.

The importance of Figure 58 is to illustrate the probability distribution of the value of the wave energy period variable in the distribution for other selected years in the historical wave dataset. Similarly, the y-axis represents the absolute values of the PDF, which provides the information on the local probability of an approximate outcome of any variable of the wave period variable in the intervals of the distribution. The x-axis represents the bin intervals for the values in the range. As in the analysis of the wind speed and significant wave height, the variables of the wave period values were initially sorted into corresponding bins.

The bin values start from zero (the minimum value) and with intervals of 1 second, up the maximum value 25 seconds in order to account for all the values within the range. As mentioned in previous pages, an interval is required because it is assumed that the PDF draws from an infinite number of possibility in the continuous distribution function. Therefore, to specify any local point on the x-axis an " approximately equal to" question is applicable. For example, referring to Table 25 of the maximum and minimum values of wave energy period values for each year; the amount of probability mass lying over the value of 22 seconds, being the maximum wave period value in 2005 is approximately equal to zero.

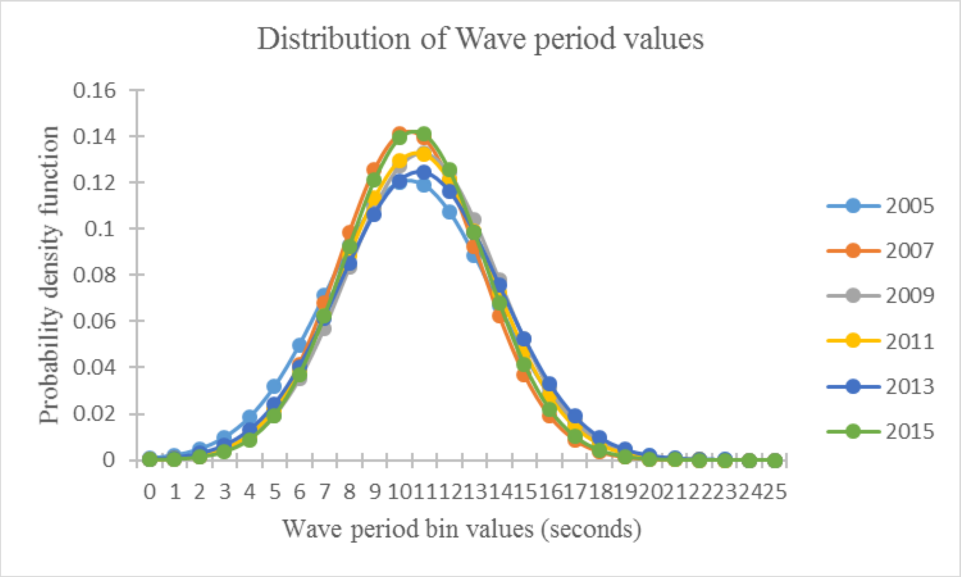


Figure 58: Probability Distribution of Wave Energy Period Values For Different Years

On the other hand, the probability of the mass value lying within the interval of 3 seconds being minimum value in the historical wave dataset in 2005 is approximately equal to a density of 0.0098. In the resource assessment methodology, the probability distribution is used to characterise the variables of the parameters in the historical wave dataset. This can help to provide more information on the combination of values that contributes most to the wave energy resource. For example, in 2005, the dominant wave period was measured at 12 seconds; this indicates that the amount of probability mass lying between that interval is approximately equal to a density of 0.12.

In addition, Figure 59 illustrates the distribution of the cumulative function for variables of the wave period values in year 2005. The y-axis represents the cumulative distribution function in absolute values. The x-axis represents specified bin intervals of the wave period values and the blue line in the graph indicates the cumulative distribution function. The CDF in Figure 59 provides the information that the probability of the wave period variable in the selected year of the distribution is less than or equal to the local point specified on the x-axis. For example, picking any point such as 3 seconds, the blue line characterises the area under the curve to the left of 3 seconds.

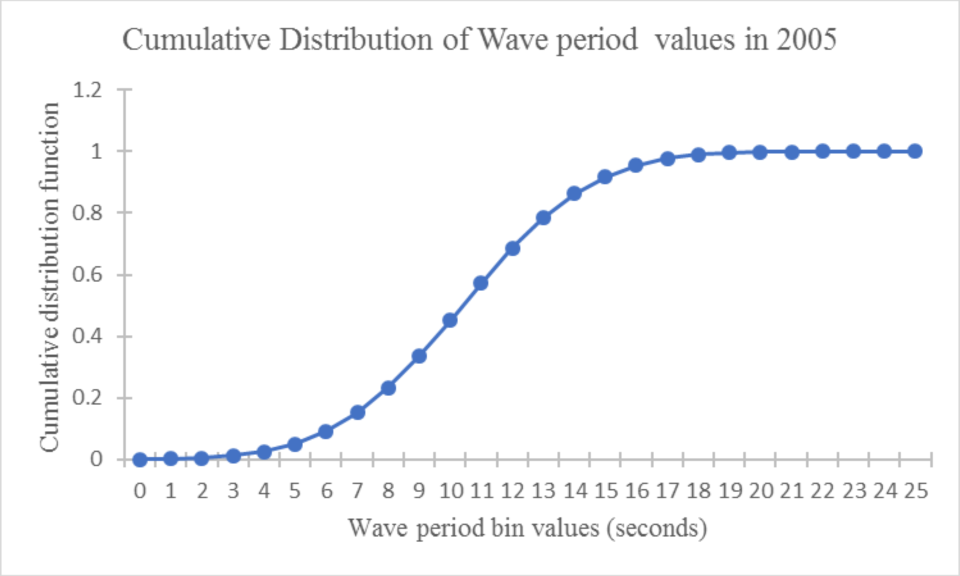


Figure 59: Cumulative Distribution of Wave Energy Period Values In 2005

Therefore, the probability will be approximately equal to or less than some value, in this case 0.96, which is approximately equal to or less than 96%. As can be seen in the graph of Figure 59, the blue line of curve in the distribution rises to the right and it asymptotic to100%. As the curve approaches, the probability of picking a value such as 4 seconds is 0.99, almost the entire area approximately equally to or less than 100%. Similarly, Figure 60 illustrate the cumulative distribution for variables of the wave period values for selected years based on the preliminary analysis of the historical wave dataset.

The key point is that instead of an approximately equal to value, the idea is to find a less than or equal to value. Having examined the annual distribution of the basic parameters (i.e. wind speed, significant wave height and wave period) the results show that the historical wave dataset fits to a normal distribution. The PMF differs from a PDF in that the PDF is associated with an infinite (continuous) random variables. The PMF is associated with finite (discrete) random variables. The values of the PDF are not probabilities as such: a PDF must be integrated over an interval to yield a probability (Abramowitz and Stegun, 1972; Evans et al., 2000).

In the resource assessment method, the distribution function is used to characterise the random variable. Depending on the perspective, a density or cumulative question is applicable. This process will ensure that the data does not violate the assumption required for the analysis. The preliminary analysis results discussed above is significant to illustrate the probability density and cumulative density functions of the wind speed, significant wave height and wave energy period values based on their annual distribution in the historical wave dataset. The wave dataset is analysed to check if the data is normal or follow a normal distribution. In the next section results of analysis of the scatter plot of hourly sea states is presented to validate the resource assessment method in the integrated framework.

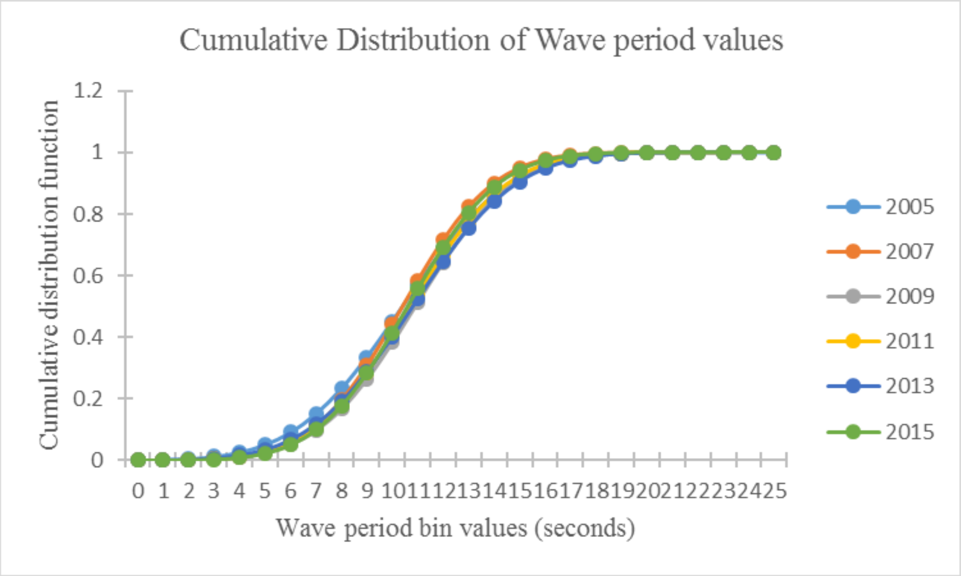


Figure 60: Cumulative Distribution of Wave Energy Period Values for selected years

5.3 Wave Data Time Series Analysis and Frequency of Occurrence

Following preliminary analysis of the historical wave dataset, the wave data time series analysis and frequency of occurrence is discussed in the methodology for preliminary assessment of the resource at the selected location. In this context, a histogram is applicable to illustrate the frequency distribution of the parameters in the dataset. A histogram is a raw count of observations or data points that fall into specified bins intervals. When the total number of data points in the dataset divides the count, this becomes probability.

The resource assessment model in the integrated framework is significant because it provides the basis for which the historical wave dataset is analysed to find out the distribution pattern and trend of the dataset. In this case the annual distribution of each of the relevant parameter are analysed. In Chapter 4 case study application of the methodology, the historical wave dataset used covers a period of 12 years with 169,828 data points. To understand and interpret the information contained in the dataset, a histogram is applicable. The histogram gives probabilities calculated from the dataset (a sample) and a PDF gives probabilities inferred from the dataset to the entire population.

For consistency, results and discussion are presented first for the wind speed values. Thereafter, the significant wave height and wave energy period values. In the case of the wind speed parameter, the values were first sorted into various bins. In this context, the bin represents the selected interval for the range of values. To investigate the number of occurrence of the dominant values, it is required that the values be sorted into bin sizes. The bin is also useful to investigate the frequency of occurrence of the minimum and maximum values.

The results of the different years (2005-2016) which represents the 1st- 12th year in the historical wave dataset analysed for the case study location is used to illustrate the results of the frequency distribution. Figure 61 illustrates the frequency of occurrence of the wind speed values in 2005 to 2008 for the case study location. The y-axis represents the number of occurrence of each bin, while the x-axis represents the bin values. The vertical red bar depicts the occurrence relative to the bins on the x-axis. The bin sizes are defined based on the maximum and minimum values for each year.

The information on maximum and minimum values for all the different years in the historical wind speed data has been shown in Table 23 above. It is assumed that there is no measurement when the value is zero. For this reason, the bin value started at 0.5m/s to account for low values that fall within the interval of 0.5m/s and 1m/s. For example, in the year 2005 the maximum and minimum wind speed value was 17.1 m/s and 0.2m/s respectively. In 2006 the maximum and minimum wind speed value was 19.8 m/s and 0 m/s respectively.

As shown in Figure 61, for year 2005 to 2008 the bin value is set at 0.5m/s with an interval of 0.5 up to the maximum value in the range. The interval is important in this case to define bin size (width) in terms of physical appearance. A bin size of 0.1, will produce much smaller bin size (width) than 0.5. Therefore, to ensure that the various bins are not too squashed together and to improve the readability of the graphs presented the bin sizes are selected accordingly. Depending on the number of data points and the spacing required to make the graphs presentable. The information presented in Figure 61 for the years 2005-2008, is useful to identify the dominant values of the wind speed for the different years in the dataset.

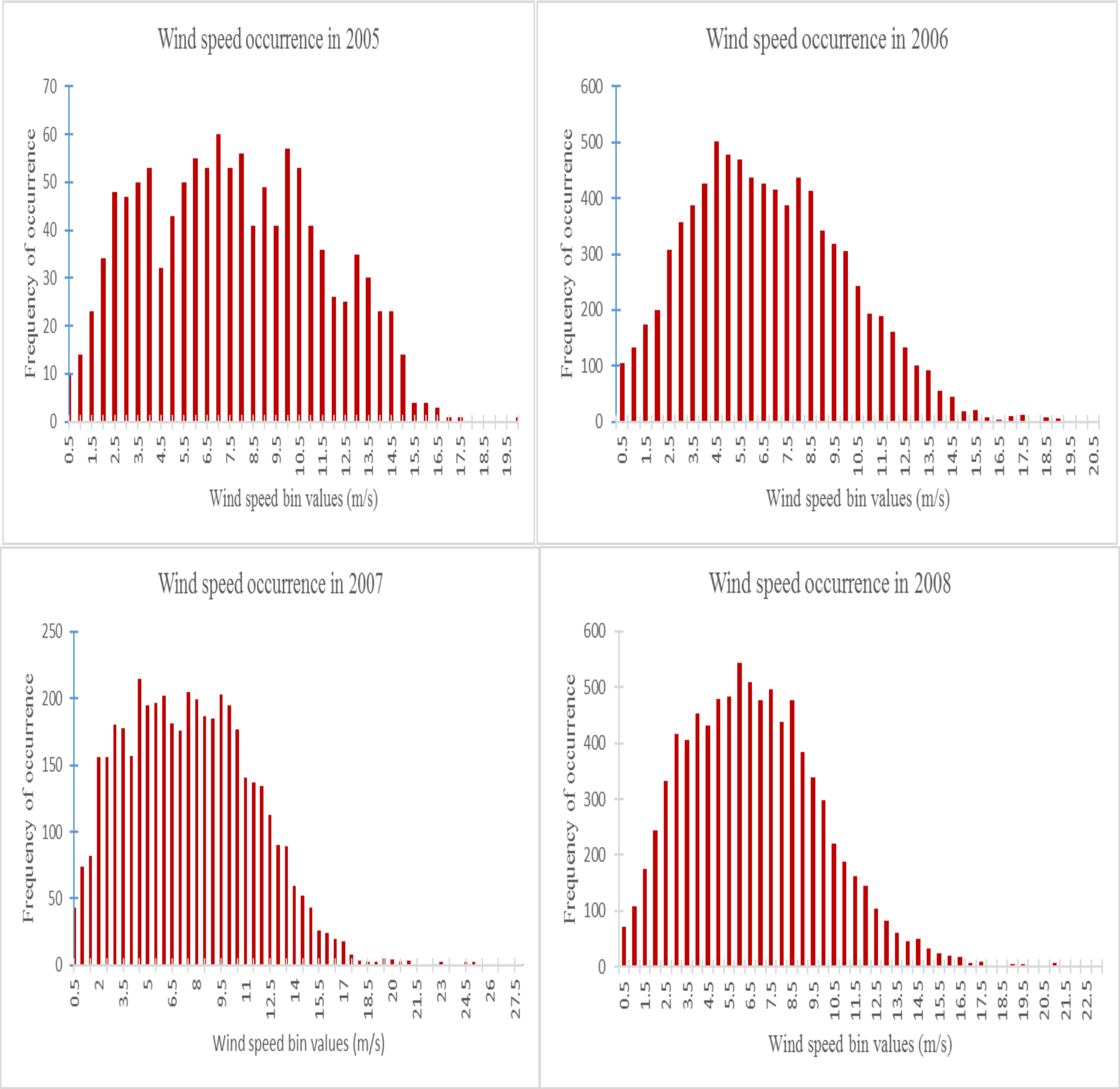


Figure 61: Wind Speed Frequency Distribution in 2005-2008 for the Case Study Location

In relation to the resource assessment method in the integrated framework, the significance of this type of information to provide a better understanding of the characteristic or behaviour of the wind speed in the location. For example, in 2005 the dominant wind speed values are in the interval of 7m/s having frequency value up 60. However, the condition is different when compared to the year 2006, where the dominant wind speed is within the interval of 4.5m/s with frequency of occurrence up to 500. It can be observed that more values were recorded in year 2006 and 2008 compared to year 2005 and 2007.

Based on results in the preliminary analysis of the historical wave dataset, it was observed that the 2005 and 2007 values where a lot lower. This is because of missing or incomplete data. Looking at the values plotted on the graphs in Figure 61, more values approximately 10 times were recorded in year 2006 than in 2005. This is evident by the low number of counts of the data points recorded for the entire year in 2005. A similar condition of missing or incomplete measurements can be noticed in the year 2007 were the total count is around 250. This is also evident by the low count of data points.

In this case, the dominant wind speed is in the interval of 4.5m/s, having a frequency occurrence slightly above 200. Moreover, in year 2008 the dominant wind speed value is within the interval of 6m/s, with occurrence above 540 data points. This again indicates that more measurements were recorded in that year 2008. In comparison to year 2006 the dominant values are in the bin of 4.5m/s having frequency of occurrence slightly above 500. Both years are observed to have good number of data points compared to year 2005 and 2007.

In addition, Figure 62 illustrates the frequency of occurrence of the wind speed values in 2009 to 2012 for the case study location. It can be observed that the wind speed dataset for the different years fit to a normal distribution. Moreover, the bin values all start at 0.5m/s, with intervals of 0.5m/s up to the maximum value in the range for each year. It is also observed that the dominant values for each year vary. For example, in year 2009 and 2010 the dominant value is in the bin interval of 5.5m/s, in year 2011 the dominant value is in bin interval 6.5m/s and 7m/s for year 2012.

In Figure 62 the wind speed dataset for 2009 to 2012 appear to be good and complete compared to year 2005 and 2007. Although the total frequency of occurrence in 2009 is around 450, more values were recorded in 2010-2012. As mention earlier, the reason why there are such big differences in the figures is because part of the wind speed data was missing. The reason can be due to a fault in the system or breakdown of the measuring equipment. This can result to either missing or incomplete measurements. Other causes can be due to bad weather conditions which can produce errors in the measuring device.

Wind speed is a fundamental atmospheric quantity and it is applicable in the resource assessment model in the integrated framework because the wind speed affects weather forecasting. It is caused by air moving from high pressure to low pressure, usually due to changes in temperature. In this thesis the wind speed values are applied to define the weather window for vessel operations. The significance of these results is that it reflects the characteristics of the parameters in the dataset. This is evident by results shown as observed in the frequency of occurrence of data points plotted in the graphs.

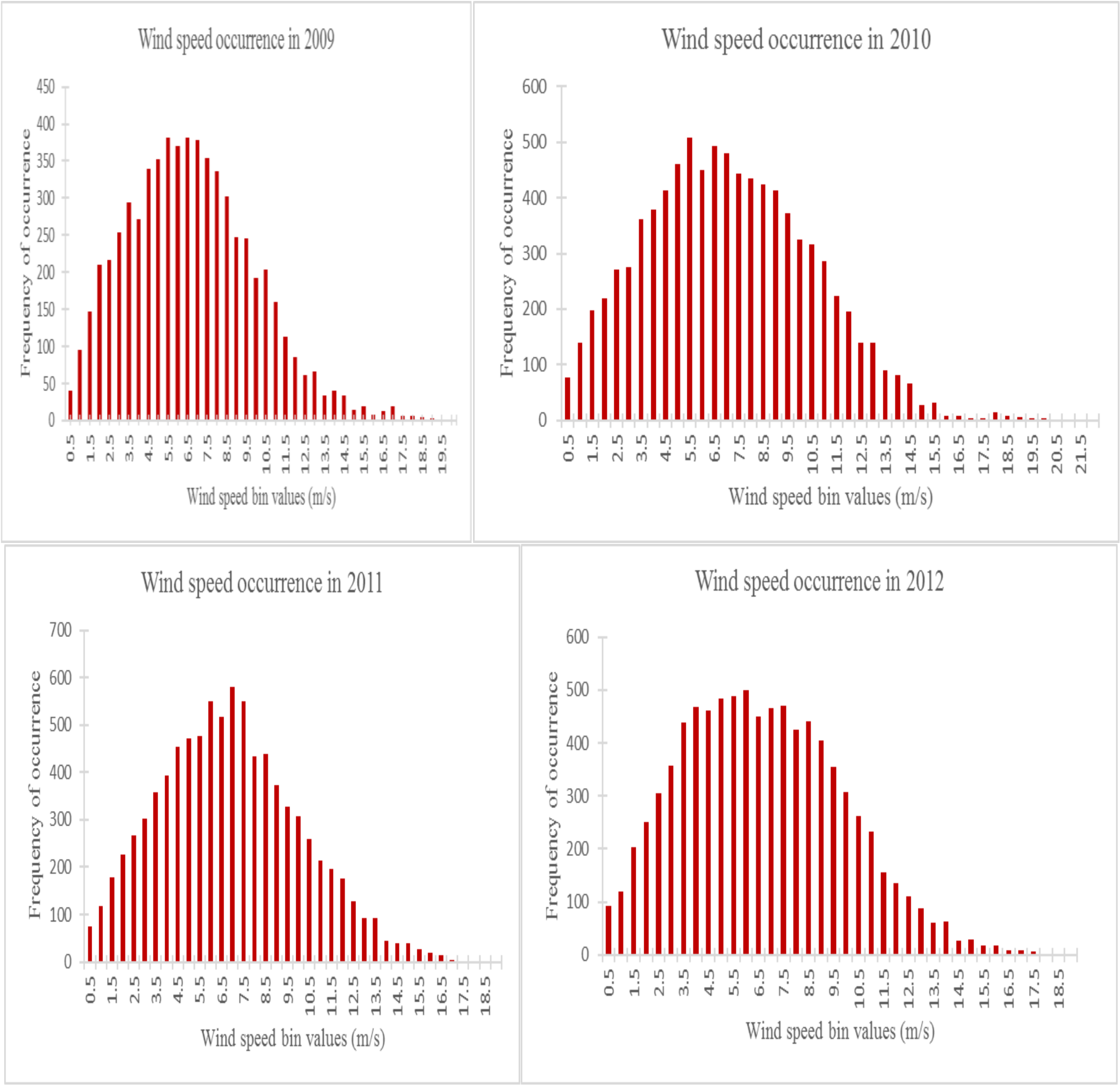


Figure 62:Wind Speed Frequency Distribution in 2009 - 2012 for the Case Study Location

In Figure 63 the frequency of occurrence of the wind speed values in 2013 to 2016 is demonstrated. However, comparing the results for the different years the important characteristic of the wind speed variable relevant to the resource assessment model in the integrated framework can be identified. For example, the results show that the dominant wind speed varies for each year of the wind speed dataset. The circumstance of complete measurement associated with the missing or incomplete data points can be identified. This is obvious as the number of data points recorded are high compared to the case of missing or incomplete measurements in the year 2005, 2007 and 2016.

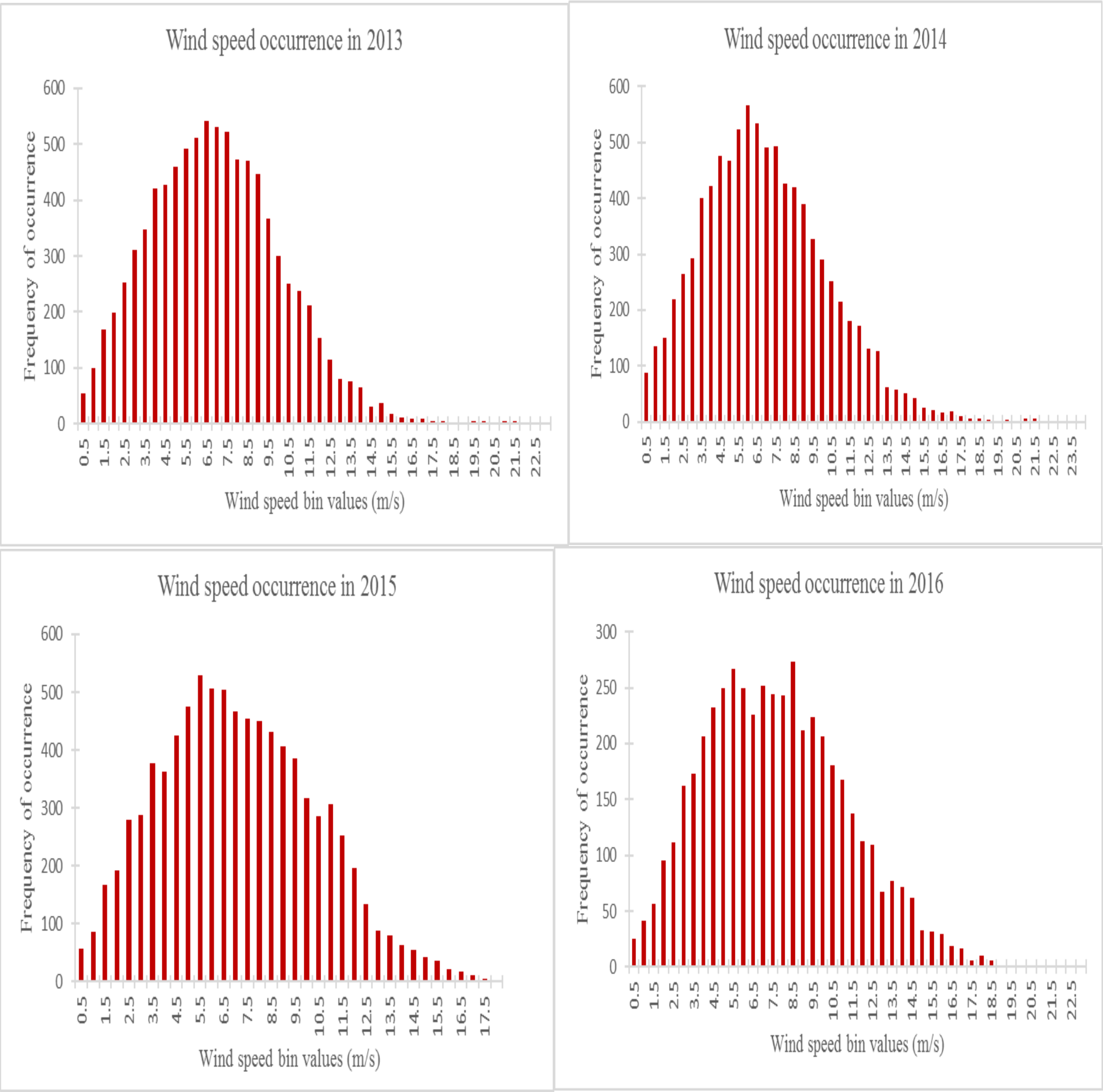


Figure 63: Wind Speed Frequency Distribution in 2013-2016 for the Case Study Location

In addition to the wind speed values the significant wave height values were also analysed. The importance of these analysis is to investigate the characteristics of the dominant values. The results presented in form of graphs are applicable to illustrate the frequency of occurrence together with long term trends in the historical wave dataset. In this respect, Figure 64 shows the frequency distribution of the significant wave height occurrence in the year 2005 to 2008. Similar to the analysis and discussions of the wind speed variables, the significant wave height values were first sorted into different bin. These bins contain the number of occurrences within the selected interval.

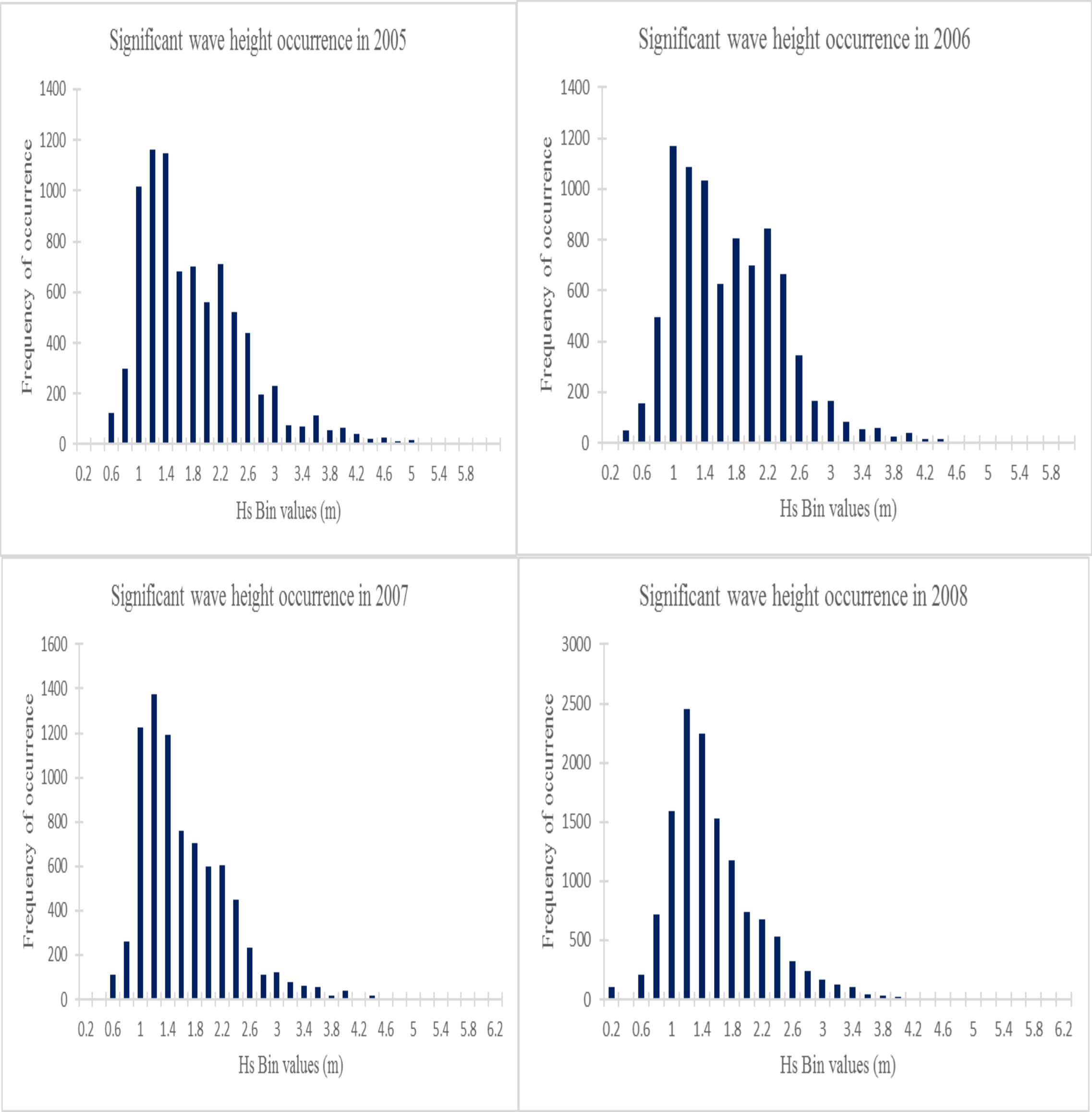


Figure 64: Significant Wave Height Frequency Distribution for The Case Study Location in Year 2005- 2008.

The bin sizes were defined based on the maximum and minimum values for each of the different years in the historical wave dataset as illustrated in Table 24 in the preceding sections. As illustrated in Figure 64 the y-axis represents the frequency or number of occurrence, while the x-axis represents the defined bin intervals. The bin is set to start at 0.2m to account for values between 0.2m to 0.4m. It is assumed that there are no measurements when the value is zero. The bin interval is increased by an incremental value of 0.2m up to the maximum value in the range for each different year.

From the analysis results of the significant wave height variables in 2005 it is observed that; the dominant values are those that fall within the bin interval of 1.2m having a frequency of occurrence of about 1160 data points. This is closely followed by the measurements that fall within the interval of 1.4m with frequency of occurrence above 1100.The situation is slightly different when compared to the year 2006. The reason is because the most dominant values fall in the bin interval of 1m, with frequency of occurrence of about 1160 data points. This is followed by 1.2m and 1.4m both having values slightly above 1000 data points.

Furthermore, in the case of year 2007 and 2008, it is observed that the dominant values fall into the interval 1.2m same as in year 2005. The difference between year 2005 and 2007, is that the number of occurrences in year 2007 is above 1370. Thus, higher than year 2005 which was around 1160. Similarly, Figure 65 shows the frequency distribution of the significant wave height variables in 2009 to 2012. As in the previous illustrations the y-axis represents the number or frequency of occurrence, while the x-axis represents the bin values.

The vertical bars depict the magnitude of the occurrence of each of the bin values relative to the x-axis. In Figure 65 for the year 2009 to 2012 the bin values start at 0.2m. This increases by an interval of 0.2m up to the maximum value of the range for each year. Comparing the results presented in Figure 64 and Figure 65 for the different years, it is observed that year 2005, 2006 and 2007 have a low number of occurrences. This is evident by the total number of occurrences depicted in the results. From year 2008 it can be observed that the frequency of occurrence is above 2500 and it is up to 3500 in year 2012.

In the year 2009 the dominant values are in the bin interval of 1.2m. These have a frequency of occurrence above 2500 data points. The condition is slightly different in year 2010 because the dominant values are in the bin interval of 1.4m and with occurrence above 2600. For year 2011 and 2012 the dominant values remain in the bin interval of 1.4m, with occurrence above 3000 in year 2012. The information obtained based on the results of these analysis for the resource assessment in the case study location can be useful to provide guidance on the type of WEC device that should be installed in that location depending on the significant wave height values. This is taking into consideration that the WEC device should have the maximum capacity to accommodate the dominant significant wave height values in the selected location.

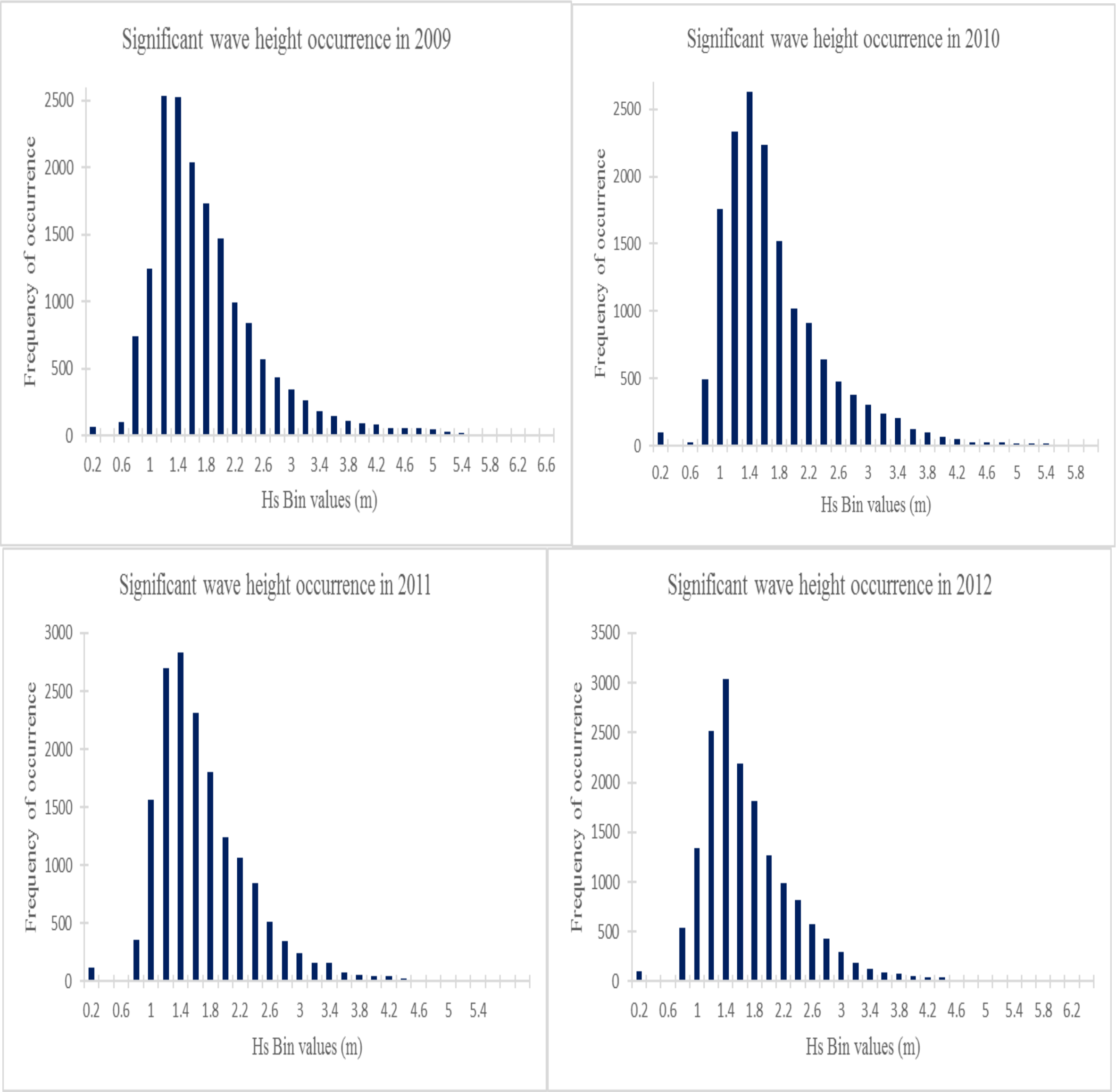


Figure 65: Significant Wave Height Frequency Distribution for The Case Study Location in Year 2009-2012.

To further identify the long-term trend in the location the results for the analysis of the significant wave height frequency distribution for the years 2013 to 2016 are presented in Figure 66. In relation to the resource assessment proposed in the integrated framework, investigating the characteristics of the sea state is important to this study. The reason is that it helps to provide better understanding of the wave environment. This is particularly useful with respect to the operation of the WEC. Moreover, the significant wave height play an important role to determine the theoretical energy that can be extracted from the resource in the location.

The analysis and results presented are significant for decisions of technical and economic improvement of the WEC farm. For example, accurate information on the dominant values of the significant wave height in the location is important for design and selection of the WEC that will be suitable in terms of applicability based on the significant wave height conditions. In this respect, the value with the highest occurrence tend to contribute the most to the resource. Therefore, the WEC should be able to accommodate the dominant values and to capture the energy available in the waves.

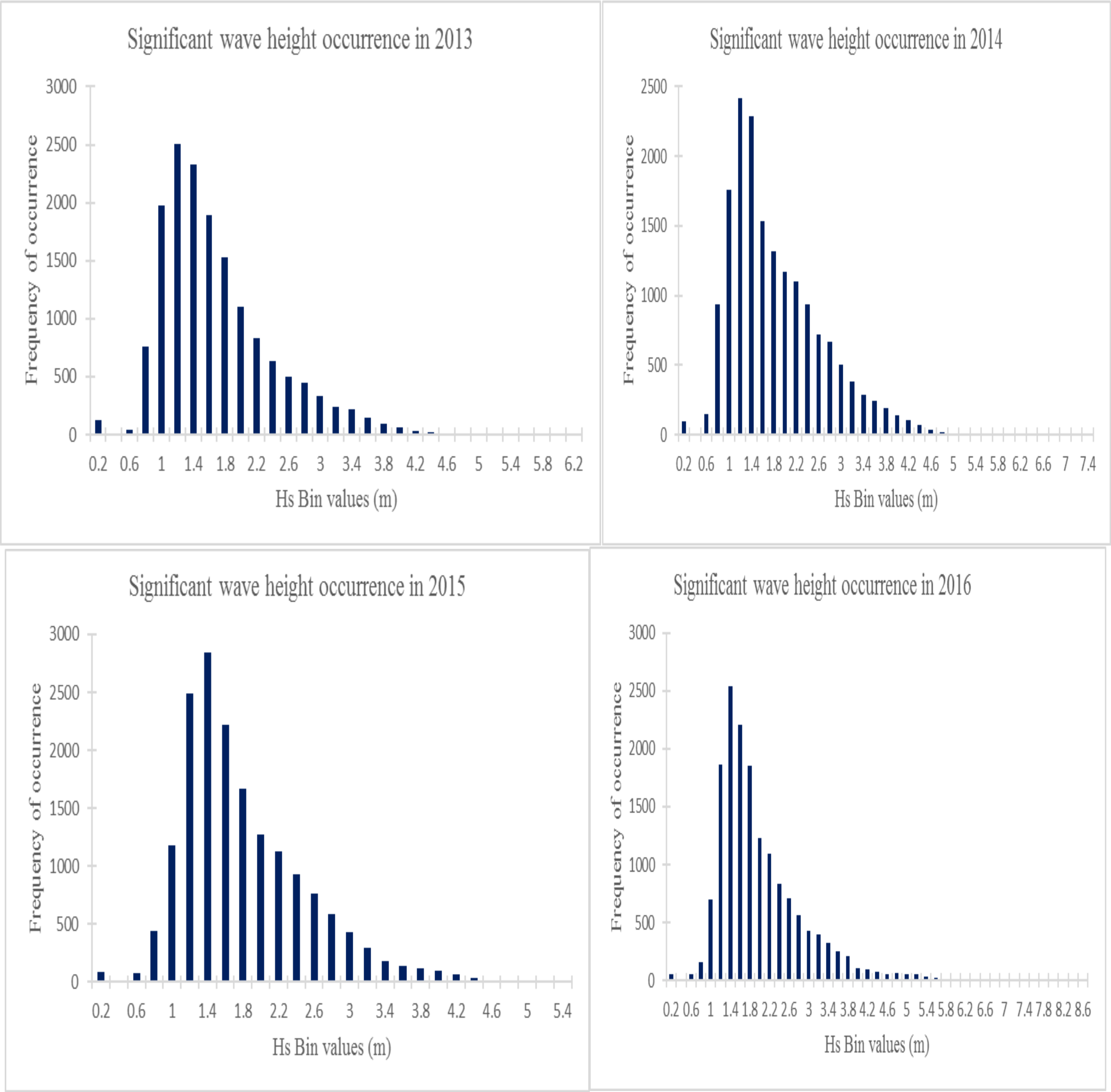


Figure 66: Significant Wave Height Frequency Distribution for The Case Study Location in Year 2013-2016.

From the resource assessment point of view, if the significant wave height value is too low, (below 1m) this may have impact on the productivity as the energy generated will be low. Considering the huge capital investment required this can be a set back to the development of the WEC farm. On the other hand, if the significant wave heights are too high (above 6m), this may present more technical challenges for the WEC O&M (O'Sullivan and Dalton, 2009;

Beaudoin et al., 2010). To conclude the presentation of results for wave data analysis using the frequency of occurrence; the results of the wave energy period analysis are presented.

The importance of Figure 67 is to shows the wave period frequency distribution for the case study location in the year 2005 to 2008. The y-axis represents the frequency of occurrence of each bin depicted by the green vertical bars. The x-axis represents the bin value measurements in seconds. The maximum and minimum values of the wave energy period measurement for the different years in the historical wave data set was illustrated in Table 25. As illustrated in the graphs of Figure 67, the bin values start from 3 seconds instead of zero or one. This is because in the preliminary analysis of the historical wave dataset, it is observed that the minimum value is 3 seconds.

Technically, this suggests that when a zero value is recorded, it is assumed that there are no measurements. The reason can be either because of an error or failure in the system. To ensure accuracy in this presentation, the bin value is set to start at the minimum value of 3 seconds as observed in the historical wave dataset as the lowest significant value for all the years. It is observed that the dominant wave period values in the year 2005 are in the bin interval of 9 seconds, having a frequency of occurrence around 2490 data points.

The case is different for year 2006 because the dominant wave period values are in the bin interval of 13 seconds having a value of 2137 data points. This demonstrates a variation of the measurements for each year. In the year 2007 and 2008 the minimum wave period value is 5 seconds. Compared to year 2005 and 2006 this value is lower. The results suggest that the measurements are more significant starting from 7 seconds. This condition is also evident in 2008 and in all other years.

It is observed that a common feature with the results presented for 2005 to 2008, is that very low values of wave period measurements are recorded for bins 3 and 5 seconds. This is also observed for bin values of 19 to 25 seconds. The value of the measurements is significant starting from 7 seconds. It is also observed that; the dominant bin values vary for the different year. The bin values begin to decline from 15 seconds until it reaches the maximum value in the range with very low bin values or zero measurements. These conditions are also applicable in Figure 68 for the year 2009 to 2012.

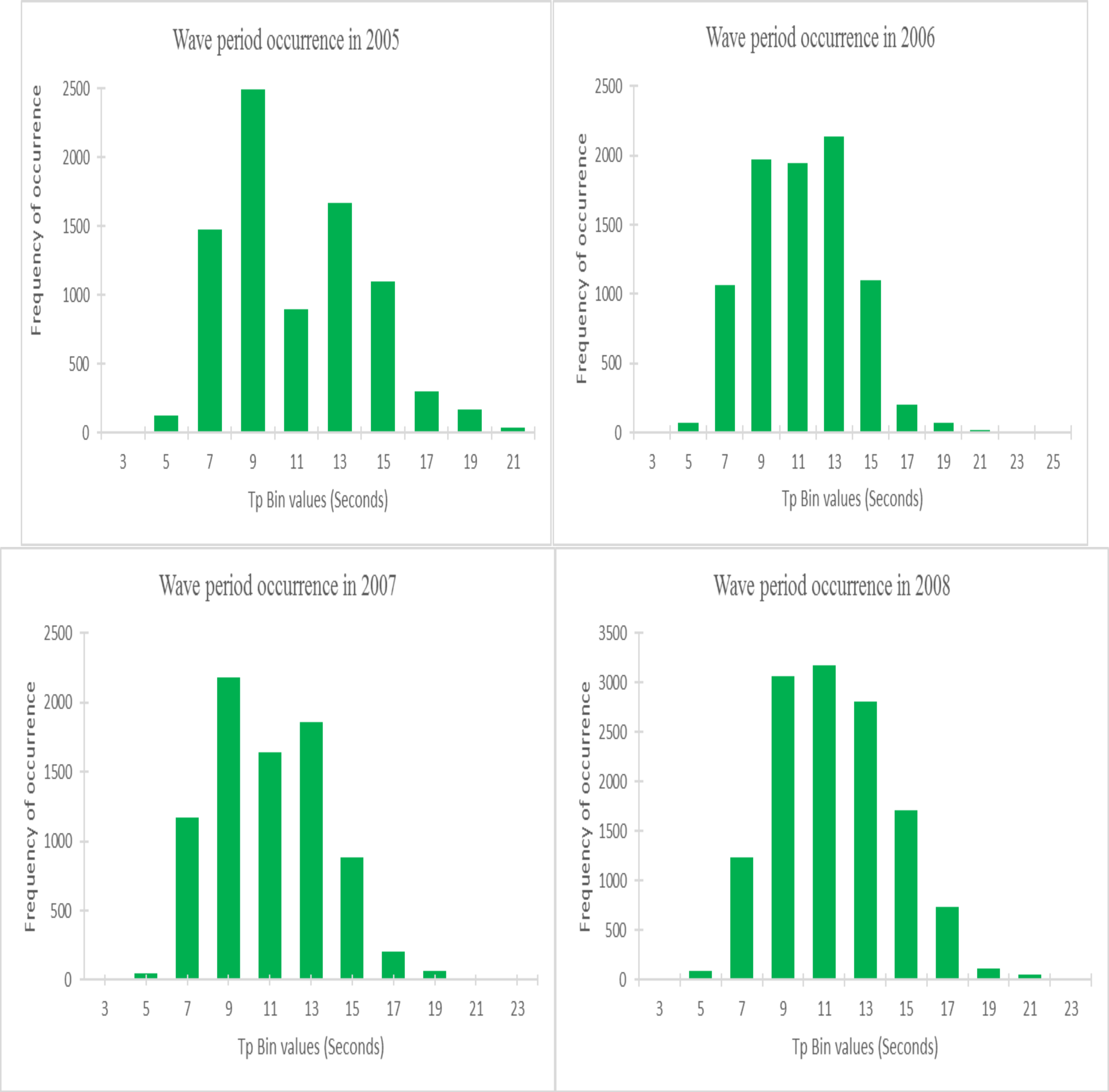


Figure 67: Wave Energy Period Frequency Distribution for The Case Study Location in Year 2005-2008

Considering year 2009 in Figure 98, it is observed that the trend presented for bins 3 and 5 seconds remains the same (i.e. having values low as in previous graphs). There is a decline in the frequency of occurrence from 15 seconds until 23 seconds with zero measurements. It is also interesting to observe that though there is a decline in the values from bin of 15 seconds, but the occurrence in this bin tends to be much greater than in previous years. This suggests that the measurements in the historical wave dataset are more complete for year 2008 and 2009.

In relation to the resource assessment model proposed in the integrated framework, it is important to emphasize that, the objective of presenting the results for the frequency distribution is to properly identify the inter-annual occurrence and long-term trends. This is important to help to understand and interpret the information contained in the data. In that respect, this analysis has shown the occurrence in terms of the dominant values for different years. The good and bad years particularly in terms of years with missing or incomplete data have been identified and illustrated.

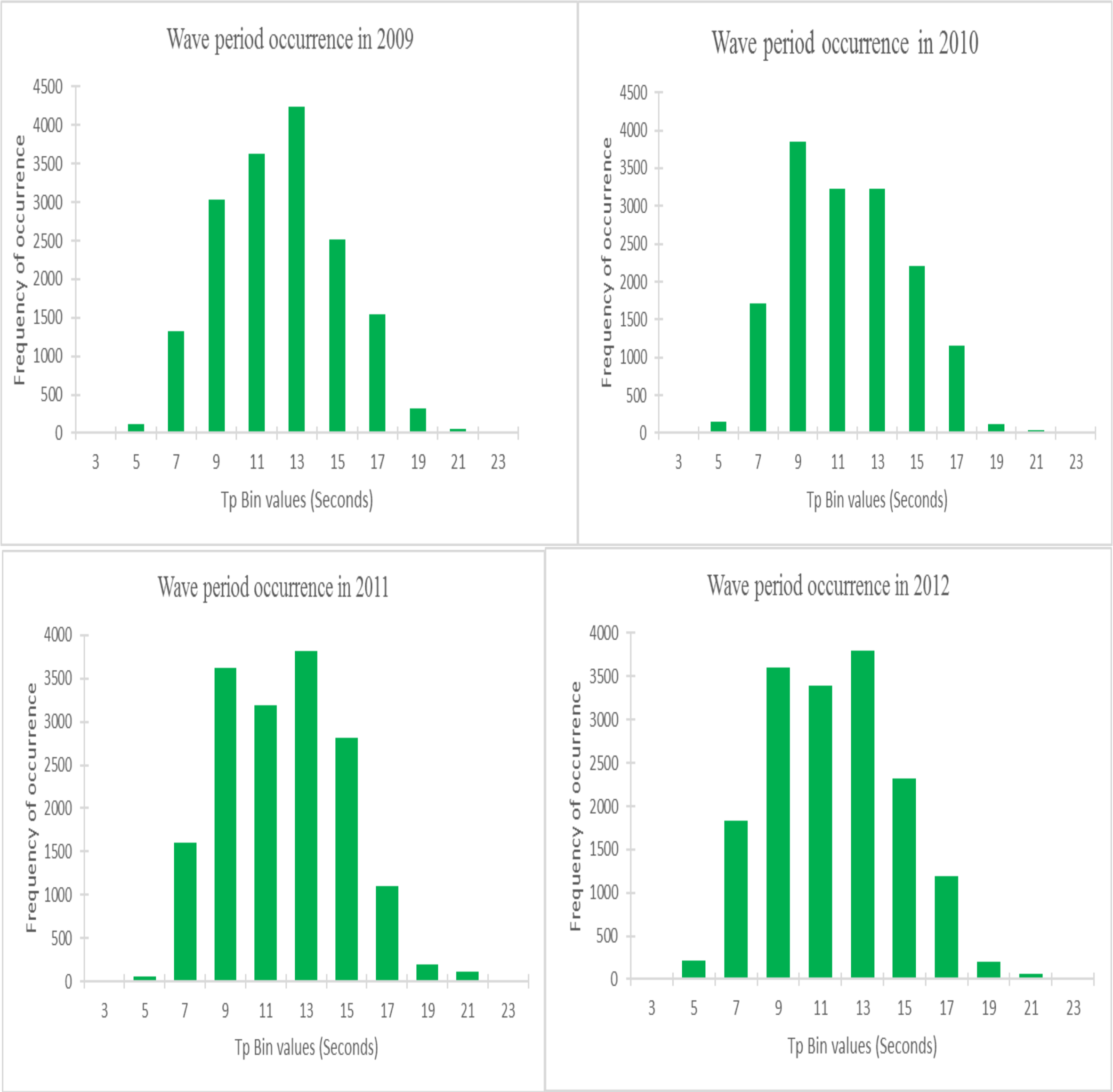


Figure 68: Wave Energy Period Frequency Distribution for The Case Study Location in Year 2009-2012

The example of years with missing or incomplete data point are year 2005 and 2007. This is evident by the total number of data points counted and observed in the preliminary analysis to be low. Although the generic characteristic remains the same as shown in the long-term trends in years 2005-2010. It is observed that the same trend is applicable in the results presented in Figure 69 illustrating the wave period occurrence in 2013 to 2016. In summary, the frequency of occurrence represents the number of times each sea state bin occurs.

