Risk Assessment of Ocean Energy Projects

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Abstract

Este trabalho apresenta os conceitos relacionados com as energias oceânicas e a avaliação de riscos, desenvolvendo uma metodologia que permite compreender as incertezas associadas a projetos ligados a esta indústria e os seus efeitos no custo do projeto, na sua viabilidade económica e na sua competitividade económica. A metodologia consiste numa avaliação de risco aplicada aos indicadores económico-financeiros usados nesta indústria. Envolve a definição do contexto da avaliação, a identificação dos riscos do projeto a análise qualitativa destes, a análise quantitativa das incertezas e riscos mais significativos, e a avaliação dos riscos segundo objetivos e critérios pré-estabelecidos. Um caso de estudo é apresentado para demonstrar a aplicabilidade e utilidade da metodologia, considerando Portugal como localização do projeto. As conclusões da avaliação são coerentes com a literatura existente sobre a indústria.

Palavras-chave: Energias Oceânicas; Avaliação de Riscos; Avaliação de Risco da Viabilidade Económica; Simulação Monte Carlo.

Abstract

This work introduces the concepts related with ocean energy and risk assessment, developing a methodology to understand the uncertainties associated with projects in the ocean industry, and their effect on project cost, feasibility and cost-competitiveness. The methodology consists of a risk assessment of project appraisal indicators used in the industry. It proceeds with the establishment of the context of the assessment, the identification and qualitative analysis of project risks, and the quantitative analysis of significant uncertainties and risks, followed by an evaluation of the results according to pre-established criteria. A case study is presented to exemplify the use of the methodology, considering Portugal as the scenario of the execution of the project. Conclusions from the assessment are coherent with the current literature about the industry.

Keywords: Ocean Energy; Risk Assessment; Project Appraisal Risk Assessment; Monte Carlo Simulation.

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Nomenclature

ALARP	As Low As Reasonably Practicable
C	Net Cost
CF	Net Cash Flow
DPP	Discounted Payback Period
FIT	Feed In Tariff
IC	Initial Cost
IRR	Internal Rate of Return
LCC	Life Cycle Costs
LCoE	Levelised Cost of Energy
MCS	Monte Carlo Simulation
MCT	Marine Current Turbines (Rotating Devices)
MIRR	Modified Internal Rate of Return
NPV	Net Present Value
O&M	Operation and Maintenance
OEC	Ocean Energy Converter
OWC	Oscillating Water Column
P-I	Probability and Impact
PTO	Power Take-Off mechanism
PV	Present Value equivalent
RBS	Risk Breakdown Structure
TEC	Tidal Energy Converter
WBS	Work Breakdown Structure
WEC	Wave Energy Converter

1. Introduction

1.1. Motivation

Renewable energies are a promising alternative to countries heavily dependent on imported fossil fuels. It is solution that will have increased importance as the energy consumption increases over time (Frid, et al., 2012). Moreover, the development and commercialisation of these energy sources bring benefits in terms of (1) de-carbonisation, (2) security of energy supply, (3) know-how, and (4) economic development.

Ocean energy has a huge potential as a clean energy source. In particular, a growing interest and focus on energy from waves and tidal currents emerged in the last decades. A gross estimate considered the global wave energy and tidal energy resource available as 1 and 1.5 times the world consumption (Dal Ferro, 2006). The ocean energy industry is developing solutions to harness this energy. Currently, with leading testing facilities and several projects under development, the United Kingdom is at the front of the ocean energy industry (Krohn et al., 2012).

Portugal has the potential to enhance and benefit from the development of the ocean energy industry. Although there are many uncertainties concerning tidal energy, the estimated wave energy levels of Portuguese territorial waters are considered as attractive for exploitation. In fact, some projects have been developed in Portugal over the last years, including the first wave farm, i.e. an array of devices placed together in the ocean to harness wave energy. Nonetheless, the current scenario consists of a reduced number of active projects, in a country that imports most of its energy.

1.2. Problem

Ocean energy technology is still at an early stage of development. According to López et al. (2013), only 5% of projects being developed in the wave energy sector have reached full scale grid connection. Likewise, in the tidal energy sector few devices have been tested, and fewer have reached full scale grid connection (Krohn et al., 2012), (Reynolds et al., 2010). The industry has limited experience, being subject to a great number of uncertainties related with technology, performance and cost (Mueller & Wallace, 2008). This is an industry based on capital intensive projects, planned for a large time horizon and service life. Uncertainties undermine the confidence of investors and other stakeholders, and delay the development of the industry. Investment in ocean energy will be largely influenced by its cost-competitiveness compared to alternative sources of energy.

1.3. Objective

This thesis proceeds with an introduction of the concepts related with ocean energy and risk assessment, providing relevant information to understand and support the methodology developed. The goal is to develop a method that is appropriate for informed decision-making and consistent, so that it can be applied to different devices, on different locations, considering different number of devices for each location. The methodology is presented and used to assess the uncertainties and risks involved in the decision making process of investment in ocean energy projects, considering aspects such as project dimension, technology, resource data, costs and performance.

In this work, an ocean energy project is considered as an endeavour made to enable the exploitation of ocean energy. The life cycle of these projects is considered as the life cycle of the device/devices considered in the project to harness ocean energy. Likewise, the cost of an ocean energy project comprises the costs of the life cycle of the device/devices built and installed in a given location to exploit the available ocean energy.

A case study is presented considering Portugal as the location of the project and the Pelamis wave energy converter as the device. These options and others provide context to proceed with the exemplification. A wave energy converter is selected for the exemplification for three reasons: (1) the lack of tidal energy resource assessments for Portugal, data that is essential to proceed with the adopted methodology; (2) the fact that Portugal is considered as an attractive region to extract wave energy and resource data is available; and (3) the existing data for the wave energy sector and the relative experience Portugal has in such projects.