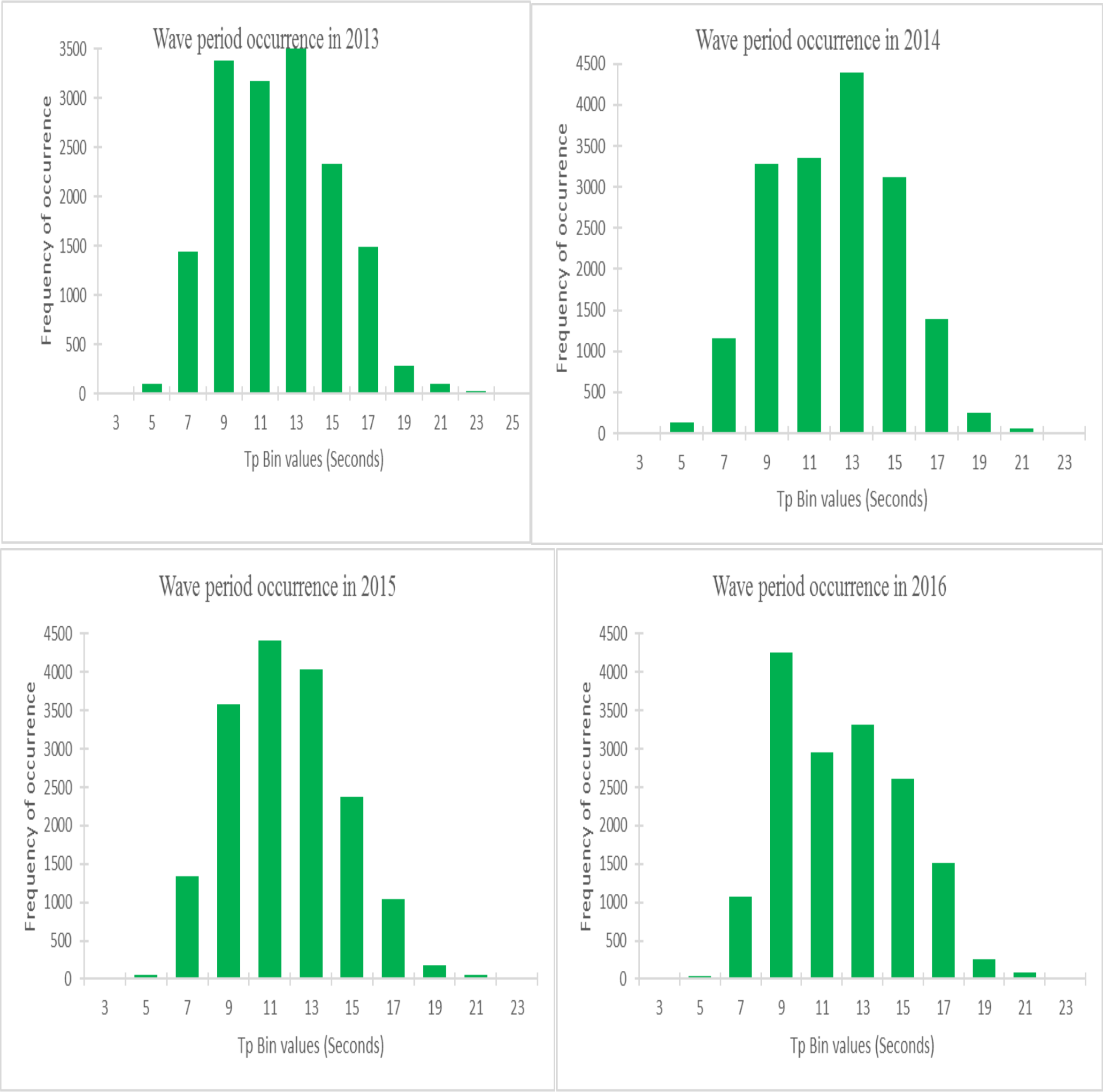


Figure 69: Wave Energy Period Frequency Distribution for The Case Study Location in Year 2013-2016.

In the context of wave energy resource assessment, a combination of the dominant wave periods and significant wave heights is relevant for assessment of the wave energy resource potential and the amount of wave power that can be generated from the resource at the selected location. Moreover, in the integrated framework on resource assessment and O&M modelling, the wind speed and significant wave height values are applicable to analyse the marine operational environment.

In this context, the importance is to determine the weather window for the vessel operation and maintenance activities. The reason for analysing and presenting results for all the years is to show that the generic characteristics of the historical wave dataset. It could be observed that the generic characteristic of the dataset is the same for all the years. In this regard, the characteristics of the distributions are similar for each year, even though minor variations are noticed between the years.

5.4 Result of Annual Averages

Following observations based on the results for frequency of occurrence of the parameters in the historical wave dataset, it is relevant to further investigate the annual and monthly averages of these variable parameters such as wind speed, significant wave height and wave period. This is because of the way the values fluctuate each year, particularly in respect to the dominant, maximum and minimum values. Information on the average annual values is significant to summarise the information about the fluctuation for each year. For example, the results of Figure 70 is applicable to illustrate the annual average wind speed values for the different years (2005-2016) in the case study location.

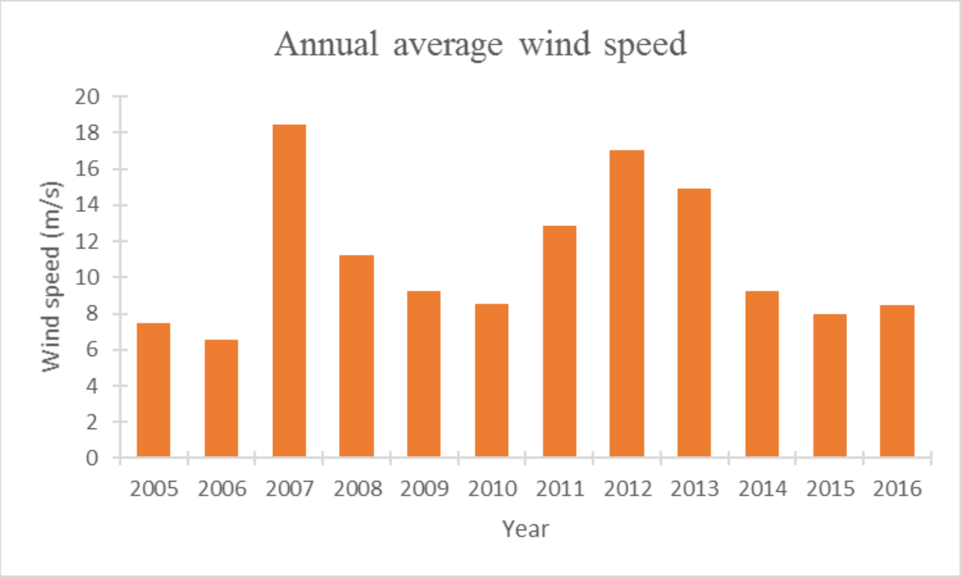


Figure 70: Annual Average Wind Speed Values in The Case Study Location

The y-axis represents the average wind speed value, while the x-axis represents the year. The vertical red bars depict the annual average wind speed value for each respective year. The information on the graph demonstrates that the maximum annual average value is about 18 m/s indicated in year 2007. This is in contrast with the information presented for the frequency of occurrence in the year 2007. As observed from the preliminary analysis, although the dominant wind speed values were in the bin interval of 4.5m/s in year 2007, the data points were very low for year 2007.

In comparison to other bin values such as bin 6m/s,7.5m/s and 9.5m/s with equally high number of occurrence, it can also be observed that the gap or difference in the margin between the occurrence of the values in each separate bin is not high. In this case, bin values of 13.5m/s, 14m/s and 15m/s had relatively high occurrence. On the contrary, year 2005 was associated with missing or incomplete measurements due to the low count of data points as observed in the preliminary analysis. Nevertheless, the average annual wind speed value appears to be in the same range as the dominant wind speed values.

As shown in Figure 70, year 2005 is the only year where the annual average wind speed has a similar value with the dominant wind speed values. For other years, the annual average wind speed is consistently higher than the dominant values for the different years. The minimum annual average wind speed is 6m/s as indicated in year 2006. Furthermore, Figure 71 shows the annual average Significant wave height values in the case study location from 2005 to 2016. It is observed that the maximum annual average significant wave height value is approximately 1.9m indicated in 2016.

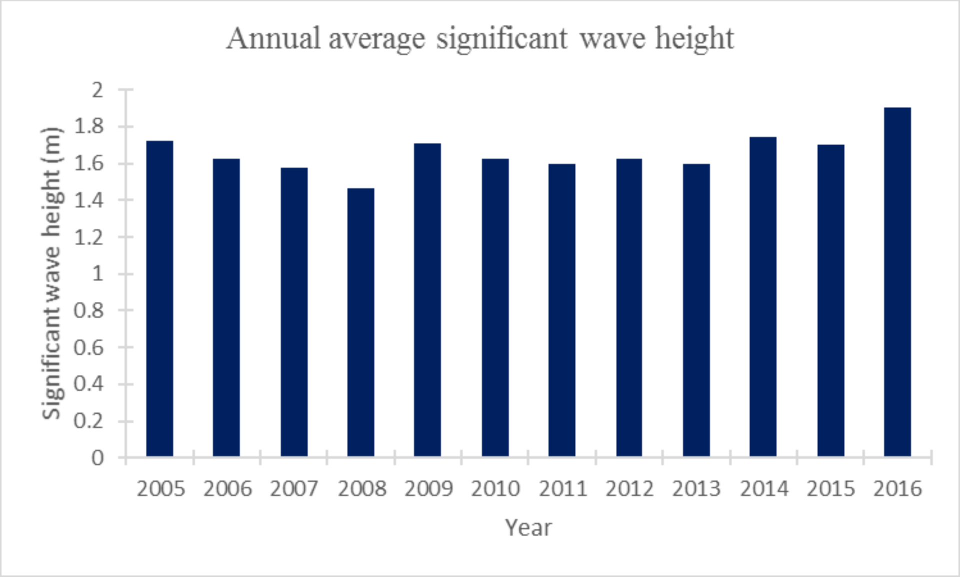


Figure 71: Annual Average Significant Wave Height Values in The Case Study Location

The minimum annual average value is approximately 1.4m as indicated in year 2008. The information presented in the graph suggest that the average annual values of the significant wave height is not less 1m and not greater than 2m. This is because they are in the range between 1.4m and 1.9m. Similarly, Figure 72 shows the annual average wave period values in the case study location from 2005 to 2016. In this case it is observed that the maximum annual average wave period is approximately 11 seconds. The value ranges from 10.03 seconds the minimum as indicated in year 2010 to 11.03 seconds the maximum indicated in year 2014.

Comparing the results in Figure 72, with the information presented for the frequency distribution of the wave period, this suggests that there is a high degree of randomness and variability in the wave period values. The reason is because most of the dominant values were in bin of 13 seconds e.g. years 2006, 2009, 2011-2014, while others were in bin 9 and 11 seconds. This suggests that the dominant values may not necessarily be the annual average values. The outcome of the dataset are strictly variables that may be influenced by the measuring system and these variables may depend on the environment and weather condition.

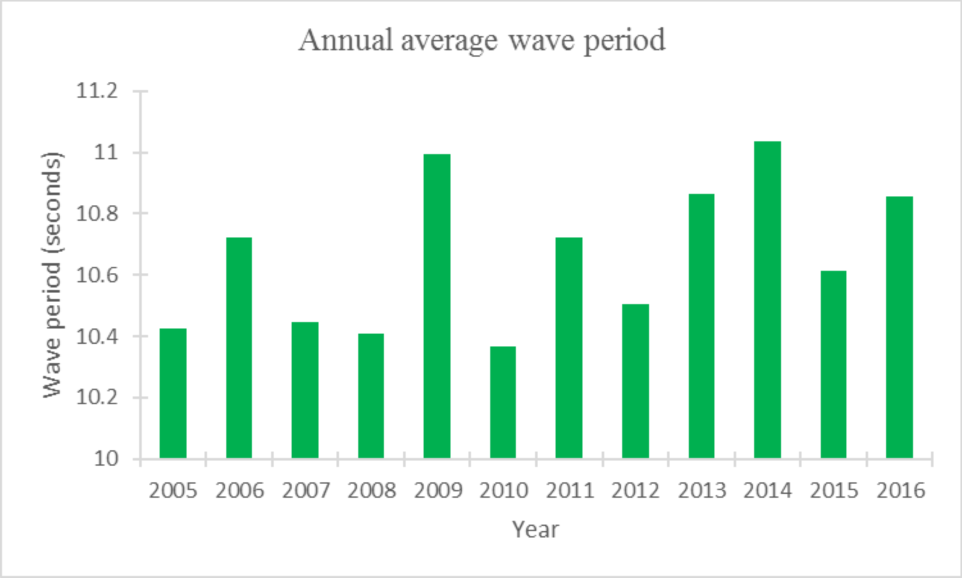


Figure 72: Annual Average Wave Period Values in The Case Study Location

The annual averages of each value of the basic parameters are investigated to express the amount that is typical for the values in the data set. In the analysis, the underlying assumptions of the dataset and distribution are investigated. The results are presented to validate the methodology and modelling in the integrated framework. Having demonstrated the results for the frequency of occurrence and annual averages, the results of the variability and seasonality is presented in the next section.

5.5 Variations and Seasonality of The Data

As observed in the results presented in previous sections the values of the parameters investigated are seen to be fluctuating with each year having a different dominant value. Hence there was a need to consider the annual averages. From the resource assessment point of view, it is relevant to further investigate the variability and seasonality effects of these parameters in the dataset. This is significant for identifying long term trends and weather patterns in the case study location. For consistency in the presentation, the results of the variability and seasonal effects of the wind speed parameter for the entire years (2005-2016) are first presented. This is followed by the results of the significant wave height and then the wave period results.

As observed in preliminary analysis, the wind speed dataset was associated with either missing or incomplete data points particularly with regards to some months in of the year. One of the important feature and benefit of the variability and seasonality results presented in this section is the ability to identify the specific months having similar problems. This is particularly in terms of areas with missing or incomplete data points or extreme weather conditions. The weather conditions could either be in the form of good or bad weather conditions. In this context, Figure 73 is applicable to demonstrate results of the variability and seasonality effects of the wind speed variables for the period of 2005-2008.

A detailed explanation of the results is provided followed by comparison of the different years. First, it is important to mention that the scaling used in the graph in this section is intended to reflect and demonstrate the true characteristics of the dataset and measurement for each year. Therefore, starting with year 2005, it can be observed that only two months of wind speed data was recorded. However, with the exception of the year 2006, other years (i.e. 2005,2007 and 2008) had issues with the wind speed data at some point in the year.

As illustrated in Figure 73, the y-axis represents the values of the wind speed variables, while the x-axis represents the time with respects to month of the year. The red portion on the graphs depicts the variability and seasonality effects of the variables relative to each month of the year. In year 2005 the wind speed is shown for only two months. In this case the maximum value of the wind speed is 19.8m/s. This occurred at some point in the month of FebuaryFebruary. Comparing year 2006 with other year (i.e. 2005,2007, and 2008) having missing or incomplete measurements, the seasonal effects can be noticed between the months of February and March.

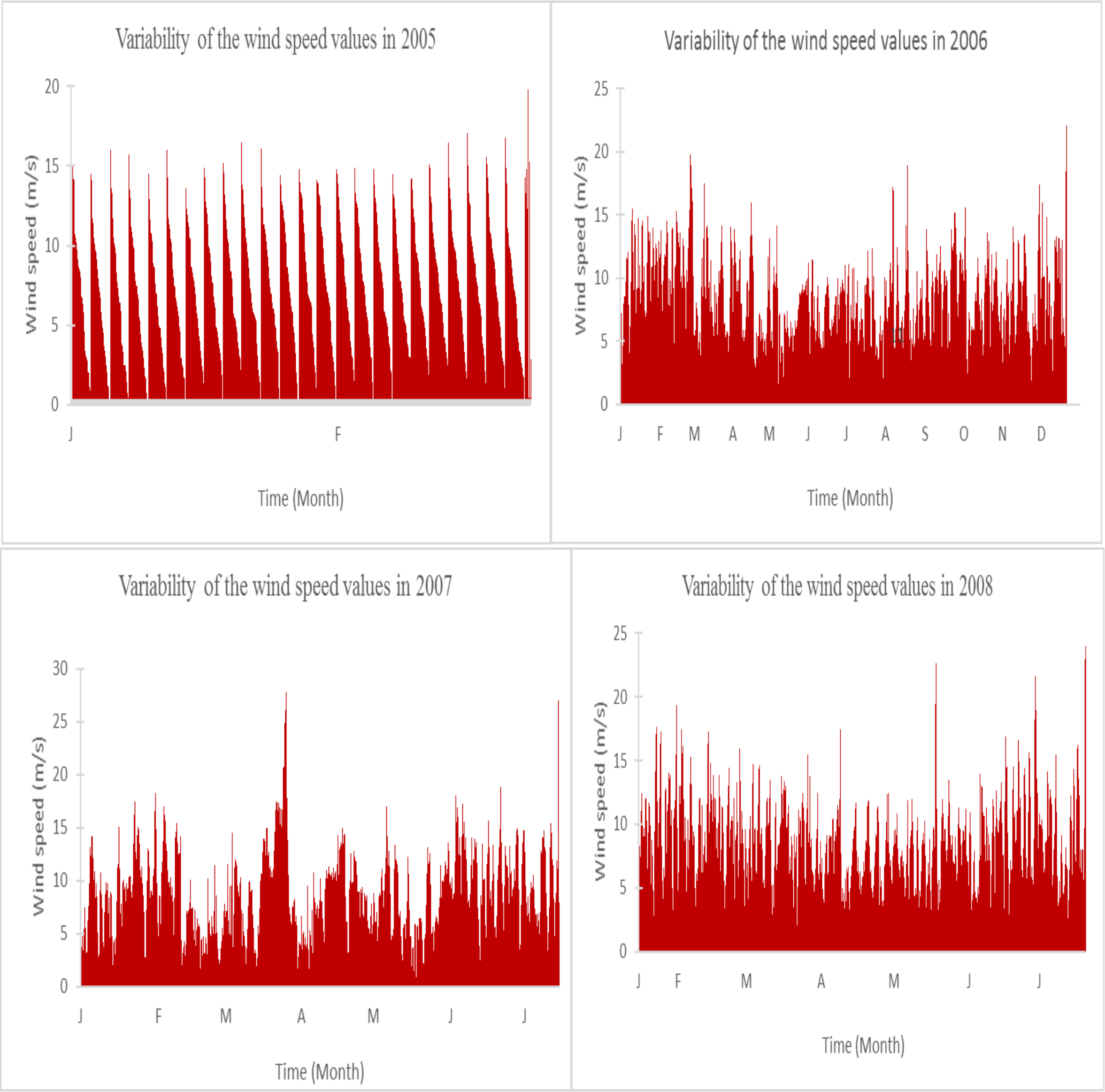


Figure 73: Variability and Seasonality of The Wind Speed Values in2005- 2008

These months are associated with higher values of wind speed. For example, in year 2006 the high wind speed is around February with peak in March. This is similar to year 2007 with wind speed around 15m/s in February and peaks at some point between February and March. Similarly, Figure 74 demonstrates the results of the variability and seasonality of the wind speed parameter in the dataset for the year 2009-2012. In this case, except for year 2009 with missing or incomplete data points or measurements, the other years (i.e. 2010, 2011 and 2012) have good or complete measurements.

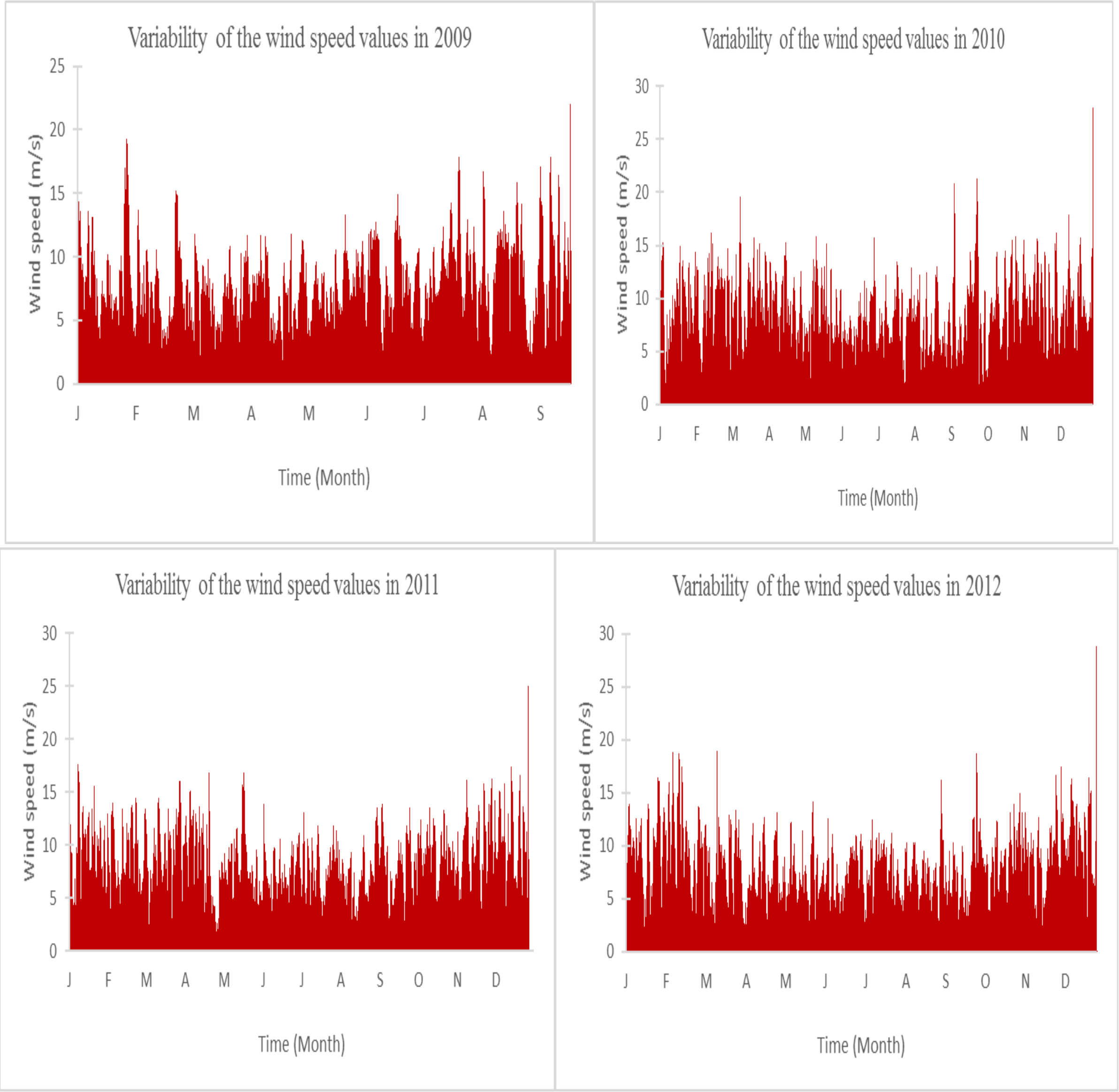


Figure 74: Variability and Seasonality of The Wind Speed Values in 2009 2012

The years with complete measurements have their months shown complete from January to December. This is not the case with year 2009 having only the months of January to September. On examination of the wind speed data in Figure 74 the seasonality can appreciated. This is reflected by more higher values of wind speed occurring at some periods particularly in the months of October, December and January. The local peaks appearing such as those in October, November and December, can be explained by the presence of storms.

From the resource assessment point of view these months can be characterised as having high values of wind speed. This can contribute to challenging conditions for the O&M activities during these months. Similarly, Figure 75 demonstrate the results of the variability and seasonality of the wind speed parameter in the dataset for the year 2013-2016. In this case, except for year 2016 with missing or incomplete measurements, the other years (i.e. 2013, 2014 and 2015) have good or complete measurements. It can also be seen that the seasonal wind speed is similar to the other years presented in Figure 69 and Figure 70.

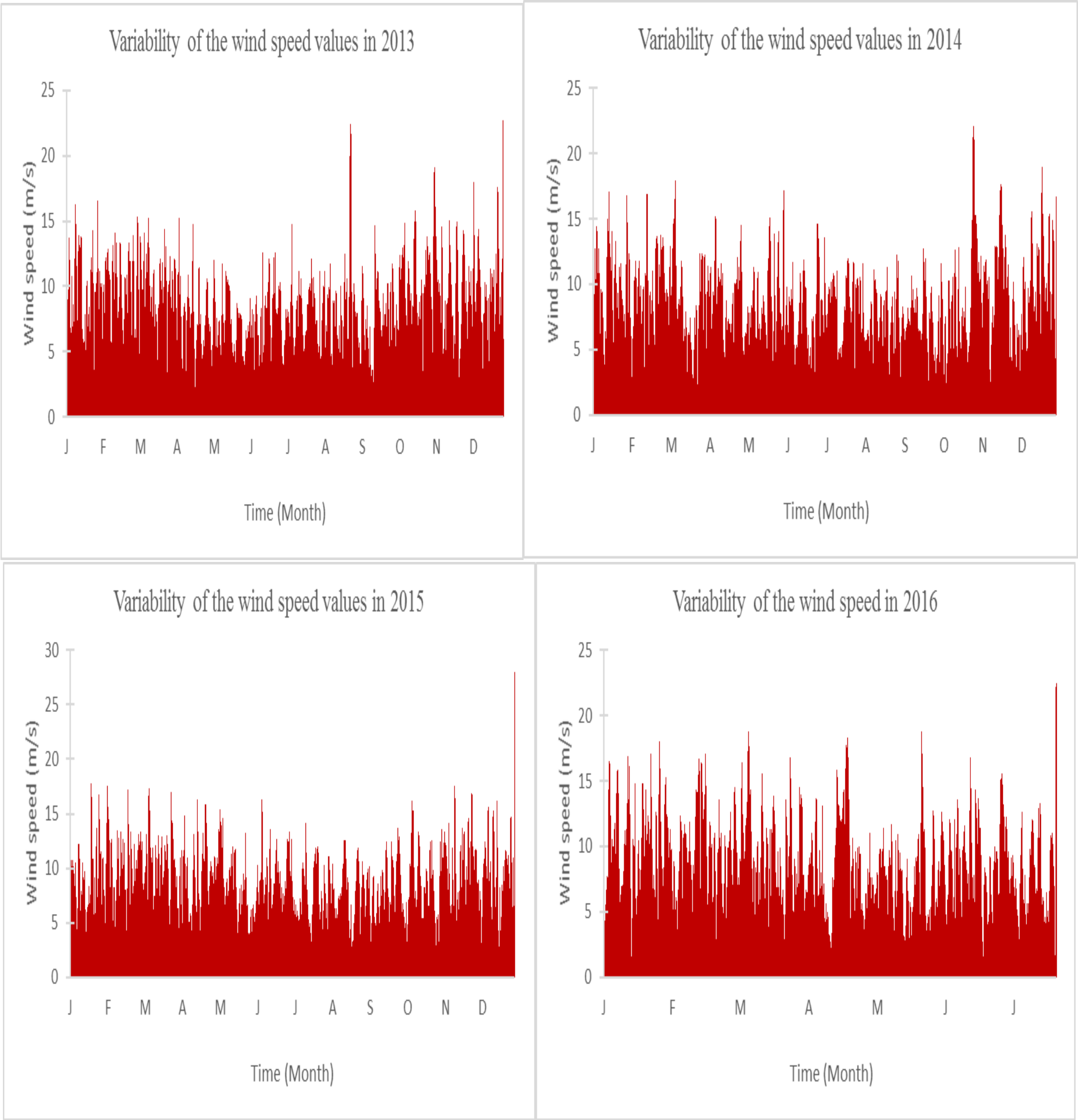


Figure 75: Variability and Seasonality of The Wind Speed Values in 2013-2016

It can be noticed that high winds are associated with the months of November, December and January. The winds appear to be at its peak in December. The months starting from April and sometimes in May is seen to have moderate wind speed values around 5m/s to 10m/s. This is applicable to all the years for the wind speed dataset. Furthermore, the concentration of the low wind speed values is particularly centred around the months of June, July and August with wind speeds around 5m/s. This trend is applicable in all the years for the wind speed dataset.

In relation to the resource assessment and O&M modelling in the integrated framework, it is important to identify this trend. The reason is that, information provided by the seasonal characteristics of the wind sped parameter can be used to assess the resources in relation to the significant wave height at the location. Ocean waves are driven by winds and low wind speed can potentially reduce the number of waves available. In addition, the seasonality and variability results are significant because it helps to easily identify any areas with potential problems or error in the dataset.

The analysis and results are relevant to ensure that the dataset is free of error and consistent in terms of applicability. The data are applied for investigation of the energy available in the waves and wave power that could be theoretically extracted from the resource. Comparing the seasonality results with the results presented in previous pages for the probability and frequency distribution, the benefits are better appreciated. This is because the points having issues are not captured in the probability or frequency distribution. The reason is because the values are sorted into bins. Any value that is not within the bin limit will not be noticed.

In addition to the wind speed results presented above the results of the significant wave height are also presented for the entire year 2005 to 2016. Figure 76 demonstrates the variability and seasonality effects of the significant wave height parameter for the year 2005-2008. In this case, the y -axis represents the significant wave height values, while the x-axis represents the time with respect to the month starting from January to December. The dark shaded region depicts the variability and seasonal effect relative to the month.

In contrast to the wind speed results presented in previous pages, the significant wave height dataset appears to be complete. This is in terms of the missing or incomplete measurements for some parts of the year. For example, in year 2005-2008, all the months of the significant wave height dataset are complete and starting from January to December. This indicates a more consistent result for the significant wave height parameter. The seasonal effects can be noticed during the months of January, February and March. During these periods, the significant wave height is as high as 3m.

Peak values of around 5m and 6m can be noticed at some point during these months. These high values can also be experienced during the months starting from October, November and December. The high values vary around 2.5m and 3m. The peak values of 5m is experienced in November and sometimes in December. From the resource assessment point of view, these periods with high significant wave height values can be characterised as a season with high energy because of the high significant wave height reflected in period. The maximum significant wave height is in the range of 6m and 7m.

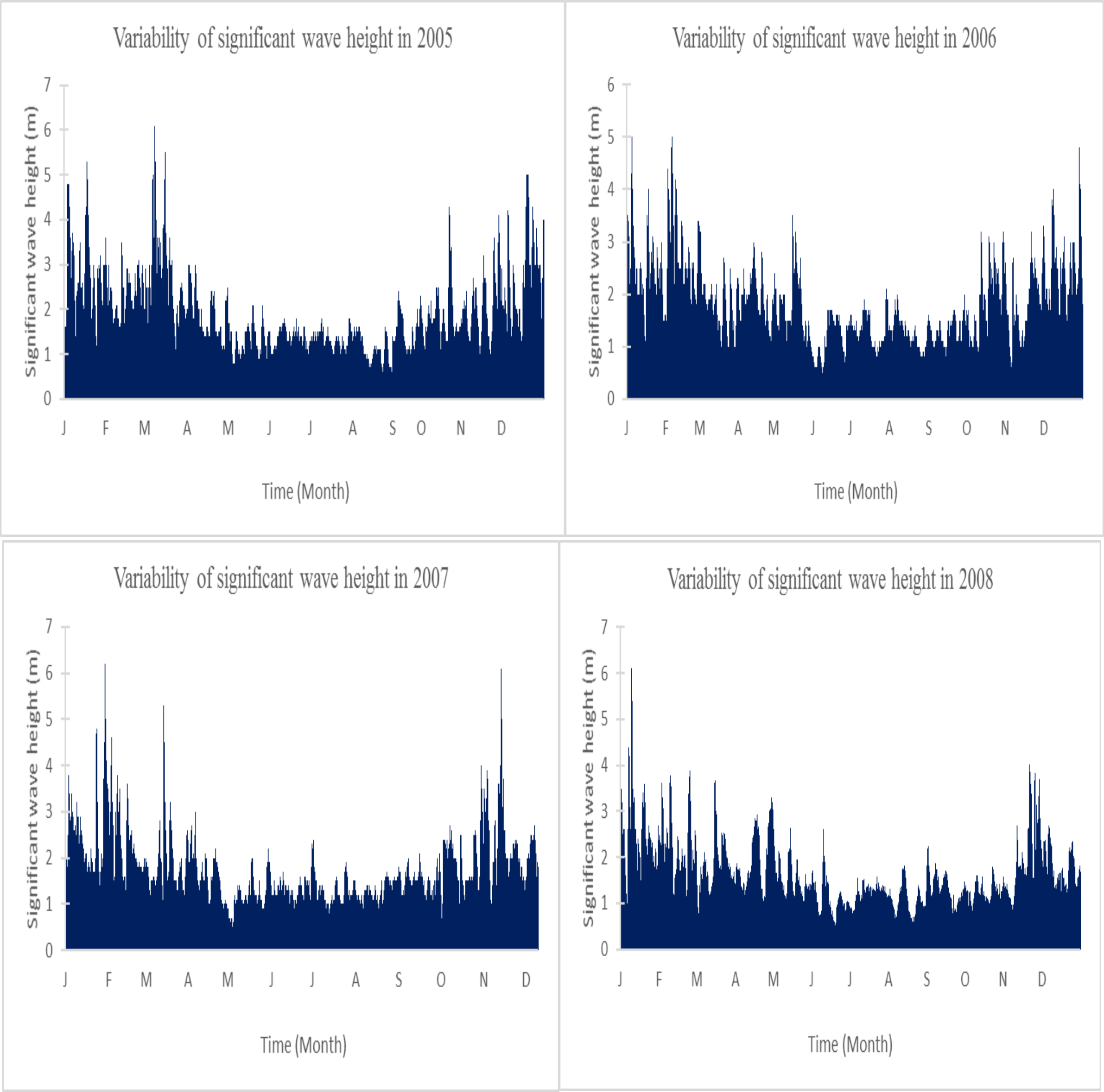


Figure 76: Variability and Seasonality of Significant Wave Height in 2005-2008

Similarly, Figure 77 demonstrates the results for the year 2009-2012. In this case all the measurements are complete starting from January to December. In comparison to Figure 76 (i.e. for 2005-2008), the common trend noticed is the more energetic significant wave height occurring in the months of January to March. The more energetic significant wave height values refer to values above 1.5m. It can be observed that the values of the significant wave height during the period of January to March are concentrated around 1.5m to 2.5m.

The peak values are noticed mostly in the months of January, February and March with very low concentration around the values in the range of 4m to 6m. The same trend can also be noticed in the months of November and December. The emphasis on these results is on identifying the areas with strong influence or repeating trend over a long period. As illustrated in Figure 76 and Figure 77 in the months particularly starting from May to September in all the years shown, the significant wave height values are concentrated in the range of 1m-1.5m.

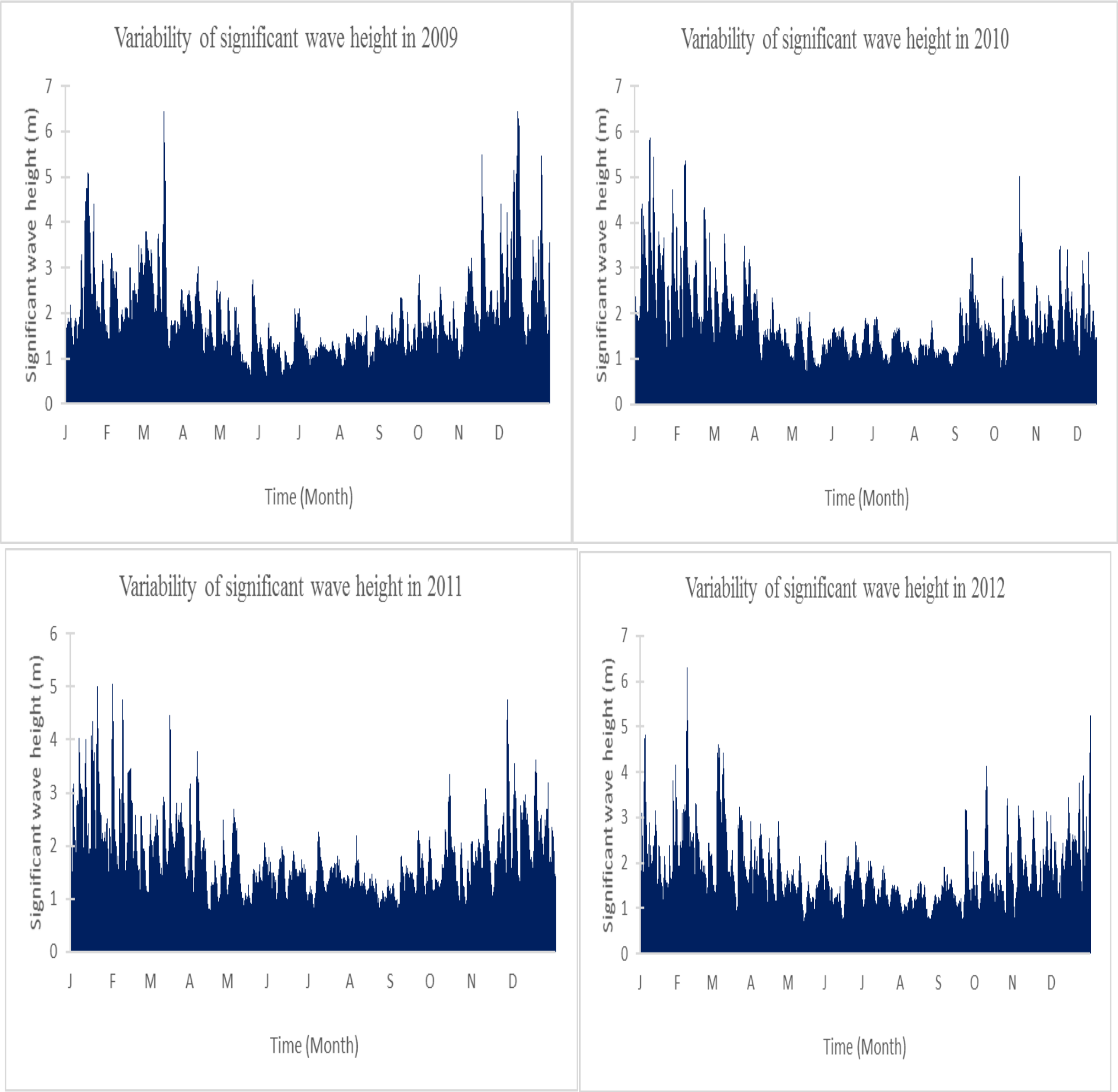


Figure 77: Variability and Seasonality of Significant Wave Height in 2009-2012

These values are low and from the resource assessment view point, this may possibly contribute to significantly low wave energy levels during these periods in the case study location. In addition, Figure 78 demonstrates the results for the year 2013-2016. A similar trend is also applicable. This is in terms of the low significant wave height values clustering around 1m particularly during the months starting from May to August in every year. Comparing the significant wave height results for the different years presented, the main difference in the results can be noticed in the year 2014 and 2016. This difference is in the peak values being up 8m.

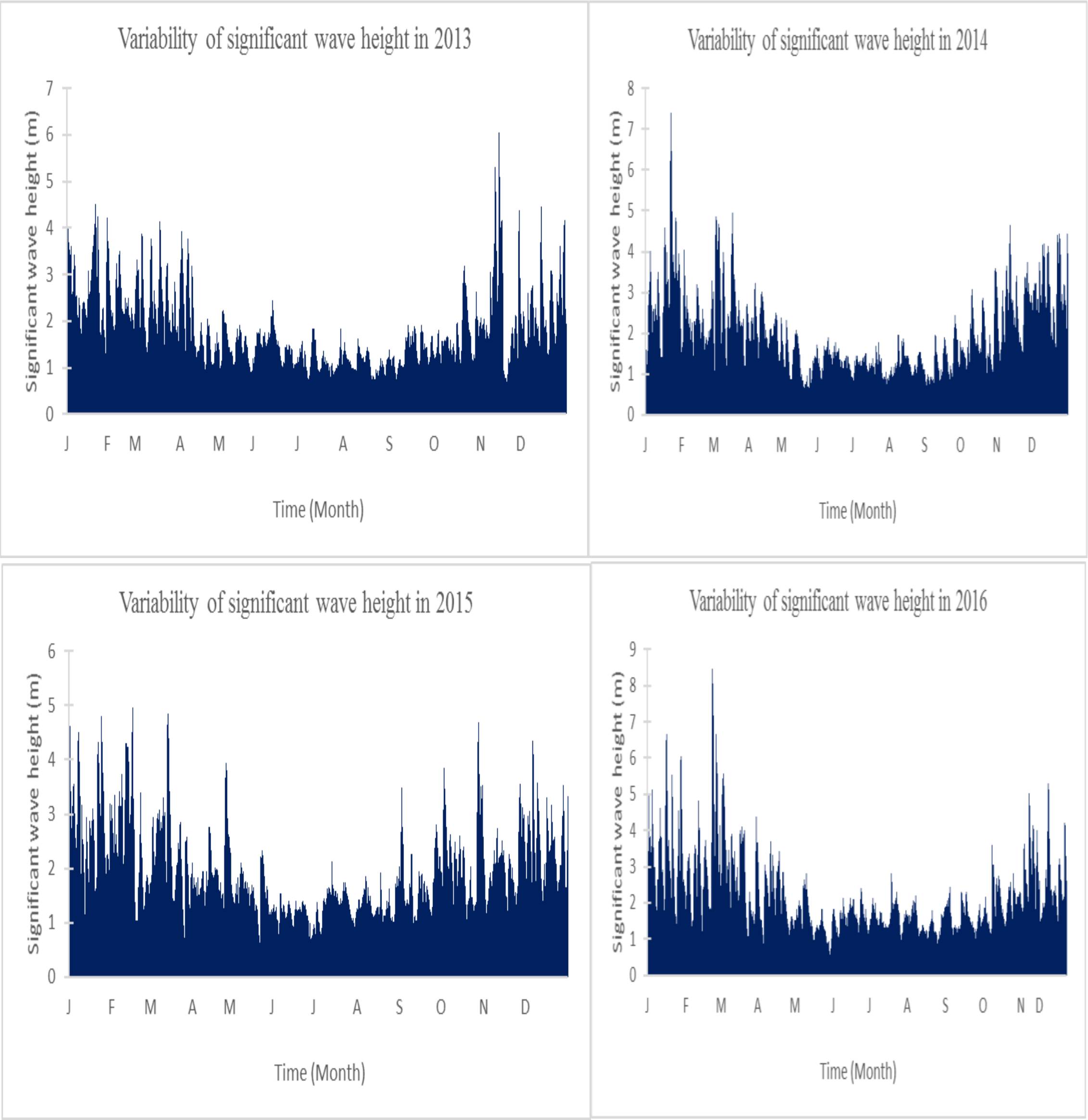


Figure 78: Variability and Seasonality of Significant Wave Height in 2013-2016

In this case the maximum values are in the range of 7m-9m. Moreover, at some point in the year 2016, particularly in the month of November and December it appears that some data where either missing or incomplete. For this reason, the months of November and December are almost squashed together in the year 2016. As mentioned earlier these present results helps to identify the area or the point when the dataset may have problems. Seasonal time series data are sometimes called periodic time series because the dataset is influenced by seasonal factors (e.g., the quarter of the year, the month), as illustrated in results presented above.

At this point it is important to mention that the term missing or incomplete measurements refers to specific periods noticed with no data for the month in that year. For example, the wind speed data for year 2016 was incomplete because only measurements for January to July was seen to be recorded. However, the significant wave height results in that same year 2016, appeared good until some point in the months of November and December, where the data appeared to be squashed together. In that case, values at that point appeared to be missing or incomplete.

Some points in the year 2010 and 2013 were also noticed to have missing or incomplete data points in November and some parts of December. Apart from 2010, 2013 and 2016 all the other years of the significant wave height dataset was examined and considered to be good and complete. Furthermore, variability is the measure of how spread out or closely clustered a set of data is. The results presented so far, has illustrated the variability of the wind speed and significant wave height in the historical wave dataset. For example, in Figure 78 (i.e. 2013-2016), a fixed pattern could be observed as the values are mostly clustered around 1m, 1.5 and 2m respectively. This pattern is repeated for the months in other years.

These results suggest that the significant wave height parameter present a strong seasonal characteristic with repeating values in each month and year. To conclude the section of results for the variability and seasonality, results for the analysis of the wave period parameter for the entire year 2005-2016 are presented in the following section. Figure 79 demonstrates the results for the year 2005-2008. In this case, the y-axis represents the wave period values. As in the presentations of the previous pages the x-axis represents the time in relation to the month January to December for each year.

In Figure 79 for results of the wave period in 2005-2008 the months of January to March is characterised with high wave period values. The reason is that peak values of around 20 seconds can be seen during this period. High values of the wave period are also experienced around November and December. Similar to the results presented in previous pages the values of the parameter vary depending on the time. Therefore, the focus is on the repeating trend. For example, in the months starting from May and mostly in June up to August, the concentration of the wave period appears to be around 5 seconds to 7 seconds. This is low compared to values at other times of the year.

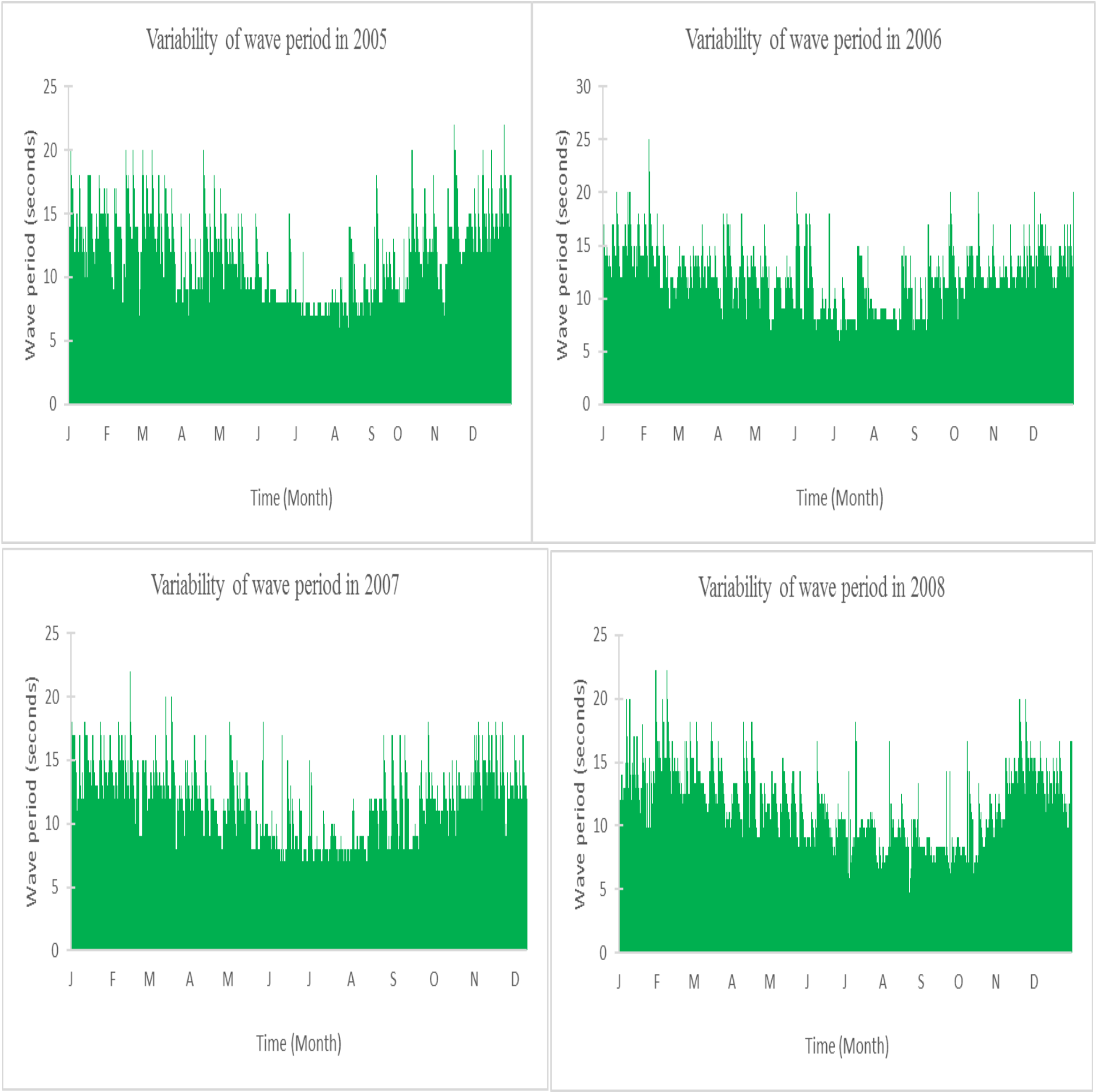
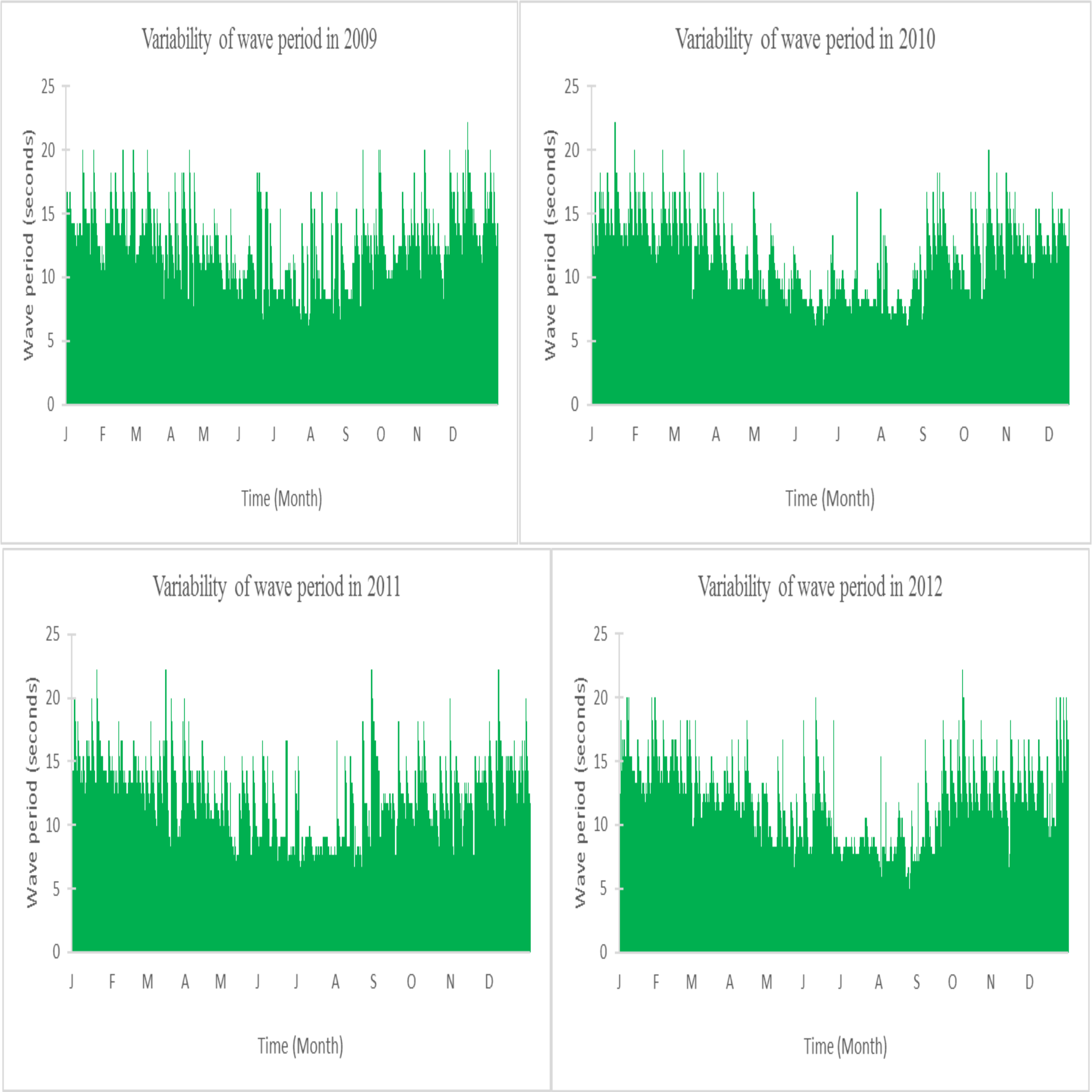


Figure 79: Variability and Seasonality of Wave Energy Period in 2005-2008

This appears to be a consistent trend for all the years. In comparison with the results presented for the wind speed and significant wave height, it can be observed that the same trend is applicable. This is particularly in terms of the more energetic sea state during this months of January, February and March. These energetic seas are also experienced around October, November and December. This trend appears to be repeating for the same time every year. In addition, Figure 80 demonstrates the variability and seasonal effects of the wave period in 2009-2012.