1.4. Work Structure

This thesis is structured as follows. First chapters introduce ocean energy: the resource, the technologies and the projects. This is followed by an introduction of the essential aspects of risk assessment and its application in project appraisal. The methodology is then introduced, and the following chapters proceed with an exemplification on how to use it. Conclusions about the methodology and the ocean energy industry are presented in the end.

2. Ocean Energy and Conversion

Ocean energy comprises all forms of energy derived from the ocean. It can be exploited from waves, tides, biomass, thermal gradients, salinity gradients or tidal currents. Here, only two of these forms of energy are considered: (1) wave energy, i.e., energy from waves; and (2) tidal energy, i.e., energy from tidal currents. Extracting energy from the ocean and converting it into useful energy is the process of conversion. Devices capable of doing this are ocean energy converters (OEC). Here, two types of devices are considered: (1) wave energy converters (WEC) and (2) tidal energy converters (TEC). Most WECs convert wave energy into electricity, just like most TECs convert tidal energy into electricity as well.

The chapter proceeds as follows. First, wave and tidal energy are explained in detail. This is followed by a discussion about the relevance of wave energy and tidal energy assessments, as well as some data. Then, WECs and TECs are described, considering their development over time and the different concepts. Then, a description of the conversion process is made, considering the different elements involved in it. The chapter ends with an overview of the network integration process from which the electricity generated can be injected to the grid.

2.1. Wave Energy

Wave energy is the energy related to surface water movements – also called waves. Waves are complex energy resources derived from wind, and influenced by it, the bathymetry and the tidal currents. They are characterised by: (1) height, i.e. their amplitude of oscillation (vertically) relative to a fixed point; (2) period, i.e. the time between successive peaks or troughs of a wave relative to a fixed point; and (3) direction. Waves tend to be quite irregular, varying their characteristics from wave to wave, with different sea states or on a seasonal basis[1] (Clément et al., 2002), (Falcão, 2010), (López et al., 2013).

From an energetic point of view, waves are characterised by the kinetic energy of the movement and by the potential energy of the surface water volume being moved. The wave energy level is typically expressed as power per unit length. It is proportional to the square of the wave height and to the wave period. Wave energy tends to dissipate as it reaches the shoreline, although it might get concentrated in near shore areas[2] (Clément et al., 2002).

2.2. Tidal Energy

Tidal energy is the energy related to water movements as a whole, from the surface to the seabed. These movements – currents – are affected by time, since they are caused by the gravitational and centrifugal forces between the Earth, the Moon and the Sun. Reynolds et al. (2010) explained with detail the basic physics of this phenomenon. Tidal currents that flow into the coast are known as flood currents and tidal currents that flow from the coast are known as ebb currents. These currents have variable speed but their regular behaviour make them a quite predictable energy source.

[1] Despite the irregularity, it might be possible to recognise some patterns in the variability of wave behaviour.
[2] These concentration areas are called hotspots.

Tidal currents are also affected by topographical features and depth (Mueller & Wallace, 2008). These currents are experienced near the coast and at narrow channels in which topographical features force the water to flow through.

From an energetic point of view, tidal energy is purely kinetic and related with the velocity of tidal currents. Tidal energy has some similarities with wind energy since for both cases the power available is proportional to the fluid density and the cube of its velocity. However, seawater is much denser than air (approximately 832 times more) and tidal power density is superior to wind (Krohn et al., 2012).

2.3. Discussion

Knowledge of wave energy and tidal energy (power, characteristics) is essential (1) to evaluate their potential, (2) to identify sites or geographic areas that can be exploited, and (3) to develop suitable solutions to extract their energy. The assessment of these resources and the understanding of these aspects will influence the development of the ocean energy industry – wave and tidal sectors in particular (López et al., 2013), (Mueller & Wallace, 2008).

Possible options to execute the assessment are (1) in situ measurements, which provide information about the existing conditions and tendencies; or (2) numerical modelling, which enables the prediction of wave climate in a given area (Rusu & Guedes Soares, 2009). The output is an estimation of the resource power and characteristics, for a short or long term period. Due to their characteristics, estimates on wave behaviour and its properties are subject to more uncertainty.

There are several references in the literature about assessments or estimates on wave energy and tidal energy. Gunn & Stock-Williams (2012) estimated the confidence interval for the mean global wave power, obtaining an interval of 2.11TW ± 0.05TW with 95% confidence. Falcão (2010, p. 901) considered offshore areas with wave energy levels between 20kW/m and 70kW/m and little seasonal variations as attractive locations to extract energy. Tidal energy assessments are relatively scarce. Reynolds et al. (2010) mentioned this problem, alerting to the need of more robust assessments for all continents. The authors (2010, p. 406) considered sites with tidal currents of at least 2.5m/s as potential sites for viable energy extraction.

According to the literature, Portugal has an annual wave power between 30kW/m and 40kW/m (Clément et al., 2002, p. 411), while estimates on mean overall resource energy vary, with Clément et al. (2002, p. 411) quoting a value of 10GW and the Instituto do Ambiente (Cruz & Sarmento, 2004, p. 7) report and Gunn & Stock-Williams (2012, p. 303) quoting a value of 15GW[3]. Portugal is a region with medium-high wave energy levels that can be exploited. Rusu & Guedes Soares (2009, p. 1502), concluded that the average wave energy levels tend to decrease from north to south over the continental area of Portugal, considering long term in situ measurements of wave conditions. The Wave Energy Centre (2004) report identified potential sites for installation of wave energy projects

[3] The Instituto do Ambiente (Cruz & Sarmento, 2004) report quoted this value for the continental area of Portugal. The authors quoted a value of 6GW for the autonomous regions of Portugal. Gunn & Stock-Williams (2012) considered a possible variation of ± 2GW for the estimation.

along the Portuguese coast. Rusu & Guedes Soares (2012) assessed the wave energy resource in the Azores islands.

2.4. Wave Energy Converters

A wide variety of WECs have been developed over the years (Falcão, 2010, p. 904). However, most concepts are at an early stage of development and no design has been favoured by developers (López et al., 2013, p. 419). The lack of consensus relative to design is pointed as one of the causes of the slow development (Krohn et al., 2012, p. 25). Guedes et al. (2012) analysed the different concepts and their advantages and disadvantages, arguing that different solutions will adapt to different conditions. According to Falcão (2010, p. 904), the variety of concepts results from the fact that wave energy can be absorbed in different ways, while aspects such as water depth or location also have to be considered. Some of the existing devices that have reached scale sea trials and their characteristics are presented in Table 1.

WECs are classified according to their characteristics and behaviour. This work classifies WECs according to three characteristics: (1) location, (2) size and direction, and (3) working principle. The classification is based on the classification systems defined by Falcão (2010, pp. 904-911) and López et al. (2013, pp. 416-419), and it is as follows:

- Classification according to the location of the device considers the distance from the coast and the water depth. WECs might be classified as: (1) onshore devices, located at the shore or above the sea in shallow water; (2) near shore devices, located in moderate water depths (10 to 25 meters); or (3) offshore devices, located far from the shoreline in high water depths (more than 40 meters). Near shore devices might be floating or resting on the seabed, whereas offshore devices are moored to the seabed, either floating on the surface or submerged.
- Classification according to size and direction of the device considers the size of the device compared to the wavelength and the direction of the device relative to the wave. WECs might be classified as: (1) point absorbers, devices that have a diameter smaller than the wavelength and collect energy from all directions; (2) attenuators, devices that have a size greater than the wavelength and are placed parallel to the predominant wave direction; or (3) terminators, devices that have a size greater than the wavelength and are placed perpendicular to the predominant wave direction.
- Classification according to the working principle of the device considers how the wave energy is converted. WECs might be classified as (1) oscillating water column (OWC) devices, (2) oscillating bodies, or (3) over topping devices. OWC might be fixed to the seabed, onshore or floating. These devices have a semi-submerged chamber open below the water surface level. As waves vary the water level inside the chamber air flows through a turbine that converts the energy associated with the air flow caused by wave motion. Oscillating bodies are either floating or submerged structures that are moved by the waves and convert the energy associated with the movement, relative to a fixed reference or another floating body of the structure. These devices are usually characterized by a hydraulic motor, hydraulic turbine or

linear electric generator as conversion mechanisms. Over topping devices force ocean water from waves through a structure above sea level and then release it back to the ocean through low-head hydraulic turbines, allowing the conversion of the kinetic and potential energy of waves. A reservoir might exist to assure stable water supply and electricity generation.

Table 1: Examples of WECs that at least have reached scale sea trials

WEC	Company	Classification	Capacity	Status	Illustration
Limpet	Voith Hydro Wavegen	Onshore; OWC	0.5MW	Full scale grid connection	
Oyster 800	Aquamarine Power	Near shore; Oscillating body	0.8MW	Full scale prototype	
Pelamis P2	Pelamis Wave Power	Offshore; Oscillating body	0.75MW	Full scale grid connection	
Power Buoy – PB150	Ocean Wave Technologies	Offshore; Point absorber; Oscillating body	0.15MW	Full scale prototype	
Wave Dragon	Wave Dragon	Overtopping	1.5MW	Scale prototype	

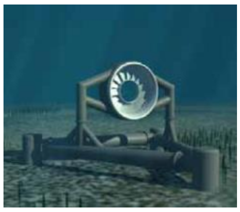
2.5. Tidal Energy Converters

TECs are still at an early stage of development as few devices have been built and tested at sea (Krohn et al., 2012, p. 25) (see Table 2). However, there is a greater design convergence in the development of TECs, a fact that partly explains their faster development relative to WECs (Krohn et al., 2012, p. 25). According to Reynolds et al. (2010, p. 407), tidal farms might be developed within the next decade considering the current progress. The classification of these devices according to their working principle is explained in detail in the following section.

Rourke et al. (2010) separated TECs in two categories: (1) reciprocating devices and (2) rotating devices – also called marine current turbines (MCT). Reciprocating devices are characterised by an oscillating hydrofoil connected to a supporting arm which oscillates due to the hydrodynamic lift force created by tidal currents that flow over. These elements, a hydraulic motor or turbine, and a generator enable electricity production (Rourke et al., 2010, pp. 1027-1030). MCTs are characterised by a number of blades connected to a supporting hub – both form the rotor – that rotate about an axis (horizontal or vertical, relative to the current flow) under the hydrodynamic effect of tidal currents. These elements, a gearbox and a generator enable electricity generation (Rourke et al., 2010, p. 1027).

MCTs have been developing faster than reciprocating devices. Khan et al. (2009) assessed several MCT designs, and their advantages and disadvantages. Most developers have favoured horizontal axis MCTs but there is no agreement to whether it is the optimum design (Krohn et al., 2012, p. 25). In these devices, concept and design similarities to wind turbines are quite significant (Khan et al., 2009, p. 1829). Vertical axis MCTs are still under research and development Rourke et al., 2010, p. 1027).

Table 2: Examples of TECs that at least have reached scale sea trials

TEC	Company	Classification	Capacity	Status	Illustration
AR1000	Atlantis Resources Corporation	Horizontal axis tidal current turbine	1MW	Full scale prototype	
Open Centre Turbine	Open Hydro	Horizontal axis tidal current turbine	0.3MW	Full scale prototype	
Pulse Stream 100	Pulse Tidal Ltd.	Reciprocating device	0.1MW	Scale prototype	
SeaGen	Marine Current Turbines	Horizontal axis tidal current turbine	1.2MW	Full scale grid connection	

2.6. Ocean Energy Conversion Process

Ocean energy conversion involves a chain of energy conversion processes in order to generate electricity. These processes are directly related to the specific characteristics of an OEC. OECs have mechanisms to extract energy from the ocean and produce usable energy. These mechanisms are called power take-off mechanisms (PTO). PTOs convert ocean energy to electricity through several conversion processes – also called stages – in which different elements act with a given efficiency (Falcão, 2010).