Variability of wave period in 2009

Variability of wave period in 2010

Variability of wave period in 2011

Variability of wave period in 2012

Figure 80: Variability and Seasonality of Wave Energy Period in 2009-2012

Comparing the results in Figure 80 with that presented in Figure 79 for the wave period in 2005-2008, it is noticed that the period starting from the months of May up to August is characterised with much lower values compared to other months such as January, February November and December. During the months of May to August, the wave period values are clustered around the values of 5 seconds and 7 seconds. It is observed that the peak wave period values are in the range of 22 seconds. For example, in year 2005 and 2007, the peak wave period occurring in January extend until Mach and can be noticed in December each year.

From the results presented so far, it can be observed that wave period time series data experiences regular and predictable changes that recur every calendar year. This phenomenon is the same for the wind speed and significant wave height parameters. It can also be observed that a predictable pattern can be identified in the period starting from the month of May but mostly in June, July and August characterised with lower values of wave period. From the resource assessment point of view, any predictable change or pattern in a time series that recurs or repeats over a one-year period can be said to be seasonal. Moreover, due to the consequences of the variability, the combination of the significant wave height values and wave period values fluctuate.

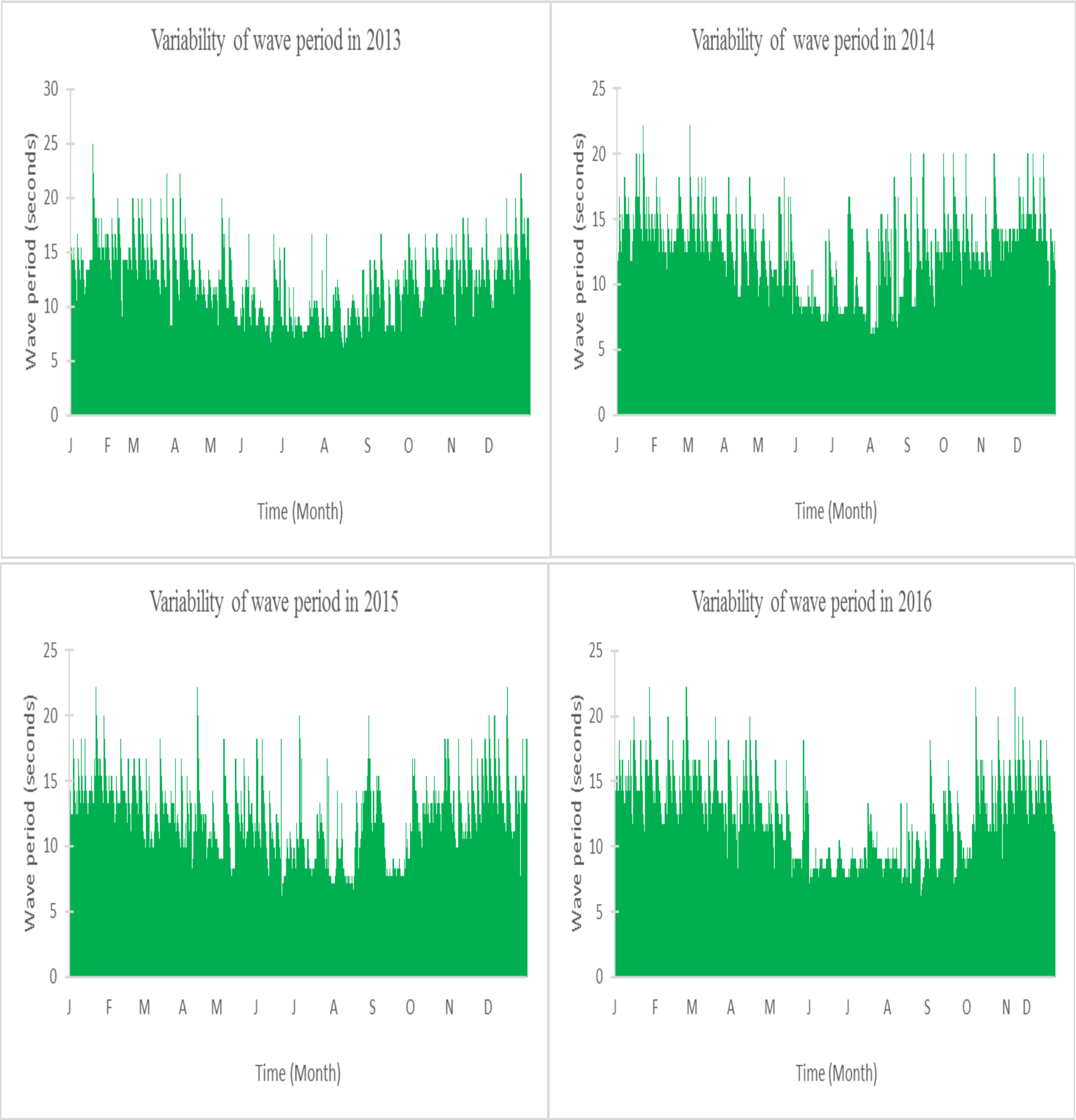


Figure 81: Variability and Seasonality of Wave Energy Period in 2013-2016

Similarly, Figure 81 demonstrates the variability and seasonality of the wave energy period in 2013-2016. It can be observed that there is no fixed or consistent value for these parameters. For this reason, the minimum, maximum and average values are considered to define the general characteristic of the dataset for the case study location. Since there is the tendency for parameters to change depending on the time and season. The seasonal effects are significant to illustrate the long-term trend to ensure the validity of the results.

The results presented above depicts strong seasonality which is reflected by a more energetic sea during the months of November, December and January. Comparing the results presented above, in the case of the maximum wind sped values, these are cluttered in the range of the average values as demonstrated in wind speed results on average values. This show annual averages of around 18m/s. The minimum values were clustered in the range of 6.5m/s. For the significant wave height values the maximum values are in the range of 6-8m, but the dominant values clustered between 1.5m-2.5m as noticed in the months of January February March and December.

In terms of the variability, the dominant values have the tendency to be concentrated around the values of 1m to 2m. This result suggests that the energy in the waves is generally low. This is applicable to the low energy months such as June, July and August. This trend is observed to be repeating every year. The seasonality is always of a fixed and known trend in period as illustrated in the variability and seasonality results. The variability is applicable in this case to illustrate the measure of how the dataset is spread out and clustering of the dataset. The predictable pattern existing in the dataset that recurs or repeats over a one-year period can be said to be seasonal.

5.6 Productivity Assessment Results

This Section demonstrates the results for analysis of the energy available in the wave resource and wave power for different years in the historical wave dataset for the case study location. This is relevant to validate the methodology and modelling developed in the integrated framework. This is also important because in the preliminary data analysis, it was observed that some years had good data, while others had data associated with either missing or incomplete data in some months following the period. The reason for the missing or incomplete measurements, is due to either bad weather conditions or technical difficulties (NDBC, 2016).

In this respect, the results for all the years (i.e. 2005- 2016) are presented and used in the discussion to assess the average monthly wave energy and wave power potential in the case study location. Figure 82 shows the average monthly wave energy available in the case study location. The y-axis represents the values of the theoretical average monthly energy available in the waves resource in the year, while the x-axis is used to illustrate the different months starting from January to December.

Figure 82: Average Monthly Energy In 2005-2008

The dark vertical bars depict the amount of energy available in each month at the case study location. For example, in the year 2005, it could be observed that the wave energy available is at its lowest values between the month of June, July and particularly in August being the lowest. It can also be observed that the wave energy gradually increases from September and doubles the amount in October as it increases in December and reaches a peak period at January. In this case the peak periods are experienced in the months of December, March and with January having the highest value.

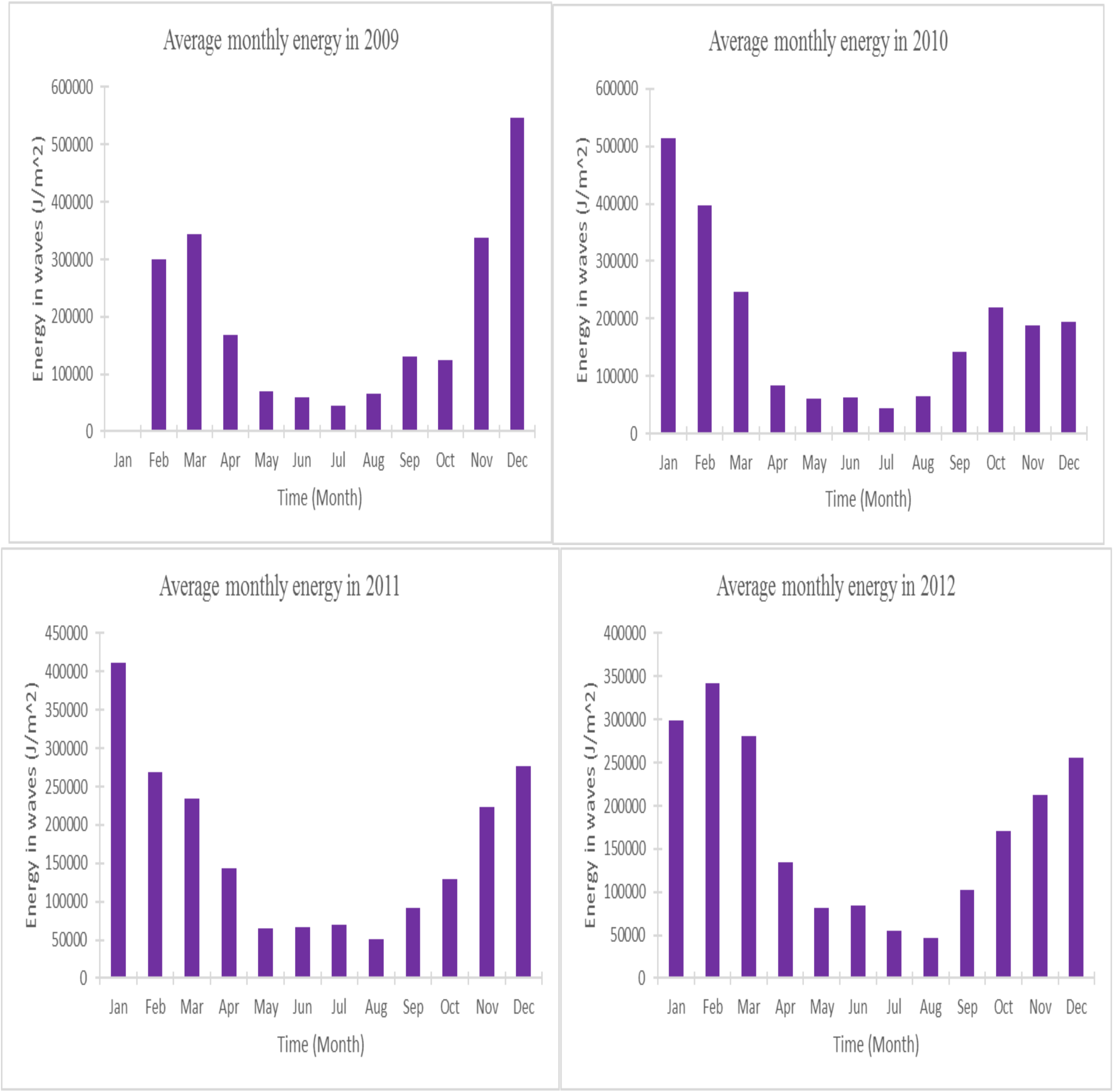


Figure 83: Average Monthly Energy In 2009-2012

It can also be observed in Figure 82 (i.e. for year 2005-2008), that the available wave energy begins to reduce from the month of May gradually until it reaches its lowest values in August. Although in the year 2006, the month of May still had a significant value of energy compared to other years (i.e. 2005, 2007 and 2008). Comparing the different years in Figure 82, the trend of the peak periods i.e. periods with hugest wave energy levels can be observed. For example, except for the year 2006, where February was the month with the highest energy level, other years had their highest wave energy levels in the month of January.

A similar tendency is applicable for some months in other years illustrated in Figure 83 (i.e. 2009-2012) and Figure 84 (i.e. 2013-2016). For example, in year 2012 and 2016 the wave energy available is at its highest level in February the same as in year 2006. The results presented suggest that the month of February can be characterised as a month with high wave energy levels. This is because the maximum monthly average value is in the range of 682,000 (J/m^2) in February 2016. The minimum monthly average values show that the energy available in the waves is in the range of 37,000 (J/m^2) in the months of August 2005 and in July 2013.

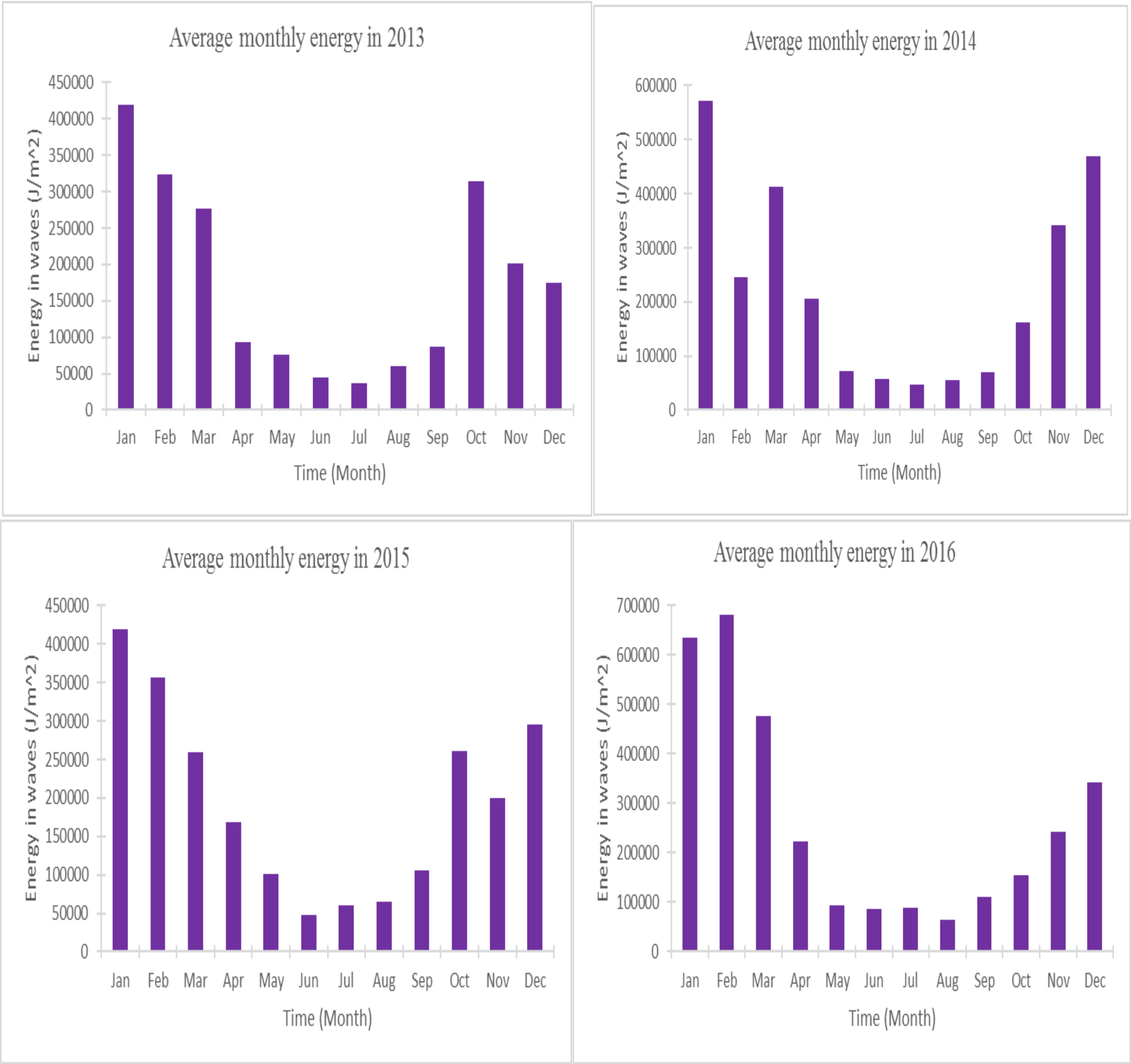


Figure 84: Average Monthly Energy In 2013-2016

The month of March can also be characterised as a month with high wave energy because the minimum and maximum monthly average values are in the range of 143,000(J/m^2) in March 2006, and 477,000 (J/m^2) in March 2016. On the average, the results presented in Figure 82-84, suggest that the energy available in the waves starts to build up in September every year and sometimes reaching its peak values in December. But generally, the highest values of wave energy are experienced in the month of January and this is often seen to extend into February as well as the month of March.

To justify the numbers presented for the wave energy available, it is significant to recall in the resource assessment model Section 3.5.3.1 that the total energy (E) generated by the wave system of regular progressive wave is the sum of its kinetic energy (E_k) and potential energy (E_p). Following Airy theory, if the potential energy is determined relative to Still Water Surface (SWL), and all waves are propagated in the same direction, potential and kinetic energy components are equal, and the total wave energy in one wavelength per unit crest width is calculated using the formula in Equation 86.

In Table 15 for energy available in waves and wave power calculated with wave data from Case Study Site, it could be observed that the higher significant wave height values are associated with greater values of energy available in the waves. In this case, the energy available in the waves was calculated for each significant wave height criteria as a function of the wave energy spectrum. However, the contribution to the average annual energy for the selected location is dependent on the frequency of occurrence of the significant wave height criteria or dominant significant wave height values. As demonstrated in Table 15, the contribution of Hs= 8m to the annual energy is zero. The reason is that the frequency of occurrence of Hs=8m for that year was zero.

It can also be observed that for the dominant significant wave height such as Hs=1.5m and Hs= 2m, the contribution to annual energy of the resource is greater. Although the energy available in waves has a lower value for Hs= 1.5m and Hs = 2m compared to Hs =6m or Hs=8m. Similarly, the wave power associated with higher significant wave height such as Hs= 6m or Hs= 8m is high compared to Hs =1.5m or Hs= 2m. Since their frequency of occurrence is low, this suggests that they will not contribute much to the total average annual energy compared to the dominant significant wave height values.

The wave power is defined as the potential available wave energy flux per unit width of wave crest. The wave power was calculated from Equation 89 using the historical wave data for the case study location. In Chapter 3 methodology and modelling in the integrated framework, the total energy available in the wave has been described. Wave energy is evaluated as a function of the total combination of the kinetic and potential energy of the resource. This was also described as the total theoretical energy available in the wave system at the case study location. In addition to the results of the average monthly wave energy available in the resource, Figure 85-87, is significant to illustrate the result average monthly incident wave power in 2005-2016.

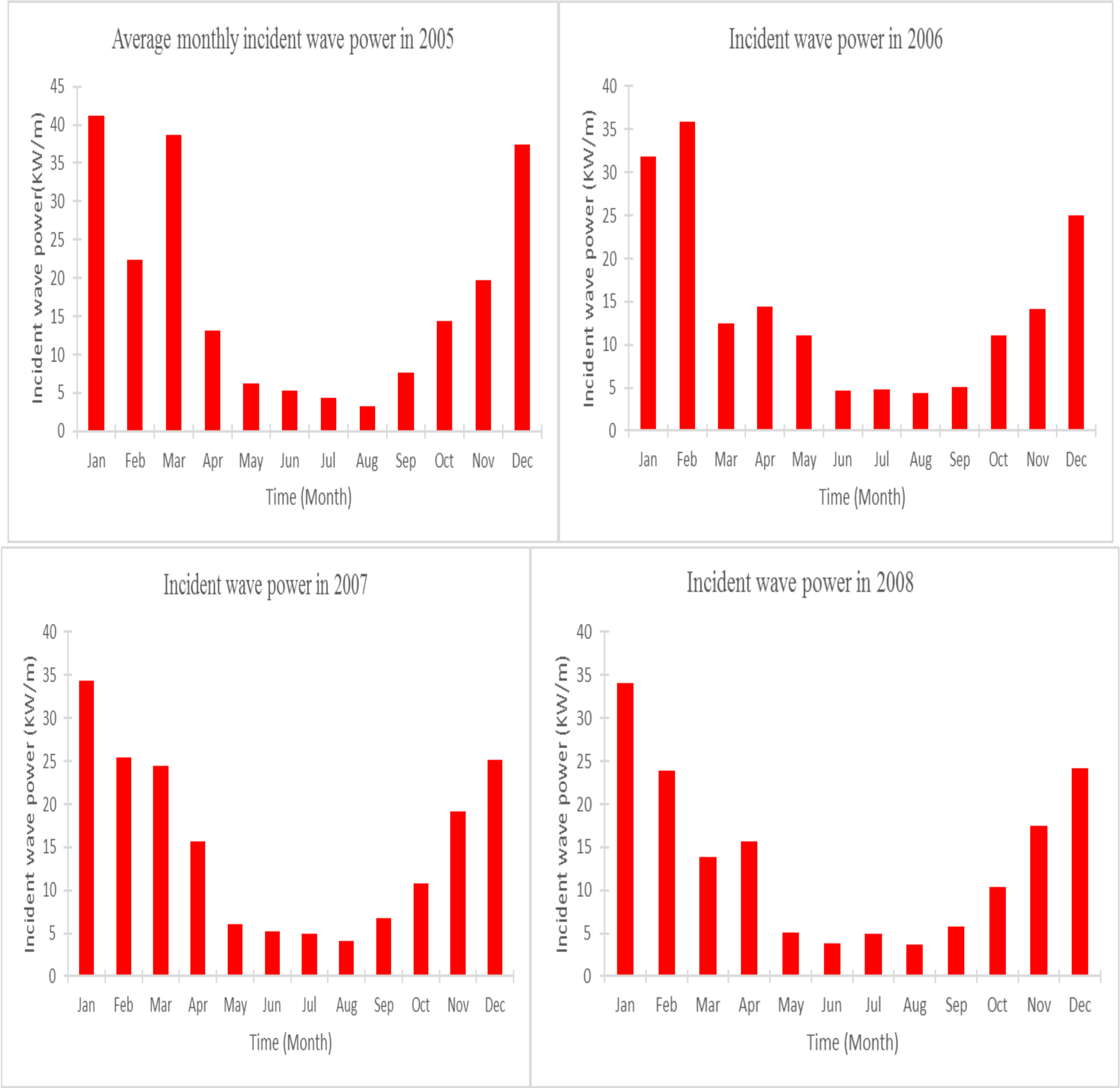


Figure 85: Average Monthly Incident Wave Power In 2005-2008

The main difference between the previous results in Figure 82-84 and the results in Figure 85-87, is the values presented on the y-axis. In this case, the y-axis represents the incident wave power instead of the total energy in the waves which is a function of the sum of the kinetic and potential energy components of the wave system. Similarly, the x-axis represents the month January to December and the vertical red bars depict the magnitude of incident wave power that can be captured by the WEC in the specific month.

Comparing the results of Figure 82 with that of Figure 85 for the years (i.e. the incident wave power in 2005-2008), it could be observed that each year presents similar features. The difference is obvious when the values on the y-axis are compared. For example, in the year 2005, it could be observed that the incident wave power is at its lowest values between the month of June, July and particularly in August being the lowest of approximately 3.2 (KW/m).

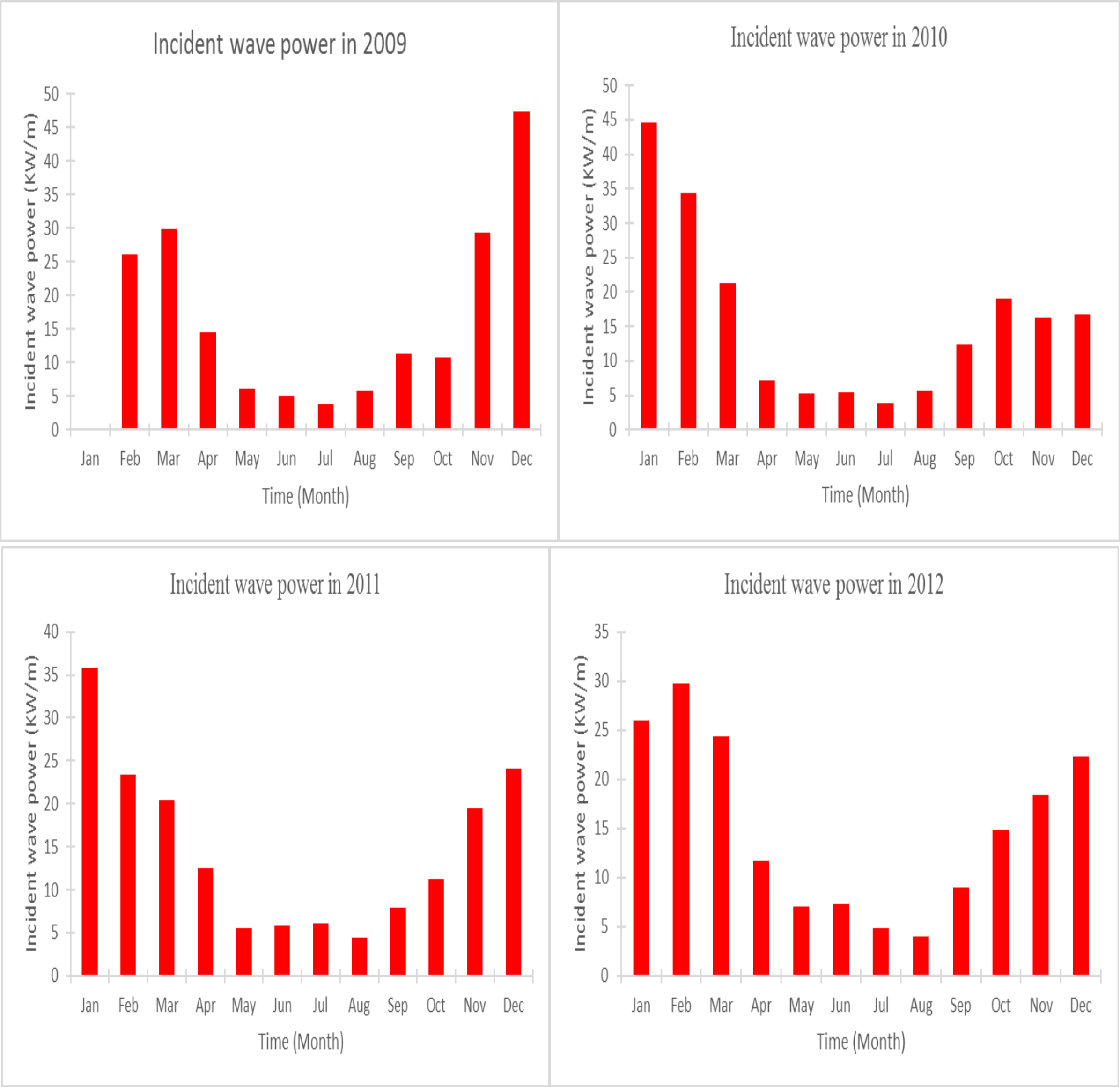


Figure 86: Average Monthly Incident Wave Power In 2009-2012

The important reason for showing this set of results is to distinguish between the theoretical energy available in the resource and the ideal maximum or minimum wave power that could be captured from a specified sea sate using a WEC technology. In relation to the resource assessment model in the developed integrated framework, the significant wave height and wave energy period are the two important sea state parameters combined to evaluate the energy available in the wave resource and the wave power that can be theoretically harvested using a WEC technology.

The energy available in the waves and the incident wave power is greater for higher values of significant wave heights and wave period than for lower values. Although very high values of the significant wave height and wave energy period may present more serious challenges for WEC O&M. Hence, it is important to know how the significant wave height and wave period fluctuate in the case study location as presented for the variability and seasonality results in Section 5.5.

On the other hand, the wave power is the transport of energy by ocean surface waves and the capture of that energy to do useful work such as electricity generation. The incident wave power which is a function of the combined sea state parameters is the wave energy that any specific WEC can capture when placed in the location of interest. The average monthly incident wave power (kW/m) at the case study location in each respective year, is the average monthly power per unit width of wave crest.

The general trend observed in all the years is that the wave energy starts to build up again from September. This is a general trend, since the low energy months always terminates or ends in August of each year. For example, comparing, Figure 86 for the incident wave power (i.e. for 2009-2012) and Figure 87 for the incident wave power (i.e. for 2013-2016), it is observed that a similar trend is applicable as the wave energy gradually builds up from September and continues to improve until it reaches a peak value in December.

Behind every resource assessment there is the possibility for installing a WEC device to harness the wave energy. As an integrated framework, the results shown in the graphs can be applicable to influence the decision relating to the time that planned O&M activities could be carried out on the WEC. In this context, planned O&M activities can be performed during low productivity months such as July and August as consistently shown in the graphs. Moreover, in terms of cost reduction in the O&M activities, smaller vessels could be employed to perform the O&M activities due to the low significant wave height threshold during these periods.

There is a noticeable variation in the year 2010 and 2013 where the wave energy drops in November and even lower in December. As observed during the preliminary data analysis, the reason for this is caused by missing or incomplete data points for these months. As could be observed from the presentation, the peak periods are experienced in the months of December, March and with January having the highest value in most cases. The wave energy begins to reduce from the April and gradually until it reaches its lowest values in August.

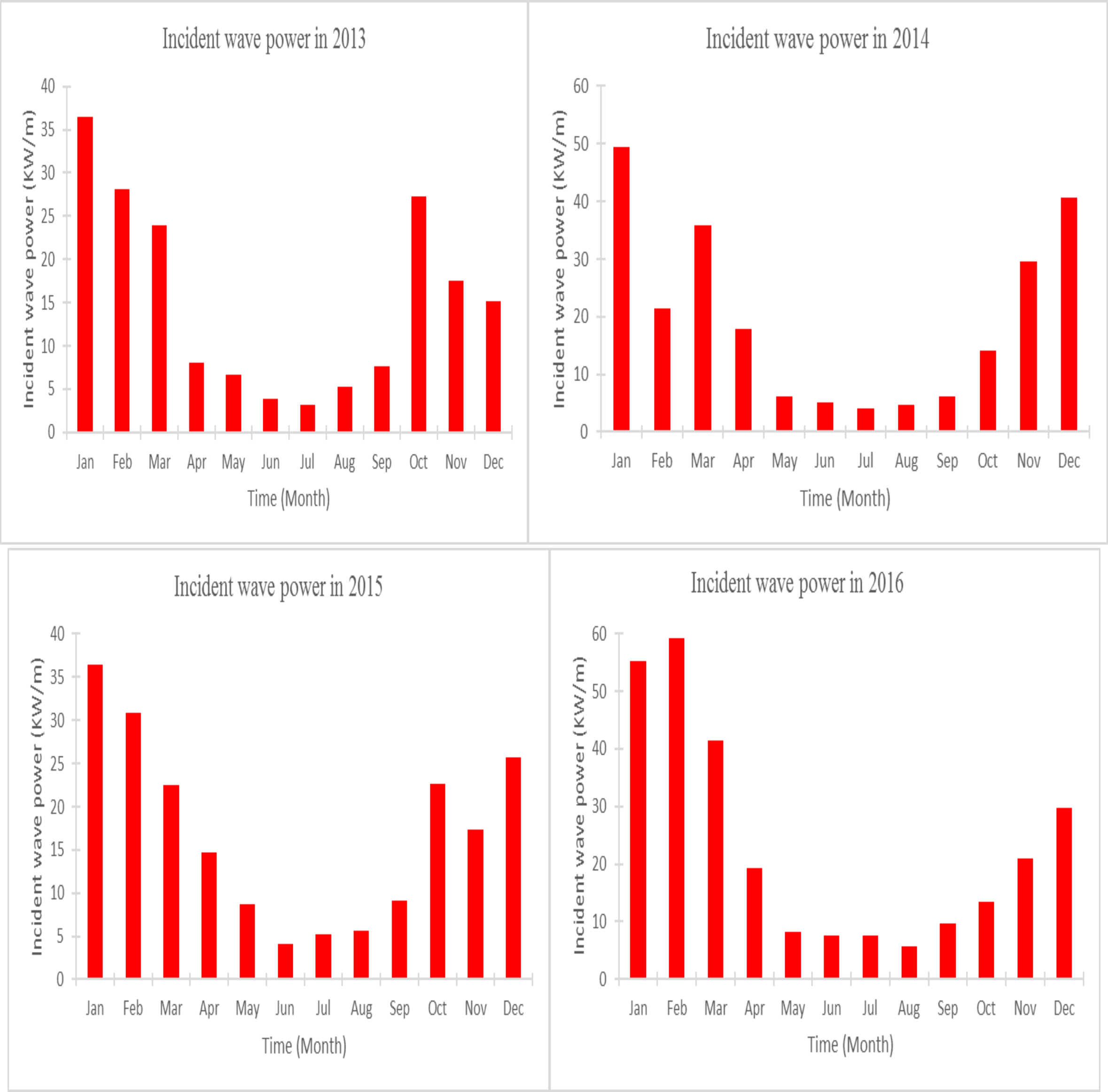


Figure 87: Average Monthly Incident Wave Power In 2013-2016

On the average depending on the year, the maximum monthly wave power is in the range 59 (KW/m). This highest value was in year 2016. In other years, the general tendency is that the maximum values fall between the range of 35-49 (KW)/m). Significant low levels of power are observed between the months of May up to September. The lowest levels are experienced in August with wave power of 3KW/m. Comparing the result for the different years, strong seasonal characteristics can be noticed and this exist in the average values of the available wave energy and incident wave power that can be captured by the WEC at the case study location.

The result presented for the average monthly wave energy available at the case study location depicts the true characteristic of the resource. This is because of the consistency in the range of the values. Moreover, the strong seasonal trend and repeating pattern exhibited for a fixed period is applicable in all the years. The energy associated with each wave field was analysed from the wave power and its probability of occurrence in an average year. This is based on the characteristics of the offshore wave energy resource as discussed in Chapter 4 case study application of the methodology.

In the methodology and modelling, the power-based availability is analysed and the average monthly energy due to availability was also considered as an output of the resource assessment. In this context, the wave power availability is the proportion of the average monthly energy production to the theoretical energy available in the waves. In this case, the energy production is the incident wave power defined based on the average monthly occurrence of the significant wave height and wave energy period in the specified year. Figure 88 is important to demonstrates the result for the average monthly wave power availability for years 2005, 2007, 2009, 2011, 2013 and 2015.

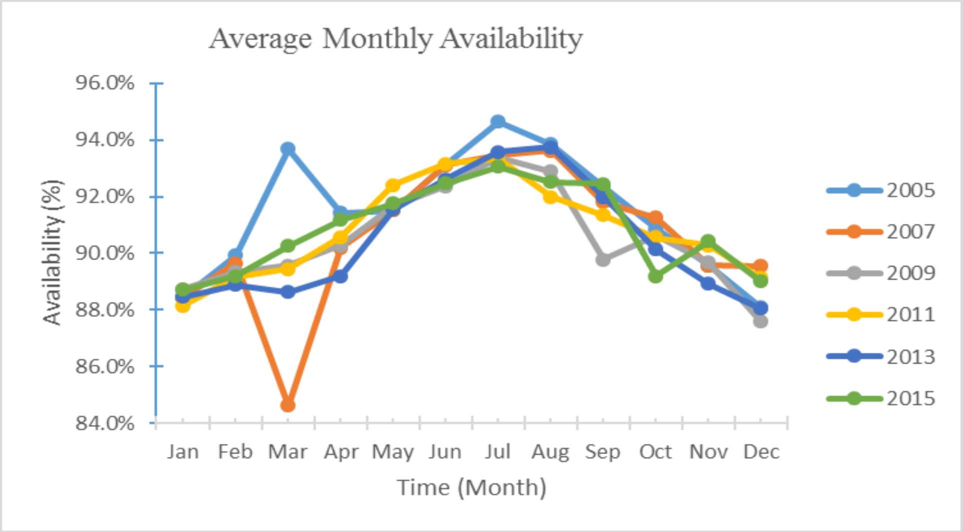


Figure 88: Average Monthly Wave Power Due to Availability

In Figure 88, the y-axis represents the availability as a percentage of the amount of energy that could be extracted from the resource. The x-axis represents the time in months from January to December in any selected year. This result is used to illustrate the example of the wave power availability in the case study location. Following the preliminary analysis results it was observed that the historical wave dataset for the case study location consist of the good and bad weather years. For example, the result of year 2005 depicted by the blue line in Figure 88 demonstrates that the peak availability period is in the month of July with value around 94%.

From the month of August, the power based availability begins to decline until the month of December with value around 87%. It can also be observed that in the month of March for year 2007, the power based availability was as low as 84% in contrast to the month of March in year 2005 with availability of around 93%. This sharp contrast can be due to error or fault in the measuring system.

As demonstrated in the variability and seasonality results in previous pages, year 2005 and 2007 where noticed to have issues relating to either missing or incomplete, measurements and as such only months with data was shown. However, apart from the year 2005 and 2007, other years such as 2009, 2011, 2013 and 2015 appears to follow a consistent trend in the month of March because the availability level is around 88% to 90%. In addition, Figure 89 shows results of average monthly wave power availability for years 2006, 2008, 2010, 2012, 2014 and 2016. This also show a similar trend in the month of March with availability around 88% to 90%.

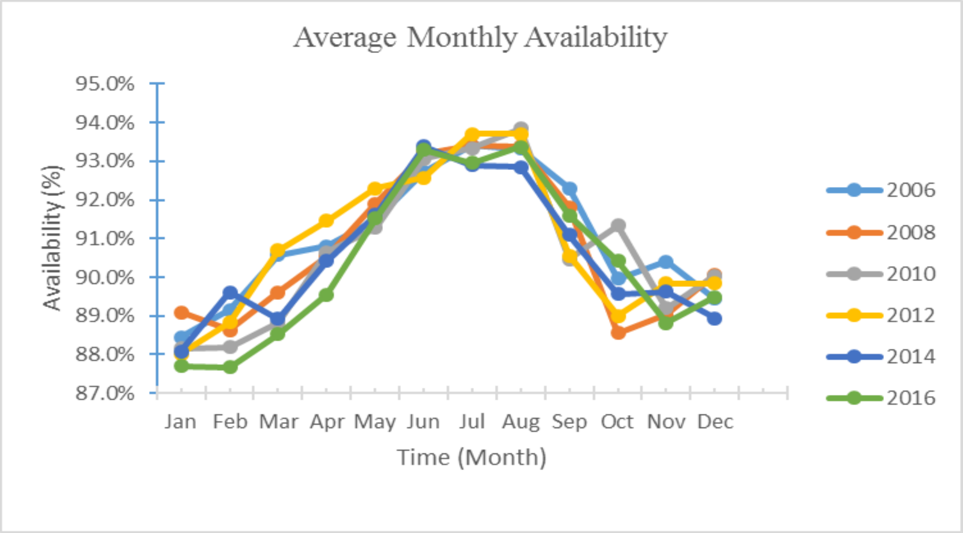


Figure 89: Average Monthly Wave Power Due to Availability

In contrast to the results presented in previous pages for the average monthly energy and incident wave power, it was observed that the wave energy is the lowest during the month of July and August. The explanation for this difference is that the wave power availability results reflects the values that contributes the most to the wave energy resource. This also reflects the sea states with the highest probability or frequency of occurrence throughout the year. As discussed in previous pages, this refers to the dominant significant wave height values.

These values were in the range of 1.0m to 1.5m and the concentration of these values seems to be clustered around the months starting from May to September each year. For this reason, the power based availability based on the dominant values will be higher during these months compared with months having higher significant wave height values but with minimum chances of occurrence. From the resource assessment point of view, these low but dominant significant wave height values can ultimately contribute to low energy productivity during these months because they have the highest occurrence in the wave energy resource.

As demonstrated in the seasonality and variability results, since these dominant significant wave height values were more frequent and concentrated around the months of July and August every year the power based availability appears to be much higher in July and August with values as illustrated in Figure 88 and Figure 89. In this case, the availability level is around 93% to 94% in all the different years. However, the higher values of the significant wave height were less frequent. In this respect, the higher significant wave height values only occurred in some months with peak periods particularly in the months of January February, March and December.

For this reason, the wave energy during these periods appears to be higher but considering the dominant monthly average values of the significant wave height parameter, the power based availability is lower during these periods. This explanation is applicable to all the years shown in Figure 88 and Figure 89. As can be observed the lowest values are experience in the months of January and December with value around 88% to 90%. On the other hand, the marine operational environment model builds the hourly history of the sea state. The dataset used should cover a period of 5 to 10 years to properly identify the inter-annual variations of long-term trends.

As mentioned earlier in previous pages, the significance of collecting the historical wave data for preliminary analysis in the resource assessment model is to achieve the objective of finding out any potential problem with the historical wave dataset. The data presented and described in this section is worthy of attention because in the process more detailed information can be acquired from the dataset. In addition, the preliminary data analysis provides the means to investigate and describe the underlying assumptions of the historical wave dataset and distribution. This is important to validate the methodology and modelling in the integrated framework developed in this thesis.

In the resource assessment model, the probability distribution is significant and applicable to characterise the variables of the parameters in the historical wave dataset. This can help to provide more information on the combination of values that contributes most to the wave energy resource. In the resource assessment method, the distribution function is used to characterise the random variable. Depending on the perspective, a density or cumulative question is applicable. This process will ensure that the data does not violate the assumption required for the analysis.

The preliminary analysis results discussed above is significant to illustrate the probability density and cumulative density functions of the wind speed, significant wave height and wave energy period values based on their annual distribution in the historical wave dataset. One of the important feature and benefit of the variability and seasonal results presented in this section is the ability to identify the specific months having similar problems. This is particularly in terms of areas with missing or incomplete data points or extreme weather conditions. In addition to results that have been presented and discussed for the resource assessment, the next step is to present the key findings for the offshore WEC accessibility and factors that may influence access for O&M planning activities based on the O&M strategy described in this integrated framework.

5.7 Offshore Accessibility Factors

Several factors can impact the offshore accessibility for example: wave height, wind speed, wave period, tidal flow, luminosity and temperature. In terms of offshore accessibility, the significant wave height (H_S), is one of the common parameters used to analyse the weather window (DNV, 2011). The reason is because the O&M activities requiring access by vessels are dependent on the significant wave height threshold. Wind speed, is a fundamental atmospheric component of weather and it is applicable in the resource assessment model in the integrated framework because the wind speed can help weather forecasting. It is caused by air moving from high pressure to low pressure, usually due to changes in temperature. In this thesis the wind speed values are applied to define the weather window for vessel operations.

In offshore engineering, a weather window may be defined as a period where quantities such as H_s, T_p, and wind speed, remain at levels which permit a given set of marine operations to be performed safely. Studies on weather window statistical analysis for offshore marine operations (Chen et al., 2008) mentioned that the weather window can be defined by the limiting significant wave height or wind speed threshold. In the integrated framework for resource assessment and O&M modelling proposed in this thesis, analysis of the weather window is significant to identify the suitable conditions when the O&M vessels can perform the O&M activities for the WEC farm.

For this reason, the integrated framework applies the historical wave dataset for the case study location to further investigate the offshore accessibility factors for the O&M activities. Following the results and discussion presented for the probability distribution, frequency of occurrence and variability based on the analysis of the parameters in the historical wave dataset, a wind speed and significant wave height threshold is defined. This is used for analysing critical conditions; particularly with respect to the weather windows. Beyond this threshold, it will not be advisable to manoeuvre vessels for O&M activities at the WEC farm.

In this context, the weather window is initially considered in terms of the number of occurrences of the defined wind speed and significant wave height threshold for each year. For O&M of offshore renewables energy devices, it is suggested that a predictable time between 8 hours to 72 hours is an ideal time to carry out a specific O&M or repair activity for a device. Therefore, this time is used as an example to illustrate the results of the weather window. The criteria for selecting the wind speed and significant wave height threshold values is based on the minimum, maximum, average and extreme values of the wind speed and significant wave height in the historical wave dataset.

As part of the output of the resource assessment in the integrated framework, the weather window results are plotted to illustrate the predictable time of the wind speed and significant wave height threshold defined in this thesis. As mentioned earlier, the historical wave dataset covers a period of 12 years from 2005-2016. The wave data for the entire period was analysed and the results were presented to help identify the trend. This is useful for validating the analysis and results presented.

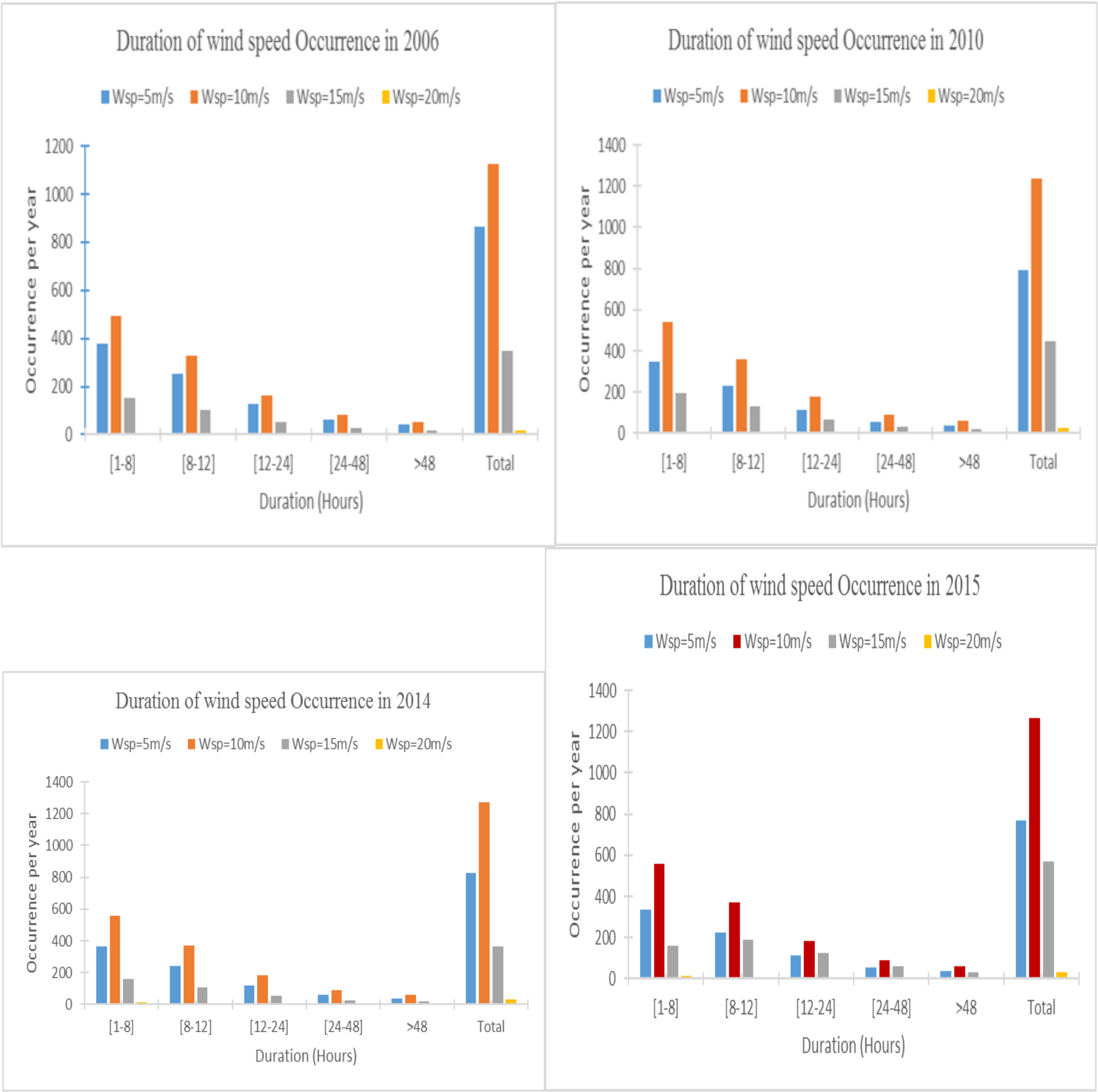


Figure 90: Number of Occurrence for Each Wind Speed Duration

Results presented in previous pages indicated that amongst other years, 2006, 2010, 2014 and 2015, reflect the true characteristics of the case study location. This is because the dataset in these years were observed to be complete and free of errors. Consequently, these years were selected and used in this analysis. Figure 90 is significant and applicable to demonstrate the results of the number of occurrence for selected wind speed weather windows per year, classified in duration order for the year 2006, 2010, 2014 and 2015. These results illustrate the frequency of experiencing the values of 5, 10, 15 and 20m/s and the chance that it would remain at the same level within the time scale of 8-72 hours.

In this context, the y-axis represents the number of occurrence in each respective year. The x-axis represents the duration within the time scale of 8-72 hours. In relation to the integrated framework on resource assessment and O&M modelling, the information presented in Figure 90 reflects the proportion of the wind speed weather condition with respect to the duration in hours. This is relevant to investigate and identify the long-term trend of the weather circumstances in case study location.

In relation to the O&M model in the integrated framework, O&M activities requiring vessels are dependent on the information of the weather circumstances. For example, in year 2006 the proportion of the wind speed value at 10m/s depicted by red bars has a greater chance of occurrence than the values of 5m/s and 15m/s. The result show that as other values such as 20m/s depicted by the yellow bars tend to disappear over the period of 8 hours, wind speed values of 10m/s will remain. As demonstrated in in Figure 90, within the period of 8 hours all the wind speed conditions are visible in all the years.