The electrical energy is produced by (1) a rotating generator or (2) a direct-drive linear generator. Direct-drive linear generators convert ocean energy directly into electrical energy, whereas rotating generators are driven by mechanical machines in order to produce electrical energy. Mechanical machines convert the motion associated with ocean energy into motion that is adequate for the rotating generator input (Falcão, 2010). Frequently used mechanical machines are (1) air turbines, (2) high-pressure oil driven hydraulic motors, or (3) hydraulic turbines (Falcão, 2010), (López et al., 2013). The description of these elements and the generators is as follows:

- Air turbines are used in OWC devices to convert the air flow into energy useful for electricity production. Three types of turbine designs have been used: (1) Wells air turbines, (2) Dennis-Auld air turbines, and (3) Impulse air turbines. Falcão (2010, pp. 912-913) addressed this in detail. These turbines are self-rectifying, rotating in one direction regardless of the direction of the air flow. Wells air turbines have been the most frequently used design and Impulse air turbines the most frequent alternative.
- Hydraulic motors are used in oscillating devices and reciprocating devices in order to convert their movement into energy useful for electricity production. Motion is converted into hydraulic energy by one or a set of hydraulic cylinders and feed into the hydraulic motor. A gas or oil accumulator system is used to store energy and maintain constant feed into the hydraulic motor, regulating power output (López et al., 2013), (Falcão, 2010).
- Hydraulic turbines are used in over topping devices to convert the water flow into energy useful for electricity production, and also in oscillating devices as an alternative to hydraulic motors (Falcão, 2010). These turbines are technologically mature and might be classified according to their characteristics or their size. Considering their characteristics, these turbines are either (1) impulse turbines or (2) reaction turbines. Considering their size, these machines might be classified as (1) high head, (2) medium head or (3) low head (López et al., 2013). Impulse turbines are used in oscillating devices whereas reaction turbines are used in overtopping devices. In order to provide regular power output impulse turbines in oscillating devices might be assisted by a gas accumulator system and reaction turbines in overtopping might be assisted by a water reservoir (Falcão, 2010).
- Rotating generators convert mechanical energy associated with the mechanical machines into electrical energy. There are several possible arrangements but most are either (1) synchronous generators or (2) asynchronous generators. Fitzgerald et al. (2002) described these types of rotating generators in detail. Synchronous generators provide reactive power control, whereas asynchronous generators might require excessive reactive power. However, asynchronous generators are less expensive, and have self-protecting characteristics against overloads.
- Linear generators have been tested in the wave energy sector in oscillating devices but are at an early stage of development yet. These generators consist of a stator and a translator. The

motion of the oscillating device corresponds to the motion of the translator. The energy is extracted from the resource and converted directly into electricity, minimising conversion losses (Falcão, 2010), (Carbon Trust, 2005, p. 49). The necessary large device dimensions turn this technology less atractive (López et al., 2013). Rhinefrank et al. (2006) described in detail a device applicable to ocean energy based on a linear generator, from design to prototype testing.

2.7. Network Integration

Network integration (i.e., grid connection) of the output power generated by OECs is achieved through power transmission systems. These systems, along with possible offshore or onshore substations, enable the transport and access to the grid. Power is lost throughout the transmission, and losses increase with distance. Substations might solve this problem if voltage levels are not adequate. These consist of transformers that step up the voltage to appropriate levels (de Alegría et al., 2009).

There are three alternatives to transmit power: (1) high voltage alternating current (HVAC), (2) high voltage direct current line commutated converter (HVDCLCC), and (3) high voltage direct current voltage source converter (HVDCVSC). de Alegría et al. (2009) described these in detail. The HVAC technology is at an advanced stage of development, being a reliable alternative used by most offshore platforms (López et al., 2013, p. 427). HDVCLCC and HDVCVSC systems are more efficient – their power loss is lower compared with HVAC systems. HVAC is a less expensive alternative.

3. Ocean Energy Projects

PMI (2008, p. 5) defined project as an endeavour with definite beginning and end that is initiated to 'create a unique product, service or result'. Here, an ocean energy project is considered as an endeavour made to enable the exploitation of ocean energy. It is a result achieved through the use of at least one OEC - these devices are at the centre of any ocean energy project.

Ocean energy projects are at an early stage of development. Several aspects of the life cycle of these devices are known, but the industry still has to gain knowledge and practical experience to improve its processes and reduce the uncertainty about costs and performance of OECs (Mueller & Wallace, 2008). This will be critical to ensure that ocean energy projects will be appraised positively and turn out more competitive.

This chapter proceeds as follows. First, the life cycle of an OEC is described, considering general aspects of each phase. Then, a description of the general cost items of these projects is made, quoting some values referenced in the literature. The chapter ends with a description of common indicators used for the economic appraisal of these projects.

3.1. Project Life Cycle

Project life cycle comprises all phases of the life cycle the device/devices involved in the ocean energy project (see Objective). The life cycle of an OEC consists of four phases: (1) the Construction phase, (2) the Installation phase, (3) the Operation and Maintenance (O&M) phase, and (4) the Decommissioning phase. These phases are explained in detail in the following sections.