In addition, the results suggest that they can remain at the same level within that specified period. As the time moves further to 48 hours, only the weather conditions of 5m/s and 10m/s appear to be visible. The weather conditions of 15m/s and 20m/s tend to approach the value of zero and eventually disappear over the period greater than 48hours. This circumstance is applicable to the years 2010, 2014 and 2015. It is noticed that the wind speed condition of 10m/s has the largest portion in the entire duration. This suggest that as other conditions tend to zero within 48 hours' period, there is the tendency of still having wind condition of 10m/s in period greater than 48hours. These results show a similar trend in all the years.

Comparing the results in Figure 90 with the results presented in previous pages for the variability and average wind speed conditions over the years, the results confirms and reflects the true characteristic of the wind speed conditions in the case study location. In addition to the results of the number of occurrence, the percentage of time whereby the wind speed condition can be experienced is also demonstrated. Figure 91 illustrates the percentage of occurrence for each wind speed duration. In contrast to Figure 90, which presents absolute values based on the number of observations or occurrence for the selected wind speed weather condition, Figure 91 presents the values in percentages of the occurrence.

In this context, when the count is divided by the total number of occurrence in the dataset, the outcome becomes probability (Abramowitz and Stegun, 1972; Evans et al., 2000). The information presented in the result is significant to describe the predictable time as the probability of experiencing the either good or bad weather condition. This is also applicable to the probability that the prevalent weather circumstance will remain the same within the specified period. This is important because the sea states in relation to the weather conditions occur at random intervals.

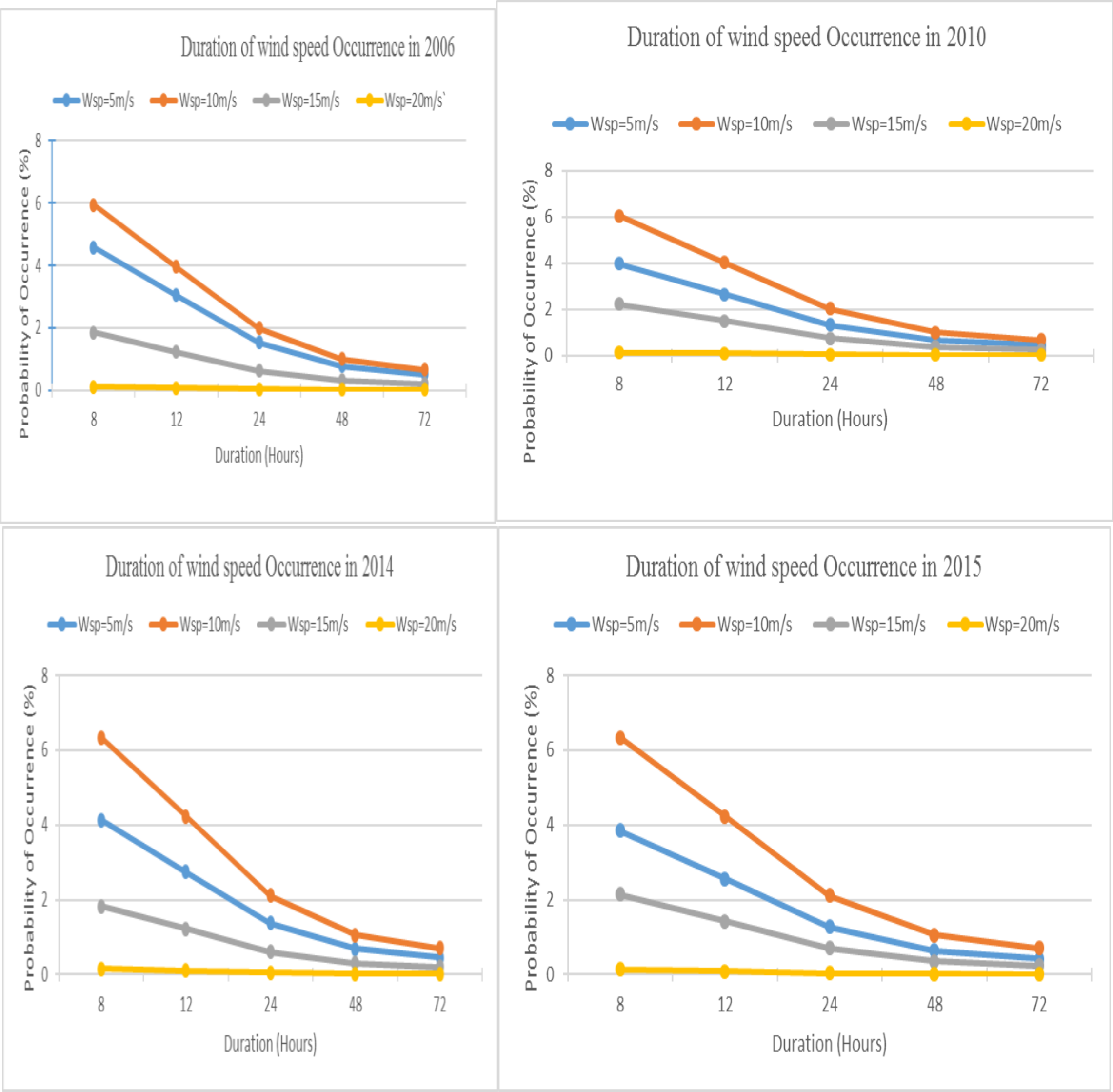


Figure 91: Percentage of Occurrence for Each Wind Speed Duration

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Thus, they can be predicted on short time scales. For example, in Figure 91 the wind speed weather condition with the highest probability of occurrence is that of 10m/s depicted by the red curve. The probability is approximately 6% in all the years demonstrated. It can also be observed that the weather conditions for 20m/s is consistently on the line at zero level. This indicates that the weather condition is not prevalent in the cases study location. But it may occur from time to time depending on the season as was observed in the results of variability and seasonality presented in previous pages.

This results in practice implies that vessel operation for O&M activities can be performed under relatively low wind speed conditions. The reason is that the low wind speed conditions are more prevalent in the case study location. The result also indicates that, while other wind speed conditions such as 5m/s, 10m/s and 15m/s occur with different frequency and relatively low probability of occurrence within the time scale, there is the tendency that weather condition of 20m/s will not occur or will remain at zero level over the period.

This condition is applicable in all the selected years and this also demonstrate the trend of the wind speed weather window in the case study location. In addition, Figure 92 is used to demonstrate the results of the number of occurrence of the significant wave height weather windows classified in duration order per year for 2006, 2010, 2014 and 2015. As in the case of the wind speed weather conditions, Figure 92 illustrates the frequency of experiencing the significant wave height values of 1m, 2m, 3m and 4.5m and the chance that it would remain at that level within the time scale of 8-72 hours.

The y-axis represents the number of occurrence in the respective year, while the x-axis represent duration within the time scale of 8-72 hours. The information presented in Figure 92 for each respective year demonstrates that the weather window of significant wave height 2m has greater number of occurrence over the period of 8 hours compared to significant wave height of 3m and 1m. The condition with the least number of occurrence is significant wave height of 4.5m. The weather condition with the total highest number of occurrences is depicted as the red vertical bar on the x-axis with description Total.

It can be observed that as the time moves further away from 8 hours the weather conditions begin to depreciate until it eventually cease to exist or at level zero. Comparing results for the different years presented in Figure 92, this indicates that a similar trend is applicable in all the years. In the results, it can be observed that within the period of 48 hours all the weather conditions are still visible. Although weather conditions such as 4.5m tend to disappear because it is consistently at zero level.

These results suggest that within the period of 8-72 hours the weather condition of significant wave height 2m is prevalent and will continue to exist. This is after lower weather conditions such as 1m or high significant wave height circumstances such as 4.5m would have vanished over the duration of 72 hours. Similarly, Figure 93 demonstrates the probability of occurrence for the different values of the significant wave height weather window. In this case, the y-axis represents the probability as a percentage of the occurrence of the weather window for the different years.

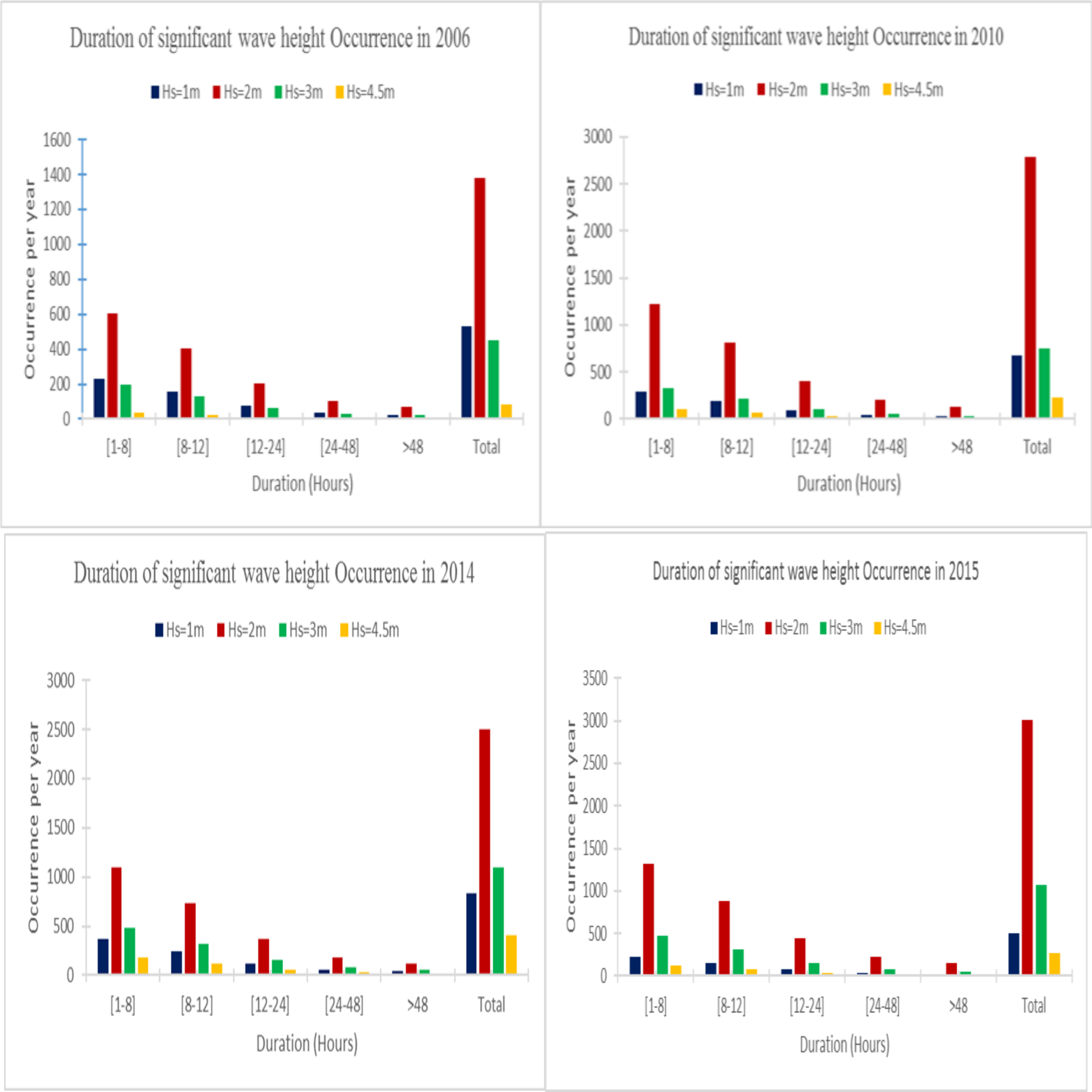

Figure 92: Number of Occurrence for Each of Significant Wave Height Duration

The result in Figure 93 illustrates that the weather condition of significant wave height 2m has the highest chance of occurrence and remaining for a period of 72 hours. The weather conditions of significant wave height of 4.5m has almost 0% chance of occurring and remaining for 72 hours as shown in years 2006, 2010 and 2015. In practice, this implies that the weather circumstance of 4.5m significant wave height is not prevalent at the case study location. In that case bigger vessels with high significant wave height threshold will hardly be required.

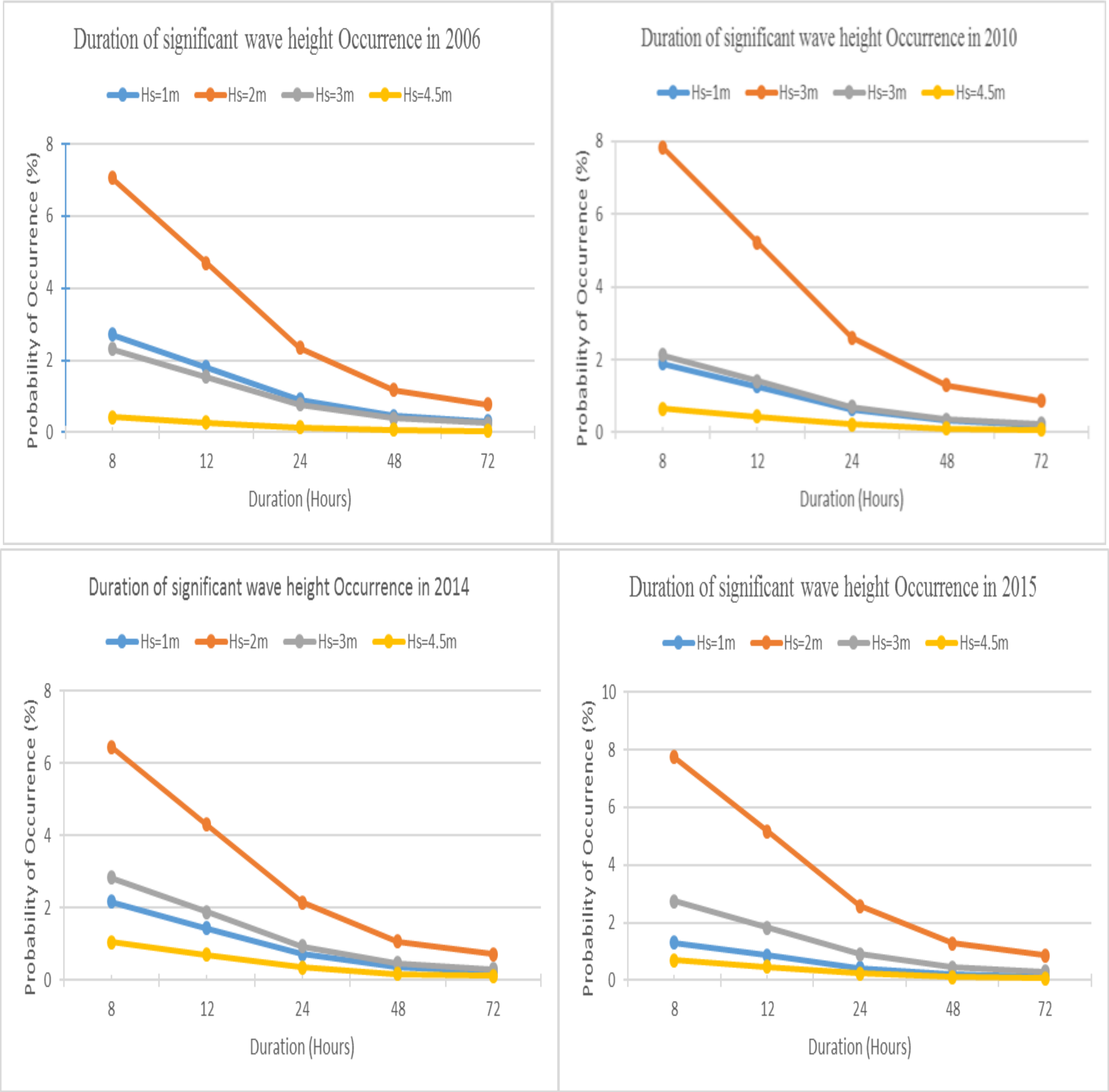

Figure 93: Percentage of Occurrence for Each Significant Wave Height Duration

From the resource assessment point of view this can present an opportunity for cost reduction in terms of the O&M vessel cost. The reason is that O&M vessels in the category of Big Vessel 2 have high charter rates and this contributes to the high cost of chartering the O&M vessel. Therefore, in the circumstance when the significant wave height threshold is consistently within the range of 1.5m to 2m throughout the year, it implies that small vessels in the category of Small Vessel 1 can have access to the WEC farm throughout the year for O&M activities. However, there is a potential disadvantage associated to low significant wave height conditions at the case study location, and this is particularly in terms of the productivity of the resource.

In this context, if the significant wave height conditions are very low less than 1m, this can contribute to low wave energy levels and the productivity of the resource will be low. In that case, to maximise the wave energy production at the case study location, it will be essential to install the WEC device that have the capacity of the dominant wave conditions at the location. In relation to the resource assessment and O&M modelling in the integrated framework, the information on the weather window is relevant for the O&M activities that need to be performed at certain significant wave height threshold.

For weather sensitive marine operations, it is useful to know the probability of experiencing acceptable weather conditions and the waiting time (or down time) distribution for such a condition. If the likelihood of experiencing a good weather window is too small, it will be advisable to suspend the O&M activity. Consequently, if the expected waiting time is long, the operation plan and schedule can be reviewed. The estimate of the anticipated starting time for each working shift is adapted from literature. The durations of the weather windows were then analysed as required for the planning of the O&M activities of the WEC farm.

In addition to the results of the weather windows durations already presented, accessibility is also considered for the case study location. Accessibility essentially describes the criteria for the O&M vessel to enter the WEC farm to perform the required maintenance activities. In this context, the underlying wave data is the same as that for the results already presented and discussed above. Therefore, the significant wave height threshold defined in the previous pages are applicable to illustrate the example of the accessibility in the case study location. Hence, the percentage or probability of occurrence of each criterion were analysed on monthly basis for the specified year 2006 and 2014.

The result is important for comparison and applicable to identify the trend in the case study location. The access limits are analysed on monthly basis by counting the number of occurrence of each significant wave height weather window in the month and taking the ratio as a percentage of the sum of occurrence of the weather criteria over the entire year. In this context, the probability of access is defined in relation to when it will be suitable to employ either a small vessel or big vessel to perform the maintenance activities considering the significant wave height criteria for the case study location.

Figure 94 is important to demonstrate the monthly access limits for O&M vessel utilisation. The result is based on the significant wave height characteristics analysed from the historical wave data for the case study location. This is significant to illustrate the ideal time when either a small vessel or big vessel can be employed to reduce the cost of O&M vessel operation. In this context, the y-axis in Figure 94 represents the percentages of O&M vessel utilisation based on the monthly significant wave height characteristics defined as the criteria for access. The x-axis represents the time of the month starting from January to December.

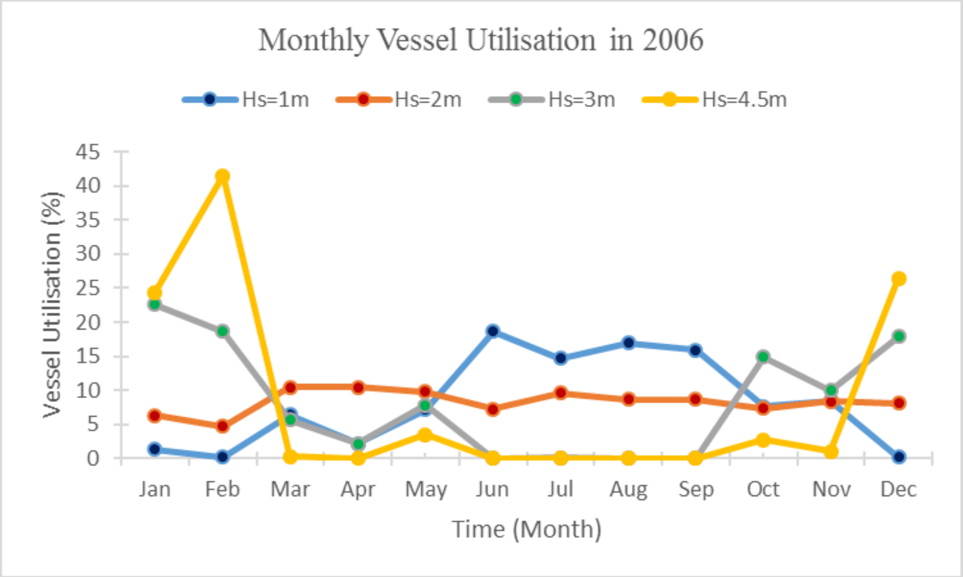

Figure 94: Monthly Vessel Utilisation for Different Significant Wave Height Criteria In 2006

It can be observed that during the month of January to February O&M vessel operation having a significant wave height limit of 1m is around 1%. This is equivalent to 0.3 days of the month, which is approximately 7.2 hours in the month. This result suggests that it will not be safe to operate or allow smaller vessels to enter the WEC farm during this period because the access criteria is limited. In this case, O&M vessels in the category of Big Vessel 2 can be utilised for the O&M activities during this period. The reason is that O&M vessels in the category of Big Vessel 2 can withstand the high significant wave height threshold during this period.

At this point, it is important to emphasize that the access limits defined based on the characteristics of significant wave height is to illustrate the ideal time of the month when suitable O&M vessels can be employed to reduce the cost associated with O&M vessel utilisation. This does not imply that the more seaworthy vessels (limit Hs = 4.5m) would not be able to gain access into the WEC farm during the period starting from March to November. In this case, the results suggest that the cost of O&M vessel operation can be reduced during this period by employing smaller vessel (limit Hs = 1m or 2m).

The significant wave height criteria defined for vessel operation reflects the true characteristics of the resource based on the resource assessment model in the integrated framework. In comparison with the results for variability and seasonality in Section 5.5, this result shows consistency because the low significant wave height period is seen to be clustered around the months of May to August. This low significant wave height period often starts from around April, May and June. The results also reflect the true circumstance of the dominant significant wave height characteristics because in Section 5.4 it was observed that the frequency of occurrence of Hs= 4.5 was low compared to that of Hs 1.5m and Hs =2m.

The months of January, February and March has been identified as periods with high significant wave height threshold, this does not imply that other lower limits such as Hs = 1m or Hs =2m does not exist. Similarly, the months starting from April to September has also been identified as months with lower significant wave height threshold, this also does not imply that other higher limits such as Hs = 3m or Hs = 4.5m does not exixt. In this context, the results in Figure 94 and 95 is important to explain the prevailing weather circumstance for O&M vessel operation in the case study location. This can help WEC farm operators keep the cost of O&M vessel operation down by deciding on the ideal time to employ the suitable O&M vessel.

In practice O&M vessels in the category of Small Vessel 1 can only be utilised for around 7 hours in the month of January and February. Assuming it is necessary for the maintenance activities to be performed during this period, O&M vessels in the category of Big Vessel 2 can be utilised. The reason is because O&M vessels in the category of Big Vessel 2 can withstand the high significant wave height threshold during the month of January and February. In Figure 94 the significant wave height limits for 3m is around 18 to 22%. In practice, this implies that Big vessel 2 can be safe to operate for approximately 5-6 days in the month.

In the case of 4.5m significant wave height weather circumstance the results indicate that O&M vessels can be utilised around 24 to 41% in the month of January to February. This implies that O&M activities employing Big Vessel 2 can be performed within approximately 7 to 12 days in the month. However, due to the low significant wave height threshold starting from the month of March up to September as illustrated in Figure 94, it can be observed that the percentage of O&M vessel operation for limit Hs =4.5m is around 0% during these periods. This does not imply that more seaworthy vessels in the category of Big vessel 2 cannot gain access into the WEC farm for O&M activities in any month of the year. In this context, the result in Figure 94 demonstrates that it can be safe to employ smaller O&M vessels with operational limit Hs=1m or 2m to access the WECs for O&M activities in any month of the year. This is because the of the low significant wave height threshold.

In this case, O&M vessel utilisation with limit Hs= 2m is around 4% in February. In other months throughout the year 2006 O&M vessels utilisation is up to 10% for the weather condition of Hs=2m. For weather conditions such as Hs=1m with 0% utilisation in February and December and Hs=4.5m with 0% utilisation around March, April, June to September, WEC farm operators can decide to employ either a big vessel or small vessel to reduce the cost of vessel operation. Similarly, Figure 95 is used to demonstrate the monthly percentage of O&M vessel utilisation for the year 2014 using the same significant wave height criteria.

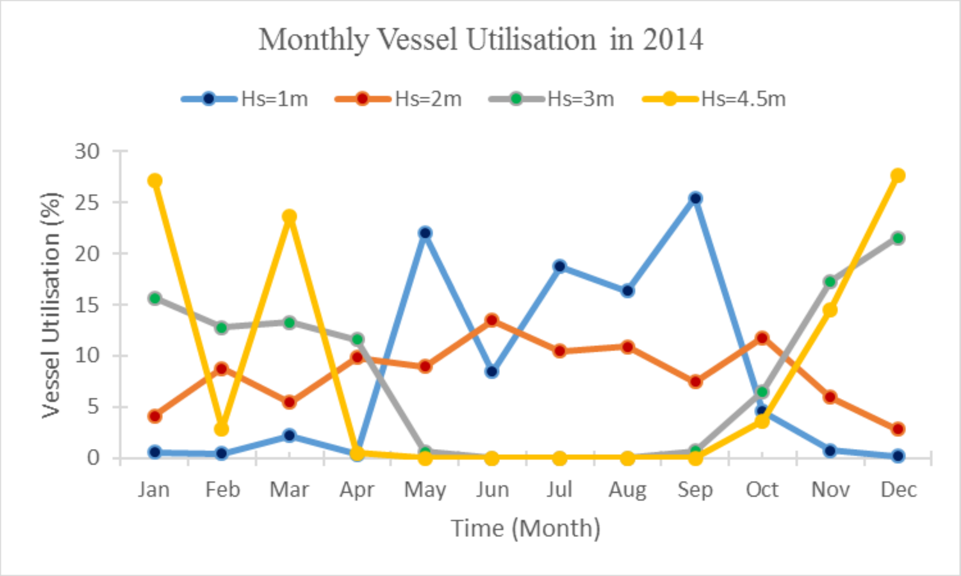

Figure 95: Monthly Vessel Utilisation for Different Significant Wave Height Criteria In 2014

In comparison to Figure 94 for the year 2006, a similar trend can be noticed in the characteristics of the significant wave height criteria. For example, O&M vessel utilisation for criteria Hs=1m is approximately 0% in the month of February and November same as in 2006. This implies that WEC far m operators can decide to employ Small vessel during this period. Although, there is the tendency that the significant wave height threshold can increase or decrease rapidly during the periods starting from January, February, March and November as illustrated in the graph. For safety reason it can be advisable to employ big vessels with limit Hs= 3m or 4.5m due to the unpredictability of the weather during these periods.

The weather circumstance for Hs= 4.5m is more predictable starting from the month of April to September same as in year 2006. This is because the significant wave height threshold during these periods are consistently low. However, there O&M vessel operations for criteria Hs=2m can be possible throughout the year 2006 and 2014. In this case, O&M vessel utilisation is the range of around 5% to 11% in 2006 and around 3% to 12% in 2014. In contrasts with Hs=1m, 3m and 4.5m O&M vessel utilisation is 0% for some months of the year. The reason is that in these months, the significant wave height threshold is often low and the probability of having high significant wave height such as Hs=3m or 4.5m is minimal.

This result reflects the characteristics of the dominant significant wave height as seen in the preliminary analysis of the historical wave data in the resource assessment model. As in the case of Hs=4.5m O&M vessel utilisation is 0% from the month of May to September in 2014 and June to September in 2006. During this period the WEC farm operators can employ O&M vessels with operational limit Hs= 1m or Hs=2m to perform the O&M activities. This can contribute to reducing the cost of O&M vessel operations. If a boat with limit Hs= 1m was to be chosen during the months of January, February November and December there will be risk of the boat capsizing and issues of safety due to the magnitude of Hs during this period.

In that case, O&M vessel operation for boats limited to Hs=1m will be 0%. The reason is that there is the tendency that the marine operations will not be performed safely using small boats during the months of January, February November and December. For boats limited by Hs= 1m, the marine operations could best be executed in summer because the significant wave height threshold is low. In that case, the percentages of O&M vessel utilisation during this period is around 7 to 18% in both year 2006 and 2014.

The results demonstrated for O&M vessel utilisation at the case study location suggests that practical usage for either Small Vessel 1 or Big Vessel 2 is possible but to some relative extent. This relative extent is defined by the maximum or minimum significant wave height threshold prevalent at the case study location during the time of the O&M activity. In this context, the results show that O&M vessels in the category of Small Vessel 1 limited by Hs=2m can be used for a minimum period of 1 day and up to 4 days in any month of the year.

In this integrated framework on resource assessment and O&M modelling, the initial statistical description and preliminary assessment results presented in the preceding sections described the methodology for the resource assessment model. In this context, the analysis attempted to find out the highest values or extreme conditions for the main parameters in the historical wave dataset. Consequently, the results of the probability distribution, which provided information on the chances of having selected variables based on the entire population in the dataset was demonstrated. Thereafter, results of the frequency distribution which provided information on the number of occurrence of the parameter in the dataset was illustrated.

As mentioned earlier, the difference between the PDF and PMF is dependent on the perspective and type of question. The PDF draws from an Infinite number of possibilities; while the PMF draws from a finite number of possibilities. This is applicable to find out the underlying assumption of the data distribution. The procedure was also relevant to check if the values in the dataset fits to a normal distribution. Associated with either the PDF or PMF is the CDF. The CDF provided the information about the probability that the variables associated with the defined parameter in the distribution is less than or equal to the local point specified on the x-axis of the distribution function.

Ocean energy technologies are designed to achieve a rated power output when design conditions are met. At any point in the ocean, the wave climate is the result of waves arriving from different directions. The wave energy is the time integral of the wave power and both terms ‘power’ and ‘energy’ are used relatively in this thesis. As an integrated framework, the output of the resource assessment model is used as input in the O&M model to define the marine operational environment for the O&M activities.

In the integrated framework, one of the key element suggested for minimising the O&M costs is maximising the weather window during which O&M activity is possible. This presents the main relationship between the resources assessment model of the case study location and the O&M modelling applicable to investigate the cost for the maintenance activities. Assuming O&M activities can only be performed in very favourable conditions, there is the probability that there will be delays in the project. This can contribute to additional O&M costs.

5.8 Chapter Summary

This Section summarises the work that has been presented in this Chapter. The results of the wave power resource and description at the location has been demonstrated. This is achieved by using a combination of the normal distribution and probability distribution functions to analyse the occurrence of the selected parameters in the dataset. Applicable methods such as the PDF gives the exact value of the probability distribution based on the integral of the area under the curve. The PDF assumes that the data is distributed the same as the population it came from (Abramowitz and Stegun, 1972; Stewart, 2011). In this context, the important thing is to analyse the probability that the random variable is in between two values.

Thus, integrating over the PDF, the interval between any two specified values turn to be the limit of integration. The theory of normal distribution is applied to investigate the probability of the sample mean or sample proportion being within any interval. The histogram gives probabilities calculated from the data (a sample) and a PDF gives probabilities inferred from the data to the entire population. Moreover, results of analysis of the average values for each month and year are relevant in the processes of estimating the theoretical energy available in the waves. This is also applicable to the wave power that could be ideally extracted from the resource when a WEC is placed in the location.

The important advantage of the seasonality and variability results presented in this Chapter is that it is applicable to identify the trend and specific areas with problem in the historical wave dataset used in the analysis. In the integrated framework, analysing the number of occurrence of weather conditions for each month of the year links the resource assessment model to the O&M model. In this context, the preliminary analysis based on the resource description provides the information relevant to maximise the weather window during which the O&M activity can be performed safely using vessels. In the next Chapter results for the O&M cost estimates are presented and discussed to validate the methodology and modelling in the integrated framework.

Chapter 6 O&M Modelling Results and Discussion

6.1 Chapter Outline

This Chapter demonstrates the results and discusses the key finding of the input metrics used to evaluate the O&M cost estimates for maintenance activities of the WEC farm project. The OPEX results are discussed and demonstrated in Section 6.2. This is followed by an analysis of the total initial cost in Section 6.3 and in Section 6.4 the economic value of the WEC farm is discussed. The Chapter summary is presented in Section 6.5 to conclude the results and discussion of the O&M modelling.

6.2 Operational Expenditure (OPEX)

In Chapter 3 methodology and modelling, the combined input of the resource assessment and O&M cost model was described within a single framework. In relation to the O&M model described in the integrated framework, two intermediate outputs are obtained. These intermediate outputs are associated with the resource assessment model in terms of the resource availability and vessel utilisation for the WEC O&M activities. The accessibility factors link the resource assessment model to the O&M model for analysis of the O&M cost estimates.

For this reason, the WEC farm availability was presented to demonstrate the results of the total amount of wave energy that is present and ready for use in terms of electricity production in an average year. Moreover, the accessibility results were also presented in Section 5.7 to demonstrate the results of the O&M vessel utilisation considered for different months in the year. This is relevant to maximise the weather windows for O&M planning activities. In this section, the input metrics of OPEX of a WEC farm project is examined to validate the results of the integrated framework described in Chapter 3 methodology and modelling.

In relation to the integrated framework, Chapter 4 Case study application of the methodology illustrates the example of the historical wave data for the case study location and O&M strategy. This is to help in achieving the objective of investigating the variation in the O&M cost estimates for the maintenance activities of the WEC farm project. In this respect, the O&M cost modelling is used to examine the main attributes contributing to the total O&M cost based on either the preventive or corrective O&M strategy. In the following sections, the results of the O&M cost modelling are presented for the O&M strategy considering different scenarios.

In this case, the different scenarios used to demonstrate the results are initially defined for clarity. The main input of the WEC farm attributes, O&M vessel specification, and specific cost input was illustrated in Section 4.4.1 and Section 4.4.2 in Chapter 4 case study application of the methodology. The wave farm attributes and O&M vessel specification input are applied in this case to define the scenarios used to demonstrate the results of the O&M cost estimates. The definition of the different scenarios is presented in the following sections.

To define the scenario applicable to demonstrate the results of the O&M cost modelling in the integrated framework, the WEC farm attribute is considered in terms of the number of WECs in the farm. The WEC farm size is applicable to the capacity of the WEC based on a single device rating. The attributes of the O&M strategy have been illustrated in Section 4.4.3 and Section 4.4.4 in Chapter 4 case study application of the methodology. Therefore, the O&M scenarios applicable are the preventive maintenance (Onsite/Onshore repair) and the corrective maintenance (Onsite/ Onshore repair).

In this context, the O&M strategy is applied to investigate the O&M cost estimate for maintenance of a single WEC device of 0.75MW and the maintenance cost of multiple WECs in a 45MW farm. Moreover, the scenario for the O&M vessel specification is applicable to the specific type of O&M activity for either the repair or deployment of a WEC farm at the case study location. This implies that, for either preventive or corrective maintenance actions, the O&M vessel is required and employed for onsite maintenance or for towing the WEC to the workshop in the case of major overhaul maintenance facility onshore.

In this context, the O&M case study results are based on the O&M vessel utilisation linked to the resource assessment result. This provides the information relevant to maximise the weather window during which the O&M activity can be performed safely. As mentioned earlier, one of the key element suggested for minimising the O&M costs is maximising the weather window during which O&M activity is possible. Therefore, to model the O&M cost estimates in this integrated framework the O&M vessel specification and scenario is defined in terms of Small Vessel 1 and Big Vessel 2.

In this respect, either Small Vessel 1 or Big Vessel 2 should have the capability of performing the O&M activities in terms of on-site servicing of the WEC or towing the WEC device to an onshore maintenance facility. Hence, the decision for employing either Small vessel 1 or Big Vessel 2 is based on the cost and benefits of employing the suitable O&M vessel. The criteria to support the decision is based on the weather circumstance or limiting significant wave height threshold prevalent at the case study location during the specific time of the O&M activity.

In this respect, Small Vessel 1 refers to small O&M vessels such as Crew Transfer Vessels (CTV) or tugboats used to access the WEC farm for maintenance or repair activities. The O&M vessel should have the capacity to return the WEC device to the onshore maintenance facility in the case of major repairs or overhaul replacement activities. The estimated charter rate of this type of Small Vessel 1 is around £5,000 per day. Big Vessel 2 refers to a big O&M vessel such as the multipurpose supply vessel having a daily charter rate of £19,000.

This type of O&M vessel is applicable in the event when the small vessel is not capable of accessing the WEC farm due to the higher significant wave height threshold or bad weather conditions in the case study location. In this case, a vessel with the maximum significant wave height threshold and the capacity to perform the maintenance activity or to return the WEC to the workshop for major repair activities is employed. The charter rates of these vessels are adapted from relevant studies on modelling vessel and equipment cost (Lazakis et al., 2013).

With respect to the O&M transport for offshore WEC farms, these two types of O&M vessels are applicable to demonstrate the results of the O&M cost estimates in this thesis. The Small Vessel 1 or Big Vessel 2 are deemed to be suitable for carrying out the O&M activities either in terms of transporting personnel and equipment’s to and from the WEC farm, performing the onsite servicing or repair maintenance or for towing the WEC (Bussel and Bierbooms, 2003). Studies (Lazakis et al., 2013) show that these vessels are applicable to offshore renewable energy devices.

Studies (Bussel and Bierbooms, 2003) also acknowledged O&M activities of offshore WEC farm require vessels for the maintenance activities. Furthermore, the O&M Cost elements and specific cost attributes in relation to the O&M cost is defined. This is applicable to investigate the most cost-effective approach to allocate O&M resources such as the O&M vessel and technicians required for each maintenance activity. The combined attributes for the wave farm, O&M vessel specification, and cost input are illustrated in Section 4.4.4 in Chapter 4 case study application of the methodology. In this respect, the scenarios used to demonstrate the results include the following:

- Scenario 1: Preventive maintenance cost (C_{pm}) Single WEC Vessel 1 or Vessel 2
- Scenario 2: Preventive maintenance cost (C_{pm}) Multiple WECs Vessel 1 or Vessel 2
- Scenario 3: Corrective maintenance cost (C_{cm}) Single WEC Vessel 1 or Vessel 2
- Scenario 4: Corrective maintenance cost (C_{cm}) Multiple WECs Vessel 1 or Vessel 2
- Scenario 5: Total maintenance cost ($\mathrm{T_{mc}}$) Single WEC Vessel 1 or Vessel 2
- Scenario 6: Total maintenance cost ($\mathrm{T_{mc}}$) Multiple WECs Vessel 1 or Vessel 2

6.2.1 O&M Costs for Preventive Maintenance Actions

A detailed model of O&M costs has been described and applied to explore the plausible range of this cost element. This is to identify the aspects and components that contribute most to cost variation. Results and findings obtained from this study should be considered as indicative and relative, bearing in mind that the focus of the section was to analyse the impacts of OPEX on O&M cost estimates for a WEC farm project. The results of the scenarios used to demonstrate the O&M cost for preventive maintenance actions is presented.

Generally, a routine on-site inspection could be performed at a chosen frequency, typically annual or bi-annual (Ben-Daya et al., 2009). Based on existing relevant studies on renewable energy device maintenance and optimisation (Besnard et al., 2009; Campbell and Jardine, 2001), it is assumed that the preventive maintenance activities of servicing the WEC on-site and performing repairs/routine inspection for the WEC components such as dynamic risers and mooring lines can be done once every year. The cost associated with the on-site service and repair activities is investigated following the method described in Section 3.5.3 OPEX Analysis in Chapter 3 methodology and modelling.

The operational expenses associated with both the on-site serving (minor/ordinary maintenance) and on-shore (major/overhaul/repairs) maintenance operations are assessed through the estimation of the cost of parts, man-hours of repair and the cost of vessel hire. In the end, the O&M model provides the summary of the maintenance activities for each unit along with the impact on both the availability for production and the O&M costs. The results of the total operational costs associated with the preventive maintenance model are illustrated in the following Scenarios.

Scenario 1: This scenario examines the preventive maintenance cost ($\mathrm{C_{pm}}$) for on-site (minor/ordinary maintenance) and on-shore (major/overhaul/repairs) of a Single WEC employing either Small Vessel 1 or Big Vessel 2. In this context, Scenario 1 demonstrates the results of the O&M cost estimates for minor/major maintenance or repair of a single WEC device based on the preventive maintenance model. In this case, the input of the wave farm attributes and O&M specific cost attributes illustrated in Chapter 4 case study application of the methodology are applied to perform the analysis.

For consistency in the method described in Chapter 3 methodology and modelling, the first step in the method is to estimate the transport cost. Thereafter the labour, workshop and equipment cost are analysed accordingly. Therefore, in the first step total transport cost (C_{trans}) is the total cost for chartering the O&M vessel to perform the minor/major repair or maintenance activities in scenario 1. In this process of estimating the total transport cost, some parameters are known while other parameters need to be calculated from the known parameters.

In this context, the known parameters include: distance to the WEC farm, distance in the WEC farm, vessel speed to WEC farm, vessel speed in the WEC farm, contingency factor for bad weather, specific fuel oil consumption, percentage of vessel maximum speed, vessel maximum engine power, number of main engines, the oil correction factor and price of fuel. A step by step approach is followed to examine the total transport cost. The example to estimate the initial charter cost (C_{vc_1}), for either the Small Vessel 1 or Big Vessel 2 is demonstrated.

In this case, the parameters relevant are initial charter time (T_1), the daily charter rate (R_1) for the O&M vessel, the vessel contingency factor and the daily cost of fuel. However, (T_1) is a function of four other parameters such as the time for vessel to reach and return from the WEC farm ($\mathrm{T_{wf1}}$), the time the vessel spends in WEC farm ($\mathrm{T_{wf2}}$), time to detach/attach one WEC ($\mathrm{T_{wf3}}$) and the inspection time per WEC ($\mathrm{T_{insp}}$). Given that the contingency factor for bad weather condition is 20%, the distance to the WEC farm is 100KM, the vessel speed to reach the WEC farm is 20 knots. In the case of on-site maintenance, the time it takes the vessel to reach and return from the WEC farm (T_{wf1}) is calculated according to Equation 108 as shown:

$$T_{wf1} = \left[2 \times \frac{2 \times Dist1}{\left(V_{sp1} \ \times 1.852\right)}\right] \times (1 + f_{ves})$$

$$T_{wf1} = \left[2 \times \frac{200}{(20 \times 1.852)}\right] \times (1 + 0.2) = 25.92 \text{ hours}$$

Therefore, time it takes the vessel to reach and return from the WEC farm (T_{wf1}) in the case of ordinary/on-site maintenance is 25.92 hours. In the case of on-shore (overhaul/repairs), the WEC will be returned to the workshop on-shore, this will entail 2 round trips according to Table 6. Therefore, given the contingency factor of 20% for bad weather condition, the distance of 100KM to the WEC farm and, the vessel speed to reach the WEC farm is 20 knots, the time it takes the vessel to reach and return from the WEC farm (T_{wf1}) is also calculated according to Equation 108 as shown:

$$T_{wf1} = \left[2 \times \frac{4 \times Dist1}{\left(V_{sp1} \ \times 1.852\right)}\right] \times (1 + f_{ves})$$

$$T_{wf1} = \left[2 \times \frac{400}{(20 \times 1.852)}\right] \times (1 + 0.2) = 51.84 \text{ hours}$$

As mentioned in previous pages, a routine on-site inspection could be performed at a chosen frequency, typically annual or bi-annual. In this case, according to Table 6, it is assumed that two visits for preventive maintenance will be performed in a year, i.e. one for ordinary/minor maintenance and one for major/overhaul maintenance. Therefore, the total estimated time it takes the vessel to reach and return from the WEC farm (T_{wf1}) is 77.75 hours. In addition, given that the distance in the WEC farm is 2KM, the vessel speed in the WEC farm is 5 knots, time the vessel spends in the WEC farm (T_{wf2}) is calculated according to Equation 109:

$$T_{wf2} = 2 \times Dist2 + \left[2 \times \frac{2 \times Dist\ 1}{\left(V_{sp2} \ \times 1.852\right)}\right] \times (1 + f_{ves})$$

$$T_{wf2} = 4 + \left[2 \times \frac{200}{(5\times1.852)}\right] \times (1 + 0.2) = 55.84 \text{ hours.}$$

In this case of on-shore maintenance, time the vessel spends in the WEC farm (T_{wf2}) is:

$$T_{wf2} = 4 + \left[2 \times \frac{400}{(5\times1.852)}\right] \times (1 + 0.2) = 107.67 \text{ hours.}$$

To reach and return from the farm there is a factor of 2 in the distance; hence the total estimated time that the vessel spends in the WEC farm (T_{wf2}) is 163.51 hours, this is approximately 7 days. As mentioned in previous pages, it is assumed the O&M vessel should have the maximum capability to perform the O&M activities at the WEC farm and to return the WEC device to the workshop in the case of activities that cannot be performed onsite. Since the focus is on investigating the variation in the O&M cost estimate, the decision of selecting the O&M vessel is based on the initial cost input being the O&M vessel charter rate.

The main criteria to support the choice or decision of employing the O&M vessel is based on the prevailing weather condition or significant wave height threshold at the case study location during the maintenance period. Therefore, given that the time to mobilise/demobilise ROV from the vessel (T_{rov}) is 0.5 hours, the time other than that required for ROV to bring WEC on board vessel (T_{other}) is 0.5 hours, the time to detach the old WEC and attach the new WEC (T_{wf3}) in place is calculated according to Equation 110 as shown:

$$T_{wf3} = (T_{rov} + T_{other}) \times (1 + f_{ves})$$

$$T_{wf3} = (0.5 + 0.5) \times (1 + 0.2) = 1.2 \text{ hours.}$$

Studies (Lazakis et al., 2013) show that in the case of offshore renewable energy converters, 2 hours is an ideal time for inspection per device. An inspection time of 2 hours per device is applied to illustrate this example calculation. This is because 2 hours is deemed to be ideal for time for inspection per WEC. Given the inspection time of 2 hours and having calculated the time it takes for the vessel to reach and return from the WEC farm, time the vessel spends in the WEC farm, and time to detach the old WEC and attach a new one in place, the time vessel is chartered is calculated according to Equation 107 as shown:

$$T_1 = T_{wf1} + T_{wf2} + T_{wf3} + T_{insp}$$

$$T_1 = 77.75 + 163.51 + 1.2 + 2 = 244.46 \text{ hours/activity}$$

Therefore, the total estimated time T_1, that the vessel will be chartered for preventive maintenance of a single WEC device in Scenario 1 is 244.45 hours, . approximately 10 days. In addition, having calculated the time that the vessel is needed (T_1), there is the requirement to estimate the cost of fuel that will be needed during the period that the O&M vessel is employed. This must be estimated before the cost of chartering the vessel can be assessed. However, the cost of fuel needed is dependent on the vessel daily fuel consumption ($\mathrm{D_{fc}}$) (tons of fuel), number of days the vessel spends at sea ($\mathrm{D_{sea}}$), the price of fuel ($\mathrm{Pr_{fuel}}$), number of main engines ($\mathrm{N_{main}}$) and the lube & diesel oil correction factor ($\mathrm{Oil_{corf}}$) set as 1.15 (constant).

In this context, parameters such as the daily fuel consumption ($\mathrm{D_{fc}}$) and the number of main engines may vary depending on the size of the vessel. Fuel consumption by a vessel is mostly a function of vessel size and cruising speed, which follows an exponential function above 14 knots. The vessel daily fuel consumption ($\mathrm{D_{fc}}$) is a function of the engine maximum power ($\mathrm{EP_{max}}$), the specific fuel oil consumption ($\mathrm{SF_{OC}}$) and the percentage of the vessel main power output ($\mathrm{F_{mean}}$). Therefore, given that $\mathrm{EP_{max}}$ is 2000KW for Small vessel 1, $\mathrm{SF_{OC}}$ is 175gr/KW/h and $\mathrm{F_{mean}}$ is 80%. The daily fuel consumption ($\mathrm{D_{fc}}$), is estimated according to Equation 112 as shown:

$$D_{fc} = EP_{max} \times SF_{oc} \times F_{mean} \times 24$$

$$D_{fc} = 2000 \times 175 \times 0.8 \times 10^{-6} \times 24 = 6.72 \text{ tons of fuel per day.}$$

In the case of Big vessel 2, the daily fuel consumption ($\mathrm{D_{fc}}$), is estimated as:

$$D_{fc} = 2500 \times 175 \times 0.8 \times 10^{-6} \times 24 = 8.4 \text{ tons of fuel per day.}$$

Since the daily fuel consumption of the vessel has been estimated, the cost of fuel needed can now be assessed. As mentioned earlier, number of days the vessel spends at sea ($\mathrm{D_{sea}}$), the price of fuel ($\mathrm{Pr_{fuel}}$), number of main engines ($\mathrm{N_{main}}$) and the lube & diesel oil correction factor ($\mathrm{Oil_{corf}}$) are relevant for the calculation of the cost of fuel needed. Scenario 1 is the case of preventive maintenance of a single WEC using either the Small Vessel 1 or Big Vessel 2; the number of days the vessel spends at sea is taken to be approximately 10 days.

The reason is that the time that the vessel is engaged is estimated and this time is 244.46 hours. For that reason, 10 days is considered as an ideal time to illustrate this example for calculating the cost of fuel needed in Scenario 1. Moreover, the price of fuel is taken as the current market value of Marine Diesel Oil (MDO). The prices of MDO can vary depending on the market and other factors. However, current MDO prises based on Bunker Index MDO available in public domain is around $785 USD being approximately £607 GBP. The number of main engines ($\mathrm{N_{main}}$) is 1 and the lube & diesel oil correction factor ($\mathrm{Oil_{corf}}$) is a constant value set as 1.15. Using these parameters, the cost of fuel needed for Small vessel 1 is estimated according to Equation 111 as shown:

$$C_f = D_{fc} \times D_{sea} \times P_{fuel} \times N_{main} \times Oil_{corf}$$

$$C_f = 6.72 \times 10 \times 607 \times 1 \times 1.15 = £46{,}908.$$

In the case of Big vessel 2, the cost of fuel needed is estimated as shown:

$$C_f = 8.4 \times 10 \times 607 \times 1 \times 1.15 = £58{,}636.$$

Having calculated the parameters $\mathrm{T_1}$ and $\mathrm{C_f}$ and given that the charter rate for the Small Vessel 1 is £5000. The vessel charter cost (C_{vc_1}) is estimated according to Equation 106 as shown:

$$C_{vc_1} = T_1 \times R_1 \times (1 + f_{ves}) + C_f$$

$$C_{vc_1} = 10 \times 5000 \times (1 + 0.2) + 46{,}908 = £106{,}908.$$

In addition, the cost of the crew employed on board the vessel is also estimated. With respect to vessel chartering and operation; crew cost refers to the cost associated with the vessel staff. These are members of the vessel crew directly responsible for providing support and assistance for the passengers on board the vessel. In this context, the vessel crew cost is estimated based on the cumulative crew cost (£) of each crew member employed on board the vessel. Studies (Dalgic et al., 2014; Alizadeh and Talley, 2011) mentioned that the crew cost varies per the rank and experience of the staff.