3.1.1. Construction Phase

The Construction phase corresponds to the concept development, design and fabrication of the device/devices. There are several concepts of OECs (see Ocean Energy and Conversion), each with their characteristics, designed and manufactured accordingly. Nonetheless, three components are common in these devices: (1) the structure, i.e., the physical structure of the device that interacts with the resource; and (2) the PTO; and (3) the foundations or moorings, alternative methods to hold the device to seabed in a given location (SI Ocean, 2012). According to Mueller & Wallace (2008, p. 4381), these devices have to be built considering three aspects: (1) survivability, (2) reliability, and (3) affordability. An OEC with appropriate design and manufacture will perform as expected, hence satisfying the aspects mentioned above.

The Carbon Trust (2005) report established some guidelines on design and operation of WECs, recommending the development of similar guidelines for TECs. The report emphasised the importance of defining, for a given device, (1) the maturity of the technology, (2) the reliability of the device, (3) the criticality of its components, and (4) the priority areas for improvement. Technical analysis, risk and reliability assessments, tests and reviews are needed to improve design and manufacturing, and reduce the existing uncertainties. Likewise, proper understanding of the resource will improve the efficiency of the design (Lam & Bhatia, 2013).

Numerical and physical modelling and scale testing provide information about the performance, survivability or reliability of components in the marine environment. According to Mueller & Wallace (2008), numerical modelling is a more reliable source of information for the tidal energy industry, while tank testing is recommended for WECs to simulate (and repeat) at scale different sea states and verify their performance and survivability.

Possible solutions to improve reliability are (1) redundancy, (2) design for robustness, or (3) the use of well-proven components (Carbon Trust, 2005). Survivability is related with the harsh environmental conditions or loads that OECs might find. Devices further away from shore are more subject to these conditions (López et al., 2013).

Manufacturing corresponds to the fabrication of equipment or structures that combine with other elements or sub-assemblies to form the device (Carbon Trust, 2005). Wave and tidal energy industries can resort to the experience of other offshore industries and ship building in fabrication, assembly and fit-out activities, being more effective and efficient (Mueller & Wallace, 2008). As these industries develop the manufacturing time is expected to decrease.

3.1.2. Installation Phase

The Installation phase is a complex activity that involves transportations, assemblies, underwater operations and any other processes needed to place the device/devices at the planned location. Throughout this phase, the device/devices must be kept safe. All operations must be planned and executed according to safe practices (Carbon Trust, 2005).

It is important to match the correct technology to a given site. Each location has a particular wave or tidal climate, and the device more appropriate to the characteristics of the location will perform better. According to the literature, there is no agreed method in how to perform the best site matching (O'Connor et al., 2013). Considering wave energy, wave height and peak period scatter diagrams provide information for specific sites on the probability distributions of the wave power available. These diagrams – also called sea state probability matrices – can be used to obtain a more realistic estimate of device performance and cost in a given site.

The selection of the installation site might be subject to some constraints, in particular environmental constraints, constraints due to fishing activities or navigation constraints. To prevent this, it is common practice to establish specific areas for the installation of OECs.

The design of a device influences the ease and speed of installation, specially three aspects: (1) size, since the greater the size the more difficult the installation; (2) placement, since location (relative to shoreline or seabed) poses different challenges; and (3) modularity, since the higher the degree of modularity of a device the easier and faster the installation. Likewise, different operations during the Installation phase might be required depending on the nature of the device. Offshore devices have to be delivered to the installation site, moored or fixed to the seabed and connected to the grid. These devices might be towed to the site or carried on a heavy-lift vessel. Also, it might be necessary to install substations onshore or offshore. Offshore operations have to occur under appropriate sea state and weather conditions – also called weather windows (Mueller & Wallace, 2008), (Entec UK Ltd, 2006).

Cable installation for offshore devices is not technologically challenging but requires careful consideration about cable adequacy, route and installation site. Cable adequacy relates to the ability to perform throughout the service life, being able to withstand the environmental loads and temperature variations of the ocean. A planned cable route enables the avoidance of hazards such as shipping lanes, rocks, wrecks or areas of high currents. Considering the installation, cables might be buried or not, depending on seabed characteristics. Installations that involve burying the cable are slower[4] but leave them less exposed to hazards (Carbon Trust, 2005), (Wave Energy Centre, 2004).

Other aspect of the installation is signalling. Devices have to be signalled at sea and an exclusion area has to be defined and limited by the signalling, prohibiting activities such as fishing or navigation inside the area (Wave Energy Centre, 2004).

3.1.3. Operation and Maintenance Phase

The O&M phase corresponds to the regular functioning of the device/devices – the Operation stage – and maintenance activities – the Maintenance stage. It follows the installation of the device and proceeds until the Decommissioning phase. It corresponds to the project service life.

Throughout the Operation stage, devices must be subject to continuous supervision. Possible practices are (1) on-site regular monitoring or inspection, (2) distance monitoring, (3) data record and monitoring of essential parameters, or (4) record of key events throughout the life cycle of the device (Carbon Trust, 2005). The goal is to monitor performance and possible hazards or failures, assuring that this stage is controlled. Failures tend to be higher in the initial and final stages of the service life (Carbon Trust, 2005). Two aspects are important in this stage: (1) operation costs, i.e., the costs of operating the device, and (2) device availability, i.e., the amount of time the device is operating without fault, relative to the amount of time of the O&M phase (Entec UK Ltd, 2006).

Maintenance activities depend on access to the device and are not always feasible, especially for devices located offshore. Access is the percentage of time a device can be accessed for maintenance (O'Connor et al., 2013). Depending on maintenance procedures of a given device, sea state conditions determine if maintenance activities can be executed safely or not (Carbon Trust, 2005).

Maintenance can be executed on-site or onshore, and be scheduled or not. These aspects are considered and defined in the design stage with the establishment of the maintenance procedures of a device. According to the Carbon Trust (2005) report, the frequency of these activities will depend on six aspects: (1) the adopted maintenance strategy, (2) device access, (3) energy demand, (4) fatigue results, (5) reliability results, and (6) availability and cost of vessels for maintenance. Maintenance activities include inspections and repairs, and intend to control, avoid or reduce failures. Their

[4] According to the Wave Energy Centre (2004) report, installation speed might vary between 10 km/h and 1 km/h, depending if the activity involves cable burying or not.

frequency should be adjusted to maintenance results and equipment performance throughout the project service life.

3.1.4. Decommissioning Phase

The Decommissioning phase consists of the removal from production of the device/devices and project closure. The occurrence of this phase might be planned or unplanned. Possible operations might be as follows: (1) removal of the device/devices from site; (2) removal of the mooring system or foundations; or (3) removal of the submarine cables (Wave Energy Centre, 2004). Removal might be partial, i.e. some equipment might remain at site, disused or re-used for other purposes. Removed equipment might be re-used too, and some materials might be recycled (Carbon Trust, 2005). The operations in this phase will have similar requirements and constraints to those faced in the Installation phase or O&M phase.

3.2. Project Cost

Project cost comprises the life cycle costs (LCC) of an ocean energy project. It is influenced by the OEC (concept, stage of development) and the specific circumstances to which it is subject. However, it can be separated into two categories, which relate to the device: (1) Capital costs and (2) O&M costs (Entec UK Ltd, 2006), (Allan et al., 2011). Moreover, in each category, there are cost items that are common to all ocean energy projects. This section proceeds as follows. First, these cost categories are described in detail, along with the common cost items in each category. The section ends with a discussion on some values and trends referenced in the literature for ocean energy projects.

3.2.1. Capital Costs

Capital costs include device cost, installation cost and decommissioning cost. Device cost is related with the costs of design and manufacturing the device/devices, incurred in the Construction phase. Installation cost relates to the cost of the elements or processes needed so that the device operates at the planned location. Decommissioning cost relate to the cost of project closure. Considering the time of occurrence, device cost and installation cost are referred to as initial Capital cost – or total initial cost.

Offshore operations require the use of vessels, which can be hired or purchased. A vessel tends to be more expensive the more specialised it is. Likewise, these specialised vessels are also harder to hire (Entec UK Ltd, 2006, p. 13). Hiring rates change with demand. Morandeau et al. (2013) quoted a rate of £160.000 per day for the hiring of a suitable vessel that was not designed exclusively for the industry and £30.000 per day for the hiring of a vessel designed for the installation of OECs.

According to Rourke et al. (2010, p. 1034), grid connection costs include the costs of the transmission cables, switchgear and infrastructure needed to connect the device/devices to the grid. Cable installation requires the use of specialised machinery and can be more costly than the cost of the cables itself (Rourke et al., 2010). Cables might be buried or placed over the seabed, the former being a more expensive option (Wave Energy Centre, 2004).

3.2.2. Operation and Maintenance Costs

Operation and Maintenance (O&M) costs are associated with the O&M phase of the project life cycle. Included in this category are (1) the costs of ongoing sea state and performance monitoring, (2) the costs of planned and unplanned maintenance, (3) the cost of overhauls, to re-fit components during the service life; (4) the consenting costs, to keep the project on site; and (5) insurance costs (Entec UK Ltd, 2006).

According to the Entec UK Ltd (2006) report, planned maintenance costs include (1) the cost of inspecting or repairing, (2) the cost of servicing the vessel, and (3) the cost of waiting for weather windows to perform the maintenance. Unplanned maintenance costs are similar in their structure but subject to higher uncertainty (Entec UK Ltd, 2006). Spares are also referenced in the literature, and might be related with maintenance activities (EPRI, 2004).

Insurance costs are due to the risk management strategy assumed for a project. The ocean energy industry has limited operational experience and data available for insurers to establish insurance rates. The Renewable UK (Green & Krohn, 2012) report addressed this problem with detail. According to the report, key criteria for insurers are (1) the profile of the insured, i.e. their experience, credibility, financial strength and track record of contractors and subcontractors; (2) the technology, i.e. the testing it has been subject to, the cost and ease of repairing, the type and availability of vessels required (if and when required) and the availability of spares; and (3) the location, i.e. the suitability of the device to location, the distance to shore and the weather windows. The Electric Power Research Institute (EPRI) (2004) report quoted an insurance rate of 2% of Capital costs as a typical rate for mature offshore technologies.

3.2.3. Discussion

Ocean energy project costs comprise the costs of building, installing, operating and decommissioning an OEC or an array of OECs. Considering the industry, there are several possible metrics for these costs (Rourke et al., 2010). Here, two metrics are considered: (1) the cost per unit of output generated and (2) the cost as percentage of Capital cost or device cost. Most data available in the literature is quoted in either of these metrics.

The number of devices that have reached full scale grid connection is limited. Numbers or estimates of some costs of some projects developed in the past and others being developed are publicly available. Capital costs are easier to estimate than O&M costs due to the lack of operational experience in the industry. Nonetheless, there is reduced available data, and the known values should not be taken as representative of the entire industry.

The EPRI (2004) report quoted a Capital cost estimate of $5.61M (US, 2004) for a single Pelamis P1, a WEC. Estimates for a project involving multiple Pelamis P1 units (EPRI, 2004) indicated a reduction of the Capital cost per device. O'Connor et al. (2013) mentioned this as a common practice in the offshore wind industry. Stallard et al. (2009) also mentioned cost reductions in the Construction, Installation and O&M phases. Considering the tidal energy sector, the Renewable UK (2012) report quoted (1) a Capital cost of £11M for the Delta Stream, a TEC; and (2) a project[5] cost estimate of £20M for the Pulse Stream 100, a reciprocating device.