The relevant crew cost for the Small Vessel 1 and Big Vessel 2 was adapted from studies (Lazakis et al., 2013). In the case of Small Vessel 1, the cost of the crew members refers to the annual cost for employing one skipper (£18,000) and two deck crew members given as £15,000 per person. Hence, the cost of crew employed on board the Small Vessel 1 is estimated according to Equation 113 as shown:

$$C_{crew} = \sum_{n}^{i=1} \mathrm{C}_{\mathrm{crew}_\mathrm{i}} = \mathrm{C}_{\mathrm{crew}_1} + \mathrm{C}_{\mathrm{crew}_2} + \cdots \mathrm{C}_{\mathrm{crew}_\mathrm{n}}$$

$$C_{crew} = 18000 + +15000 + 15000 = £48{,}000/\text{year}.$$

Therefore, the total transport cost (C_{trans}) which is the total cost for hiring Small Vessel 1 excluding the cost of crew, for the duration of 10 days to perform the maintenance activity is given as C_{trans}=£106,908. Similarly, using the same parameters and given that the charter rate for the Big Vessel 2 is £19,000. The vessel charter cost (C_{vc_2}) is estimated according to Equation 106 as shown:

$$C_{vc_2} = T_1 \times R_1 \times (1 + f_{ves}) + C_f$$

$$C_{vc_2} = 10 \times 19000 \times (1 + 0.2) + 58{,}636 = £286{,}636.$$

In addition, the annual crew cost for the Big Vessel 2 is considered. This is based on the annual cost of one captain (£30,000), one engineer (£27,000) and two deck crew members are given as £20,000 per person employed on board the O&M vessel. Therefore, the cost of crew employed on board the Big Vessel 2 is estimated according to Equation 113 as shown:

$$C_{crew} = \sum_{n}^{i=1} \mathrm{C}_{\mathrm{crew}_\mathrm{i}} = \mathrm{C}_{\mathrm{crew}_1} + \mathrm{C}_{\mathrm{crew}_2} + \cdots \mathrm{C}_{\mathrm{crew}_\mathrm{n}}$$

$$C_{crew} = 30000 + +27000 + 20000 + 20000 = £97{,}000/\text{year}$$

Therefore, the total transport cost (C_{trans}) which is the total cost for hiring Big Vessel 2 excluding the cost of the crew for the period of 10 days is given as C_{trans} =£286,636. At the completion of step 1 to calculate total transport cost as illustrated above, Figure 96 demonstrates the result of the O&M vessel transport cost for the Small Vessel 1 and Big Vessel 2 employed to perform the maintenance activities for the period of 10 days in Scenario 1.

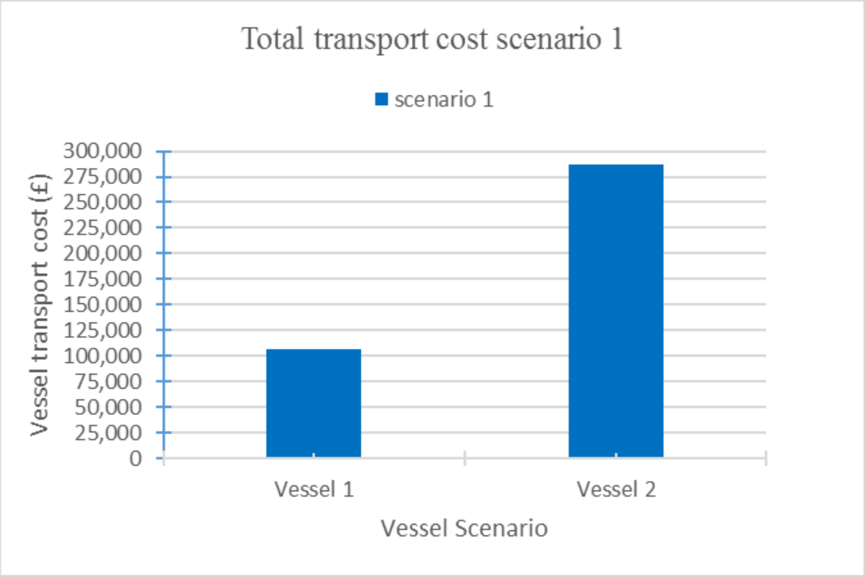

Figure 96: O&M Vessel Transport Cost Scenario 1

From the results shown in Figure 96, it is obvious that the cost of hiring Small Vessel 1 to perform the O&M activities in Scenario 1 is cheaper than the cost of employing Big Vessel 2. The reason for presenting this result is to provide an idea of the cost associated with any of the options. This is particularly to support the decision of cost and benefit of spending the additional money in the case when access for small vessels will not be permitted due to bad weather or high significant wave height threshold. In such cases, the decision to employ the alternative Big Vessel 2 is considered based on the cost and benefit of the WEC farm.

Comparing the results of both O&M vessel transport cost, it is observed that the high cost of the Big Vessel 2 is because of the high daily charter rate together with the increase in the cost of fuel. This situation is true because the daily charter rate increased from £5000 to £19000 and the fuel cost for the Big vessel 2 also increased. Apart from the daily charter rate and fuel cost, all other parameter used in assessing the transport cost in Scenario 1 remained the same. Based on the analysis, the vessel transport cost is seen to be influenced by the charter rate, fuel cost and the number of days the vessel spends at sea.

For this reason, time for which the O&M vessel is initially chartered should be estimated to consider the initial duration that the vessel will be needed. This is also considering the number of devices based on the wave farm attributes. This initial time is influenced by the inspection time given in this case as 2 hours per WEC and the time required to attach/detach the WEC estimated in this case as 1.2 hours. In this context, the initial O&M vessel charter time for Scenario 1 is estimated at approximately 244.46 hours. This may be regarded as the actual time that the O&M vessel will be used to perform the maintenance activities in Scenario 1.

In estimating the fuel cost, the main parameters that contribute to either increase or reduction in the fuel cost include the daily fuel consumption, size of the vessel and number of days the vessel spends at sea. The reason is that these parameters can vary considerably. Other parameters such as the number of main engines, oil correction factor and the price of fuel are constant. Therefore, in Scenario 1 the cost of hiring the O&M vessel to perform the maintenance operation is examined to investigate the influence of transport cost on total O&M cost estimate. In this context, the charter rate of O&M vessel is considered in the analysis to validate the method for estimating the total transport cost.

It is relevant to have an idea of parameters such as the daily charter rates, number of days the vessel will be hired, the inspection time per WEC. The reason is that these parameters can vary and are relevant to determine the total cost of hiring the O&M vessel in Scenario 1. In addition to the transportation cost, the labour, workshop and equipment cost were also examined to arrive at the total O&M cost estimate in Scenario 1. Therefore, the second step involves the method of analysing labour cost. The labour cost ($\mathrm{C_{lab}}$) refers to the cost of technicians or personnel responsible for performing the on-site maintenance or repair work.

To estimate the labour cost, the relevant parameters include number of technicians (on board the vessel) ($\mathrm{N_{tech}}$), the working time/vessel operation time (hours per day) ($\mathrm{Tw_{ves}}$), total working time (days) ($\mathrm{T_{wt}}$) and the rate/hour on vessel (£) ($\mathrm{R_{ves}}$). In the analysis, it is observed that all these parameters can vary depending on the wave farm attributes or circumstance.

Parameters such as the number of technicians (on board the vessel) and the total working time spent on repairing all the devices in the WEC farm can vary considering the WEC farm size or number of WEC devices.

Other parameters such as the O&M vessel operation time (hours per day) and the rate per hour on the vessel can be constant. The reason is that the vessel is initially assumed to be in operation 24 hours per day. Studies (Alizadeh and Talley, 2011) acknowledged that the rate per hour on the vessel is always a fixed negotiated cost. Therefore, the labour cost ($\mathrm{C_{lab}}$) is assessed by multiplying the number of technicians together with the total working time per day, the estimated maintenance time and the per hour labour rate.

Therefore, given that the total working time spent on repairing the WEC or performing the onsite preventive maintenance on a single device at the WEC farm is 244.46 hours (approximately 10 days), number of technicians required on board the vessel is 4, the working time/vessel operation time is 24 hours per day and the rate/hour on vessel is £50. Assuming the technicians are being paid to work for 8 hours in 1 day, the labour cost is estimated according to Equation 115 as shown:

$$\mathrm{C_{lab}} = \mathrm{N_{tech}} \times \mathrm{Tw_{ves}} \times \mathrm{T_{wt}} \times \mathrm{R_{ves}}$$

$$\mathrm{C_{lab}} = 4 \times 8 \times \left(\frac{244.46}{24}\right) \times 50 = £16{,}297.$$

In addition to the labour cost, the workshop cost is also analysed, and this is relevant in the case when the preventive maintenance activities in Scenario 1 is required to be performed onshore. In that case, the relevant parameters for calculating the workshop cost ($\mathrm{C_{work}}$) are: the workshop labour cost ($\mathrm{Cw_{lab}}$) and spare parts cost ($\mathrm{C_{sp}}$). This process involves first calculating the workshop labour cost and then the cost of spare parts needed. The calculation of the workshop labour cost is similar to the onsite labour cost because it employs similar parameters.

For example, given that the number of technicians required at the workshop is 4 (minimum), the workshop working/operation time is 24 hours per day. Following Table 6, the total man hours of repair (i.e. time spent on repairing the WEC or performing the preventive maintenance on a single device at the workshop onshore is 130 hours. Given that the workshop labour rate/hour is £50, the workshop labour cost ($\mathrm{Cw_{lab}}$) is estimated according to Equation 117 as:

$$\mathrm{Cw_{lab}} = \mathrm{N_{tech}} \times \mathrm{T_w} \times \mathrm{T_{wt}} \times \mathrm{R_w}$$

$$\mathrm{Cw_{lab}} = 4 \times 8 \times (\frac{130}{24}) \times 50 = £8{,}666.$$

Studies (Teillant et al., 2012) mentioned that the components of the WEC that require onshore maintenance at the workshop may include: the hull structure, the bearing pads and motor. The cost of these components spare parts is adapted from existing literature and used to illustrate the calculation of the cost of spare parts needed in Scenario 1. Therefore, following Table 6, given that the cost of spare for the hull structure is £50,000, the cost of 12 bearings is 2000, and the cost of motor is £25,000, the workshop spare parts cost ($\mathrm{C_{sp}}$) is calculated according to Equation 118 as shown:

$$C_{sp} = \sum_{n}^{i=1} \mathrm{C_{sp_i}} = \mathrm{C_{sp_1}} + \ \mathrm{C_{sp_2}} + \cdots \mathrm{C_{sp_n}}$$

$$C_{sp} = 50000 + 2000 + 25000 = £77{,}000$$

Having calculated the workshop labour cost and the spare part cost, the total workshop cost can be assessed as the sum of the workshop labour cost and the cumulative spare parts cost of each spare part used in the workshop for the onshore repair of the WEC device in Scenario 1. This is calculated according to Equation 116 as shown:

$$\mathrm{C_{work}} = \mathrm{Cw_{lab}} + \mathrm{C_{sp}}$$

$$\mathrm{C_{work}} = 8{,}666 + 77{,}000 = £85{,}666.$$

Furthermore, the cost of the equipment and tools ($\mathrm{C_{eq}}$) required for the maintenance is also examined to complete the analysis for the O&M cost estimate in Scenario 1. The method requires that the cost of using the ROVs is initially analysed before calculating the equipment cost. However, the cost of using the ROVs depend on parameters such as the rate per day for ROV, the contingency factor for not using ROV due to weather conditions and the time ROV is working. In this case, given that the working time for the inspection ROV 1 is 244.46 hours, equal to vessel operation time which is approximately 10 days. The contingency factor for not using ROV 1 due to weather conditions is given as 20% and the rate per day for ROV 1 is £2000. The cost for employing ROV 1 is calculated according to Equation 120 as shown:

$$\mathrm{C_{rov_1} = T_{rov_1} \times (1 + f_{rov_1}) \times\ R_{rov_1}}$$

$$\mathrm{C_{rov_1}} = 10 \times (1 + 0.2) \times 2000 = £24{,}000$$

Similarly, given that the time for the working ROV 2 is 244.46 hours, equal to vessel operation time. The contingency factor for not using ROV 2 due to weather conditions is given as 20% and the rate per day for ROV 2 is £5000. The cost for employing the working ROV 2 is calculated according to Equation 121 as shown:

$$\mathrm{C_{rov_2} = T_{rov_2} \times (1 + f_{rov_2}) \times\ R_{rov_2}}$$

$$\mathrm{C_{rov_2}} = 10 \times (1 + 0.2) \times 5000 = £60{,}000$$

The equipment cost is a function of the cost for using ROV 1-inspection ROV ($\mathrm{C_{rov_1}}$), the cost for using ROV 2-working ROV ($\mathrm{C_{rov_2}}$) and any other equipment cost including tools ($\mathrm{C_{other}}$). Therefore, given that the $\mathrm{C_{rov_1}}$ is £24,000; $\mathrm{C_{rov_2}}$ is £60,000 and $\mathrm{C_{other}}$ is £32,500, the total equipment cost ($\mathrm{C_{eq}}$) is estimated according to Equation 119 as shown:

$$\mathrm{C_{eq} = C_{rov_1} + C_{rov_2} + C_{other}}$$

$$\mathrm{C_{eq}} = 24{,}000 + 60{,}000 + 32{,}500 = £116{,}500/\text{Inspection}$$

The different cost components that contribute to the preventive maintenance cost for a single WEC device in Scenario 1 have been illustrated and discussed. This is achieved by examining the wave farm attributes and O&M specific cost attributes. This includes the transport cost, being the total cost for chartering a O&M vessel for the estimated duration of 10 days. The total cost of labour, workshop and equipment cost as described in Chapter 3 methodology and modelling. Therefore, in the case of employing Small Vessel 1 in Scenario 1, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 106{,}909 + 16{,}297 + 85{,}666 + 116{,}500 = \pounds 325{,}372.$$

$C_{pm} = \pounds 325{,}372$, for employing Small Vessel 1 for a duration of 10 days in a project year.

Similarly, in the case of employing Big Vessel 2 in Scenario 1, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 286{,}636 + 16{,}297 + 85{,}666 + 116{,}500 = \pounds 505{,}100.$$

$C_{pm} = \pounds 505{,}100$, for employing Big Vessel 2 for a period of 10 days in a project year.

Figure 97 demonstrates the results for the cost of preventive maintenance for a single WEC employing either Small Vessel 1 or Big Vessel 2 for a period of 10 days in Scenario 1. The y-axis represents the O&M cost estimates and the x-axis represents the different cost components analysed. The blue bars depict the O&M cost estimates for the different cost component for Small Vessel 1 and the red bars depict O&M cost estimates for the different cost components for Big Vessel 2. The importance of presenting this result is to illustrate the cost components as they contribute to the variation in the O&M cost and the cost components that tend to contribute the most to the O&M cost estimates.

From the results of the analysis presented in Figure 97, the labour, workshop and equipment cost remain the same for either Small Vessel 1 or Big Vessel 2 employed to perform the maintenance activities for a duration of 10 days in Scenario 1. This shows that the cost of employing the Small Vessel 1 is not so prohibitive compared to the Big Vessel 2. In this case, the cost of employing Big Vessel 2 is almost equivalent to twice the workshop cost and equipment/tool cost. However, the workshop cost and equipment/tool cost are also major contributors to increase in O&M cost estimate in Scenario 1. Although, the cost of employing Big Vessel 2 is seen to be the most significant contributor to the O&M cost estimate because of the high daily charter rate. This is in comparison to the workshop and equipment/tool cost.

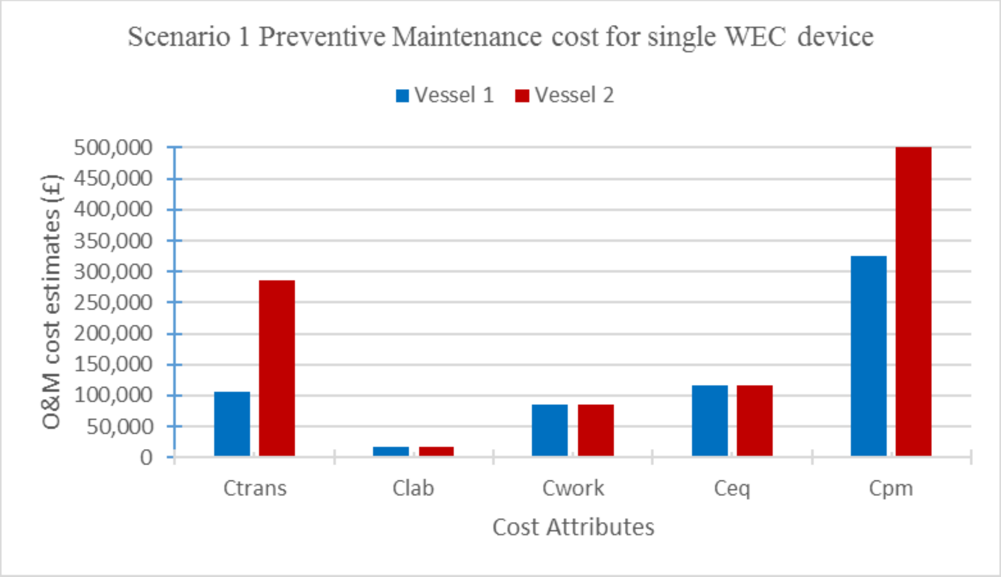

Figure 97: Scenario 1 Cost Preventive Maintenance (C_{pm}) for Single WEC per Project Year

It is noticed that the cost of spare parts can potentially be a significant contributor to increase in the O&M cost. However, it is observed that increase in transport, labour and equipment costs are dependent on the duration of the maintenance time. The workshop cost is dependent on both maintenance time and the cost of spare parts required. It is also noticed that the maintenance time is influenced by the hourly or daily rate of the different cost components examined. The type of equipment needed affects both the equipment cost and the transportation cost. Offshore onsite preventive maintenance requires vessels and the vessel operation cost is assessed by vessel charter rate, type, speed and offshore farm distance.

In the following pages results of the analysis for preventive maintenance cost for 60 WEC devices employing either Small Vessel 1 or Big Vessel 2 is illustrated in Scenario 2. In this case, Scenario 2 examines the O&M cost estimates for on-site (ordinary) and on-shore (overhaul) maintenance of 25% of the total number of WECs in the farm. This is relevant to illustrate the preventive maintenance cost (C_{pm}) employing either Small Vessel 1 or Big Vessel 2. For clarity Scenario 2 is divided into Scenario 2a, and Scenario 2b to demonstrates the results of the O&M cost estimates for the onsite servicing and onshore repair of 15 WECs in a WEC farm consisting of 60 WECs. The method involves analysing and comparing the influence of the O&M specific cost components on the array of WECs in Scenario 2.

In Scenario 2a it is assumed that two visits can be undertaken in a year for on-site (ordinary) maintenance activities. In this case, 15 WECs will be serviced on-site during each visit. For consistency the first step in the method is to estimate the transport cost. Thereafter the labour, workshop and equipment cost are analysed accordingly. In Scenario 2a, the first step is to examine the total time it takes the vessel to reach and return from the WEC farm (T_{wf1}) to perform the on-site maintenance activities for 15 WECs in scenario 2. The relevant parameters used to analyse the total transport cost have been explained in previous pages.

Given that the contingency factor for bad weather condition is 20%, the distance to the WEC farm is 100KM, the vessel speed to reach the WEC farm is 20 knots, the time it takes the vessel to reach and return from the WEC farm (T_{wf1}) was calculated according to Equation 108 as explained and shown in previous pages. In Scenario 2a, the case of ordinary/on-site maintenance the time it takes the vessel to reach and return from the WEC farm (T_{wf1}) is 25.92 hours per WEC multiplied by 15 WECs. This implies that the total time it takes the vessel to reach and return from the WEC farm (T_{wf1}) in Scenario 2a = 388.76hours.

In the case of Scenario 2b, the overhaul does not happen frequently. In this case, it is assumed that 1 overhaul will be undertaken every 5 years. In this respect, 15 WECs will be returned to the workshop on-shore. For clarity, it is assumed that the vessel carries 2 WEC to workshop per trip. This will entail 2 round trips per WEC according to Table 6. Similarly, in Scenario 2b the estimated time it takes the vessel to reach and return from the WEC farm (T_{wf1}) is 77.75 hours per WEC multiplied by 15 WECs. The total estimated time (T_{wf1}) in Scenario 2b =583.15 hours.

In Scenario 1, the time the vessel spends in the WEC farm (T_{wf2}) was calculated according to Equation 109 as explained and shown in previous pages. This was estimated as 55.84 hours per WEC. Therefore, in the case of ordinary/on-site maintenance of 15 WECs in Scenario 2a, (T_{wf2}) is multiplied by 15 WECs and given as 837.54 hours. In case of Scenario 2b, the time the vessel spends in the WEC farm (T_{wf2}) was calculated according to Equation 109 and given as 163.51 hours per WEC. Assuming the vessel returns 2 WECs per trip, (T_{wf2}) in Scenario 2b = 1,645.08 hours.

Figure 98 demonstrates the results for cost of preventive maintenance for 60 WECs employing either Small Vessel 1 or Big Vessel 2 for a duration of 53 days in Scenario 2a and 95 days in Scenario 2b. The y-axis represents the O&M cost estimates and the x-axis represents the different cost components. The blue bars depict the O&M cost estimates for the different cost component for Small Vessel 1 and the red bars depict O&M cost estimates for the different cost components for Big Vessel 2 in Scenario 2a. Similarly, the gray bars depict the O&M cost estimates for the different cost component for Small Vessel 1 and the gold bars depict O&M cost estimates for the different cost components for Big Vessel 2 in Scenario 2b.

The importance of this result is to investigate the influence of cost attributes on preventive maintenance cost estimates and possible areas where cost reduction can be achieved. In Figure 98, the cost of employing Small Vessel 1 is cheaper compared to Big Vessel 2 either in Scenario 2a or in Scenario 2b. The labour cost will increase as the number of technicians and working time increases. This will remain the same for either Small Vessel 1 or Big Vessel 2 employed in Scenario 2a or Scenario 2b. It is noticed that the workshop cost is a significant contributor to the increase in the O&M cost estimates. The reason is that it is a function of the number of technicians, and the cost of spare parts needed. But the cost of spare parts accounts for around 73% of the workshop cost.

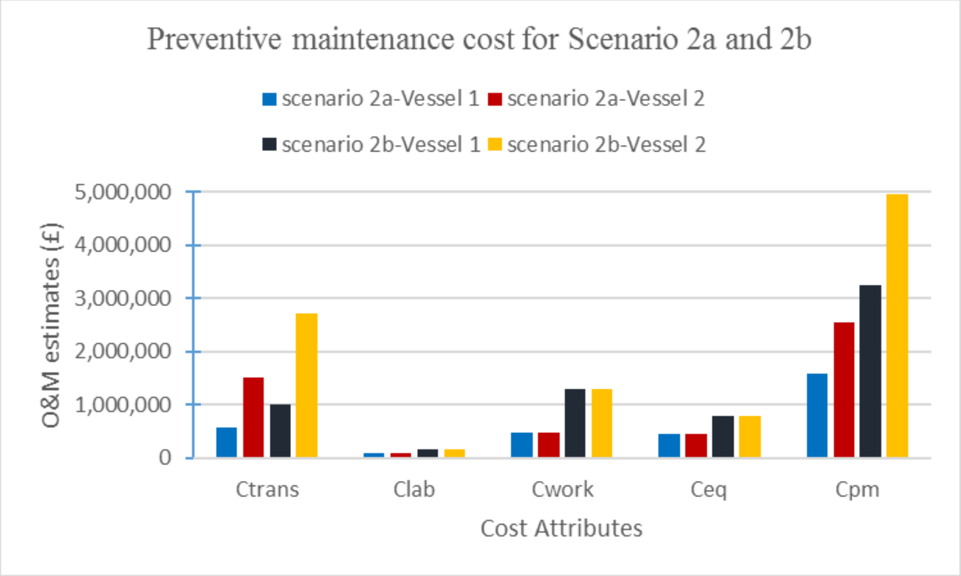

Figure 98: Preventive Maintenance Cost (C_{pm}) for Scenario 2a and 2b

In Scenario 2a and Scenario 2b, it can be observed that the O&M vessel transport cost accounts for the highest contribution to the variation in the O&M cost estimates. For example, the cost of employing Small Vessel 1 in Scenario 2a, accounts for approximately 36% of the O&M cost estimates. and In Scenario 2b, approximately 31% of the O&M cost estimates. In the case of employing Big Vessel 2, the O&M vessel transport cost accounts for approximately 60% of the O&M cost estimates in Scenario 2a; and approximately 55% in Scenario 2b.

The labour cost contributes the lowest to the total O&M cost estimates. This accounts for approximately 3 to 5% of the total O&M cost estimate. In this case the workshop cost accounts for around 25 to 40% of the total O&M cost in Scenario 2a and Scenario 2b. In the case of employing Small Vessel 1, the workshop cost accounts for approximately 30% of the total O&M cost estimate in Scenario 2a, while Scenario 2b the workshop cost accounts for around 39% of the total O&M cost estimate. The results show that there is a significant cost benefit for employing the Small Vessel 1.

As in Scenario 1 the results of the analysis showed that the labour, workshop and equipment cost remained the same either for Small Vessel 1 or Big Vessel 2 employed. As mentioned in previous pages, the labour, equipment and transportation costs are dependent on the required maintenance time. The same type of O&M vessel employed in Scenario 1 is used in the analysis of Scenario 2. This is to ensure consistency in the method of estimating the O&M cost and validity of the result presented. In Scenario 1 the initial charter time for the O&M vessel was estimated as 244.46 hours approximately 10 days.

The estimated initial charter time was influenced by the inspection time of 2 hours per device and time to detach/attach a single WEC calculated as 1.2 hours for the single WEC device. It is expected that more time will be needed to maintain 60 devices than for one device. Parameters such as time to the WEC farm and time spent in the WEC farm remain the same. This is because the distance to the WEC farm, distance in WEC farm and the vessel speed remain the same as in Scenario 1.

In addition, the time to detach the old WEC and attach the new WEC (T_{wf3}) was calculated according to Equation 110 as shown in previous pages. Given that the time to mobilise/demobilise ROV from the vessel (T_{rov}) is 0.5 hours per WEC, the time other than that required for ROV to bring WEC on board vessel (T_{other}) is 0.5 hours per WEC. In Scenario 2a, (T_{rov}) is multiplied by 15 WECs=7.5 hours. Similarly, time other than that required for ROV to bring WEC on board vessel (T_{other}) is multiplied by 15 WECs=7.5 hours. The time to detach/attach the WEC (T_{wf3}) is calculated according to Equation 110 as shown:

$$T_{wf3} = (T_{rov} + T_{other}) \times (1 + f_{ves})$$

$$T_{wf3} = (7.5 + 7.5) \times (1 + 0.2) = 18 \text{ hours.}$$

In Scenario 2, in the case of ordinary/on-site maintenance of 15 WECs in Scenario 2a, (T_{wf3}) =18 hours. Similarly, given that 15 WECs will be returned to the workshop, this implies that (T_{wf3}) in Scenario 2b =18 hours. In Scenario 2a and 2b, the difference compered to Scenario 1 is the inspection time and time required to detach/attach new WEC in place. The initial charter time is estimated based on an inspection time of 2 hours per WEC. In Scenario 2a, the inspection time is 30 hours for 15 WECs. Having calculated the time, it takes for the vessel to reach and return from the WEC farm, time the vessel spends in the WEC farm, and time to detach the old WEC and attach a new one in place, the time vessel is chartered is calculated according to Equation 107 as shown:

$$T_1 = T_{wf1} + T_{wf2} + T_{wf3} + T_{insp}$$

$$T_1 = 388.77 + 837.54 + 18 + 30 = 1{,}274.31 \text{ hours.}$$

Therefore, the total estimated time (T_1) that the vessel will be chartered for preventive maintenance of 15 WECs in Scenario 2a =1,274.31 hours, approximately 53 days. This is the initial estimated time that the vessel will be required to perform the on-site maintenance activities in Scenario 2a. Similarly, in Scenario 2b, the inspection time is 30 hours for 15 WECs. Having calculated the time, it takes for the vessel to reach and return from the WEC farm, time the vessel spends in the WEC farm, and time to detach the old WEC and attach a new one in place, the time vessel is chartered is calculated according to Equation 107 as shown:

$$T_1 = T_{wf1} + T_{wf2} + T_{wf3} + T_{insp}$$

$$T_1 = 583.15 + 1{,}645.07 + 18 + 30 = 2{,}276.23 \text{ hours.}$$

Therefore, the total estimated time (T_1) that the vessel will be chartered for preventive maintenance of 15 WECs in Scenario 2b =2,276.23 hours, approximately 95 days. This is the initial estimated time that the vessel will be required to perform the overhaul maintenance activities in Scenario 2b. Hence, the cost of fuel that will be needed is also analysed accordingly. As in Scenario 1, this must be examined before the cost of chartering the vessel can be assessed. To analyse the cost of fuel needed in Scenario 2a and 2b, parameters such as the vessel daily fuel consumption ($\mathrm{D_{fc}}$), the price of fuel ($\mathrm{Pr_{fuel}}$), number of main engines ($\mathrm{N_{main}}$) and the lube & diesel oil correction factor ($\mathrm{Oil_{corf}}$) remain the same as in Scenario 1.

The reason is that the same type of vessel and distance is considered. The difference is the number of days the vessel spends at sea ($\mathrm{D_{sea}}$). In contrast to the analysis in Scenario 1, the number of days the vessel spends at sea is taken as 53 days and 95 days for Scenario 2a and 2b respectively. The reason is that, the time that the vessel is assumed to be engaged is the estimated actual time that the vessel will be utilised for the maintenance in any specified time of the year. In the case of Small Vessel 1 in Scenario 2a, (C_f) is calculated according to Equation 111 as shown:

$$C_f = D_{fc} \times D_{sea} \times P_{fuel} \times N_{main} \times Oil_{corf}$$

$$C_f = 6.72 \times 53 \times 607 \times 1 \times 1.15 = £249{,}068.$$

In the case of Big vessel 2, the cost of fuel needed is estimated as shown:

$$C_f = 8.4 \times 53 \times 607 \times 1 \times 1.15 = £311{,}335.$$

Similarly, in the case of Small Vessel 1 in Scenario 2b, (C_f) is calculated according to Equation 111 as shown:

$$C_f = D_{fc} \times D_{sea} \times P_{fuel} \times N_{main} \times Oil_{corf}$$

$$C_f = 6.72 \times 95 \times 607 \times 1 \times 1.15 = £445{,}635.$$

In the case of Big vessel 2, the cost of fuel needed is estimated as shown:

$$C_f = 8.4 \times 95 \times 607 \times 1 \times 1.15 = £557{,}043.$$

Having calculated the parameters T_1 and C_f , as shown and given that the charter rate for the Small Vessel 1 is £5000. The vessel charter cost (C_{vc_1}) for Scenario 2a is calculated according to Equation 106 as shown:

$$C_{vc_1} = T_1 \ \times R_1 \ \times (1 + f_{ves}) + C_f$$

$$C_{vc_1} = 53 \times 5000 \times (1 + 0.2) + 249{,}068 = £567{,}068.$$

In Scenario 2a, total transport cost (C_{trans}) which is the total cost for hiring Small Vessel 1 excluding the cost of crew is given as: $C_{trans} = £567{,}068$, being the cost of employing the O&M vessel for duration of 53 days in a year. Similarly, using the same parameters and given that the charter rate for Big Vessel 2 is £19,000. The vessel charter cost (C_{vc_2}) is estimated according to Equation 106 as shown:

$$C_{vc_2} = T_1 \ \times R_1 \ \times (1 + f_{ves}) + C_f$$

$$C_{vc_2} = 53 \times 19000 \times (1 + 0.2) + 311{,}335 = £1{,}519{,}735.$$

Therefore, the total transport cost (C_{trans}) which is the total cost for hiring Big Vessel 2 excluding the cost of crew is given as: C_{trans} =£1,519,735, being the cost of employing the O&M vessel for duration of 53 days in a year. Furthermore, using the same parameters T_1 and C_f , as shown and given that the charter rate for the Small Vessel 1 is £5000. The vessel charter cost (C_{vc_1}) for Scenario 2b is calculated according to Equation 106 as shown:

$$C_{vc_1} = T_1 \ \times R_1 \ \times (1 + f_{ves}) + C_f$$

$$C_{vc_1} = 95 \times 5000 \times (1 + 0.2) + 445{,}635 = £1{,}015{,}635.$$

In Scenario 2b, total transport cost (C_{trans}) which is the total cost for hiring Small Vessel 1 excluding the cost of crew is given as: $C_{trans} = £1{,}015{,}635$, being the cost of employing the O&M vessel for duration of 95 days in a year. Similarly, using the same parameters and given that the charter rate for Big Vessel 2 is £19,000. The vessel charter cost (C_{vc_2}) is estimated according to Equation 106 as shown:

$$C_{vc_2} = T_1 \times R_1 \times (1 + f_{ves}) + C_f$$

$$C_{vc_2} = 95 \times 19000 \times (1 + 0.2) + 557{,}043 = £2{,}723{,}043.$$

Therefore, the total transport cost (C_{trans}) which is the total cost for hiring Big Vessel 2 excluding the cost of crew is given as: C_{trans} =£2,723,043, being the cost of employing the O&M vessel for duration of 95 days in a year. At the completion of step 1 to examine total transport cost in Scenario 2a and 2b, the results of the analysis in Scenario 2 confirms that the daily charter rate and duration for which the O&M vessel is hired to perform the maintenance activities directly contributes to significant increase in the cost of the O&M vessel transport. This situation remains true even for maintenance of 15 WECs in Scenario 2a and 2b.

Comparing the results of O&M vessel transport cost in Scenario 1, Scenario 2a and 2b, it is observed that the cost of employing Big Vessel 2 in Scenario 1 was high because of the high daily carter rate. In Scenario 2a and 2b, the transport cost is influenced by both the charter time and charter rate. Due to the increase in charter time, the cost of fuel also increased. Moreover, the daily fuel consumption remained the same, but the cost of fuel increased due to the number of days the vessel spends at sea. Parameters such as the number of main engines, oil correction factor and price of fuel were constant.

Figure 99 compares the result of the vessel transport cost in Scenario 1, Scenario 2a and Scenario 2b. Based on the analysis, it is observed that there is potential for significant reduction in the cost of transportation when the total cost per WEC is considered. In Figure 99 the blue bars depict transport cost for employing Small vessel 1 in the different Scenarios. The red bars the transport cost for employing Big vessel 2 in the different Scenarios. In this case, Scenario 1 represent the transport cost for employing either Small Vessel 1 or Big Vessel 2 for a duration of 10 days to perform the maintenance activities for a single WEC in the farm. In the result presented, it can be observed that the transport cost becomes reduced in Scenario 2a and Scenario 2 compared to scenario 1 when the total transport cost is divide by 15 WECs.

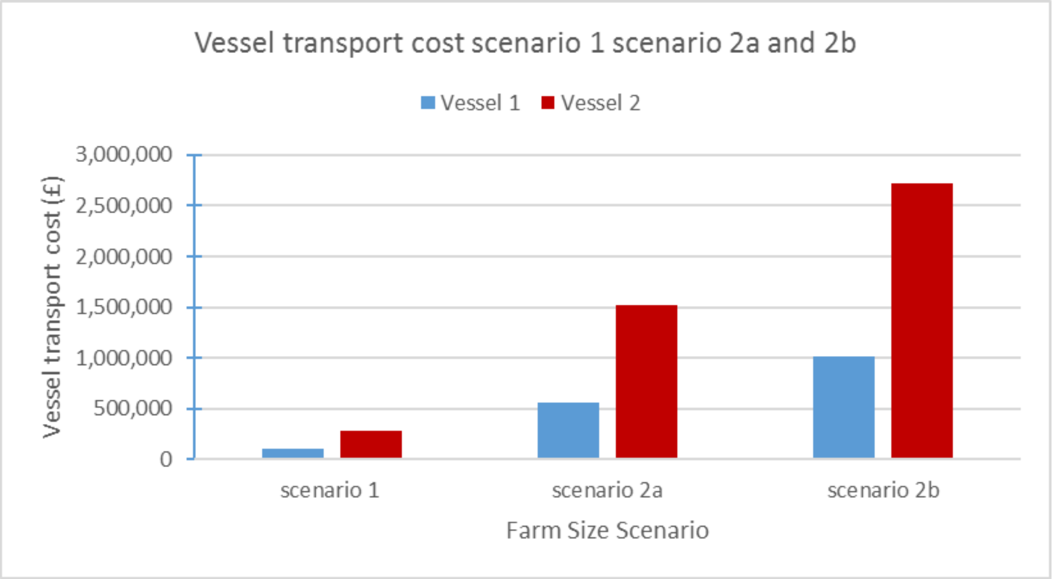

Figure 99: Comparison of vessel transport cost scenario 1, scenario 2a and 2b

In this respect, the transport cost for a single WEC employing Small Vessel 1 in Scenario 1 is estimated as £106,909. In Scenario 2a, the total transport cost for employing the Small Vessel 1 to perform the maintenance activities for a duration of 53 days is around £567,068. In the case of Scenario 2b, the total transport cost for employing the Small Vessel 1 is estimated as £1,015,635 for a duration of 95 days. When the total transport cost in either Scenario 2a or Scenario 2b is divided by the 15 WECs, the optimal transport cost per WECs becomes approximately £37,804 and £67,709 in Scenario 2a and Scenario 2b respectively.

Similarly, when the Big Vessel is considered as an alternative for transport, the total transport cost for a single WEC in Scenario 1 is estimated as £286,636. In Comparison to Scenario 2a and Scenario 2b, the total transport cost for employing the Big Vessel 2 is around £1,519,735 and £2,723,043 respectively. When the total transport cost in Scenario 2a and Scenario 2b is divided by 15 WECs, then the optimal transport cost per WEC becomes £101,315 and £181,536 respectively. This shows that despite the increased cost of transport there is the benefits for considering transport of multiple devices.

In addition to the transportation cost, the labour, workshop and equipment cost were examined to arrive at the total cost for the preventive maintenance in Scenario 2. As mentioned in the analysis of labour cost in Scenario 1, the relevant parameters include number of technicians (on board the vessel) ($\mathrm{N_{tech}}$), the working time/vessel operation time (hours per day) ($\mathrm{Tw_{ves}}$), total working time (days) ($\mathrm{T_{wt}}$) and the rate/hour on vessel ($\mathrm{R_{ves}}$). These parameters can vary depending on the wave farm attributes or circumstance. In Scenario 2 it is expected that more technicians will be required and the total working time for the preventive maintenance activities will increase due to the number of WECs in the farm.

In that case, the minimum number of 4 technicians are employed. In assessing the initial charter time for the vessel, the total working time varies depending on the number of days the vessel spends at sea. This is considered as the actual time the vessel is used to perform the maintenance activities on the WECs in the WEC farm. The vessel working time and the rate/hourly pay on board the vessel remains the same as in Scenario 1. The reason is because of the assumption that the vessel working time per day is 24 hours and the rate/hourly pay on board the vessel is a fixed negotiated amount.

In Scenario 2a, the total working time spent on repairing the WECs or performing the onsite preventive maintenance on 15 WECs at the WEC farm is 1,274.31 hours (approximately 53 days). The labour cost ($\mathrm{C_{lab}}$) is assessed by multiplying the number of technicians (4) together with the total working time (24/7), the estimated maintenance time for Scenario 2a, and the per hour labour rate (£50). Assuming the technicians are being paid to work for 8 hours in 1 day, the labour cost is estimated according to Equation 115 as shown:

$$\mathrm{C_{lab}} = \mathrm{N_{tech}} \times \mathrm{Tw_{ves}} \times \mathrm{T_{wt}} \times \mathrm{R_{ves}}$$

$$\mathrm{C_{lab}} = 4 \times 8 \times (\frac{1{,}274.31}{24}) \times 50 = £84{,}953.$$

In that case, the labour cost is estimated as £84,953, being the labour cost when 4 technicians are employed to perform the on-site maintenance activities in Scenario 2a. in the case of Scenario 2b,

$$\mathrm{C_{lab}} = 4 \times 8 \times (\frac{2{,}276.23}{24}) \times 50 = £151{,}748.$$

In that case, the labour cost is estimated as £151,748, being the labour cost when 4 technicians are employed to perform the overhaul maintenance activities in Scenario 2b. This completes the second step of analysing the labour cost. The third step is to examine the workshop cost ($\mathrm{C_{work}}$). In this case, the relevant parameters include the workshop labour cost ($\mathrm{Cw_{lab}}$) and spare parts cost ($\mathrm{C_{sp}}$). As in Scenario 1, the method involves first calculating the workshop labour cost and then the cost of spare parts needed. In the case of Scenario 2a, the workshop labour cost is zero (0). The reason is only on-site maintenance are performed in Scenario 2a.

Following Table 6, cost of spare for the on-site maintenance in Scenario 2a, include the cost of dynamic riser (£1000), the Mooring line (£2000) and the generic component (£2500) The workshop spare parts cost ($\mathrm{C_{sp}}$) for 15 WECs is calculated according to Equation 118 as shown:

$$C_{sp} = \sum_{n}^{i=1} \mathrm{C_{sp_i}} = \mathrm{C_{sp_1}} + \mathrm{C_{sp_2}} + \cdots \mathrm{C_{sp_n}}$$

$$C_{sp} = 150{,}000 + 300{,}000 + 37{,}500 = £487{,}500$$

The total workshop cost is estimated as the sum of the workshop labour cost and the cumulative spare parts cost of each spare part used for the on-site maintenance in Scenario 2a. This is calculated according to Equation 116 as shown:

$$\mathrm{C_{work}} = \mathrm{Cw_{lab}} + \mathrm{C_{sp}}$$

$$\mathrm{C_{work}} = 0 + 487{,}500 = £487{,}500.$$

In the case of Scenario 2b, the workshop labour cost is calculated following Table 6. In this case, the total man hours of repair (i.e. time spent on repairing the WEC or performing the preventive maintenance on a single device at the workshop on-shore is 130 hours. Assuming, the number of technicians required at the workshop is a minimum of 4 persons, the workshop working/operation time is 24 hours per day, the total working time is 1,950 hours and the workshop labour rate/hour is £50. Assuming the technicians are being paid to work for 8 hours per day, the workshop labour cost ($\mathrm{Cw_{lab}}$) is estimated according to Equation 117 as shown:

$$\mathrm{Cw_{lab}} = \mathrm{N_{tech}} \times \mathrm{T_w} \times \mathrm{T_{wt}} \times \mathrm{R_w}$$

$$\mathrm{Cw_{lab}} = 4 \times 8 \times (\frac{1{,}950}{24}) \times 50 = £130{,}000$$

In Scenario 2b, the WEC components that require maintenance at the workshop may include: the hull structure, the bearing pads and motor (Teillant et al., 2012). In this case, the cost of each spare part used is multiplied by 15. Following Table 6, given that the cost of spare for the hull structure is £50,000, the cost of spare bearing pad is £2000, and the cost of the spare motor is £25,000. The workshop spare parts cost ($\mathrm{C_{sp}}$) is calculated according to Equation 118 as shown:

$$C_{sp} = \sum_{n}^{i=1} \mathrm{C_{sp_i}} = \mathrm{C_{sp_1}} + \mathrm{C_{sp_2}} + \cdots \mathrm{C_{sp_n}}$$

$$C_{sp} = 750{,}000 + 30{,}000 + 375{,}000 = £1{,}155{,}000$$

Having calculated the workshop labour cost and spare part cost for 15 WECs in Scenario 2b, the total workshop cost is estimated as the sum of the workshop labour cost and the cumulative cost of spare parts considering each spare part used for the WEC device calculated according to Equation 116 as shown:

$$\mathrm{C_{work}} = \mathrm{Cw_{lab}} + \mathrm{C_{sp}}$$

$$\mathrm{C_{work}} = £130{,}000 + £1{,}155{,}000 = £1{,}285{,}000$$

To complete the analysis for the O&M cost estimate in Scenario 2a, and 2b, the final step is calculating the cost of the equipment and tools ($\mathrm{C_{eq}}$) required for the maintenance activities. As in Scenario 1, the method requires that the cost of employing the ROVs is initially calculated. In this case the parameter that changed is the time ROV is working, equal to vessel operation time (days /year). Parameters such as the rate per day for ROV and the contingency factor for not using ROV due to weather conditions remained the same as in Scenario 1.

In Scenario 2a, given that the working time for the inspection ROV 1 is 1,274.31 hours, equal to vessel operation time which is approximately 53 days. The contingency factor for not using ROV 1 due to weather conditions is given as 20% and the rate per day for ROV 1 is £2000. The cost for employing ROV 1 is calculated according to Equation 120 as shown:

$$\mathrm{C_{rov_1}} = \mathrm{T_{rov_1}} \times (1 + \mathrm{f_{rov_1}}) \times \ \mathrm{R_{rov_1}}$$

$$\mathrm{C_{rov_1}} = 53 \times (1 + 0.2) \times 2000 = £127{,}200$$

Similarly, given that the time for the working ROV 2 is 1,274.31 hours, equal to vessel operation time. The contingency factor for not using ROV 2 due to weather conditions is given as 20% and the rate per day for ROV 2 is £5000. The cost for employing the working ROV 2 is calculated according to Equation 121 as shown:

$$\mathrm{C_{rov_2}} = \mathrm{T_{rov_2}} \times (1 + \mathrm{f_{rov_2}}) \times \ \mathrm{R_{rov_2}}$$

$$\mathrm{C_{rov_2}} = 53 \times (1 + 0.2) \times 5000 = £318{,}000$$

The equipment cost is a function of the cost for using ROV 1-inspection ROV ($\mathrm{C_{rov_1}}$), the cost for using ROV 2-working ROV ($\mathrm{C_{rov_2}}$) and any other equipment cost including tools ($\mathrm{C_{other}}$). Therefore, given that the $\mathrm{C_{rov_1}}$ is £127,200; $\mathrm{C_{rov_2}}$ is £318,000 and $\mathrm{C_{other}}$ is £0, the total equipment cost ($\mathrm{C_{eq}}$) is estimated according to Equation 119 as shown:

$$\mathrm{C_{eq}} = \mathrm{C_{rov_1}} + \mathrm{C_{rov_2}} + \mathrm{C_{other}}$$

$$\mathrm{C_{eq}} = 127{,}200 + 318{,}000 + 0 = £445{,}200\text{/Inspection.}$$

In scenario 2b, given that the working time for the inspection ROV 1 is 2,276.23 hours, equal to vessel operation time which is approximately 95 days. The contingency factor for not using ROV 1 due to weather conditions is given as 20% and the rate per day for ROV 1 is £2000. The cost for employing ROV 1 is calculated according to Equation 120 as shown:

$$\mathrm{C_{rov_1}} = \mathrm{T_{rov_1}} \times (1 + \mathrm{f_{rov_1}}) \times \ \mathrm{R_{rov_1}}$$

$$\mathrm{C}_{\mathrm{rov}_1} = 95 \times (1 + 0.2) \times 2000 = £228{,}000$$

Similarly, given that the time for the working ROV 2 is 2,276.23 hours, equal to vessel operation time. The contingency factor for not using ROV 2 due to weather conditions is given as 20% and the rate per day for ROV 2 is £5000. The cost for employing the working ROV 2 is calculated according to Equation 121 as shown:

$$\mathrm{C}_{\mathrm{rov}_2} = \mathrm{T}_{\mathrm{rov}_2} \times (1 + \mathrm{f}_{\mathrm{rov}_2}) \times \ \mathrm{R}_{\mathrm{rov}_2}$$

$$\mathrm{C}_{\mathrm{rov}_2} = 95 \times (1 + 0.2) \times 5000 = £570{,}000$$

In scenario 2b, given that the $\mathrm{C}_{\mathrm{rov}_1}$ is £228,000; $\mathrm{C}_{\mathrm{rov}_2}$ is £570,000 and $\mathrm{C}_{\mathrm{other}}$ is £0, the total equipment cost (C_{eq}) is estimated according to Equation 119 as shown:

$$\mathrm{C}_{\mathrm{eq}} = \mathrm{C}_{\mathrm{rov}_1} + \mathrm{C}_{\mathrm{rov}_2} + \mathrm{C}_{\mathrm{other}}$$

$$\mathrm{C}_{\mathrm{eq}} = 228{,}000 + 570{,}000 + 0 = £798{,}000\text{/Inspection.}$$

The different cost components that contribute to the preventive maintenance cost for 60 WEC devices in Scenario 2 have been examined. This is achieved by analysing the wave farm attributes and O&M specific cost attributes. This includes the transport cost, being the total cost for chartering a O&M vessel for the actual maintenance duration of 53 days and 95 days in Scenario 2a and Scenario 2b respectively. Also, the total cost of labour, workshop and equipment/tools cost have been examined. Therefore, in the case of employing the Small Vessel 1 for a duration of 53 days in Scenario 2a, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 567{,}068 + 84{,}953 + 487{,}500 + 445{,}200 = £1{,}584{,}722$$

$C_{pm} = £1{,}584{,}722$ for employing Small Vessel 1 for a duration of 53 days in a project year.

Similarly, in the case of employing the Big Vessel 2 in Scenario 2a, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 1{,}519{,}735 + 84{,}953 + 487{,}500 + 445{,}200 = £2{,}537{,}389.$$

$C_{pm} = £2{,}537{,}389$, for using Big Vessel 2 for a duration of 53 days in a project year.

Furthermore, employing the Small Vessel 1 for a duration of 95 days in Scenario 2b, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 1{,}015{,}635 + 151{,}748 + 1{,}285{,}000 + 798{,}000 = £3{,}250{,}383$$

$C_{pm} = £3{,}250{,}383$ for employing Small Vessel 1 for a duration of 95 days in a project year.

In addition, employing the Big Vessel 2 in Scenario 2b, the total preventive maintenance cost (C_{pm}) is calculated according to Equation 99 as shown:

$$C_{pm} = C_{trans} + C_{lab} + C_{work} + C_{eq}$$

$$= 2{,}723{,}043 + 1{,}285{,}000 + 798{,}000 = £4{,}957{,}792.$$

$C_{pm} = £4{,}957{,}792$, for using Big Vessel 2 for a duration of 53 days in a project year.

There is potential for cost reduction when the maintenance of multiple devices is considered for either employing Small Vessel 1 or the Big Vessel 2. But the cost of employing Big Vessel 2 remains significantly high due to the charter rate of the Big Vessel 2. Hence, for offshore onsite preventive maintenance requiring vessels a small vessel with low charter rate is preferable to reduce the vessel operation cost. In Figure 100 results of Scenario 2a and Scenario

2b are compared with that of Scenario 1 to illustrate the variation in the O&M cost estimates and potential for cost reduction in the cost of preventive maintenance in the scenarios.

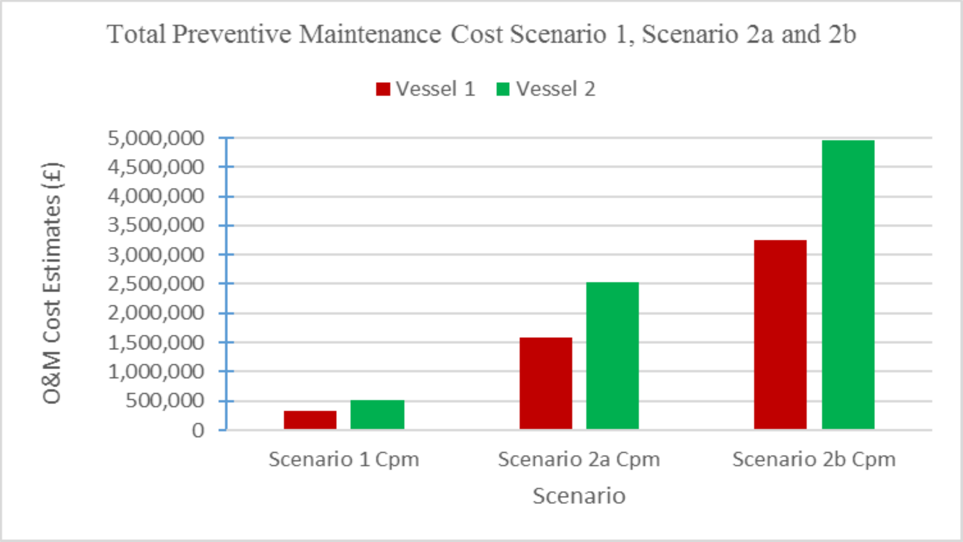

Figure 100: Comparison of The Total Preventive Maintenance Cost for Scenario 1, Scenario 2a and 2b.