O&M costs are estimated on a yearly basis. The data found in the literature usually quotes these costs as a percentage of the Capital costs or the device costs[6]. O&M costs of 4,5% for WECs are referenced in the literature (O'Connor et al., 2013). Lam & Bhatia (2013, p. 469) quoted these costs as 5% of the Capital costs for TECs. Rourke et al. (2010, p. 1032), observed that O&M costs of TECs are higher than those of other renewable industries.

Table 3 and Table 4 present cost breakdowns of wave energy projects in terms of Capital costs and O&M costs respectively. These projects differ in dimension: in one case are presented the costs of a single unit project (Single WEC – isolated) and in the other case the costs of a single unit that is part of a wave farm project (Single WEC – wave farm). The SI Ocean (2013) report also presented estimates for 10MW early arrays of WECs and TECs, considering a service life of 20 years[7]. The report quoted average values in terms of LCC for the Installation costs (18% for the array of WECs, 27% for the array of TECs) and the O&M costs (17% for the array of WECs, 19% for the array of TECs).

Table 3: Capital cost breakdown of for a WEC (isolated project or wave farm) (Carbon Trust, 2006)

Capital cost	Single WEC – isolated	Single WEC – wave farm
Device cost	20%	41%
Network integration	21%	14%
Installation	25%	17%
Commissioning	5%	4%
Decommissioning	21%	10%
Insurance	2%	2%
Mooring	2%	7%
Design, engineering and management	4%	5%

[5] The report is not clear on whether this cost represents the Capital costs incurred or the life cycle costs of the project.
[6] The distinction is not often clear in some literatures. O'Connor et al. (2013) mentioned this problem in their work.
[7] The assessment considered a discount rate of 12%.

Table 4: O&M cost breakdown of for a WEC (isolated project or wave farm) (Carbon Trust, 2006)

O&M costs	Single WEC – isolated	Single WEC – wave farm
Monitoring	22%	4%
Planned maintenance	34%	29%
Unplanned maintenance	14%	28%
Insurance	15%	14%
Refit	14%	24%
Consenting costs	1%	1%

3.3. Project Appraisal Indicators

A project involves the application of resources to produce a specific result. It is an investment in that sense, and must be appraised to determine its feasibility and attractiveness. Ocean energy projects are large, complex and capital intensive. These projects have costs and benefits estimated for different periods of their service life that must not be valued the same – an appraisal in terms of present value equivalent (PV) is needed (Brealey & Myers, 2003), (Soares et al., 1999).

Most appraisal methods are based on the time value of money concept. These methods apply a discount factor to future cash flows to obtain its PV. Cooper et al. (2005) defined cash flow as (1) cash inflows (revenues, primarily) and (2) cash outflows (expenditures). The discount rate is set to the appropriate opportunity cost of capital, increased by a risk premium[8], and reflects the reward demanded by the investors. Different discount rates might be considered for the different periods being appraised (Soares et al., 1999), (Brealey & Myers, 2003), (Cooper et al., 2005).

There are four indicators that are most used to appraise projects in the ocean energy industry: (1) the Net Present Value, (2) the Internal Rate of Return, (3) the Discounted Payback Period, and (4) the Levelised Cost of Energy. The section proceeds with a detailed explanation of these indicators.

3.3.1. Net Present Value

Net Present Value (NPV) corresponds to the sum of the discounted cash-flows of a project. It quantifies in terms of PV the future payoffs of an investment, being an indicator of the expected increase in profit (Soares et al., 1999), (Carbon Trust, 2005, p. 18). Each net cash flow CF of a period i is discounted, considering a discount rate j, and added for the n distinct periods in which project cash flows occur (see equation 1).

[8] The risk premium is a form to account with the effects of risk on project objectives. It is simple but ignores the information on specific risks. Project appraisal risk assessment is an alternative to this option (see Project Appraisal Risk Assessment).

$$NPV = \sum_{i=0}^{n} \frac{CF_I}{(1+j)^i} \tag{1}$$

A project with positive NPV is considered as worth pursuing, whereas a project with negative NPV is not. A project is more attractive the higher the NPV is. This rule is applicable when comparing several projects with similar risk profiles. The decision will depend on the risk profile of decision-makers. Likewise, if different projects being appraised have significant differences in terms of invested capital or service life then other criteria besides the NPV should support the decision. Regardless, the NPV is the most consistent indicator for project appraisal, especially when considering several projects (Brealey & Myers, 2003), (Soares et al., 1999).

3.3.2. Internal Rate of Return

Internal Rate of Return (IRR) corresponds to the rate j to which the sum of discounted cash flows CF of each period i equals to zero (see equation 2). It is an indicator of the rate of return of the project, comparable with interest rates or discount rates (Soares et al., 1999).

$$\sum_{i=0}^{n} \frac{CF_i}{(1+j)^i} = 0 \tag{2}$$

If the IRR is higher than the discount rate then the project is seen as attractive and might be worth pursuing – it will depend on the risk profile of decision-makers. IRR and NPV lead to the same conclusions when appraising a single project with conventional cash-flows. However, the indicator should be interpreted with careful on other situations, for the following reasons: (1) it is not adequate to appraise projects in which different discount rates are considered for different periods; (2) it is not adequate to appraise projects with unconventional cash-flows as it might lead to multiple rates (or none); and (3) it is not adequate to evaluate several projects, especially if mutually exclusive (Brealey & Myers, 2003), (Soares et al., 1999).