In Figure 100 and Figure 101, the red bar depicts the total preventive maintenance cost for employing Small Vessel 1 in Scenario 1, Scenario 2a and Scenario 2b. The green bars depict the total preventive maintenance cost for employing Big Vessel.2. In the case of employing Small Vessel 1 in Scenario 1, it is observed that the actual preventive maintenance cost C_{pm}=£325,373 per WEC, can potentially be reduced to £105,648 per WEC in Scenario 2a, and £216,692 per WEC in Scenario 2b, if the total maintenance cost in Scenario 2a, or Scenario 2b is divided by 15 WECs as demonstrated in Figure 101.

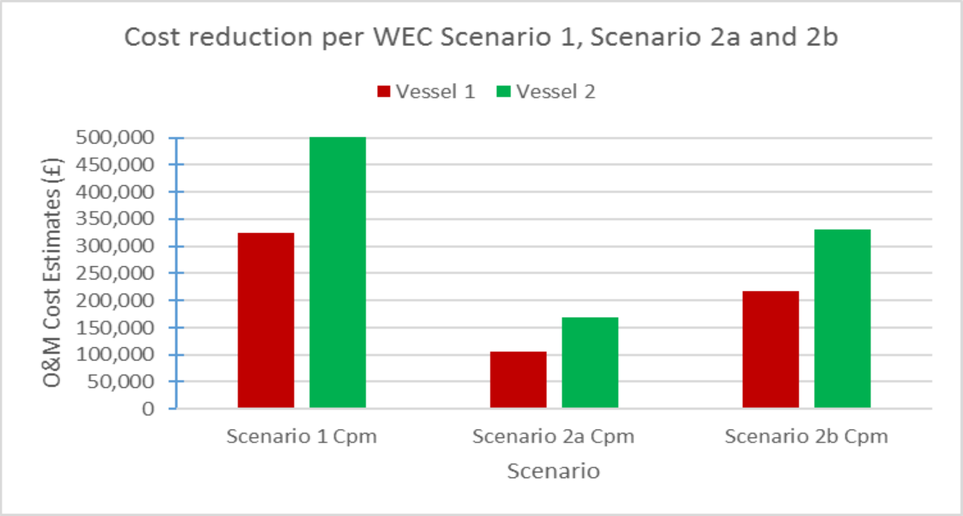

Figure 101: Cost reduction per WEC Scenario 1, Scenario 2a and 2b

Similarly, if Big Vessel 2 is employed the maintenance cost of a single WEC is actually C_{pm}= £505,100 per WEC depicted by the green bar in Scenario 1. This cost can potentially be reduced to £169,159 per WEC in Scenario 2a and £330,519 per WEC in Scenario 2b as depicted with the green bar in Figure 101. This becomes the optimal cost when the total cost of preventive maintenance in Scenario 2a and Scenario 2b in Figure 100 is divided by 15 WECs as illustrated in Figure 101.

It could be observed that despite the additional cost either in terms of employing Big Vessel 2 with daily charter rate of £19000 or increase in the cost of labour because of increase in the total working time, there is an added advantage in terms of cost reduction when maintenance of 60 WECs is considered against maintenance of a single WEC device in a WEC farm. It is suggested that the preventive maintenance for minor repairs including various tasks that can easily be performed on site be performed employing Small Vessel 1. In the next section results of the analysis and O&M cost estimates for the corrective maintenance cost for a single WEC and multiple WECs in a WEC farm is presented.

6.2.2 O&M Costs for Corrective Maintenance Actions

In this section, the results of O&M cost estimates for corrective (unscheduled) maintenance activities is presented. The O&M strategy identifies the type of maintenance activity that is performed. In the corrective maintenance strategy breakdown events are assumed to occur randomly. Generally, the failure rate parameters are defined based on the specific turbine components shown in the FMEA table and the likelihood or frequency rates of failure is shown. Depending on the level of the nature and the availability of both the repair equipment and technicians the recovery time can be adjusted (Teillant et al., 2012).

A vessel will be required to perform the onsite corrective maintenance activities as well as for towing the device to the workshop onshore. As in the preventive maintenance model discussed in previous pages, the expenses associated with every maintenance operation are assessed through the estimation of hourly rates, the cost of parts and the cost of vessel hire per activity. Therefore, the operational expenses associated with either the on-site or on-shore repairs are assessed through estimating the cost of parts, man hours of repair and the cost of vessel hire.

The parameters for analysing the corrective maintenance cost are typically the same as the parameters for analysing the preventive maintenance cost. The main difference in the corrective maintenance model is the additional cost factor for hiring the O&M vessel in the case of the unplanned event. It is expected that the cost of hiring the O&M vessel on short notice to perform the corrective maintenance activities can be higher than the normal cost. In most cases, the O&M vessel charter rate increases up to 50% of the normal charter rate. Results of the O&M cost estimates for corrective maintenance is illustrated in Scenario 3 and Scenario 4.

In this context, in Scenario 3 and Scenario 4 provide the summary of the maintenance cost for each cost components. In Scenario 3 the corrective maintenance cost ($\mathrm{C_{cm}}$) for a Single WEC employing either Small Vessel 1 or Big Vessel 2 are examined. As in the analysis of Scenario 1, input of the wave farm attributes and O&M specific cost attributes are applied to perform the analysis. The method follows a similar process and the first step is to evaluate the total transport cost (C_{trans}). This is the cost of hiring the vessel to perform the corrective maintenance operation in Scenario 3.

To ensure consistency in the method and validity of the results, the charter rate and same types of O&M vessels used in the analysis of previous examples is used in Scenario 3. To estimate the charter cost (C_{vc_1}) for either the Small Vessel 1 or Big Vessel 2, the relevant parameters include the initial charter time (T_1), the O&M vessel charter rate (R_1), the vessel contingency factor and daily cost of fuel. As in Scenario 1, (T_1) is a function of four other parameters such as time for the vessel to reach the WEC farm ($\mathrm{T_{wf1}}$), time the vessel spends in WEC farm ($\mathrm{T_{wf2}}$), time to detach/attach one WEC ($\mathrm{T_{wf3}}$) and the inspection time per WEC ($\mathrm{T_{insp}}$).

A detailed explanation of the step by step procedure on how these parameters are calculated is shown in the analysis of Scenario I presented in previous pages. The same procedure is applicable to calculate the transport cost in Scenario 3. Given that the contingency factor for bad weather conditions, distance to the WEC farm, vessel speed to and from the WEC farm are the same as in Scenario 1; the time it takes the vessel to reach and return from the WEC farm (T_{wf1}) = 77.75 hours. Also, time vessel spends in the WEC farm (T_{wf2}) = 163.51 hours. In addition, time to detach the old WEC and attach the new WEC (T_wf3) in place is 1.2 hours.

An inspection time of 2 hours per device is applied to illustrate this example calculation and the time vessel is chartered for Scenario 3 is 244.46 hours, approximately 10 days. All other parameters for estimating the fuel cost remain the same as in Scenario 1. The main difference in Scenario 3 compared to Scenario 1 is the additional cost factor (f_{rate}) of 50% in the normal charter rate. Since the parameters T_1 and C_f , have been calculated and given that the charter rate for the Small Vessel 1 is £5000. The vessel charter cost (C_{vc_1}) is estimated according to Equation 106 as shown:

$$C_{vc_1} = T_1 \ \times R_1 \ \times (1 + f_{rate}) \times (1 + f_{ves}) + C_f$$

$$= 10 \times 5000 \times (1 + 0.5) \times (1 + 0.2) + 46{,}908 = £136{,}908.96 \text{ for 10 days in a year}$$

As mentioned in the analysis of Scenario 1, the vessel crew cost is estimated based on the cumulative crew cost of each crew member employed on board the vessel. The crew cost for Small Vessel 1 and Big Vessel 2 remain the same as in the analysis of Scenario 1 and scenario 2. Therefore, the cost of crew employed on board the Small vessel 1 is £48,000. Thus, the total transport cost (C_{trans}) which is the total cost for hiring Small Vessel 1 excluding the cost of crew is given as: C_{trans} = £136,908.96, for 10 days in a year. Similarly, given that the charter rate for the Big Vessel 2 is £19,000. The vessel charter cost (C_{vc_2}) is estimated according to Equation 106 as shown:

$$C_{vc_2} = T_1 \ \times R_1 \ \times (1 + f_{rate}) \times (1 + f_{ves}) + C_f$$

$$= 10 \times 19000 \times (1 + 0.5) \times (1 + 0.2) + 58{,}636 = £371{,}318 \text{ for 10 days in a year.}$$

In addition, the annual crew cost for the Big Vessel 2 is £97,000. Therefore, the total transport cost (C_{trans}) which is the total cost for hiring Big Vessel 2 excluding the cost of crew is given as: $C_{trans} == £371{,}318$ for 10 days in a year. Figure 102 demonstrate the results of the O&M vessel transport cost by comparing the total transport cost in scenario 3 to the total transport cost in scenario 1. The blue bars depict the cost of employing Small Vessel 1, while the red bars depict the cost of hiring Big Vessel 2.

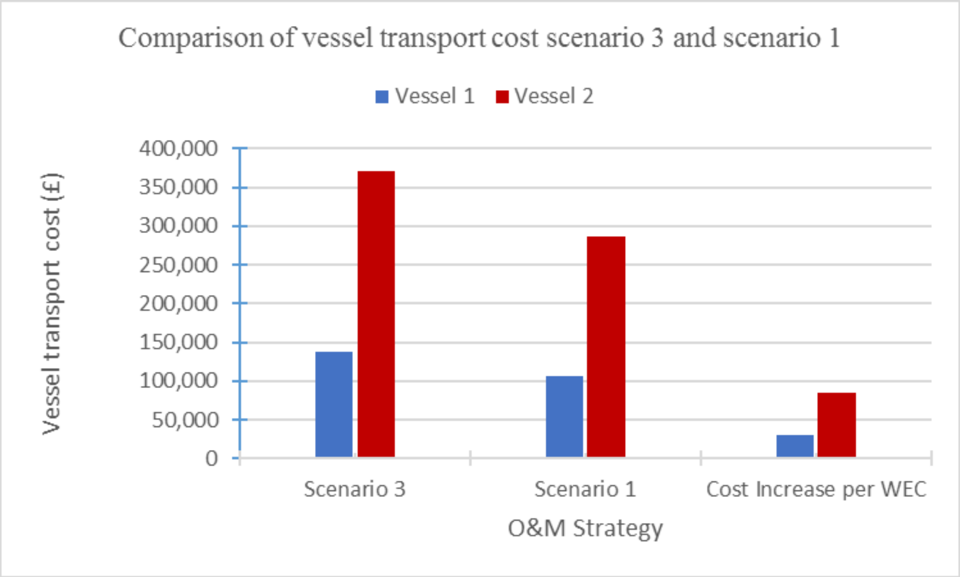

Figure 102: Comparison of transport cost based on O&M Strategy

In Figure 102 Scenario 3 is compared to Scenario 1 because there is a decision to make in the choice of employing the Big Vessel 2 and to spend the additional cost in terms of the O&M strategy. Moreover, both scenarios refer to the maintenance of a single WEC device and the difference is the choice of the O&M strategy. The corrective maintenance model demonstrates the influence of the additional cost factor on the on the variation of total O&M cost estimate. In Scenario 3, total transport cost for Small Vessel 1 is estimated as C_{trans}= £136,909 and in Scenario 1, total transport cost is estimated as C_{trans}= £106,909 for Small Vessel 1.

Comparing by O&M strategy illustrated in Figure 102, the results show an additional cost depicted by the blue bar for cost increase around £30,000 in the case of employing Small Vessel 1 for the duration of 10 days to perform the O&M activities for corrective maintenance of a single WEC device. If due to bad weather conditions or the limiting significant wave height threshold does not permit the use of small vessels, there is the decision to either wait until the weather conditions are suitable or to employ the big vessel to perform the O&M activities. In that case, there is an additional cost of around £84,682 depicted by the red bar for cost increase. This is attributed to the cost of employing Big Vessel 2 in Scenario 3.

In this respect, the results demonstrate that the cost of employing Big Vessel 2 in either Scenario 1 or Scenario 3 is expensive. This is particularly true for the maintenance of a single WEC irrespective of the O&M strategy. These results suggest that the O&M vessel transport cost will have a significant effect on the total O&M cost estimates. The influence is greater when considering the choice of employing the Big Vessel 2. It is shown that the high daily carter rate is the main cause of the high cost attributed to the O&M vessel transport.

The increased cost in Scenario 3 is due to the contingency factor for the cost of the O&M vessel hired on short notice for the unplanned maintenance operation. This is valid because all other parameters used in estimating the O&M transport cost in Scenario 1 for a single WEC remained the same as in the case of Scenario 3. To arrive at the total cost of the corrective maintenance operation in Scenario 3, the labour, workshop and equipment cost must be analysed as in Scenario 1 and Scenario 2. Nevertheless, the procedure' for estimating the cost of the remaining cost attributes for the total corrective maintenance model is the same as in the preventive maintenance model.

Consequently, all the parameters that influence the cost of labour, workshop and equipment/tools cost are the same and can be varied depending on the circumstance. As mentioned earlier, these parameters include the number of technicians (on board the vessel) and the total working time spent for repairing all the devices in the WEC farm. Moreover, the vessel is assumed to be in operation 24 hours per day and the rate per hour on the vessel is a fixed negotiated amount. It has been demonstrated in Scenario 1 and Scenario 2 that labour, workshop and equipment/tool cost remain the same either for Small Vessel 1 or Big Vessel 2 employed to perform the maintenance activities.

Given the same total working time of 244.46 hours spent on repairing the single WEC device, the results of the labour, workshop and equipment/tool cost in Scenario 3 and Scenario 1 is compared. In this case the number of technicians working on board the vessel and the number of technicians at the workshop was kept at the minimum number of 4 to investigate the influence of the cost of labour (technician) cost on the O&M cost estimate. Figure 103 demonstrates the results for the analysis of labour, workshop and equipment/tools cost in Scenario 3 compared to Scenario 1.

The red bars represent the specific cost components of scenario 3; while the blue bars represent the specific cost components of Scenario 1. In scenario 1 4 technicians were employed and the labour cost was estimated as £16,297. In the case of corrective maintenance operation that need to be performed in the workshop, the estimate for workshop cost is inclusive of the workshop labour cost and the cumulative spare parts cost of each spare part used for maintenance of the

WEC. However, it is observed that the equipment /tool cost is the highest contributor to the variation in the O&M cost estimate in Scenario 1 and Scenario 3.

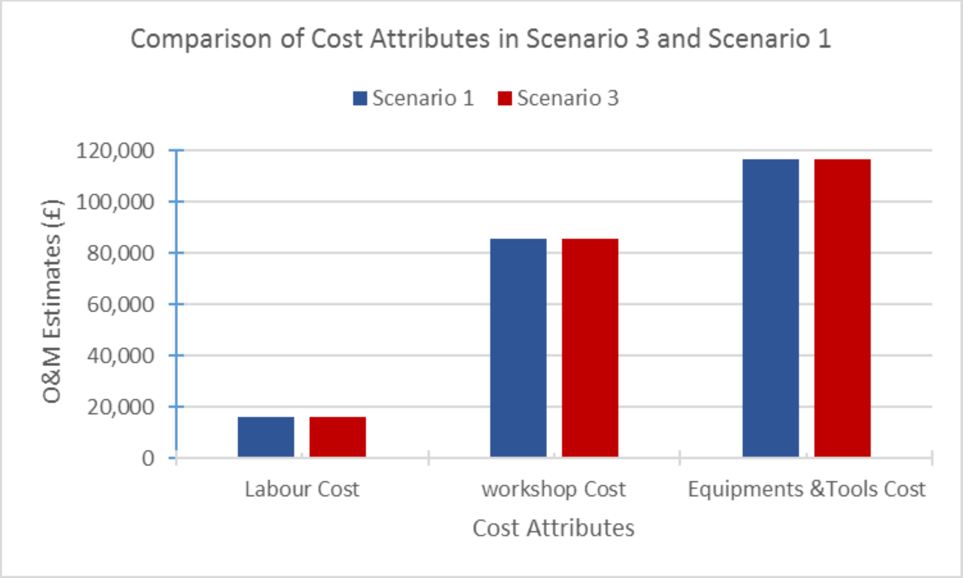

Figure 103: Comparison of Cost Attributes in Scenario 3 and Scenario 1

Figure 104 shows that the total cost of corrective maintenance in Scenario 3 is higher than the total cost of preventive maintenance in Scenario 1. In the case of employing Small Vessel 1 (depicted with the blue bars), corrective maintenance is estimated as: C_{cm} = £355,373, compared to Small Vessel 1 in Scenario 1 estimated as C_{pm}=£325,373. This is a difference of around £30,000 depicted by the blue bar on cost increase. The cost of the corrective maintenance in Scenario 3 remans higher because of the additional contingency factor in the transport cost. The result suggests that employing cheaper O&M vessels can play a significant role in the reduction of the total O&M cost estimate.

In the case of employing Big Vessel 2 in Scenario 3 (depicted with the red bars) the cost is estimated as: C_{cm}= £589,782, compared to Scenario 1 estimated as: C_{pm}=£505,100. It could be observed that there is an additional cost of approximately £84,682 depicted by the red bar in cost increase. This additional cost can be attributed to the additional contingency factor for transport cost in corrective maintenance model in Scenario 3. The cost of maintenance for a single WEC remains high if expensive vessels are employed and as such the influence of the transport cost can be greater even with the attempt to reduce other cost components.

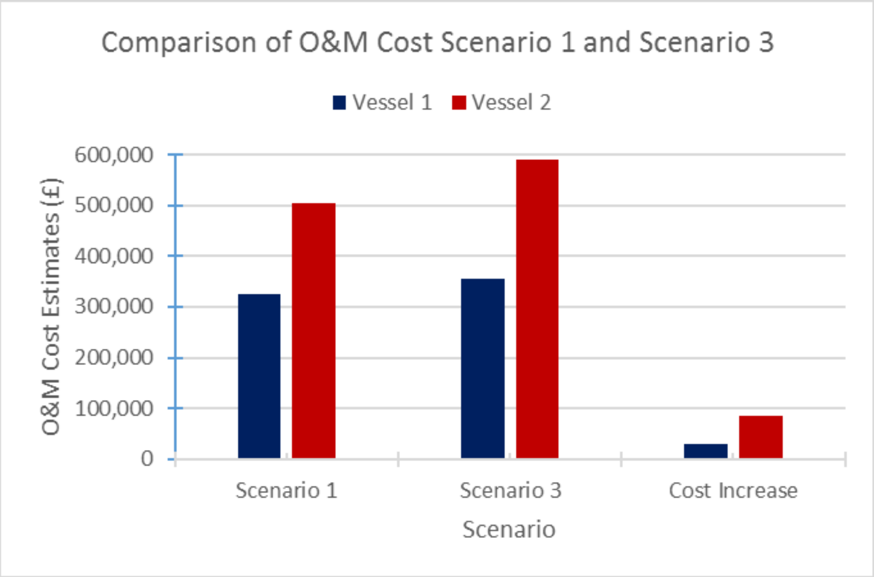

Figure 104: Comparison of O&M Cost Scenario 3 and Scenario 1

The maintenance activities involving a single WEC devices should be carefully considered. As observed in the literature there is wide variation in cost of using WEC technology for electricity power generation. However, the different cost components contributing to the corrective maintenance model for a single WEC device have been investigated in scenario 3. The issue of variation in the O&M cost can be attributed, in this case to the decision or O&M strategy of employing O&M vessel for maintenance of a single WEC. In the following section, results of the analysis and O&M cost estimates for the corrective maintenance cost for 60 WEC devices in a WEC farm is presented in Scenario 4.

Scenario 4 demonstrates the results for corrective maintenance (C_{cm}) O&M cost for repair or maintenance of 60 WECs employing either Small Vessel 1 or Big Vessel 2. It is relevant to further investigate the influence of the O&M specific cost attributes on an array of WECs because it is shown that the corrective maintenance for a single WEC device is high. In this case, Scenario 4 examines the O&M cost estimates for on-site (ordinary) and on-shore (overhaul) maintenance of 25% of the total number of WECs in the farm. For clarity Scenario 4 is divided into Scenario 4a, and Scenario 4b to demonstrates the results of the O&M cost estimates for the onsite servicing and onshore repair of 15 WECs in a WEC farm.

In addition, failures are certain to occur in the operational life of the WECs and there will be need for corrective maintenance. For consistency and to ensure validity of the result, the same type of O&M vessel considered in the previous analysis is used in the analysis of Scenario 4.

As discussed in previous analysis the first step is to examine the transport cost. A detailed analysis of the step by step procedure for estimating the transport cost and the variable parameters has been shown in previous pages. The procedure is the same for analysing the transport cost in Scenario 4.

As in the preceding analysis in Scenario 2, parameters such as the O&M vessel contingency factor for bad weather, the price of fuel, the daily fuel consumption and the number of days the vessel spends at sea remain the same. As discussed in Scenario 3 the difference between the preventive maintenance model and corrective maintenance model is the additional contingency cost factor of 50% added to the normal charter rate. In Scenario 4a it is assumed that two visits can be undertaken in a year for on-site (ordinary) corrective maintenance activities. In this case, 15 WECs will be serviced on-site during each visit.

In Scenario 4a, the actual time O&M vessel is chartered to perform the maintenance activities is estimated as 1274.31 hours, approximately 53 days. As discussed in Scenario 2a, the actual time is influenced by the inspection time given as 30 hours and the time needed to detach/attach 15 WECs estimated as 18 hours. In contrast to the analysis in Scenario 3 for the corrective maintenance of a single device, the time O&M vessel is chartered was determined as 244.46 hours approximately 10 days, with an inspection time of 2 hours and the time to attach/detach the WEC given as 1.2 hours.

As in Scenario 2b, the overhaul for corrective maintenance does not happen frequently in Scenario 4b. In this case, it is assumed that 1 overhaul will be undertaken every 5 years in the corrective maintenance model. In this respect, 15 WECs will be returned to the workshop on-shore. For clarity, it is assumed that the vessel carries 2 WEC to workshop per trip. This will entail 2 round trips per WEC according to Table 6. In Scenario 4b, the actual time O&M vessel is chartered to perform the maintenance activities is estimated as 2276.23 hours, approximately 95 days. The results of the O&M vessel transport cost in Scenario 4a, and Scenario 4b is demonstrated in Figure 105.

These results are compared with that obtained in Scenario 2a, and Scenario 2b for preventive maintenance of 15 WECs. The comparison is based on the farm size and O&M strategy. In Figure 105 the green bars depict the total transport cost for employing Small Vessel 1 to perform the maintenance activities for 60 WECs in Scenario 2 and Scenario 4. The red bars depict the total transport cost for employing the Big Vessel 2 to perform the same maintenance activities for 15 WECs in the different scenarios.

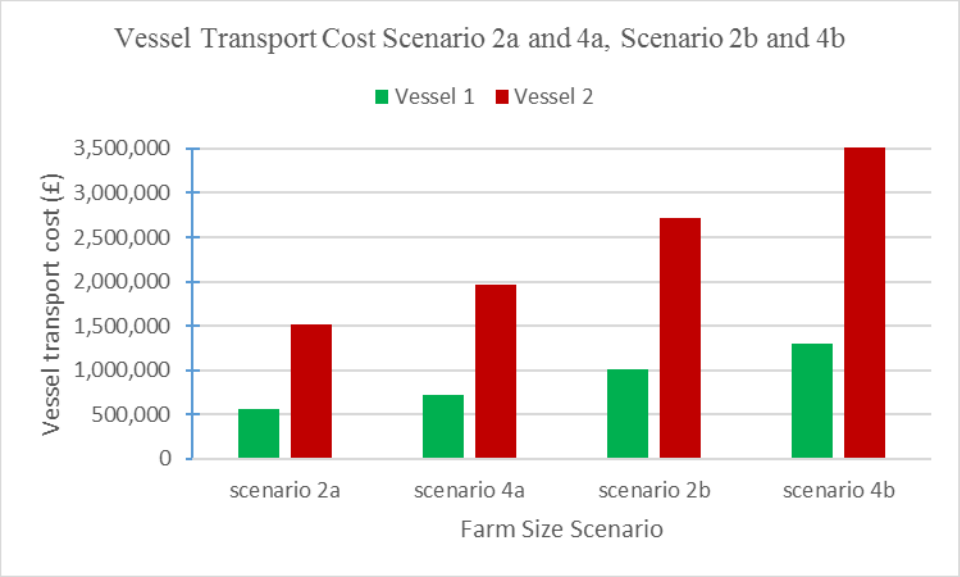

Figure 105: Comparison of Transport Cost Scenario 2a and 4a, Scenario 2b and 4b

In Scenario 4a, the results indicate that the transport cost for hiring Small Vessel 1 for a duration of 53 days is estimated as C_{trans}= £726,068. This cost is high when compared to result obtained in Scenario 2a estimated as C_{trans}=£567,068. This represents an additional cost of approximately £159,000. This additional cost is due to the cost contingency factor for hiring Small Vessel 1 in the corrective maintenance model. In the case of employing Big Vessel 2 in Scenario 4a, the total transport cost is estimated as C_{trans}= £1,968,268. Compared to C_{trans}= £1,519,735 obtained in Scenario 2a. This represents an additional increase of around £448,532.

This high cost is attributed to the higher daily charter rate of Big Vessel 2 and the added cost contingency factor in the Scenario 4a. Similarly, the transport cost for hiring Small Vessel 1 for a duration of 95 days in Scenario 4b, is estimated as C_{trans}= £1,300,635. This cost is high when compared to result obtained in Scenario 2b estimated as C_{trans}=£1,015,635.12. This represents an additional cost of approximately £285,000. In the case of employing Big Vessel 2 in Scenario 4b, the total transport cost is estimated as C_{trans}= £3,527,521. Compared to C_{trans}= £2,723,043 obtained in Scenario 2b. This represents an additional increase of around £804.478. The result of the O&M transport in Scenario 4 suggest that the corrective maintenance strategy contributes to high cost of transport for the WEC farm operations.

Furthermore, in Figure 105 it is observed that the additional cost increase in case of employing Big Vessel 2 in Scenario 4b is higher than the normal total transport cost for employing Small Vessel 1 in Scenario 2a and Scenario 4a. The results suggest that the cost of employing Big Vessel 2 is not encouraging due to the added cost contingency factor and high charter rate. In this respect, the corrective maintenance can be considered employing smaller vessels. Moreover, comparing results of total transport cost in Scenario 3 with results obtained in Scenario 4a and Scenario 4b; it could be observed that there is potential for significant cost reduction in O&M vessel transport.

In Figure 106 the transport cost in Scenario 3 is compared with transport cost in Scenario 4. The importance is to demonstrate the potential for significant cost reduction when maintenance of 15 WECs is considered in Scenario 4a and Scenario 4b. The green bars depict the total transport cost of Small Vessel 1, while the red bars depict the total transport cost of Big Vessel 2. The result demonstrates that the cost of employing the Big Vessel 2 is expensive. This is particularly true with the additional cost contingency factor in Scenario 3 and Scenario 4.

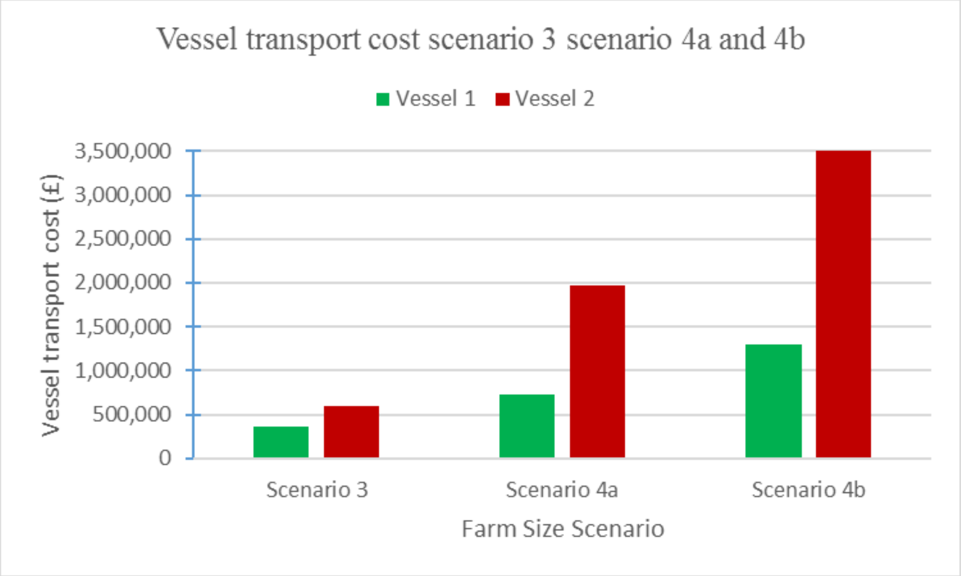

Figure 106: Comparison of O&M Vessel Transport Cost in Scenario 3, Scenario 4a and 4b

In the case of employing Small Vessel 1 in Scenario 3, the transport cost has the potential to decrease from £136,909, per WEC to £48,404 per WEC in Scenario 4a. In the case of employing Big Vessel 2, the transport cost per WEC has the potential to reduce from £371,318 to £131,217 per WEC in Scenario 4a. The results suggest that if the total transport cost in Scenario 4a or Scenario 4b, is divided by 15 WECs in Scenario 4, there is a significant reduction in the cost of transport per WEC compared to the transport cost for the corrective maintenance of a single WEC device in Scenario 3. The corrective maintenance model is seen to contribute significantly to the increased cost of O&M activities, this can be largely compensated considering the maintenance of multiple WECs in a WEC farm.

To arrive at the total cost for the corrective maintenance action in Scenario 4, the labour, workshop and equipment/tools cost were also estimated in addition to the transportation cost. As discussed in previous pages, the parameters that influence the cost of labour can be varied depending on the requirement and circumstance. In Scenario 4a and Scenario 4b, the minimum of 4 technicians are employed to perform the O&M activities for 15 WECs. This is the same as 4 technicians employed in Scenario 2 for maintenance of 15WECs. In this case, all the parameters for estimating the labour, workshop and equipment/tool cost in Scenario 4 remain the same as in Scenario 2.

In addition to the labour cost for onsite maintenance, the workshop labour cost for Scenario 4a and Scenario 4b was also examined. In this case, 4 technicians were employed, and a total working time of 1,274.31 hours was estimated for the on-site maintenance of 15 WECs in Scenario 4a. The results of the labour, workshop and equipment/tools cost in Scenario 4a and Scenario 4b is demonstrated. In Figure 107, the blue bars depict the O&M specific cost attribute and total O&M cost estimate for employing Small Vessel 1 in Scenario 4a, while the red bars depict the O&M cost attributes and total O&M cost estimate for Big Vessel 2 Scenario 4a.

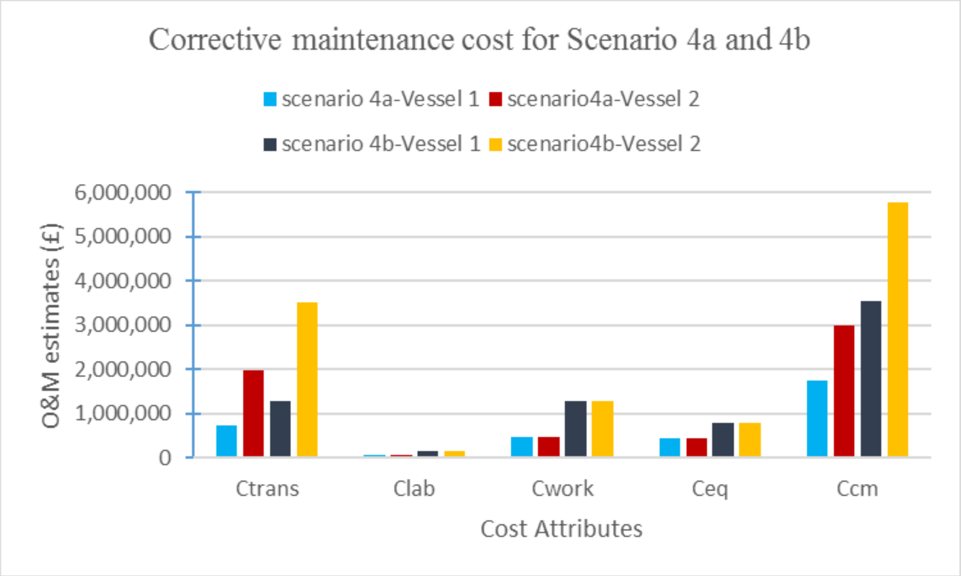

Figure 107: Comparison of Corrective maintenance cost for Scenario 4a and 4b

It can be observed that the labour, workshop and equipment/tool cost for employing either Small Vessel 1 or Big Vessel 2 is the same in Scenario 4a. The labour cost in Scenario 4a is estimated around £84,953 and £151,748 in Scenario 4b, being the cost of 4 technicians employed to work for 8 hours per day in Scenario 4. The workshop cost in Scenario 4b is estimated around £1,285,000 for employing either Small Vessel 1 or Big Vessel 2. This is inclusive of the workshop labour cost and spare part cost in Scenario 4b.

This result suggests that the cost of spare parts required for the maintenance or repair of the 15 WECs can be a significant contributor to variation in the O&M cost estimate. In Scenario 2b and Scenario 4b, the high O&M cost estimate associated with the workshop cost is due to the cumulative or bulk purchasing cost of spare parts for repair or maintenance of the 15 WECs. This is because the estimated workshop cost is inclusive of the workshop labour cost and the cumulative spare parts cost of each spare part used for the repair or maintenance of 15 WECs.

As observed in Figure 107, the contribution of the labour cost is very small compared to the workshop and equipment/tool cost. For that reason, the labour cost component is barely visible. In the case of the equipment/tools cost, the cost is estimated as £445,200, the same for employing either Small Vessel 1 or Big Vessel 2 in Scenario 4a. In Scenario 4b, equipment/tools required for the corrective maintenance is estimated as £798,000. The O&M specific cost attributes for the corrective maintenance model in Scenario 4 is the same as that shown in Scenario 2. The main difference is the O&M vessel transport cost.

The results of Scenario 4 are compared with the results in Scenario 2 to identify the main difference. Figure 108 shows the cost associated with employing Small Vessel 1 depicted as the blue bars and the cost for employing Big Vessel 2 depicted as the red bars. The result shows that the cost of employing Small Vessel 1 in Scenario 2a estimated as C_{pm}=£1,584,722 is lower than the cost of employing Small Vessel 1 in Scenario 4a estimated as C_{cm}= £1,584,722. The cost reduction is around £159,000. Similarly, the cost of employing Big Vessel 2 in Scenario 2a estimated as C_{pm}=£2,537,389 is lower than the cost of employing Big Vessel 2 in Scenario 4a estimated as C_{cm}= £2,985,921. The cost reduction is around £448,532.

The results show that the corrective maintenance model in Scenario 4a and 4b, contributes significantly to the variation in the O&M cost estimates. This is particularly true when Big Vessel 2 is employed to perform the O&M activities. It is suggested that care should be taken when considering the labour cost as criteria to compensate for the high cost of O&M vessel charter. O&M vessels with lower daily charter rate should be employed to reduce the high cost of corrective maintenance in Scenario 4b. In the case of employing Small Vessel 1 for the corrective maintenance in Scenario 2b and 4b, the O&M cost is estimated at C_{pm}=£3,250,383 and C_{cm}= £3,535,383 respectively.

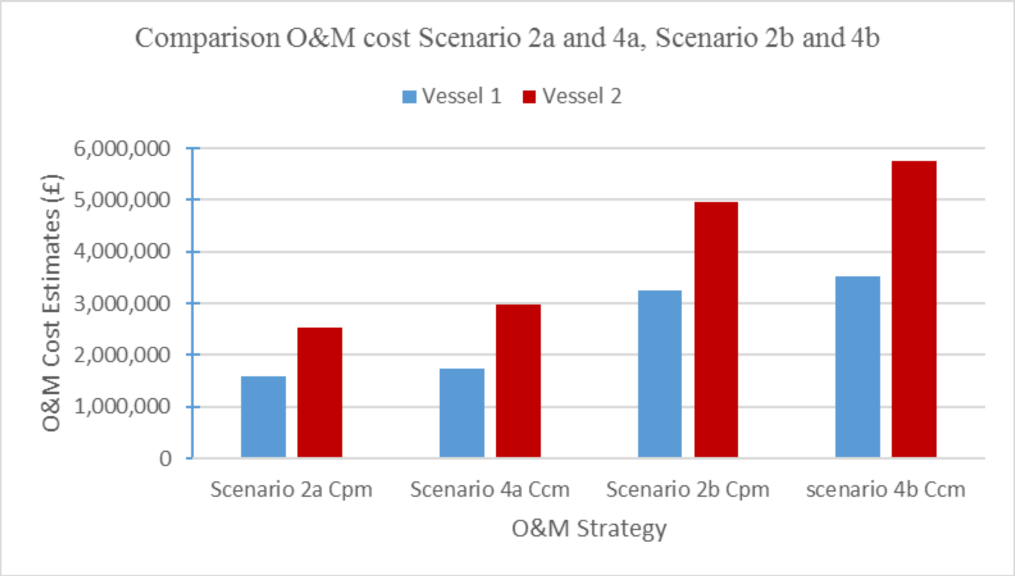

Figure 108: Comparison of Total O&M Cost for Scenarios 2 and Scenario 4

Comparing this result with that obtained in Scenario 2b and 4b for Big Vessel 2 i.e. C_{pm} = £4,957,792 and C_{cm}= £5,762,270; it is observed that the cost of the corrective maintenance is high. The results suggest that employing vessels with lower charter rates could significantly contribute to the reduction in the total O&M cost. Vessels with higher charter rate will ultimately contribute to higher O&M cost either in the corrective or preventive maintenance model. On the other hand, comparing the results obtained in Scenario 3 with that obtained in Scenario 4 as illustrated in Figure 109; it is observed that there is potential for reduction in the cost of corrective maintenance per WEC.

Figure 109 shows the cost of corrective maintenance in Scenario 3 depicted as the blues bars. In this respect, the estimated cost C_{cm}=£355,3733 per WEC has the potential to reduce to approximately £116,248 per WEC in Scenario 4a, and £235,692 in scenario 4b, if the total O&M cost in scenario 4a or 4b is divided by 15 WECs. If Big Vessel 2 is employed, the cost per single WEC in Scenario 3 depicted as the red bars has the potential to reduce from C_{cm}=£589,782 per device to approximately £ 199,061 per WEC in Scenario 4a, and £384,151 respectively considering maintenance of 15 WECs in Scenario 4b. It is observed that there is still a high prospect for cost reduction when the maintenance of 15 WECs is considered in either Scenario 2 or Scenario 4.

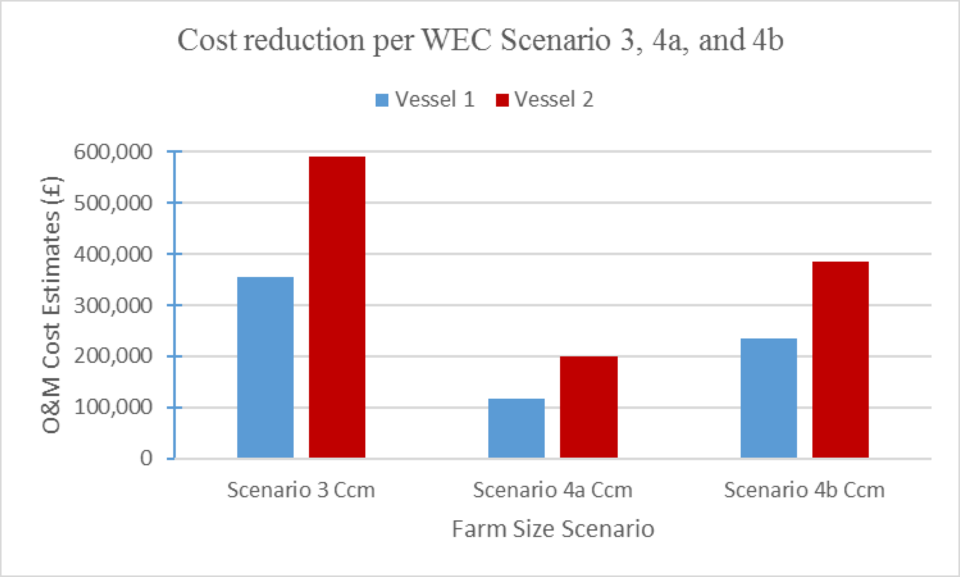

Figure 109: Comparison of Total O&M Cost reduction per WEC Scenario 3, 4a, and 4b

Despite the additional cost in terms of high daily charter rate or the 50% added contingency fee for employing Big Vessel 2 in Scenario 4, the cost reduction is applicable when compared to the O&M cost in Scenario 3. The results have demonstrated that the cost of labour contributes the lowest share to the variation in the total O&M cost compared to other cost components such as the workshop or equipment/tools cost. The O&M vessel cost is the major contributor to the high cost and variation in the O&M cost estimates. This is particularly true when the choice of employing Big Vessel 2 is considered.

Since offshore-onsite corrective maintenance requires vessels; it is suggested that the activities of minor repairs that can easily be performed onsite should employ small vessels. In the next section results of the analysis on total O&M cost estimates for the combined activities of the preventive and corrective maintenance cost for a WEC farm is presented.

6.2.3 Estimating the Total Maintenance Cost

The results of the preventive and corrective maintenance cost model have been demonstrated in the previous analysis. The O&M strategy identifies the type of maintenance activity that is performed. However, the O&M cost is driven by the Total Maintenance Cost (TMC), derived as the summation of the preventive and corrective maintenance costs. The results of Scenarios

1,2a, 2b, 3, 4a and 4b for the maintenance of a single WEC once a year and maintenance of multiple WECs once a year and once in 5 years is summarised and presented in Table 26.

Table 26: Summary of Results for Maintenance Scenarios per year

Maintenance Type	Single WEC 0.75MW	60 WECs 45MW	
Preventive Maintenance	Scenario 1	Scenario 2a	Scenario 2b
Small vessel 1	£325,372	£1,584,722	£3,250,383
Big vessel 2	£505,100	£2,537,389	£4,957,792
Corrective Maintenance	Scenario 3	Scenario 4a	Scenario 4b
Small vessel 1	£355,372	£1,743,722	£3,535,383
Big vessel 2	£589,782	£2,985,921	£5,762,270

The Total Maintenance Cost (TMC) could be maximised for an array of WECs and not just for a single device alone. In this context, other attributes relating to the overall WEC farm project are analysed based on the results of O&M cost estimates presented in Table 26 The Total Maintenance Cost is examined as a function of the parameters such as the preventive and corrective maintenance cost. These parameters are investigated in Scenario 5, Scenario 6a and 6b. Example, of preventive and corrective maintenance attributes examined, are listed below.

- Preventive and corrective maintenance cost per device ($\mathrm{C_{pm1}}$ and $\mathrm{C_{cm1}}$) (£)
- Preventive and corrective maintenance cost per MW gross ($\mathrm{C_{pm2}}$$and$ $\mathrm{C_{cm2}}$) (£)
- Preventive and corrective maintenance cost per MW net ($\mathrm{C_{pm3}}$ and $\mathrm{C_{cm3}}$) (£)
- Preventive and corrective maintenance cost per kWh ($\mathrm{C_{pm4}}$ and $\mathrm{C_{cm4}}$).(pence)

Scenario 5 investigates the Total maintenance cost ($\mathrm{T_{mc}}$) for employing either Small Vessel 1 or Big Vessel 2 for maintenance of a Single WEC. In this context, the Total maintenance cost ($\mathrm{T_{mc}}$) per WEC device is evaluated by the summation of the preventive ($\mathrm{C_{pm1}}$) and corrective ($\mathrm{C_{cm1}}$) maintenance cost per device. In this case, the relevant parameters include the preventive, corrective maintenance cost and the total number of WEC device. The method for calculating the TMC is described in Section 3.5. in Chapter 3 methodology and modelling. In the case of employing Small Vessel 1, given that for a total number of one WEC device $\mathrm{C_{pm}}$==£325,372, and $\mathrm{C_{cm}}$==£355,372; the procedure for estimating $\mathrm{T_{mc1}}$ is calculated according to Equation 124 as shown:

$$\mathrm{C_{pm1}} = \frac{\mathrm{C_{pm}}}{\mathrm{N_{WEC}}} = \frac{£325{,}372}{1} = £325{,}372$$

$$\mathrm{C_{cm1}} = \frac{\mathrm{C_{cm}}}{\mathrm{N_{WEC}}} = \frac{£355{,}372}{1} = £355{,}372$$

$$\mathrm{T_{mc1}} = \mathrm{C_{Pm1}} + \mathrm{C_{cm1}} = £325{,}372\ + £355{,}372 = £680{,}745$$

Similarly, in the case of employing the Big Vessel 2, given that for a total number of one WEC device $\mathrm{C_{pm}}$=£505,100, and $\mathrm{C_{cm}}$=£589,782; the procedure for estimating $\mathrm{T_{mc1}}$ is calculated according to Equation 124 as shown:

$$\mathrm{C_{pm1}} = \frac{\mathrm{C_{pm}}}{\mathrm{N_{WEC}}} = \frac{£505{,}100}{1} = £505{,}100$$

$$\mathrm{C_{cm1}} = \frac{\mathrm{C_{cm}}}{\mathrm{N_{WEC}}} = \frac{£589{,}782}{1} = £589{,}782$$

$$\mathrm{T_{mc1}} = \mathrm{C_{Pm1}} + \mathrm{C_{cm1}} = £505{,}100\ + £589{,}782 = £1{,}094{,}882$$

Having examined the first attribute, the next attribute in Scenario 5 is the preventive and corrective maintenance cost per MW gross ($\mathrm{C_{pm2}}$and $\mathrm{C_{cm2}}$). This refers to the total cost of the electric power generated by the WEC device. In this case, the information required includes the preventive, corrective maintenance cost, the total number of WECs and the WEC farm gross capacity ($\mathrm{Cap_{wec_{gr}}}$). The WEC farm gross capacity is evaluated as the single device output capacity gross ($\mathrm{Cap_{Sgr}}$) multiplied by the total number of WECs. Given that $\mathrm{Cap_{Sgr}}$= 0.75MW is the actual value and the total number of WEC is 1, $\mathrm{Cap_{wec_{gr}}}$ is calculated according to Equation 126 as shown:

$$\mathrm{Cap_{wec_{gr}}} = \mathrm{Cap_{Sgr}} \times \mathrm{N_{WEC}} = 0.75 \times 1 = 0.75\mathrm{MW\ actual}$$

In the case of employing the Small Vessel 1, given that for a total number of one WEC device C_{pm}==£325,372, and C_{cm}==£355,372; the procedure for estimating T_{mc2} is calculated according to Equation 125 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£325,372}{0.75} = £433,830$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£355,372}{0.75} = £473,830$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £433,830 + £473,830 = £907,661$$

Similarly, in the case of employing Big Vessel 2, given that for a total number of one WEC device C_{pm}=£505,100, and C_{cm}=£589,782; the procedure for estimating T_{mc2} is calculated according to Equation 125 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£505,100}{0.75} = £673,466$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£589,782}{0.75} = £786,376$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £673,466 + £786,376 = £1,459,843$$

In addition, the preventive and corrective maintenance cost per MW net (C_{pm3} and C_{cm3}) is analysed. In this case, the relevant parameters or information required include the preventive, corrective maintenance cost and the WEC farm net capacity ($Cap_{WEC_{net}}$). However, the WEC farm net capacity is evaluated as a function of the single device output capacity net ($Cap_{S_{net}}$) multiplied by the WEC farm gross capacity. Given that the capacity factor (f_{cap}) for the WEC device is 40% and power generation availability (f_p) is 98%; the single device output capacity gross (Cap_{Sgr}) is 0.75MW; single device output capacity net is calculated according to Equation 129 as shown:

$$\mathrm{Cap}_{\mathrm{S}_{\mathrm{net}}} = \mathrm{Cap}_{\mathrm{Sgr}} \times \mathrm{f}_{\mathrm{cap}} \times \mathrm{f}_{\mathrm{p}}$$

$$= 0.75 \times 0.4 \times 0.98 = 2.1\mathrm{MW}$$

The WEC farm net capacity is ($\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}$) calculated as shown:

$$\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}} = \mathrm{Cap}_{\mathrm{S}_{\mathrm{net}}} \times \mathrm{Cap}_{\mathrm{wec}_{\mathrm{gr}}} = 2.1 \times 0.75 = 1.57\mathrm{MW}$$

In the case of employing the Small Vessel 1, given that for a total number of one WEC device C_{pm}==£325,372, and C_{cm}==£355,372; the procedure for estimating $\mathrm{T}_{\mathrm{mc3}}$ is calculated according to Equation 127 as shown:

$$\mathrm{C}_{\mathrm{pm3}} = \frac{\mathrm{C}_{\mathrm{pm}}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}} = \frac{£325{,}372}{1.57} = £207{,}243$$

$$\mathrm{C}_{\mathrm{cm3}} = \frac{\mathrm{C}_{\mathrm{cm}}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}} = \frac{£355{,}372}{1.57} = £226{,}352$$

$$\mathrm{T}_{\mathrm{mc3}} = \mathrm{C}_{\mathrm{Pm3}} + \mathrm{C}_{\mathrm{cm3}} = £207{,}243 + £226{,}352 = £433{,}596$$

Similarly, in the case of employing Big Vessel 2, given that for a total number of one WEC device C_{pm}=£505,100, and C_{cm}=£589,782; the procedure for estimating $\mathrm{T}_{\mathrm{mc3}}$ is calculated according to Equation 127 as shown:

$$\mathrm{C}_{\mathrm{pm3}} = \frac{\mathrm{C}_{\mathrm{pm}}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}} = \frac{£505{,}100}{1.57} = £323{,}937$$

$$\mathrm{C}_{\mathrm{cm3}} = \frac{\mathrm{C}_{\mathrm{cm}}}{\mathrm{Cap}_{\mathrm{WEC}_{\mathrm{net}}}} = \frac{£589{,}782}{1.57} = £378{,}247$$

$$\mathrm{T}_{\mathrm{mc3}} = \mathrm{C}_{\mathrm{Pm3}} + \mathrm{C}_{\mathrm{cm3}} = £323{,}937 + £378{,}247 = £702{,}185$$

To conclude the analysis of the total maintenance cost in Scenario 5, the preventive and corrective maintenance cost per Kwh ($\mathrm{C_{pm4}}$ and $\mathrm{C_{cm4}}$) is examined. This is the ratio of the maintenance cost over the total WEC farm net capacity output (GW/hr/year). Therefore, relevant parameters or information required include the preventive, corrective maintenance cost and the total WEC farm net capacity output ($\mathrm{Cap_{WEC_T}}$). Given that a single WEC net capacity is 1.57MW, total WEC farm net capacity is calculated according to Equation 131 as shown:

$$\mathrm{Cap_{WEC_T}} = \mathrm{Cap_{WEC_{net}}} \times N_{WEC} = 1.57 \times 1 = 1.57\mathrm{MW}$$

In the case of employing the Small Vessel 1, given that for a total number of one WEC device $\mathrm{C_{pm}}$==£325,372, and $\mathrm{C_{cm}}$==£355,372; the procedure for estimating $\mathrm{T_{mc4}}$ is calculated according to Equation 130 as shown:

$$\mathrm{C_{pm4}} = \frac{\mathrm{C_{pm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{325{,}372 \ \times 10^2}{1.57 \times 10^6} = 20.72\mathrm{Pence/kwh/year}$$

$$\mathrm{C_{cm4}} = \frac{\mathrm{C_{cm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{355{,}372 \times 10^2}{1.57 \times 10^6} = 22.64\mathrm{Pence/kwh/year}$$

$$\mathrm{T_{mc4}} = \mathrm{C_{Pm4}} + \mathrm{C_{cm4}} = 20.72 + 22.64 = 43.35\mathrm{Pence/kwh/year}$$

Similarly, in the case of Employing Big Vessel 2, given that for a total number of one WEC device $\mathrm{C_{pm}}$=£505,100, and $\mathrm{C_{cm}}$=£589,782; the procedure for estimating $\mathrm{T_{mc4}}$ is calculated according to Equation 130 as shown:

$$\mathrm{C_{pm4}} = \frac{\mathrm{C_{pm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{505{,}100 \ \ \times 10^2}{1.57 \times 10^6} = 32.17\mathrm{Pence/kwh/year}$$

$$\mathrm{C_{cm4}} = \frac{\mathrm{C_{cm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{589{,}782 \times 10^2}{1.57 \times 10^6} = 37.57\mathrm{Pence/kwh/year}$$

$$\mathrm{T_{mc4}} = \mathrm{C_{Pm4}} + \mathrm{C_{cm4}} = 32.17 + 37.57 = 69.74\mathrm{Pence/kwh/year}$$

In Table 27 and 28 results of the analysis for preventive and corrective cost parameters are summarised. In Table 29 results of the analysis for total maintenance cost as a function of the preventive and corrective maintenance cost parameters are summarised.

Table 27: Summary of the Preventive Maintenance Cost Parameters for Scenario 5

Attributes	Unit	Small vessel 1	Big vessel 2
Preventive cost per device	C_{pm1} £	325,372	505,100
Preventive cost per MW gross	C_{pm2} £	433,830	673,466
Preventive cost per MW net	C_{pm3} £	207,243	323,937
Preventive cost per kwh	C_{pm4} Pence	20.72	32.17

Table 28: Summary of the Corrective Maintenance Cost Parameters for Scenario 5

Attributes	Unit	Small vessel 1	Big vessel 2
Corrective cost per device	C_{cm1} £	355,372	589,782
Corrective cost per MW gross	C_{cm2} £	473,830	786,376
Corrective cost per MW net	C_{cm3} £	226,352	378,247
Corrective cost per Kwh	C_{cm4} Pence	22.64	37.57

Table 29: Summary of the Total Maintenance Cost Parameters for Scenario 5

Attributes	Unit	Small vessel 1	Big vessel 2
Total cost per device	T_{mc1} £	680,745	1,094,882
Total cost per MW gross	T_{mc2} £	907,661	1,459,843
Total cost per MW net	T_{mc3} £	433,596	702,185
Total cost per Kwh	T_{mc4} Pence	43.35	69.74

In the following the analysis of Scenario 6 is presented. Scenario 6 is divided into Scenario 6a, and 6b. Scenario 6a investigates the Total maintenance cost (T_{mc}) for employing either Small Vessel 1 or Big Vessel 2 for ordinary maintenance of 15 WECs once in a year. Scenario 6b investigates the Total maintenance cost (T_{mc}) for employing either Small Vessel 1 or Big Vessel 2 for overhaul maintenance of 15 WECs once in 5 years.

As in Scenario 5, the Total maintenance cost (T_{mc}) for a WEC farm consisting of 60 WECs is evaluated Scenario 6. This is the summation of the preventive (C_{pm1}) and corrective (C_{cm1}) maintenance cost for the total number of WECs to be serviced at any specific time. In this context, the relevant parameters include the preventive, corrective maintenance cost and the total number of WEC device. In the case of employing the Small Vessel 1 in Scenario 6a, given that for the total number of 15 WECs C_{pm}=£1,584,722, and C_{cm}=£1,743,722; the procedure for estimating T_{mc1} is calculated according to Equation 124 as shown:

$$C_{pm1} = \frac{C_{pm}}{N_{WEC}} = \frac{£1{,}584{,}722}{15} = £105{,}648$$

$$C_{cm1} = \frac{C_{cm}}{N_{WEC}} = \frac{£1{,}743{,}722}{15} = £116{,}248$$

$$T_{mc1} = C_{Pm1} + C_{cm1} = £105{,}648 + £116{,}248 = £221{,}896$$

Similarly, in the case of employing Big Vessel 2 in Scenario 6a, given that for a total number of 15 WECs C_{pm}=£2,537,389, and C_{cm}=£2,985,921; the procedure for estimating T_{mc1} is calculated according to Equation 124 as shown:

$$C_{pm1} = \frac{C_{pm}}{N_{WEC}} = \frac{£2{,}537{,}389}{15} = £169{,}159$$

$$C_{cm1} = \frac{C_{cm}}{N_{WEC}} = \frac{£2{,}985{,}921}{15} = £199{,}061$$

$$T_{mc1} = C_{Pm1} + C_{cm1} = £169{,}159 + £199{,}061 = £368{,}220$$

In the case of employing the Small Vessel 1 in Scenario 6b, given that for the total number of 15 WECs C_{pm}=£3,250,383, and C_{cm}=£3,535,383; the procedure for estimating T_{mc1} is calculated according to Equation 124 as shown:

$$C_{pm1} = \frac{C_{pm}}{N_{WEC}} = \frac{£3{,}250{,}383}{15} = £216{,}692$$

$$C_{cm1} = \frac{C_{cm}}{N_{WEC}} = \frac{£3{,}535{,}383}{15} = £235{,}692$$

$$T_{mc1} = C_{Pm1} + C_{cm1} = £216{,}692 + £235{,}692 = £452{,}384$$

Similarly, in the case of employing Big Vessel 2 in Scenario 6b, given that for a total number of 15 WECs C_{pm}=£4,957,792, and C_{cm}=£5,762,270; the procedure for estimating T_{mc1} is calculated according to Equation 124 as shown:

$$C_{pm1} = \frac{C_{pm}}{N_{WEC}} = \frac{£4,957,792}{15} = £330,519$$

$$C_{cm1} = \frac{C_{cm}}{N_{WEC}} = \frac{£5,762,270}{15} = £384,151$$

$$T_{mc1} = C_{Pm1} + C_{cm1} = £330,519 + £384,151 = £714,670$$

In addition, the preventive and corrective maintenance cost per MW gross: ($C_{pm2}$and C_{cm2}) in Scenario 6a, and 6b is also examined. As in Scenario 5, the information required includes the preventive, corrective maintenance cost, the total number of WECs and the WEC farm gross capacity ($Cap_{wec_{gr}}$). Given that the actual single device output capacity gross (MW) is Cap_{Sgr}= 0.75MW and the total number of WECs to be serviced is 15; the $Cap_{wec_{gr}}$ is calculated according to Equation 126 as shown:

$$Cap_{wec_{gr}} = Cap_{Sgr} \times N_{WEC} = 0.75 \times 15 = 11.25\text{MW actual}$$

In the case of employing Small Vessel 1 in Scenario 6a, given the total number of 15 WECs, C_{pm}=£1,584,722, and C_{cm}=£1,743,722; the procedure for estimating T_{mc2} is calculated according to Equation 126 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£1,584,722}{15} = £140,864$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£1,743,722}{15} = £154,997$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £140,864 + £154,997 = £295,861$$

In the case of employing the Big Vessel 2 in Scenario 6a, given that for a total number of 15 WECs C_{pm}=£2,537,389, and C_{cm}=£2,985,921; the procedure for estimating T_{mc2} is calculated according to Equation 126 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£2,537,389}{15} = £225,545$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£2,985,921}{15} = £265,415$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £225,545 + £265,415 = £490,960$$

In Scenario 6b, employing Small Vessel 1 for 15 WECs, C_{pm}=£3,250,383, and C_{cm}=£3,535,383; the procedure for estimating T_{mc2} is calculated according to Equation 126 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£3,250,383}{15} = £288,922$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£3,535,383}{15} = £314,256$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £288,922 + £314,256 = £603,179$$

In the case of employing the Big Vessel 2 in Scenario 6b, given that for a total number of 15 WECs C_{pm}=£4,957,792, and C_{cm}=£ 5,762,270; the procedure for estimating T_{mc2} is calculated according to Equation 126 as shown:

$$C_{pm2} = \frac{C_{pm}}{Cap_{wec_{gr}}} = \frac{£4,957,792}{15} = £440,692$$

$$C_{cm2} = \frac{C_{cm}}{Cap_{wec_{gr}}} = \frac{£5,762,270}{15} = £512,201$$

$$T_{mc2} = C_{Pm2} + C_{cm2} = £440{,}692 + £512{,}201 = £952{,}894$$

As in Scenario 5, the preventive and corrective maintenance cost per MW net: (C_{pm3} and C_{cm3}) is analysed in Scenario 6a, and 6b. First, the gross output capacity of a Single WEC is multiplied by the WEC capacity factor (%) and the power generation availability (%) to obtain the single WEC net capacity. Secondly, the WEC farm net capacity is obtained by multiplying the single WEC net capacity with the gross capacity of the farm as shown in previous pages. The preventive and corrective maintenance cost per MW net was then obtained by dividing the total preventive maintenance cost by the WEC farm net capacity.

In the case of employing the Small Vessel 1 in Scenario 6a, given that the WEC farm net capacity is 23.39MW for a total number of 15 WECs, C_{pm}=£1,584,722, and C_{cm}=£1,743,722; the procedure for estimating T_{mc3} is calculated according to Equation 127 as shown:

$$C_{pm3} = \frac{C_{pm}}{Cap_{WEC_{net}}} = \frac{£1{,}584{,}722}{23.39} = £67{,}755$$

$$C_{cm3} = \frac{C_{cm}}{Cap_{WEC_{net}}} = \frac{£1{,}743{,}722}{23.39} = £74{,}553$$

$$T_{mc3} = C_{Pm3} + C_{cm3} = £67{,}755 + 74{,}553 = £142{,}309$$

Similarly, in the case of employing the Big Vessel 2 in Scenario 6a, given that the WEC farm net capacity is 23.39MW for a total number of 15 WECs, C_{pm}=£2,537,389, and C_{cm}=£2,985,921; the procedure for estimating T_{mc3} is calculated according to Equation 127 as shown:

$$C_{pm3} = \frac{C_{pm}}{Cap_{WEC_{net}}} = \frac{£2{,}537{,}389}{23.39} = £108{,}487$$

$$C_{cm3} = \frac{C_{cm}}{Cap_{WEC_{net}}} = \frac{£2{,}985{,}921}{23.39} = £127{,}664$$

$$T_{mc3} = C_{Pm3} + C_{cm3} = £108{,}487 + £127{,}664 = £236{,}152$$

In the case of employing the Small Vessel 1 in Scenario 6b, given that the WEC farm net capacity is 23.39MW for a total number of 15 WECs, $\mathrm{C_{pm}}$=£3,250,383, and $\mathrm{C_{cm}}$=£3,535,383; the procedure for estimating $\mathrm{T_{mc3}}$ is calculated according to Equation 127 as shown:

$$\mathrm{C_{pm3}} = \frac{\mathrm{C_{pm}}}{\mathrm{Cap_{WEC_{net}}}} = \frac{£3,250,383}{23.39} = £138,972$$

$$\mathrm{C_{cm3}} = \frac{\mathrm{C_{cm}}}{\mathrm{Cap_{WEC_{net}}}} = \frac{£3,535,383}{23.39} = £151,157$$

$$\mathrm{T_{mc3}} = \mathrm{C_{Pm3}} + \mathrm{C_{cm3}} = £138,972 + £151,157 = £290,129$$

Similarly, in the case of employing the Big Vessel 2 in Scenario 6b, given that the WEC farm net capacity is 23.39MW for a total number of 15 WECs, $\mathrm{C_{pm}}$=£4,957,792, and $\mathrm{C_{cm}}$=£5,762,270; the procedure for estimating $\mathrm{T_{mc3}}$ is calculated according to Equation 127 as shown:

$$\mathrm{C_{pm3}} = \frac{\mathrm{C_{pm}}}{\mathrm{Cap_{WEC_{net}}}} = \frac{£4,957,792}{23.39} = £211,973$$

$$\mathrm{C_{cm3}} = \frac{\mathrm{C_{cm}}}{\mathrm{Cap_{WEC_{net}}}} = \frac{£5,762,270}{23.39} = £246,369$$

$$\mathrm{T_{mc3}} = \mathrm{C_{Pm3}} + \mathrm{C_{cm3}} = £211,973 + £246,369 = £458,342$$

Similarly, to end the analysis of the total maintenance cost in Scenario 6a and 6b, the preventive and corrective maintenance cost per Kwh ($\mathrm{C_{pm4}}$ and $\mathrm{C_{cm4}}$) is examined. As in Scenario 5, the information required includes the preventive, corrective maintenance cost and the total WEC farm net capacity output ($\mathrm{Cap_{WEC_T}}$). Given that a single WEC net capacity is 1.57MW, total WEC farm net capacity in Scenario 6 is calculated as shown:

$$\mathrm{Cap_{WEC_T}} = \mathrm{Cap_{WEC_{net}}} \times N_{WEC} = 1.57 \times 15 = 23.55\mathrm{MW}$$

To obtain the cost for maintenance of 15 WECs, the WEC farm net capacity in MW was first multiplied by the number of WECs to obtain the total WEC farm net capacity. Thereafter, the total cost of preventive maintenance for the 15 WECs was divided by the total WEC farm net capacity to obtain the maintenance cost per Kwh. In the case of employing the Small Vessel 1 in Scenario 6a, given the total number of 15 WECs, C_{pm}=£1,584,722, and C_{cm}=£1,743,722; the procedure for estimating T_{mc4} is calculated according to Equation 130 as shown:

$$C_{pm4} = \frac{C_{pm} \times 10^2}{Cap_{WEC_T} \times 10^6} = \frac{1{,}584{,}722 \times 10^2}{23.55 \times 10^6} = 67.29 \text{Pence/kwh/year}$$

$$C_{cm4} = \frac{C_{cm} \times 10^2}{Cap_{WEC_T} \times 10^6} = \frac{1{,}743{,}722 \times 10^2}{23.55 \times 10^6} = 74.04 \text{Pence/kwh/year}$$

$$T_{mc4} = C_{Pm4} + C_{cm4} = 67.29 + 74.04 = 141.3 \text{Pence/kwh/year}$$

Similarly, for employing Big Vessel 2 in Scenario 6a, given the total number of 15 WECs C_{pm}=£2,537,389, and C_{cm}=£2,985,921; the procedure for estimating T_{mc4} is calculated according to Equation 130 as shown:

$$C_{pm4} = \frac{C_{pm} \times 10^2}{Cap_{WEC_T} \times 10^6} = \frac{2{,}537{,}389 \quad \times 10^2}{23.55 \times 10^6} = 107.75 \text{Pence/kwh/year}$$

$$C_{cm4} = \frac{C_{cm} \times 10^2}{Cap_{WEC_T} \times 10^6} = \frac{2{,}985{,}921 \times 10^2}{23.55 \times 10^6} = 126.79 \text{Pence/kwh/year}$$

$$T_{mc4} = C_{Pm4} + C_{cm4} = 107.75 + 126.79 = 234.535 \text{Pence/kwh/year}$$

In the case of employing the Small Vessel 1 in Scenario 6b, given the total number of 15 WECs, C_{pm}=£3,250,383, and C_{cm}=£3,535,383; the procedure for estimating T_{mc4} is calculated according to Equation 130 as shown:

$$\mathrm{C_{pm4}} = \frac{\mathrm{C_{pm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{3{,}250{,}383 \times 10^2}{23.55 \times 10^6} = 138.02\mathrm{Pence/kwh/year}$$

$$\mathrm{C_{cm4}} = \frac{\mathrm{C_{cm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{3{,}535{,}383 \times 10^2}{23.55 \times 10^6} = 150.12\mathrm{Pence/kwh/year}$$

$$\mathrm{T_{mc4}} = \mathrm{C_{Pm4}} + \mathrm{C_{cm4}} = 138.02 + 150.12 = 288.14\mathrm{Pence/kwh/year}$$

Similarly, for employing Big Vessel 2 in Scenario 6b, given the total number of 15 WECs $\mathrm{C_{pm}}$=£4,957,792, and $\mathrm{C_{cm}}$=£5,762,270; the procedure for estimating $\mathrm{T_{mc4}}$ is calculated according to Equation 130 as shown:

$$\mathrm{C_{pm4}} = \frac{\mathrm{C_{pm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{4{,}957{,}792 \quad \times 10^2}{23.55 \times 10^6} = 210.52\mathrm{Pence/kwh/year}$$

$$\mathrm{C_{cm4}} = \frac{\mathrm{C_{cm}} \times 10^2}{\mathrm{Cap_{WEC_T}} \times 10^6} = \frac{5{,}762{,}270 \times 10^2}{23.55 \times 10^6} = 244.68\mathrm{Pence/kwh/year}$$

$$\mathrm{T_{mc4}} = \mathrm{C_{Pm4}} + \mathrm{C_{cm4}} = 210.52 + 244.68 = 455.20\mathrm{Pence/kwh/year}$$

Table 30 presents the summary of results for analysis of the preventive maintenance cost parameters, Table 31 the summary of results for analysis of the corrective maintenance cost parameters .and, Table 32 presents the results of the analysis of the total maintenance cost as a function of the preventive and corrective maintenance cost parameters in Scenario 6a.

Table 30: Summary of the Preventive Maintenance Cost Parameters for Scenario 6a

Attributes	Unit	Small vessel 1	Big vessel 2
Preventive cost per device	$\mathrm{C_{pm1}}$ £	105,648	169,159
Preventive cost per MW gross	$\mathrm{C_{pm2}}$ £	140,864	225,545
Preventive cost per MW net	$\mathrm{C_{pm3}}$ £	67,755	108,487
Preventive cost per Kwh	$\mathrm{C_{pm4}}$ Pence	67.29	107.75

In addition, Table 33 presents the summary of results for analysis of the preventive maintenance cost parameters, Table 34 the summary of results for analysis of the corrective maintenance cost parameters .and, Table 35 presents the results of the analysis of the total maintenance cost as a function of the preventive and corrective maintenance cost parameters in Scenario 6b.

Table 31: Summary of the Corrective Maintenance Cost Parameters for Scenario 6a

Attributes	Unit	Small vessel 1	Big vessel 2
Corrective cost per device	C_{cm1} £	116,248	199,061
Corrective cost per MW gross	C_{cm2} £	154,997	265,415
Corrective cost per MW net	C_{cm3} £	74,553	127,664
Corrective cost per Kwh	C_{cm4} Pence	74.04	126.79

Table 32: Summary of the Total maintenance cost parameters for scenario 6a

Attributes	Unit	Small vessel 1	Big vessel 2
Total cost per device	T_{mc1} £	221,896	368,220
Total cost per MW gross	T_{mc2} £	295,861	490,960
Total cost per MW net	T_{mc3} £	142,309	236,152
Total cost per Kwh	T_{mc4} Pence	141.3	234.535

Table 33: Summary of the Preventive Maintenance Cost Parameters for Scenario 6b

Attributes	Unit	Small vessel 1	Big vessel 2
Preventive cost per device	C_{pm1} £	216,692	330,519
Preventive cost per MW gross	C_{pm2} £	288,922	440,692
Preventive cost per MW net	C_{pm3} £	138,972	211,973
Preventive cost per Kwh	C_{pm4} Pence	138.02	210.52

Table 34: Summary of the Corrective Maintenance Cost Parameters for Scenario 6b

Attributes	Unit	Small vessel 1	Big vessel 2
Corrective cost per device	C_{cm1} £	235,692	384,151
Corrective cost per MW gross	C_{cm2} £	314,256	512,201
Corrective cost per MW net	C_{cm3} £	151,157	246,369
Corrective cost per Kwh	C_{cm4} Pence	150.12	244.68

Table 35: Summary of the Total maintenance cost parameters for scenario 6b

Attributes	Unit	Small vessel 1	Big vessel 2
Total cost per device	T_{mc1} £	452,384	714,670
Total cost per MW gross	T_{mc2} £	603,179	952,894
Total cost per MW net	T_{mc3} £	290,129	458,342
Total cost per Kwh	T_{mc4} Pence	288.14	455.20

Having examined other attributes relating to the overall WEC farm project based on the results of O&M cost estimates presented, Figure 110 demonstrates the results of the total maintenance cost by comparing the results of Scenario 5 with Scenario 6a, and Scenario 6b. The reason is to compare the advantages or disadvantages. This will also show situations where cost reduction can be achieved. Applicable to both Scenario 5, Scenario 6a, and Scenario 6b, in Figure 110, the total cost per device is depicted by the blue bars. The total cost per MW gross is depicted by the red bars and the total cost per MW net is shown by the grey bars.

First, the results show that there is more advantage in Scenario 6a, and Scenario 6b compared to Scenario 5. In the case of employing Small Vessel 1 in Scenario 5, the total maintenance cost per device is estimated at $\mathrm{T_{mc1}}$= £680,745. This is the total cost for hiring the Small Vessel 1 to perform the maintenance operation for a duration of 10 days in a year. In Scenario 6a the total maintenance cost per device reduces to $\mathrm{T_{mc1}}$ =£221,896. This represents a significant reduction in the cost of on-site maintenance of 15 WECs. In the case of Scenario 6b, the total maintenance cost per device reduces to $\mathrm{T_{mc1}}$ =£452,384.

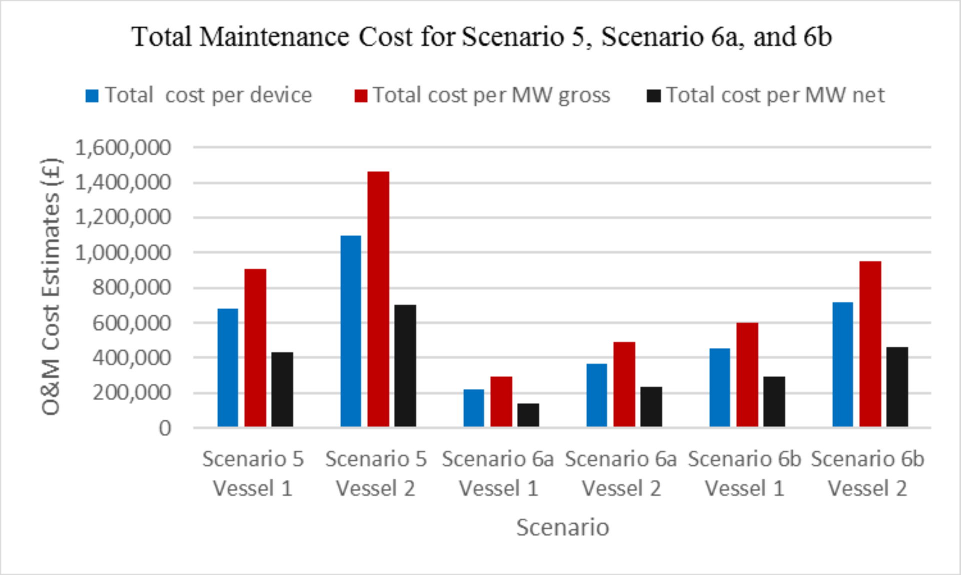

Figure 110: Total Maintenance Cost for Scenario 5, Scenario 6a, and Scenario 6b

This also contributes to greater cost savings and reduction in the overall O&M cost estimates for major repairs; considering that the O&M vessel is utilised for a duration of 95 days in a year in Scenario 6b. In the case of employing Big Vessel 2 to perform the same maintenance activities in Scenario 5, the total cost per device is estimated at $\mathrm{T_{mc1}}$ =£ 1,094,882. Compared to Scenario 6a and 6b, the total cost per device is estimated at $\mathrm{T_{mc1}}$ = £368,220, and £714,670 respectively. This also represents a significant reduction in the O&M cost estimates and contributes to greater cost savings.

These results suggest that the high cost and variation associated with the O&M cost estimates can be attributed to the decision or condition of employing either the Small Vessel 1 or Big Vessel 2 for maintenance activities of a single device in a WEC farm. The variation in cost is greater particularly when the Big Vessel 2 is employed in Scenario 5. However, the decision of employing Big Vessel 2 can be compensated in Scenario 6a, and Scenario 6b. The reason is that for situations where access for small vessels is limited, a balance can be achieved in the cost and benefits of employing a big vessel to perform the O&M activities.

In Scenario 6a, and Scenario 6b, the total maintenance cost per MW gross can be maximised for the WEC farm This refers to the total cost of the electric power generated by the WEC device. In Figure 110, considering the case of employing Small Vessel 1 in Scenario 5 the total maintenance cost for electric power generated by a single WEC device is estimated at $\mathrm{T_{mc2}} =$ £ 907,661. Compared to Scenario 6a, and Scenario 6b, the total maintenance cost for electric power generated by a single WEC in a WEC farm is estimated at $\mathrm{T_{mc2}} =$£ 295,861, and £603,179 respectively. This represents a significant cost reduction and demonstrates that there is greater benefit for considering the maintenance operation for multiple WECs.

In the case of employing Big vessel 2 the total maintenance cost of electric power generated by the single WEC is estimated as $\mathrm{T_{mc2}} =$£1,459,843, in Scenario 5. In comparison to Scenario 6a, and 6b, the cost is estimated at $\mathrm{T_{mc2}} =$£490,960, and £952,894 respectively. In the case of employing Small Vessel 1 in Scenario 5 $\mathrm{T_{mc3}} =$£433,596. This refers to the total maintenance cost per MW net which is the total maintenance cost of the actual maximum power output that can be generated by a single WEC based on its capacity factor.

In comparison with Scenario 6a, and 6b, this cost is significantly reduced for 15 WECs in a farm and for employing Small Vessel 1 in Scenario 6a $\mathrm{T_{mc3}} =$£142,309, and £290,129, in Scenario 6b. in addition, employing Big Vessel 2 in Scenario 5 $\mathrm{T_{mc3}} =$£702,185, for the total maintenance cost per MW net. In comparison with Scenario 6a, and 6b $\mathrm{T_{mc3}} =$£236,152, and £458,342 respectively, for employing Big Vessel 2. The results suggest that in all cases there is more prospect for considering the maintenance of multiple WECs in a WEC farm. This is because the total cost is not so prohibitive when the decision to employ the Big Vessel 2 for maintenance activities of 15 WECs is considered.

In any case, employing the Big Vessel 2 for maintenance of a single WEC device in a WEC farm is highly prohibitive. In Figure 111 the results of the total maintenance cost per kwh for Scenario 5, Scenario 6a, and 6b are demonstrated. The results in Figure 111 show that the total maintenance cost per kwh is prohibitive. This is particularly true in the case of Scenario 5 employing either Small Vessel 1 or Big Vessel 2. The O&M cost is estimated at approximately 43pence/ kwh for employing the Small Vessel 1 depicted by the blue bar in Scenario 5.

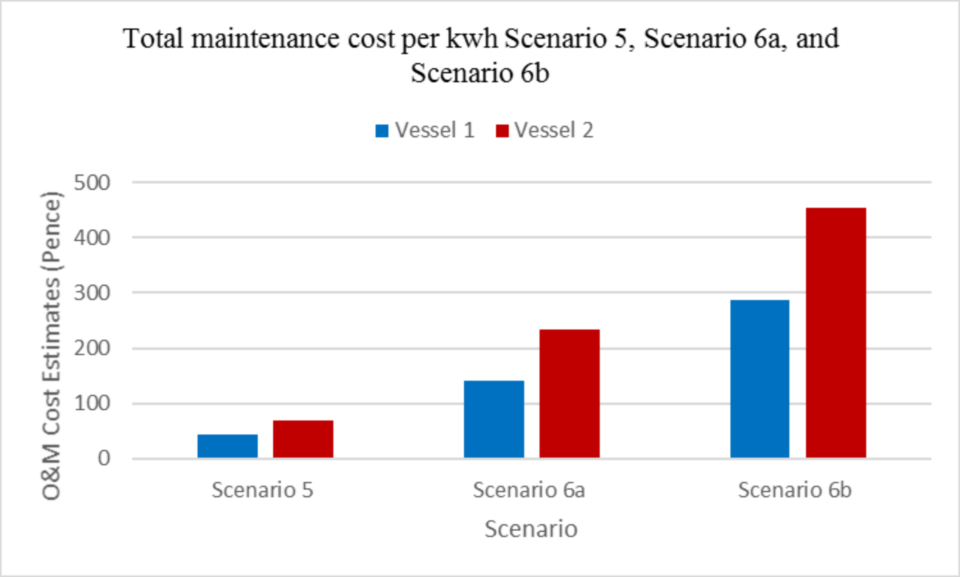

Figure 111: Total Maintenance Cost Per Kwh Scenario 5, Scenario 6a, and 6b

In the case of employing Big Vessel 2 depicted by the red bar, the O&M cost estimated is approximately 70pence/ kwh in Scenario 5. In comparison to employing either Small Vessel 1 or Big Vessel 2 in Scenario 6a, or Scenario 6b, there appears to be greater reduction in the cost. The reason is that the total maintenance cost per kwh in Scenario 6 is estimated for 15 WECs. In this context, if the total maintenance cost per kwh in Scenario 6a, or Scenario 6b, is divided by the total number of WECs the reduction in cost can be appreciated.

Therefore, in the case of employing Small Vessel 1 in Scenario 6a, the total O&M cost is estimated at approximately £1.41pence/kwh. Dividing this amount by 15 WECs, the cost per WEC reduces from 43pence/kwh to 10pence/kwh for employing the Small Vessel in Scenario 6a, and 19pence/kwh in Scenario 6b. In the case of employing the Big Vessel 2, the cost per WEC reduces from 70pence/kwh to 15pence/kwh in Scenario 6a, and 30pence/kwh in Scenario 6b. This result suggests that even for maintenance of single device, the decision of employing a small vessel with relatively low charter rate will contribute to reducing the O&M cost of energy generation using WECs.

The decision for employing the O&M vessel for maintenance of the single WEC is the main cause of the high variation in the O&M cost estimates. The results also suggest that the total maintenance cost in Scenario 6a, and 6b, can be preferable compared to the O&M cost estimates in Scenario 5. The reason is that for either employing the Small Vessel 1 or Big Vessel 2 the O&M cost estimate is much lower. This result illustrates that there is opportunity for cost reduction in the O&M cost estimates for WEC farm.

This is particularly true considering the decision of maintenance of 15 WECs in a WEC farm. However, the decision of employing the O&M vessel for maintenance activities of a single WEC will potentially lead to increase and more variation in the O&M cost estimates. The O&M cost becomes highly prohibitive with the strategy of employing a big vessel for maintenance activities of a single WEC device. In the following section, the results of analysis of the Total Initial Cost in terms of the WEC farm project capital cost are presented.

6.3 Total Initial Costs

The Total Initial Cost (TIC) is the cost incurred in purchasing the WEC device and constructing the WEC farm. For economic assessment of the WEC farm it is relevant to analyse the Annual Cash Flow (ACF). Ideally ACF is the sum of the revenue in the TIC and OPEX. Theoretically the OPEX includes all cost associated with O&M, insurance, utility charges and rent. Studies (Teillant et al., 2012; O'Connor et al., 2013) mentioned that ACF is calculated as the sum of the revenue in TIC and OPEX. To illustrate the economic value of the WEC farm, the ACF of a WEC farm is estimated for the different project category. In this case, the TIC only considers the initial capital cost of the WEC device.

To evaluate the TIC the main elements contributing to the annual cash flow of the WEC farm project are examined based on the maintenance of the single WEC and maintenance of 15 WECs. It is assumed that the same amount of electricity is generated each year, hence the relative income will be the same. Given that the TIC for a single 075MW WEC device is £6,400/KW, the energy generation income is based on the FIT. The revenue from 1(kWh) of electricity is estimated at £0.30(kWh) (DoE et al., 2013) based on an anticipated purchase price from a utility company and the added value from the ROCs.

As illustrated in Table 21 Section 4.4.5 in Chapter 4 case study application of the methodology, the TIC of a 0.75MW (750KW) WEC farm is estimated as £6,400/KW. If the revenue from 1(kWh) of electricity is given as £0.30(kWh); in that case the estimated revenue for the single 750KW WEC farm is £1,920(kWh). As discussed in Scenario 5 and summarised in Table 29, the O&M cost estimate for employing Small Vessel 1 to perform the O&M activities for a single WEC device at the WEC farm is estimated as £680,745. In that case, the annual cash flow is calculated according to Equation 145 as shown:

$$ACF = TIC - O\&M + Revenue(FIT)$$

$$= 4{,}800{,}000 - 680{,}745 + (1{,}920 * 24 * 365)$$

$$= 4{,}800{,}000 - 680{,}745 + 16{,}819{,}200 = £20{,}938{,}455$$

Furthermore, as illustrated in Table 21, the TIC for a 45MW (45,000KW) WEC farm is given as £3,680/KW. In this case, the estimated revenue is £1,104(kWh) based on a FIT of £0.30(kWh). As discussed in Scenario 6b and summarised in Table 35, the O&M cost estimate for employing Small Vessel 1 to perform the O&M activities for 15 WECs is estimated as £452,384. In that case, the annual cash flow is calculated according to Equation 145 as shown:

$$ACF = TIC - O\&M + Revenue(FIT)$$

$$= 165{,}600{,}000 - 452{,}384 \ + (1{,}104 * 24 * 365)$$

$$= 165{,}600{,}000 - 452{,}384 \ + 9{,}671{,}040 = £174{,}818{,}656.00$$

It is assumed that these costs are all incurred at the beginning of the project (i.e. year 0); hence discount rates are not applied in year 0. The discounted present value of the annual cash flow is applied to examine the present value of the future annual cash flow over a period of 25 years. This is based on the actual cost and an annual real interest or borrowing rate. Studies (O'Connor et al., 2013; Dalton and Gallachóir, 2010) acknowledged that a borrowing rate of 7.5% is ideal for long term projects span of around 25years.

Figure 112 demonstrates the results of the discounted present values of future annual cost based on the actual present cost of the project. In this respect, all future cash flows are estimated and discounted by using cost of capital to give their present values (PVs). The sum of all future annual cost (cash flows), both incoming and outgoing, is the net present value (NPV). In this context, the DCF analysis takes as input the annual cost and a discount rate and gives as output a present value. In this respect three real annual discount rate (3%, 7.5%, 12.5%) are examined in the analysis. The discount rate used is generally the appropriate Weighted Average Cost of Capital (WACC), that reflects the risk of the cash flows.

The y axis represents the discounted present value of the future annual cash flow. The x axis represents time in terms of year when the cost occurs. For example, considering a WEC farm project with 3% discount rate for a Single WEC, the actual annual cash flow is a function of the TIC, O&M cost and revenue estimated around £21,000,000 at the beginning of the project. In the first year of the project the present value of the future annual cash flow is around £20,000,000 as illustrated using the red line marker for R=3% at the top section of Figure 112. In other words, we would need to invest around £20,000,000 in present to get £21,000,000 in 1 year almost risk free.

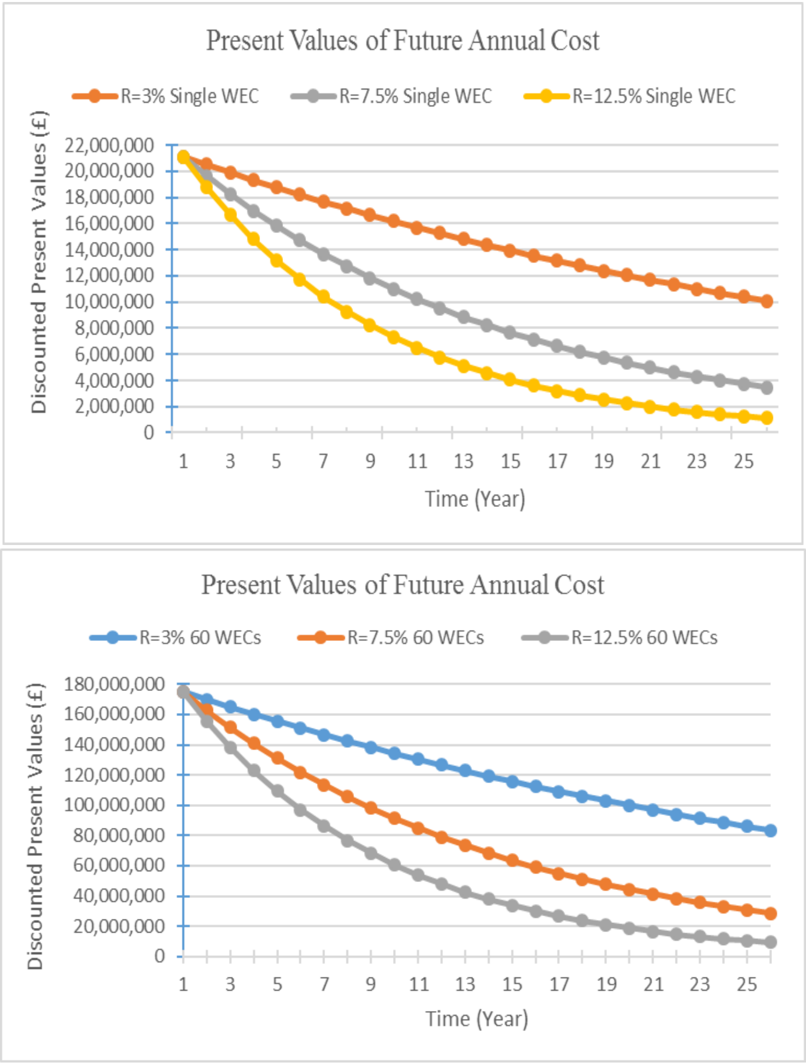

Figure 112: Discounted Present Values of future Annual Cash Flow

It can be observed that as the number of years increases the present value of the future annual cost for 3% discount rate on investment for a Single WEC decreases. Moreover, for higher interest rate such as 7.5% or 12.5% for investment on WEC farm having a Single WEC, it could be observed that the discounted present value of the future annual cash flow in the first year is lower. In the case of 7.5% and 12.5% interest rate, the present value of the future annual cash flow is around £19,000,000 and £18,00,000 respectively. This is a quantitative way of showing that money in the future is not as valuable as money in the present.

As mentioned earlier, it is assumed that these costs are all incurred at the beginning of the project (i.e. year 0); hence discount rates are not applied in year 0. The ACF in year 0 is the actual present worth of the project because it signifies the amount being spent as capital at the beginning of the project. However, it can be observed that the investment on 60 WECs attracts higher cost. This is because of the initial cost of purchasing the 60 WECs. Although, there is a significant reduction in the O&M cost estimate as demonstrated in Scenario 6a, and Scenario 6b, compared to Scenario 5; this suggests that the TIC of the WEC is a significant contributor to the variation of the cost in the beginning of the project.

In Figure 112 depending on the interest rate, the discounted present value of the future cost continues to decrease over time for either investment on a single WEC or 15 WECs. Assuming there is a choice of earning cash now or in a year's time, investors would all prefer to earn it now. This concept is known as the time value of money. In order to make an investor indifferent to earning the cash now, in a year's time the investor would require the cash plus interest. Alternatively, if an investor were to earn cash in a year's time, in order to be indifferent today the investor would accept an amount less than the actual cash since the investor could earn interest if he had the cash today. In the latter case, the future cash flow is discounted.

Figure 113 demonstrates the results of the future worth of the present annual cash flow at the end of the period. This is based on compounding interest for three different interest rates 3%, 7.5% and 12.5%. The y-axis represents the present value of the future cost of capital. The x-axis represents the time when the loan is payable based on single payment of the compound amount. In the case of investing on a project consisting of a single WEC device, the annual cash flow is estimated as =£20,938,455. This is the actual present value of the capital investment at the beginning of the project. At that point the interest rate is 0%. This is because the cost is assumed to be incurred at the beginning of the project i.e. year 0.

Figure 113 shows that investing at an interest rate of 3% is not prohibitive compared to the rate of return for investing at 12.5%. In case of investing at an interest rate of 3% or 7.5% for the single WEC, the present value of the future cost of capital at the end of the 25 years period is less than £50M. Depending on the cost of capital (rate of return or interest), the amount owed at the end of the first year is the original sum (actual present value) plus the cost of capital. This process involves accumulating interest of both the principal and undistributed interest.

Figure 113: NPV Cost of Capital for different interest rates

In addition, the results in Figure 113 also shows the present value of the future cost of capital for 15 WECs. In this case, the annual cash flow was estimated as £174,818,656.00, at the beginning of the project. This is assumed to be the actual present value of the capital investment on the WEC farm project consisting of 15 WECs. It can be observed that the present value of the future capital cost is highly prohibitive at an interest rate of 12.5%. This is particularly true when the payment period exceeds 10 years.

As in the investment for maintenance of a single WEC, the present value of the future cost of capital increases as the interest rate increases. The main difference between the two project is the value of the initial capital requirement in relation to the annual cash flow. The initial financial requirement for investment on 15 WECs is higher. This can present a significant advantage for investment on single WEC. Apart from the huge capital requirement for investing on 15 WECs, there is high prospect for cost reduction in the O&M cost estimate.

6.4 NPV and IRR Sensitivity Analysis

The NPV profile is used to illustrate the criteria to support the investment decisions for the WEC farm project. Considering that investing in a single WEC device has a different cost from the investing in 15 WECs; there is decision of whether to spend the extra money. The NPV considers the timing and size of cash inflows (e.g., revenues, salvage value of assets on wind up), and cash outflows (e.g., initial asset construction costs, working capital costs and annual operating costs), as well as the riskiness inherent in investing in the WEC farm project. In this context, the riskiness is reflected in the risk adjusted discount rate or required rate of return.

The NPV profile is applicable to support the investment decisions. The procedure involves estimating the market value of the project using discounted cash flow valuation. NPV can be interpreted as the increase in wealth in present cash value because of undertaking the project. A successful project is one whose NPV is positive (Ashley, et al, 1987). In this context, each of the future net cash flows that occurred in the different years of the project are translated into the present value and the sum is taken. At the start of the time interval e.g. year 0 of the project, the cash flow is regarded as a negative value because it is going out (as amount spent).

The first-year cash flow as well as cash flow of all the different years except year 0, is considered as income. The NPV is then analysed subject to the specified interest rate. The specified annual interest rate is the relative discount rate applied in the discount factor formula. In this context, the discount factor formula is used to arrive at a present value estimate which is used to evaluate the potential or viability of the project. In this case, the discount rate is the interest rate that is required to earn a certain amount of money today to end up with a certain amount of money in the future.

The NPV analysis uses “discount factor” in terms of the discount rate to show that the value of money today will not be the same as its value at the end of the project. In this context, different interest rates are used as a "test" or "hurdle" for the investments. This is applicable to examine the sensitivity of the annual cost to the discount rates at the beginning of the project and the future annual cost. Figure 114 illustrates the project investment criteria using the net present value approach. In this case an interest rate of 3% was initially considered to examine the NPV of future annual cost for the investment on a single WEC device.

The y-axis represents the NPV of future annual cost and the x-axis represents the range of discount factor corresponding to the required rate of return for the specified interest rate. In this respect, the discount factor is used relatively as the discount or interest rate because the discount factor is the percentage rate used to evaluate the present value of a future cash flow. This is applicable to examine the risk and general financial benefit of WEC farm. Considering interest rate of 3%, it is observed that the NPV of the annual cost is approximately £400M for a discount factor of 0%. This is the single payment present worth of the future annual cost.

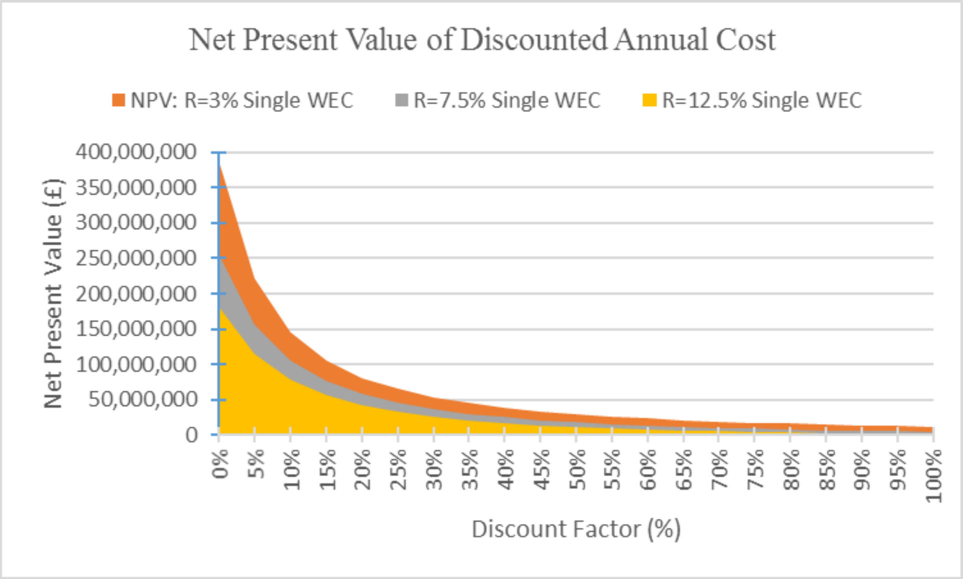

Figure 114: Net Present Value of Discounted Annual Cost for Investment on Single WEC

For higher interest rates such as 7.5% and 12.5%, the NPV of the annual cost is approximately £250M and £150M respectively for a discount factor of 0%. This is based on the total initial cost and associated operational expenses for maintenance activities of the single WEC. As the discount factor increases from 0% to 100%, there is a reduction in the value of annual cost as depicted in Figure 114. The IRR is the rate inherent in the cash flow and in the case of an investment with 3% interest rate, the IRR is around 29%. Studies (Feibel et al., 2003) acknowledged that a project can be evaluated based on the IRR of that project.

If the percentage of IRR is high, this indicates that the project is probably worth investing on. If the percentage of IRR is low, this indicates that the project has high financial risk. The NPV of the annual cost is high because the interest rate of 3% is low compared to 7.5% or 12.5%. For this reason, the present value of annual cost is also high as illustrated in Figure 114. The result suggests that the investment can be accepted because it has a positive NPV. In the case of investment using 7.5% and 12.5% interest rate, the IRR is around 33% and 35% respectively.

In this case, a project with these interest rates can be acceptable because the NPV is positive and the IRR is not too close to the interest rate. However, the concern or disadvantage may include committing the huge amount of capital for only a single WEC in the WEC farm. Assuming the interest rate is higher than 12.5%, the circumstance of the annual cost will be different. In this context, a discount factor greater than 35% can result to a loss of capital for investment on the single WEC.

It is observed that as the interest rate increases the NPV of the annual cost reduces. In this case, any discount factor above IRR will begin to yield negative NPV on the annual cost. In this context, the financial risk starts to become visible at discount factor greater than the percentage of the IRR. The point when NPV becomes a negative value suggest that the investment can be rejected at that point. For investment at an interest rate of 3%, 7.5% or 12.5%, the project is deemed to be secure. The reason is that the IRR is much greater than the interest rate. Moreover, the IRR is the highest value of interest rate that a project can consider giving NPV of zero.

This implies that as the discount factor increase the IRR also increases up to the point when the NPV of the annual cost becomes equal to 0. The reason is that the IRR is the percentage which corresponds to the discount rate used and this makes the NPV of all cash flows from the project equal to zero. Any value above the IRR will result to a negative cost as illustrated in the red area on the x-axis in Figure 115. In the case of applying 3%, 7.5% or 12.5% interest rate, the criteria for rejecting the investment is minimal, indicating that the financial risk is low. For this reason, “NPV Reject” is barely visible.

In comparison to the results of the interest rate of 55% in Figure 115, the “NPV Reject” is visible. In this case, the financial risk starts to increase, and the investment begin to loss capital as illustrated with the negative NPV depicting the red area in Figure 115. At an interest rate of 55% the IRR is around 70%. In this case the financial risk is greater, and this also suggest that any discount factor above 70% will yield a negative NPV because all the NPV cash flow equals 0 at that point. It can be observed that the value of the capital reduces as the discount factor increase.

Studies on forecasting long term financial investment (Cheremushkin, 2010) mentioned that the NPV can be used alongside with the IRR to assess the desirability of a project. In the context where the interest rate is the cost of the capital, the NPV is used to assess if it is worth investing in the project. This is applicable by comparing the NPV with the IRR. If the NPV of the cash flow at the specified interest rate is negative, it implies that the investment or project is losing money. A positive NPV suggest that the investment is profitable (Cheremushkin, 2010).

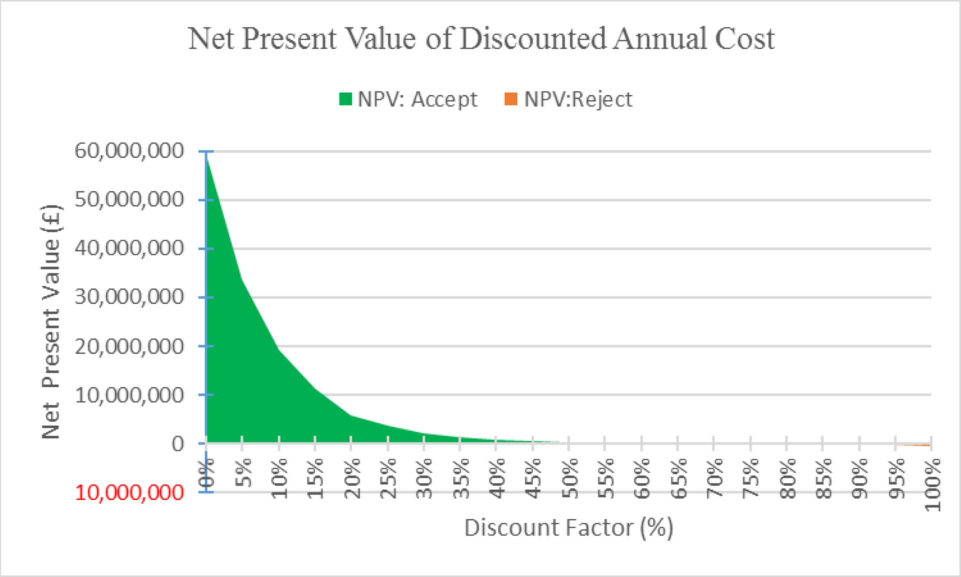

Figure 115: Net Present Value of Discounted Annual Cost for Investment on Single WEC R=55%%

In this case, it can be observed that the NPV cash flow is low compared to previous examples of investment with relatively low interest rates. In this respect, the result suggests that investing in the single WEC using relatively low interest rate such as 3%, 7.5% and 12.5% can be viable. In this case, the project is deemed to be desirable. However, investing at an interest rate of 55% has high financial risk If the discount factor is closer to or greater than the IRR the project is deemed risky and should not be accepted.

NPV assessment considers a breakdown of the TIC of the WEC, O&M costs and the electricity revenue generated across a life-time of the WEC farm project. The key number needed to determine NPV is the interest (discount) rate. The reason is that it is the factor by which future monies received are multiplied to obtain net present value. As discussed in NPV results for investment on a single WEC, it was observed that relatively low interest rates such as 3%, 7.5% or 12.5% makes the value of the capital to appear high. Consequently, the NPV of the annual cost become high.

Figure 116, demonstrate the results of the NPV analysis for 15 WECs in a WEC farm projects. In contrast to the project investment criteria for the single WEC device, it can be observed that the present value of the discounted annual cost is much higher. The reason for this high annual cost is due to the total initial cost for 60 WECs, together with the total cost of O&M activities for 15 WECs in the WEC farm. As illustrated and discussed in previous pages, the estimated annual cash flow for a single WEC device in a WEC farm is around £20M. In comparison to the cost for 15 WECs, the estimated annual cash flow is around £174M.

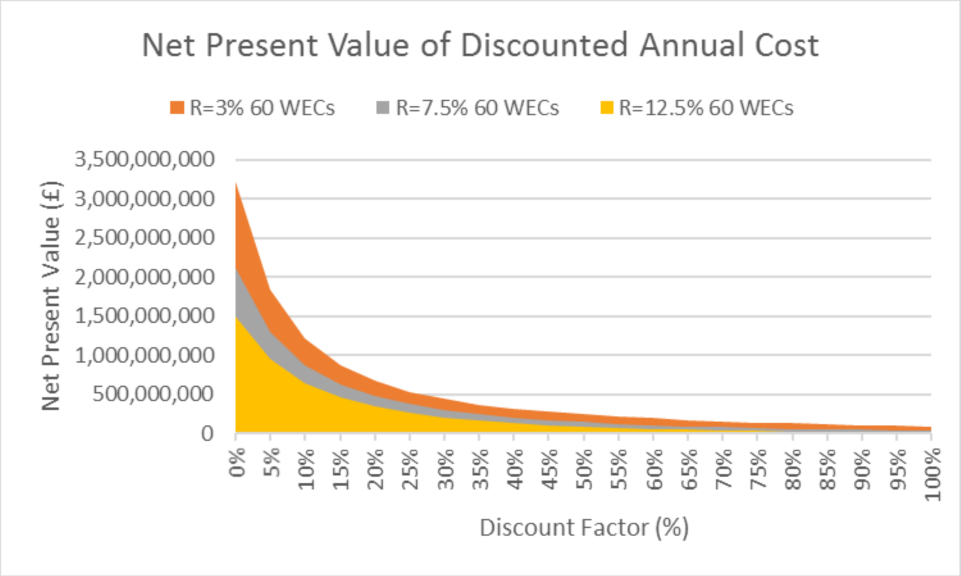

Figure 116: Net Present Value of Discounted Annual Cost for Investment on 60 WECs

There is financial benefit for the cost of capital, in terms of reduction in the total initial cost when the discount factor is applied. There is also financial risk or disadvantage of committing the huge amount of capital for only a single device in WEC farm. However, the NPV of annual cost as illustrated in Figure 116 is influenced by the interest rate. In this respect, the NPV of the discounted annual cost is around £3,000,000,000 for an interest rate of 3%. In this case, the discount factor is 0% for the investment on 15 WECs. For interest rates such as 7.5% and 12.5%, the NPV of the discounted annual cost is around £2,000,000,000 and £1,500,000,000 respectively for discount factor of 0%.

As the discount factor increases, the NPV of the annual cost reduces. In this context, the NPV of the annual cost represents the present value of the future annual cost for investing on 15 WECs over a period of 25 years at compound interest. Similarly, the annual cash flow values begin to depreciate in present value as the discount factor increases for investment on 15 WECs. As in the investment on a single WEC with interest rate of 12.5%, the value of the annual cash flow reduces as the discount factor increase. The IRR is also around 35% indicating the point where the NPV cash flow starts to become negative.

The result suggests that the NPV of the project is acceptable for discount factors below 35%. The difference is that the annual cash flow is higher. The results show that investment on the WEC offer financial benefits. Similarly, Figure 117 demonstrates the net present value of the discounted annual cost for investment on 15 WECs using interest rate of 55%. It can be observed that the net present value of the discounted annual cost is high. The investment can begin to lose capital if the discount factor exceeds 45%. This is the IRR for the NPV of the investment criteria.

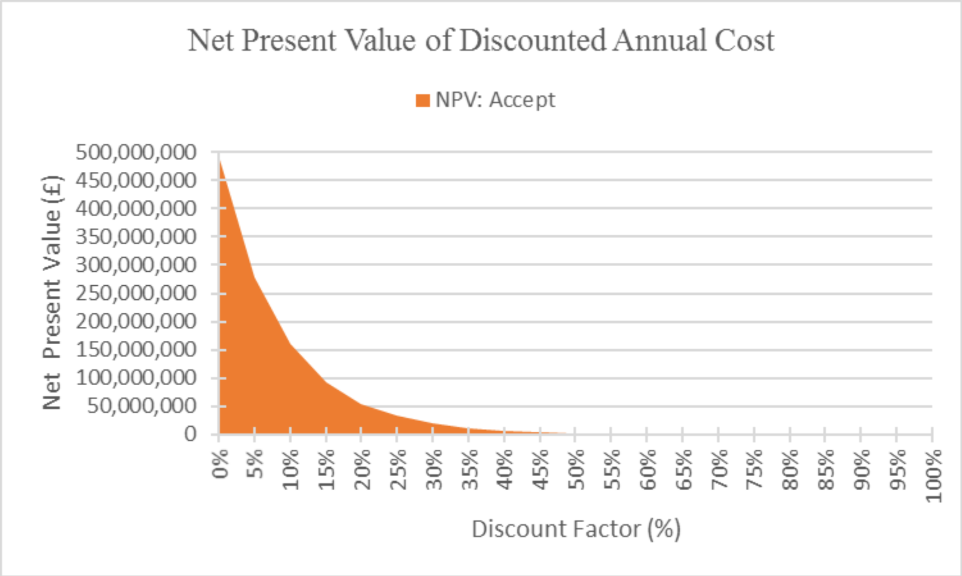

Figure 117: Net Present Value of Discounted Annual Cost for Investment on 60 WECs R=55%%

In this context, the project is evaluated based on the IRR of 45%. The IRR is the rate inherent in the cash flows. If the percentage of IRR is high, this indicates that the project is probably worth investing on. If the percentage of IRR is low, this indicates that the project has high financial risk. This confirms that the IRR is the highest value of interest rate that a project can consider, to give a NPV of zero amount. In this context, the desirability of the project is assessed to support the decision on whether to spend the additional capital when comparing projects with different cost.

It can be observed in that the financial risk is greater for an interest rate of 55%. As in the case of the investment for single WEC, the IRR is round 45% and this is close to the interest rate. For this reason, the NPV of the cash flow can be rejected because the financial risk is high. The approach used for economic assessment of the wave energy facility usually involves the method which incorporates some information about potential impacts into a framework that can be used in parallel to a formal cost-benefit analysis. The results presented are applicable to provide answers on whether it will be worth investing time and capital resources towards deploying a wave energy farm.

The total nominal profit can be adjusted for cash depreciation by multiplying the total nominal profit by a discount factor. By integrating the area under the curves, an impression of the average overall financial benefit of a WEC is estimated. This considers the increased revenue from the sale of electricity and the added capital cost of the WEC. NPV is crucial for determining the time value of money when evaluating long-term projects. In this context, the net present value is used to help evaluate profit and losses in the present value of cash based on future payments.

6.5 Chapter Summary

This section summarises the work that has been presented in this Chapter. This thesis has presented an integrated approach that enables the wave energy resource and O&M cost estimates for a WEC farm to be investigated. In this context, a novel integrated framework has been developed for the preliminary assessment of the wave resource using the historical wave data for the case study location. Moreover, it enables investigation of the O&M cost to evaluate the economic viability of the WEC farm project at any selected location.

This framework improves the reliability of decisions and allows operators to recognise the consequence of operating decisions at a new level of detail. Economic valuation of wave energy facility can be used to compare the net benefits across sites and device-specific technologies. It is envisioned that wave energy may be economically feasible in the near future, with hope that wave energy could become a source for clean, safe, reliable, and affordable energy without significant greenhouse gas emissions.

The O&M model can assist operators in making best decisions and planning as far as cost effective WEC farm operations are concerned. The integrated framework will assist the WEC operators to follow an optimized maintenance strategy which considers the whole farm and not just a single device in the WEC farm. The economics of operating an array of WEC as an energy farm is analysed based on the O&M costs. The impact of OPEX on project net present value (NPV) and internal rate of return (IRR) are illustrated. A cost analysis is performed to explore how the key inputs to the assessment affect the economic performance of the case study project. In this respect, the proposed methodology of the O&M cost estimation model is validated.

Chapter 7- Conclusion and Recommendations for Future Work

7.1 Chapter Outline

This Chapter summarises the information for the work presented in this thesis. First, the contributions of the thesis to theory and practice are presented in Section 7.2. Subsequently, the novelty of the research is highlighted in Section 7.3. This is then followed by the recommendations for future research in Section 7.4 and the concluding remarks in Section 7.5.

7.2 The Significant Contributions of The Thesis

Given the nascent stage of wave energy sector, this thesis contributes to providing the relevant tools to investigate the future market potential, together with opportunities for cost reduction of electricity generation using WECs. This will help to accelerate the rate of deployment of WEC technology and provide the motivation for developing new and alternative markets for WECs. Considering the enhancement of the offshore WEC farm power generation and minimisation of the total O&M cost, the analysis in the integrated framework enables operators to decide the vessel specification which will bring more financial benefit.

The need for understanding the offshore environment is highlighted in order to facilitate more reliable energy yield predictions and strategies for O&M of the WEC farm. This thesis significant contribution is in the area relating to the methodology and modelling, wave data analysis and quantitative techniques applied in the development of the integrated framework. This is significant in developing countries where facilities and reliable information for wave energy assessment are not readily available. This study can provide a basis for developing new policies that will encourage sustainable development in areas of marine renewable energy.

7.2.1 Contribution to the Thesis Main Aim and Research Objectives

The main aim of the thesis has been to develop and test the integrated framework for resource assessment and O&M cost modelling for wave energy farm project, providing a decision-making support for investment options.

Objective 1 in this thesis contributes to the research objectives because it enables the examination of different research work in the field; collecting relevant information available on wave energy resource, technology, O&M studies, and economic data to develop the integrated framework for the preliminary assessment of the WEC farm project. To achieve the objective a thorough literature and critical review is provided in Chapter 2 of this thesis. This is significant to develop an integrated framework that is consistent with research and developments in the wave energy industry.

Objective 2 in this integrated framework, is achieved through the preliminary analysis and application of the historical wave data. This is significant to analyse and evaluate the offshore wave energy resource. In this respect, the historical wave data of any location can be applied to evaluate potential resource, using any selected WEC technology. This contribution will help to support future growth of the marine renewable energy industry in terms of providing a basis for considering wave energy generation projects in other parts of the world.

Objective 3 involves investigating the weather windows for O&M vessel operation and using different scenarios and cost of O&M activities to account for variation in the cost of the O&M estimates. this is significant to help in assessing the feasibility of deploying the WEC and O&M activities of the WEC. In relation to the O&M modelling in the integrated framework, the output of the preliminary analysis in the resource assessment model is applied to define the marine operational environment for vessel operation, in relation to O&M activities of the WEC.

Objective 4 contributes to developing an integrated framework for resource assessment and modelling of the O&M cost estimates for maintenance activities of the WEC. This has been achieved using existing theoretical models to establish the criteria for assessing the economic value of the wave energy farm project, together with the method for that could be used for validating the proposed methodology and framework.

7.2.2 Contribution of The Specific goal to Theory and Practice

Through the development of the integrated framework for resource assessment and O&M cost modelling, this research accomplishes the specific goal of providing an intellectual lead in the pursuit of the low-carbon economy of the future. In this respect, an analysis routine (method) to analyse any chosen location for installing WECs has been provided. This is achieved by estimating the power generation at the location and total operational cost of running the project.

This thesis presents the methodology for analysing the total O&M costs, including real weather data and O&M activities for the WEC farm. The O&M cost is evaluated and described based on relevant maintenance strategies where the overall repair costs including costs due to lost electricity production are minimized. One of the key metric used to demonstrate the added value of the extra O&M activity on the power production is the cost per unit production (O&M cost/MWh). The developed model can be used to validate the future models.

In conclusion, the lack of operational experience in the wave energy sector is identified as one problem experienced when attempting to quantify the profitability of a WEC farm project. This situation is directly linked to the high level of variation in the operational costs and device availability estimates. To address this problem, operational simulations which draw on the experience of industries that carry out similar activities such as offshore wind and oil and gas exploration can be used to assess the costs and effectiveness associated with a wave farm O&M.

7.3 Novelty of The Research

In this research, an integrated framework for resource assessment and O&M cost modelling has been developed for preliminary assessment of wave energy farm projects. The motivation is due to the requirement for increasing research and development in electricity generation projects using WEC technology. Thus, this research provides a basis for considering the resource assessment and O&M cost modelling for WEC O&M activities. This research is different from other studies because it provides a systematic development of a methodology which incorporates the resource assessment and O&M cost modelling for preliminary assessment of a WEC farm project. In this respect, the aim of the thesis has been achieved.

The gaps in existing literature reveal that one important issue undermining the growth of the wave energy industry is the lack of a single consistent and well-documented source of information; which clearly defines the approach for preliminary assessment of the wave energy resource at a potential site. The novelty of the work presented in this thesis relates to the research gap because it uses well-defined parameters that are consistent with the existing literature to describe the method for preliminary assessment of the wave energy farm project.

The integrated framework developed in this thesis is applicable to avoid the problem of ambiguity and difficulty in comparing preliminary assessments results. In this respect, the integrated framework provides a methodology for investigating and presenting the variables which are relevant for estimating the wave resource for preliminary assessments of the selected location. The integrated framework is unique because, within the framework, the issue relating to offshore access for WEC O&M activities is considered. These aspects are not included in the existing framework and feasibility studies for WEC farm project. The influence of O&M vessel transport cost on WEC O&M activities is not thoroughly considered in existing methods.

This brings about the variations surrounding the WEC O&M cost estimates. Existing resource assessment methods have also failed to include the O&M planning aspects. These aspects have been identified as major contributors to the high cost attributed to energy production using WEC technology. The integrated framework provides the tool for analysing and identifying the areas contributing to the variation in the cost of the electricity generating project using WECs. The integrated framework considers the preliminary investigation of the wave energy resource and O&M cost for maintenance activities required to keep the WEC in continuous operation.

The novelty of this research is identified in the methodology and modelling presented in Chapter 3. In this context, Chapter 3 methodology and modelling provides within a single framework an integrated approach for resource assessment and O&M cost modelling. In relation to the methodology and modelling in Chapter 3, historical wave data for the case study location is applied to assess the characteristics of the wave energy resource in Chapter 4 case study application of the methodology. As an integrated framework, the same historical wave data, as an output of the resource assessment is applied to describe the marine operational environment for O&M activities at the case study location.

This method is unique because it provides a comprehensive framework not only for assessing the site but also providing the requirements for O&M planning of the WEC farm based on pre-defined O&M strategies. The benefits of incorporating an O&M model within the framework for the preliminary assessment of a WEC farm project will provide offshore WEC developers and operators with the relevant information. The information is applicable to examine the total

O&M cost and to identify the areas of the variation in the O&M cost estimates. Possible solutions to minimise the variation are investigated because behind every resource assessment there is a possibility of deploying a WEC device to harness the resource.

7.4 Recommendations for Future Research

- Further studies are recommended to investigate other distribution as well as datasets for resource assessment. The future work is relevant to develop code in Java and Python.

- There is a need for future work to discuss alternate investment and comparisons between wave and other marine renewables, e.g. into another renewable source like tidal or subsea currents. For WECs to succeed they must harvest the wave energy at a considerably low cost with feasible O&M practices.

- In relation to the O&M model, cable cost for WEC farm is another important area which requires further study. This is important because, in existing literature and study of WEC applications, simplistic estimates are often adapted and applied. Hence further work based on preliminary simulations of detailed cable costs is recommended. This will be useful in terms of comparing detailed cable costing for different sizes of WEC farms.

- Further study is required to investigate and discuss the reliability of multiple WECs in relation to the influence on the O&M cost estimates.

- Further study is required to investigate the risk-based approach where only boats are used and another approach where the target is to minimize the downtime of the device. Limited availability of maintenance equipment may drive the O&M costs.

7.5 Concluding Remarks

- In this thesis, a novel integrated framework for resource assessment and O&M cost modelling has been introduced and a preliminary assessment of a WEC farm has been performed. The factors affecting the O&M cost of a WEC Farm have been analysed and discussed. The link between Resource assessment and O&M models is illustrated in the flowchart of the integrated framework in Chapter 3. Overall, the concluding remarks of this research study are summarised in the following:

- At any point in the ocean, the wave climate is the result of waves arriving from different directions. The wave energy is the time integral of the wave power and both terms ‘power’ and ‘energy’ are used in this thesis. For time averages, ‘power’ and ‘energy’ are numerically equal.

- In relation to the resource assessment model in the integrated framework, investigating the characteristics of the sea state is important to this study. The reason is that it helps to provide a better understanding of the wave environment. This is particularly useful with respect to the operation of the WEC.

- In the integrated framework, the resource assessment model is employed to generate the hourly wave power production over the lifetime of the WEC farm. By combining the power matrix of any selected device, the captured wave power and total energy output due to availability can be ascertained.

- The significant wave height plays an important role to determine the theoretical energy that can be extracted from the resource in the location. Based on the preliminary assessment using the historical wave dataset, the results show that the bin values of sea state corresponding to $\mathrm{H_s} = 1.5\mathrm{m}$ and $\mathrm{H_s} = 2.0\mathrm{m}$ have the highest yearly occurrence in hours. This implies that they have the tendency to contribute more to the wave energy resource.

- The preliminary assessment results demonstrate that the theoretical energy available in the waves is around 1,256.91 to 321,768 ($\mathrm{J/m^2}$). The theoretical wave power that could be extracted at the case study location is around 0.47 to 282.24($\mathrm{KW/m}$). This provides an idea of the energy associated with the wave field.

- The average values of the parameters in the historical wave dataset have the tendency to fluctuate each year and depending on the season. The average annual wind speed values are around 6 to 18m/s. In the case of the significant wave height, the average values are 1.4m to 1.8m, while the average wave period values are around 10.3 seconds to 11 seconds. The variability and seasonality results have been presented.

- The wave dataset selected for the case study application is a good representation of the offshore wave environment for this research. The parameters in the historical wave dataset were analysed to investigate the characteristics of the resource based on their frequency of occurrence and probability distribution in the dataset.

- The characteristics of the wave resource show that the wave power is based on the probability of occurrence of the dominant values at the case study location. A combination of the dominant significant wave height and wave period represents the sea states that contribute most to the wave energy resource. From the resource assessment point of view, it is important to ensure that the WEC to be installed should have maximum efficiency for the sea states providing the bulk of the wave energy at the chosen location for deploying the WEC farm.

- In relation to the O&M model described in the integrated framework, two intermediate outputs are obtained from the resource assessment model. These intermediate outputs are related to the resource description in terms of the resource availability and accessibility of the WEC for the O&M activities. The accessibility factors link the resource assessment model to the O&M model for analysis of the O&M cost estimates.

- This thesis has identified the costs components that contribute the most to the variation in the O&M cost estimates and the overall costs of the WEC farm project. The study also identified the possible approaches to reduce the O&M costs and additional actions which should be considered. Offshore WEC farm operators can perform cost-benefit analysis by using the O&M model in the developed integrated framework.

- Following the detailed O&M costs model described in Chapter 3 and applied in Chapter 4 to explore the plausible range of the cost elements; the results demonstrated that the cost elements contributing most to variation in the O&M cost estimates are the O&M

vessel cost and potentially the cumulative cost of spare parts required for maintenance of 15 WECs. The cost of spare parts is an additional component in the workshop cost.

- The results of the analysis show that the two most important control variables for O&M cost are farm size and O&M vessel specification. These two important factors contribute to variation in the O&M cost estimates. Opportunities for cost reductions relate to the distance of the WEC farm from shore, choice of maintenance strategy and location (onshore or in situ), frequency/duration of maintenance visits and the type of vessels used for the O&M activities.

- In this thesis, suitable O&M vessels that can lead to a reduction in the cost of O&M activities have been identified. It is relevant to have a good understanding of the options available for WEC O&M Vessel. This will contribute to sustaining the productivity of the WEC at the highest level. It has been shown that the benefits of employing Small Vessel 1, with low charter rate bring great financial and economic advantages. This is particularly true in terms of reducing the total O&M cost.

- Employing either Small Vessel 1 or Big Vessel 2 for maintenance activities of a single WEC in the WEC farm does not bring an economic advantage since the cost increase cannot be compensated by the production increase. The important attributes which significantly influence the decision of employing Small Vessel 1 are due to their capability and operational limitations.

- On the other hand, the cost of employing Big Vessel 2 to perform the O&M activities is significantly higher compared to the cost of employing the Small Vessel 1 for the same operational activities. This is particularly due to the difference in the charter rate. Big vessel charter period should be investigated carefully before chartering.

- In addition, the results show that chartering the O&M vessel for a long period increases the total O&M cost and eventually the total financial loss, especially for the maintenance of a single WEC. The O&M vessel transport cost is seen to be influenced by the charter rate, the number of days the vessel spends at sea and the fuel cost. For this reason, time for which the O&M vessel is initially chartered is estimated to consider the initial duration that the vessel will be needed.

- The results demonstrate that the cost of employing Big Vessel 2 in either Scenario 1 or Scenario 3 is expensive. This is particularly true for the maintenance of a single WEC irrespective of the O&M strategy. It is observed that the additional cost increase in the case of employing Big Vessel 2 in either Scenario 4a, or 4b, is almost equivalent to the normal total transport cost for employing Small Vessel 1 in Scenario 2.

- There is a significant reduction in the O&M cost estimates in Scenario 6 compared to Scenario 5. This equally confirms that the decision of employing Big Vessel 2 can be compensated in Scenario 6. The cost of employing Big Vessel 2 is not encouraging due to the added cost contingency factor and high charter rate. The corrective maintenance can be considered employing smaller vessels. This will help to bring down the cost particularly when the vessel will be utilised for a longer period.

- In Scenario 2b and Scenario 4b, the high O&M cost estimate associated with the workshop cost is due to the cumulative or bulk purchasing cost of spare parts for repair 15WECs. In Scenario 1 the total transport cost (C_{trans}) which is the total cost for hiring Small Vessel 1 excluding the cost of crew, for the duration of 10 days to perform the maintenance activity is given at $C_{trans} =$ =£106,908. For Big Vessel 2 the total transport cost is given at C_{trans} =£286,636. This show that the cost of employing Small Vessel 1 is cheaper compared to Big Vessel 2.

- In Scenario 1, the total cost of preventive maintenance is estimated at $C_{pm} = £325{,}372$, for employing Small Vessel 1 for 10 days in a project year. For employing Big Vessel 2 in Scenario 1, the total preventive maintenance cost is estimated at $C_{pm} = £505{,}100$, for a period of 10 days in a project year. The contribution of the labour cost to the total O&M cost estimate is minimal compared to the workshop and equipment/tool cost. The labour cost will increase as the number of technicians and working time increases. This will remain the same for either Small Vessel 1 or Big Vessel 2 employed in either Scenario 1 or Scenario 2.

- The workshop cost is also a significant contributor to the increase in the O&M cost estimates. This is because the workshop cost is a function of the number of technicians, and the cost of spare parts needed. However, the labour cost is minimal compared to the cost of spare parts needed for the O&M activities. This is particularly true when the technicians are being paid to work for 8 hours per day. The cost of spare parts accounts for over 95%, while the workshop labour cost accounts for less than 5% of the workshop cost in Scenario 2a, and 2b. The workshop cost accounts for around 30% of the total O&M cost estimate in Scenario 2a, and 20% of the total O&M cost estimate in Scenario 2b.

- The cost of hiring the Small Vessel 1 accounts for around 36% of the total O&M cost in Scenario 2a, and 31% of the total O&M cost estimate in Scenario 2b. This show that there is a significant cost benefit for employing the Small Vessel 1. In contrast to Scenario 1, the results showed that the labour, workshop, and equipment cost remained the same either for Small Vessel 1 or Big Vessel 2. This is because only one device is maintained, the cost of employing the vessel is not easily compensated.

- The cost of spare parts required for the maintenance or repair of the 15 WECs is a significant contributor to the total workshop cost. In Scenario 2b and Scenario 4b, the high O&M cost estimate associated with the workshop cost is due to the cumulative or bulk purchasing cost of spare parts for repair or maintenance of the 15 WECs. This is because the estimated workshop cost is inclusive of the workshop labour cost and the cumulative spare parts cost of each spare part used for the repair or maintenance.

- The results suggest that the high level of variation in the cost associated with the O&M cost estimates can be attributed to the decision of employing either the Small Vessel 1 or Big Vessel 2 for maintenance activities of a single device in a WEC farm. The variation in the O&M cost estimates is greater particularly when the total cost for maintenance of 60 WECs is considered in Scenario 6 compared to Scenario 5.

- In the integrated framework, the O&M case study results are based on the WEC farm attributes, O&M vessel utilisation and specific cost linked to the resource description output in the resource assessment model. The O&M accessibility factors provide the information relevant to maximise the weather window during which the O&M activity can be performed safely.

- One of the key element suggested for minimising the O&M costs is maximising the weather window during which O&M activity is possible. If O&M activities can only be carried out in very favourable conditions, there is the probability that there will be delays in the project. This can contribute to additional O&M costs.

- By analysing the number of occurrence of weather conditions for each month, this can provide the information relevant to maximise the weather window during which the O&M activity can be performed safely. The historical wave data for the case study location is applied to further investigate the offshore accessibility factors and O&M vessel utilisation for the O&M activities.

- The results demonstrated for O&M vessel utilisation suggests that practical usage for either Small Vessel 1 or Big Vessel 2 is possible but to some relative extent. This relative extent is defined by the maximum or minimum significant wave height threshold prevalent at the case study location during the time of the O&M activity. The results show that O&M vessels in the category of Small Vessel 1 limited by Hs=2m can be used for a minimum period of 1 day and up to 4 days in any month of the year.

- In the integrated framework, analysis of the weather window is relevant to identify the suitable conditions when the O&M vessels can perform the O&M activities for the WEC farm. These aspects distinguish this study from other studies. The WEC O&M financial consequences with respect to vessel operation are generally neglected in existing studies, thus contributing to the variation in the O&M cost estimates.

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Appendices 1. Device Developers, Concepts, Country and Classification

Table 36: Device Developers, Concepts, Country and Classification

S/No.	Company Name	Country Base	Device Name	Device Type
1	Wave Energy Conversion Corporation of America (WECCA)	USA	Advanced Wave Energy Conversion System (AWECS)	A
2	Ecomerit Technologies	USA	Centipod	A
3	Waveenergyfyn	Denmark	Crestwing	A
4	DEXAWAVE A/S	Denmark	DEXAWAVE converter	A
5	Ocean Energy Laboratory of Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences	China	Duck	A
6	Ocean Energy Laboratory of Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences	China	Eagle	A
7	Martifer Energia	Portugal	FLOW	A
8	Group Captain SM Ghouse	India	Free Floating Wave Energy Convertor (FFWEC)	A
9	Navatek Ltd	USA	Navatek WEC	A
10	Oceantec Energias Marinas SL	Spain	Oceantech Energy Convertor	A
11	Pelamis Wave Power	UK	Pelamis	A
12	Pontoon Power	Norway	Pontoon Power Converter	A
13	Floating Power Plant AS	Denmark	Poseidon – Wave wind hybrid	A
14	Tecnalia	Spain	PSE-MAR	A
15	University of Edinburgh	UK	Salter's Duck	A
16	Sea Power Ltd	Ireland	Sea Power Platform	A
17	GEdward Cook	USA	Syphon Wave Generator	A
18	Fred Olsen Ltd	Norway	The B1 Buoy	A
19	Vigor Wave Energy AB	Sweden	Vigor Wave Energy Convertor	A
20	Vortex Oscillation Technology Ltd	Russia	Vortex Oscillation Technology	A
21	Kneider Innovations	France	Wave Energy Propulsion	A
22	Greencat Renewables	UK	Wave Turbine	A
23	Waveberg Development	USA	Waveberg	A
24	AlbaTERN	UK	WaveNET (Squid)	A
25	WavePiston	Denmark	WavePiston	A
26	Atmocean Inc	United States, with subsidiary in Peru	WES - Wave Energy System	A
27	Perpetuwave	Australia	Xtracta (Hybrid Attenuator)	A
28	Nualgi Nanobiotech	India	Rock n Roll wave energy device	A/B
29	Columbia Power Technologies	USA	StingRAY	A/B
30	Blue Power Energy Ltd	Ireland		B
31	Euro Wave Energy	Norway		B
32	Renewable Energy Pumps	Lebanon/USA		B
33	Seatricity	UK		B
34	Brandl Motor	Germany	Brandl Generator	B
35	Carnegie Wave Energy Ltd	Australia	CETO	B
36	Norwegian University of Science and Technology	Norway	CONWEC	B

37	CorPower Ocean AB	Sweden	CPO2	B
38	Delbuoy	USA	Delbuoy Wave Powered Desalination	B
39	Hann-Ocean	Singapore	Drakoo	B
50	AeroVironment Inc	USA	Eel Grass	B
41	Aqua-Magnetics Inc	USA	Electric Buoy	B
42	Able Technologies LLC	USA	Electric Generating Wave Pipe	B
43	Applied Technologies Company, Ltd (ATC)	Russia	Float Wave Electric Power Station (FWEPS)	B
44	SEEWEC Consortium	UK	FO3	B
45	HidroFlot SA	Spain	Hidroflot	B
46	ELGEN Wave	USA	Horizon Platform	B
47	Indian Wave Energy Device	India	IWAVE	B
48	Sea based AB	Sweden	Linear generator (Islandberg Project)	B
49	Motor Wave	Hong Kong	Motor Wave	B
50	Ocean Energy Laboratory of Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences	China	Neza II	B
51	Tremont Electric	USA	nPower WEC	B
52	Ocean Harvesting Technologies	Sweden	Ocean Harvester	B
53	Ocean Hydropower Systems Ltd	UK	OHS Wave Energy Array	B
54	Ocean Motion International	USA	OMI Combined Energy System	B
55	OWEC Ocean Wave Energy Company	USA	OWEC Ocean Wave Energy Converter	B
56	Ocean Power Technologies (OPT)	UK/USA	Power Buoy	B
57	Trident Energy Ltd	UK	Power Pod linear generator power take-off system and wave energy converter	B
58	Protean Energy Limited	Australia	Protean	B
59	Lancaster University	UK	PS Frog	B
60	Float Inc	USA	Rho-Cee	B
61	Aquagen Technologies	Australia	Rig Drive	B
62	Hydrocap Energy SAS	France	Seacap	B
63	Independent Natural Resources	USA	SEADOG	B
64	Oceanic Power	Spain	SeaHeart	B
65	Ecotricity	UK	Searaser	B
66	Fred Olson & Co./Ghent University	Norway/EU	SEEWEC	B
67	Snapper Consortium	UK	Snapper	B
68	Spindrift Energy	USA	Spindrift Energy Device	B
69	Seawood Designs Inc	Canada	SurfPower	B
70	Oscilla Power, Inc	USA	TDB (magnetostrictve wave enargy harvester_	B
71	Joules Energy Efficiency Services Ltd	Ireland	TETRON	B
72	Purneco AS	Norway	The “Fisherman” WEC	B
73	Balkee Tide and Wave Electricity Generator	Mauritius	TWPEG	B
74	Pelagic Power AS	Norway	W2Power	B
75	Ocean Electric Inc	USA	Wave platform	B
76	Ocean Wave and Wind Energy (OWWE)	Norway	Wave Pump Rig	B
77	Wave Star Energy ApS	Denmark	Wave Star	B
78	WaveBob Limited	Ireland	WaveBob	B
79	Waves4Power	Sweden	WaveEL-buoy	B
80	Marine Power Systems	UK	WaveSub	B
81	Ocean Energy Industries Inc	USA	WaveSurfer	B
82	Wave Energy Technologies Inc	Canada	WET EnGen	B
83	Wave Energy Technology New Zealand (WET-NZ)	New Zealand	WET-NZ device	B
84	Embley Energy Limited	UK	Sperboy	B/D
85	RESEN ENERGY	Denmark	Resen Waves LOPF buoys	B/I

86	Marine Energy Corporation	USA	Wave Catcher	B/I
87	Langlee Wave Power	Norway	Langlee System	C
88	Polygen Ltd	UK	Ocean WaveFlex	C
89	Offshore Wave Energy Ltd (OWEL)	UK	OWEL WEC	C
90	Aquamarine Power	UK	Oyster 800	C
91	Wave Electricity Renewable Power Ocean (WERPO)	Israel	SDE	C
92	Resolute Marine Energy Inc	USA	SurgeWEC	C
93	Polygen Ltd	UK	Volta WaveFlex	C
94	Daedalus Informatics Ltd	Greece	Wave Energy Conversion Activator	C
95	AW Energy	Finland	WaveRoller	C
96	Yu Energy Corp	USA	Yu Oscillating Generator "YOG"	C
97	BioPower Systems Pty Ltd	Australia	bioWave	C/E
98	Oceanlinx	Australia	blueWAVE	D
99	Havkraft	Norway	Evolver (Havkraft Wave Energy Converter – H-WEC)	D
100	Fobox AS	Norway	FO3	D
101	Oceanlinx	Australia	greenWAVE	D
102	Voith Hydro Wavegen	UK	Limpet	D
103	Leancon Wave Energy	Denmark	Multi Absorbing Wave Energy Convertor (MAWEC)	D
104	Ocean Energy Ltd	Ireland	Ocean Energy Buoy	D
105	Oceanlinx	Australia	ogWave	D
106	GasNatural Fenosa	Spain	OWC	D
107	OWC Power AS	Norway	OWC Power	D
108	Pico	Portugal	Pico OWC	D
109	Wave Energy Centre (WavEC)	Portugal	Pico Plant	D
110	SDK Marine	Madrid, Spain	SDK Wave Turbine	D
111	Ecole Centrale de Nantes	France	SEAREV	D
112	Spar Buoy	Portugal	Spar Buoy	D
113	Grays Harbor Ocean Energy Company	USA	Titan Platform	D
114	Joules EES Ltd	Ireland	Wave Train	D
115	AWS Ocean Energy	UK	AWS III	E
116	JAMSTEC	Japan	Mighty Whale	E
117	Ocean Wave and Wind Energy (OWWE)	Norway	OWWE-Rig	E
118	Kinetic Wave Power	USA	PowerGin	E
119	Wave Energy AS	Norway	Seawave Slot-Cone Generator	E
120	Wave Dragon	Wales/Denmark	Wave Dragon	E
121	WavePlane Production	Denmark	WavePlane	E
122	Portsmouth Innovation Limited	UK	WAVESTORE	E
123	Inerjy	USA	WaveTORK	E
124	Bombora Wave Power	Australia	Bombora	F
125	M3 Wave LLC	USA	DMP Device	F
126	GEdward Cook	USA	Floating Wave Generator	F
127	College of the North Atlantic	Canada	SARAH Pump	F
128	SeaNergy	Israel	Turbo Outburst Power/Top Desalination System	F
129	Checkmate Seaenergy UK Ltd	UK	Anaconda	G
130	Waves for Energy	Italy	ISWEC	H
131	Wello OY	Finland	Penguin	H
132	WavElectric Inc	USA	WE 10/WE 50/WE 125	H
133	Aimmer UK	UK/ Hong Kong	Aimmer	I
134	Atargis Energy Corporation	USA	Cycloidal Wave Energy Converter (CycWEC)	I
135	Etymol Ocean Power SpA	Chile	Etymol WEC - Alfa Series	I

136	SRI International	USA	Generator utilizing patented electroactive polymer artificial muscle (EMPAMT) technology	I
137	Greenheat Systems Ltd	UK	Gentec WaTS	I
138	GyroWaveGen	USA	GyroWaveGen	I
139	Intentium AS	Norway	Intentium Offshore Wave Energy Convertor	I
140	Jospa Ltd	Ireland	Irish Tube Compressor	I
141	SARA Inc	USA	MHD Wave Energy Conversion (MWEC)	I
142	NEMOS GmbH	Germany	NEMOS	I
143	Nodding Beam	UK	Nodding Beam	I
144	Ocean RusEnergy	Russia	Ocean 160	I
145	Ocean RusEnergy	Russia	Ocean 3	I
146	Ocean RusEnergy	Russia	Ocean 640	I
147	Muroran Institute of Technology	Japan	Pendulor	I
148	Eco Wave Power	Israel	Power Wing	I
149	PAULEY (Phil Pauley Innovation)	UK	Solar Marine Cells	I
150	Seamax Energy	Korea	Triton	I
151	Eco Wave Power	Israel	Wave Clapper	I
152	Caley Ocean Systems	UK/Denmark	Wave Plane	I
153	IHC Tidal Energy	Netherlands	Wave Rotor	I
154	Wind Waves And Sun	USA	WaveBlanket	I
155	Sea Wave Energy Ltd (SWEL)	UK	Waveline Magnet	I
156	Weptos	Denmark	WEPTOS WEC	I
157	Avium AS	Turkey	Yeti Cluster System	I

Appendices 2. Description of Wave Data measurement and units

WDIR	Wind direction (the direction the wind is coming from in degrees clockwise from true N) during the same period used for WSPD.
WSPD	Wind speed (m/s) averaged over an eight-minute period for buoys and a two-minute period for land stations. Reported Hourly.
GST	Peak 5 or 8 second gust speed (m/s) measured during the eight-minute or two-minute period. The 5 or 8 second period can be determined by payload, .
WVHT	Significant wave height (meters) is calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period.
DPD	Dominant wave period (seconds) is the period with the maximum wave energy.
APD	Average wave period (seconds) of all waves during the 20-minute period.
MWD	The direction from which the waves at the dominant period (DPD) are coming. The units are degrees from true North, increasing clockwise, with North as 0 (zero) degrees and East as 90 degrees.
ATMP	Air temperature (Celsius). For sensor heights on buoys.
WTMP	Sea surface temperature (Celsius). For buoys the depth is referenced to the hull's waterline. For fixed platforms, it varies with tide, but is referenced to, or near Mean Lower Low Water (MLLW)
DEWP	Dew point temperature taken at the same height as the air temperature measurement.
VIS	Station visibility (nautical miles).
PTDY	Pressure Tendency is the direction (plus or minus) and the amount of pressure change (hPa)for a three hour period ending at the time of observation. (not in Historical files)
TIDE	The water level in feet above or below Mean Lower Low Water (MLLW).

Appendices 3: Initial Statistical Description of The Historical Wave Data

Table 37: Initial Statistical Description of The Historical Wave Data 2005

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	7.4416667	Mean	1.6229436	Mean	10.426712
Standard Error	0.1086205	Standard Error	0.0072979	Standard Error	0.0361347
Median	7.3	Median	1.5	Median	10
Mode	2.9	Mode	1	Mode	8
Standard Deviation	3.7249062	Standard Deviation	0.6765853	Standard Deviation	3.291237
Sample Variance	13.874926	Sample Variance	0.4577677	Sample Variance	10.832241
Kurtosis	-0.837479	Kurtosis	1.5459072	Kurtosis	-0.462387
Skewness	0.1755366	Skewness	1.0408468	Skewness	0.529602
Range	16.9	Range	4.7	Range	19
Minimum	0.2	Minimum	0.3	Minimum	3
Maximum	17.1	Maximum	5	Maximum	22
Sum	8751.4	Sum	13949.2	Sum	86500
Count	1176	Count	8595	Count	8296
Largest (1)	17.1	Largest (1)	5	Largest (1)	22
Smallest (1)	0.2	Smallest (1)	0.3	Smallest (1)	3
Confidence Level (95.0%)	0.2131117	Confidence Level (95.0%)	0.0143057	Confidence Level (95.0%)	0.0708331

Table 38: Initial Statistical Description of The Historical Wave Data 2006

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.5484411	Mean	1.6229436	Mean	10.720684
Standard Error	0.0364521	Standard Error	0.0072979	Standard Error	0.0305831
Median	6.3	Median	1.5	Median	11
Mode	4.3	Mode	1	Mode	12
Standard Deviation	3.3223428	Standard Deviation	0.6765853	Standard Deviation	2.8355009
Sample Variance	11.037961	Sample Variance	0.4577677	Sample Variance	8.0400654
Kurtosis	-0.215281	Kurtosis	1.5459072	Kurtosis	-0.078543
Skewness	0.403122	Skewness	1.0408468	Skewness	0.296877
Range	19.8	Range	4.7	Range	22
Minimum	0	Minimum	0.3	Minimum	3
Maximum	19.8	Maximum	5	Maximum	25
Sum	54397.9	Sum	13949.2	Sum	92155
Count	8307	Count	8595	Count	8596
Largest (1)	19.8	Largest (1)	5	Largest (1)	25
Smallest (1)	0	Smallest (1)	0.3	Smallest (1)	3
Confidence Level (95.0%)	0.0714552	Confidence Level (95.0%)	0.0143057	Confidence Level (95.0%)	0.0599502

Table 39: Initial Statistical Description of The Historical Wave Data 2007

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	7.4238538	Mean	1.5749194	Mean	10.445671
Standard Error	0.058785	Standard Error	0.0074106	Standard Error	0.031299
Median	7.2	Median	1.4	Median	11
Mode	9.1	Mode	1	Mode	8
Standard Deviation	3.9499853	Standard Deviation	0.6653873	Standard Deviation	2.8102923
Sample Variance	15.602384	Sample Variance	0.4427402	Sample Variance	7.8977427
Kurtosis	0.1694976	Kurtosis	4.5966214	Kurtosis	-0.356
Skewness	0.4683659	Skewness	1.7183007	Skewness	0.3999242
Range	27.8	Range	5.8	Range	18
Minimum	0	Minimum	0.4	Minimum	4
Maximum	27.8	Maximum	6.2	Maximum	22
Sum	33518.7	Sum	12697	Sum	84213
Count	4515	Count	8062	Count	8062
Largest (1)	27.8	Largest (1)	6.2	Largest (1)	22
Smallest (1)	0	Smallest (1)	0.4	Smallest (1)	4
Confidence Level (95.0%)	0.1152474	Confidence Level (95.0%)	0.0145267	Confidence Level (95.0%)	0.0613541

Table 40: Initial Statistical Description of The Historical Wave Data 2008

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.5190961	Mean	1.4676712	Mean	10.410428
Standard Error	0.0349623	Standard Error	0.0054719	Standard Error	0.0257651
Median	6.3	Median	1.31	Median	9.88
Mode	5.8	Mode	1	Mode	8.33
Standard Deviation	3.2685588	Standard Deviation	0.6244725	Standard Deviation	2.9403891
Sample Variance	10.683477	Sample Variance	0.3899659	Sample Variance	8.6458878
Kurtosis	0.458316	Kurtosis	2.9937365	Kurtosis	-0.053072
Skewness	0.5730057	Skewness	1.2858544	Skewness	0.4846991
Range	22.7	Range	6.1	Range	22.22
Minimum	0	Minimum	0	Minimum	0
Maximum	22.7	Maximum	6.1	Maximum	22.22
Sum	56976.9	Sum	19114.95	Sum	135585.42
Count	8740	Count	13024	Count	13024
Largest (1)	22.7	Largest (1)	6.1	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	0
Confidence Level (95.0%)	0.0685344	Confidence Level (95.0%)	0.0107258	Confidence Level (95.0%)	0.0505035

Table 41: Initial Statistical Description of The Historical Wave Data 2009

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.5065988	Mean	1.7064096	Mean	10.994917
Standard Error	0.0408905	Standard Error	0.0062206	Standard Error	0.023562
Median	6.3	Median	1.51	Median	11.11
Mode	5.9	Mode	1	Mode	12.5
Standard Deviation	3.2427487	Standard Deviation	0.8064255	Standard Deviation	3.0545295
Sample Variance	10.515419	Sample Variance	0.650322	Sample Variance	9.3301502
Kurtosis	0.2062265	Kurtosis	3.8614301	Kurtosis	-0.343568
Skewness	0.5171065	Skewness	1.6400911	Skewness	0.2638043
Range	19.3	Range	6.44	Range	22.22
Minimum	0	Minimum	0	Minimum	0
Maximum	19.3	Maximum	6.44	Maximum	22.22
Sum	40920	Sum	28677.92	Sum	184780.58
Count	6289	Count	16806	Count	16806
Largest (1)	19.3	Largest (1)	6.44	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	0
Confidence Level (95.0%)	0.0801594	Confidence Level (95.0%)	0.012193	Confidence Level (95.0%)	0.046184

Table 42: Initial Statistical Description of The Historical Wave Data 2010

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.9178856	Mean	1.6252465	Mean	10.368279
Standard Error	0.0362807	Standard Error	0.0057888	Standard Error	0.0242013
Median	6.7	Median	1.45	Median	9.88
Mode	5.4	Mode	1	Mode	8.33
Standard Deviation	3.3991781	Standard Deviation	0.7258222	Standard Deviation	3.034437
Sample Variance	11.554412	Sample Variance	0.5268178	Sample Variance	9.2078078
Kurtosis	-0.12396	Kurtosis	3.319589	Kurtosis	-0.475654
Skewness	0.3565206	Skewness	1.5172496	Skewness	0.3938033
Range	21.3	Range	5.88	Range	22.22
Minimum	0	Minimum	0	Minimum	0
Maximum	21.3	Maximum	5.88	Maximum	22.22
Sum	60725.2	Sum	25550.5	Sum	162999.71
Count	8778	Count	15721	Count	15721
Largest (1)	21.3	Largest (1)	5.88	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	0
Confidence Level (95.0%)	0.0711188	Confidence Level (95.0%)	0.0113468	Confidence Level (95.0%)	0.0474373

Table 43: Initial Statistical Description of The Historical Wave Data 2011

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.6877332	Mean	1.5976271	Mean	10.721566
Standard Error	0.0341194	Standard Error	0.0049194	Standard Error	0.0239121
Median	6.5	Median	1.46	Median	10.53
Mode	6.8	Mode	1	Mode	13.33
Standard Deviation	3.1895735	Standard Deviation	0.6326944	Standard Deviation	3.0753783
Sample Variance	10.173379	Sample Variance	0.4003022	Sample Variance	9.4579514
Kurtosis	-0.258682	Kurtosis	2.5031683	Kurtosis	-0.279515
Skewness	0.3284689	Skewness	1.2459183	Skewness	0.3761455
Range	17.6	Range	5.06	Range	22.22
Minimum	0	Minimum	0	Minimum	0
Maximum	17.6	Maximum	5.06	Maximum	22.22
Sum	58444.1	Sum	26426.35	Sum	177345.43
Count	8739	Count	16541	Count	16541
Largest (1)	17.6	Largest (1)	5.06	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	0
Confidence Level (95.0%)	0.0668821	Confidence Level (95.0%)	0.0096426	Confidence Level (95.0%)	0.0468703

Table 44: Initial Statistical Description of The Historical Wave Data 2012

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.4750575	Mean	1.6258665	Mean	10.504222
Standard Error	0.0345441	Standard Error	0.0052101	Standard Error	0.0238537
Median	6.2	Median	1.46	Median	10.53
Mode	5.7	Mode	1.29	Mode	8.33
Standard Deviation	3.2213191	Standard Deviation	0.6715415	Standard Deviation	3.0745327
Sample Variance	10.376897	Sample Variance	0.450968	Sample Variance	9.4527512
Kurtosis	-0.207468	Kurtosis	3.5242233	Kurtosis	-0.425448
Skewness	0.3839182	Skewness	1.4272128	Skewness	0.329116
Range	18.9	Range	6.32	Range	19.36
Minimum	0	Minimum	0	Minimum	2.86
Maximum	18.9	Maximum	6.32	Maximum	22.22
Sum	56307.1	Sum	27010.52	Sum	174506.64
Count	8696	Count	16613	Count	16613
Largest (1)	18.9	Largest (1)	6.32	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	2.86
Confidence Level (95.0%)	0.0677146	Confidence Level (95.0%)	0.0102124	Confidence Level (95.0%)	0.0467557

Table 45: Initial Statistical Description of The Historical Wave Data 2013

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.7915414	Mean	1.595222	Mean	10.863523
Standard Error	0.0343851	Standard Error	0.0057185	Standard Error	0.0255513
Median	6.6	Median	1.42	Median	10.53
Mode	6.4	Mode	1	Mode	8.33
Standard Deviation	3.2096214	Standard Deviation	0.7200282	Standard Deviation	3.2172355
Sample Variance	10.30167	Sample Variance	0.5184406	Sample Variance	10.350604
Kurtosis	0.4670461	Kurtosis	2.2698659	Kurtosis	-0.279013
Skewness	0.4832721	Skewness	1.2679389	Skewness	0.4342979
Range	22.4	Range	6.06	Range	21.3
Minimum	0	Minimum	0	Minimum	3.7
Maximum	22.4	Maximum	6.06	Maximum	25
Sum	59174.7	Sum	25290.65	Sum	172230.3
Count	8713	Count	15854	Count	15854
Largest (1)	22.4	Largest (1)	6.06	Largest (1)	25
Smallest (1)	0	Smallest (1)	0	Smallest (1)	3.7
Confidence Level (95.0%)	0.0674029	Confidence Level (95.0%)	0.0112089	Confidence Level (95.0%)	0.0500835

Table 46: Initial Statistical Description of The Historical Wave Data 2014

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.7314536	Mean	1.7429836	Mean	11.035727
Standard Error	0.0357185	Standard Error	0.0065639	Standard Error	0.0228339
Median	6.4	Median	1.51	Median	11.11
Mode	5.6	Mode	1	Mode	13.33
Standard Deviation	3.3465023	Standard Deviation	0.8588486	Standard Deviation	2.987666
Sample Variance	11.199078	Sample Variance	0.7376209	Sample Variance	8.9261482
Kurtosis	0.4004107	Kurtosis	2.6259924	Kurtosis	-0.492696
Skewness	0.5554855	Skewness	1.2748188	Skewness	0.1691124
Range	22.1	Range	7.4	Range	18.65
Minimum	0	Minimum	0	Minimum	3.57
Maximum	22.1	Maximum	7.4	Maximum	22.22
Sum	59088.7	Sum	29839.88	Sum	188931.65
Count	8778	Count	17120	Count	17120
Largest (1)	22.1	Largest (1)	7.4	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	3.57
Confidence Level (95.0%)	0.0700166	Confidence Level (95.0%)	0.012866	Confidence Level (95.0%)	0.0447568

Table 47: Initial Statistical Description of The Historical Wave Data 2015

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	6.9284653	Mean	1.7041363	Mean	10.611936
Standard Error	0.0349383	Standard Error	0.0054341	Standard Error	0.0217251
Median	6.7	Median	1.52	Median	10.53
Mode	5.5	Mode	1.2	Mode	9.09
Standard Deviation	3.2683626	Standard Deviation	0.7101389	Standard Deviation	2.8390966
Sample Variance	10.682194	Sample Variance	0.5042973	Sample Variance	8.0604694
Kurtosis	-0.331754	Kurtosis	1.3677692	Kurtosis	-0.115417
Skewness	0.3225005	Skewness	1.0807086	Skewness	0.4475338
Range	17.8	Range	4.97	Range	18.99
Minimum	0	Minimum	0	Minimum	3.23
Maximum	17.8	Maximum	4.97	Maximum	22.22
Sum	60631	Sum	29103.24	Sum	181230.64
Count	8751	Count	17078	Count	17078
Largest (1)	17.8	Largest (1)	4.97	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	3.23
Confidence Level (95.0%)	0.0684872	Confidence Level (95.0%)	0.0106513	Confidence Level (95.0%)	0.0425834

Table 48: Initial Statistical Description of The Historical Wave Data 2016

Wind Speed (m/s)		Wave Height-Hs (m)		Wave Period- Tp'(s)	
Mean	7.4857904	Mean	1.9044257	Mean	10.855459
Standard Error	0.0504839	Standard Error	0.0071603	Standard Error	0.0246594
Median	7.2	Median	1.64	Median	10.53
Mode	5.4	Mode	1.32	Mode	8.33
Standard Deviation	3.5255712	Standard Deviation	0.9087033	Standard Deviation	3.1295147
Sample Variance	12.429652	Sample Variance	0.8257418	Sample Variance	9.793862
Kurtosis	-0.307953	Kurtosis	5.2987789	Kurtosis	-0.500174
Skewness	0.3792305	Skewness	1.8414058	Skewness	0.4363016
Range	18.8	Range	8.48	Range	18.22
Minimum	0	Minimum	0	Minimum	4
Maximum	18.8	Maximum	8.48	Maximum	22.22
Sum	36508.2	Sum	30672.68	Sum	174838.02
Count	4877	Count	16106	Count	16106
Largest (1)	18.8	Largest (1)	8.48	Largest (1)	22.22
Smallest (1)	0	Smallest (1)	0	Smallest (1)	4
Confidence Level (95.0%)	0.0989712	Confidence Level (95.0%)	0.0140349	Confidence Level (95.0%)	0.0483352