An alternative to the IRR is the modified IRR – or MIRR. This indicator is interpreted in the same way as the IRR, i.e. it should be higher than the discount rate, but it is more adequate to appraise projects with unconventional cash-flows. The MIRR assumes that the positive cash-flows are reinvested at the cost of capital and the negative cash-flows are financed at the financing cost (Kierulff, 2008). The formula is illustrated on equation 3, where r is the cost of capital and j the financing cost.

$$MIRR = \sqrt[n]{\frac{\sum_{i=0}^{n} CF_k^+ \times (1+r)^{n-k}}{\sum_{k=0}^{n} \frac{CF_k^-}{(1+j)^k}}} - 1 \tag{3}$$

3.3.3. Discounted Payback Period

Discounted Payback Period (DPP) corresponds to the period of time needed for a project to generate the same amount as the invested capital, i.e. to reach the break-even. Soares et al. (1999) described it in detail. It measures how quickly the invested capital is expected to be recovered. DPP discounts and adds the net cash flow CF of each period i considering a discount rate j, until the sum equals to zero (see equation 4).

$$\sum_{i=0}^{Pb} \frac{CF_i}{(1+j)^i} = 0 \tag{4}$$

The DPP considers the time value of money, being a better indicator than the traditional Payback Period indicator, in which cash flows of different periods are weighted the same. However, DPP does not consider the remaining cash-flows of the project. It is not the most adequate economic indicator but rather an indicator of risk, providing information on how fast the invested capital is expected to be recovered. It can be compared (1) with the service life of a project, (2) with other projects, or (3) with established criteria on the acceptable payback period for the project.

3.3.4. Levelised Cost of Energy

Levelised Cost of Energy (LCoE) corresponds to the cost per unit of electricity produced throughout the life cycle of a project. It is an indicator of cost-competitiveness. Allan et al. (2011) described two possible formulas for this indicator: (1) LCoE is calculated as the ratio between the PV of the project LCC and the PV of the produced output (see equation 5); and (2) LCoE is calculated as the ratio between the equivalent annuity of LCC and the average output produced throughout the project life cycle (see equation 6).

$$LCoE = \frac{PV(LCC)}{PV(Output)} = \frac{\sum_{i=0}^{n} \frac{C_i}{(1+j)^i}}{\sum_{i=0}^{n} \frac{O_i}{(1+j)^i}} \tag{5}$$

$$LCoE = \frac{Ann(LCC)}{Ave(Output)} = \frac{\left(\sum_{i=0}^{n} \frac{C_i}{(1+j)^i}\right) \times \left(\frac{j}{1-(1+j)^{-n}}\right)}{\frac{\sum_{i=0}^{n} O_i}{n}} \tag{6}$$

There is limited information about the output discount rate in the literature. A project is cost-competitive if its LCoE is lower or equal than its selling price of energy (Rourke et al., 2010).

4. Risk Assessment

Cooper et al. (2005) explained how risk and uncertainty relate with each other, defining risk as being exposed to the consequences of uncertainty. Some references in the literature (PMI, 2008), (Vose, 2008) differentiate (1) risk, the exposure to the negative consequences of uncertainty given the occurrence of a random event, from (2) opportunity, the exposure to the positive consequences of uncertainty given the occurrence of a random event. Throughout the work, risk and opportunity will be considered as negative and positive risks, respectively. The likelihood of these random events might be lower or higher, and the consequences of their occurrence might have a smaller or larger impact on project objectives. Project risk is the effect of risk on project objectives.

Risk assessment is a process that is structured to provide information on how project objectives might be affected (IEC, 2009, p. 6). It is applied within a context that must be clear and pre-established, considering (1) the project context, i.e., aspects such as project objectives or project scope; (2) the risk management context, i.e., aspects such as risk criteria or risk tolerance; and (3) the external context, i.e., the macro environment aspects (IEC, 2009, p. 9).

According to Cooper et al. (2005), this process enables (1) an overview of the level of risk of the project, (2) a focus on most significant risks, (3) decision-making about the timing and urgency of risk responses, and (4) easier allocation of resources. Risk assessment comprises three stages: (1) the Risk Identification stage, (2) the Risk Analysis stage, and (3) the Risk Evaluation stage. The chapter proceeds with a detailed description of each of these stages, followed by the application of this process for project appraisal. Then it ends with a discussion on the relevance of this process for the ocean energy industry.

4.1. Risk Identification

Risk identification consists of determining and documenting the risks that may affect a project. It is a process that should be (1) comprehensive, since non identified risks are not subject to further analysis and therefore not prevented; (2) iterative, to identify new risks that might arise or become known throughout the life cycle of a project; and (3) consistent, to enable comparisons between different risks or risks at different phases of the project life cycle (PMI, 2008), (Cooper et al., 2005), (ISO, 2009).

Up-to-date information and new, project-specific, additional information should be considered. Likewise, it is important to involve people with the appropriate knowledge (ISO, 2009). Several tools and techniques are mentioned in the literature that support the risk identification process (Cooper et al., 2005). These tools and techniques should be suited to the project objectives, project risks and available capabilities (ISO, 2009).

The identified risks are registered in the Risk Register of the project. This is a list that describes with reasonable detail each risk, considering aspects such as (1) the event that might occur, (2) the impact of the event, (3) the likelihood of the event, (4) the root causes of the event, or (5) the potential responses to the risk (PMI, 2008). The Risk Register is described in detail by several authors (Cooper et al., 2005), (Vose, 2008), (PMI, 2008).

4.2. Risk Analysis

Risk analysis is the process of understanding the identified risks. It consists of determining the impact and likelihood of each risk, considering the existing controls, in order to measure their level of risk (IEC, 2009). The process provides information for decision-making on the response strategies for each risk (ISO, 2009).

The degree of detail of the analysis might vary depending on the purpose of the analysis and resources available, the risk and the existing information and data (ISO, 2009). Risk analysis can be (1) qualitative, (2) semi-quantitative, or (3) quantitative. In the following sections the qualitative risk analysis and the quantitative risk analysis are described in detail.

4.2.1. Qualitative Risk Analysis

Qualitative risk analysis consists of analysing risks in terms of their probability of occurrence and impact on project objectives (PMI, 2008). These attributes, along with the level of risk, are described through nominal or descriptive scales (Cooper et al., 2005). The analysis is rapid and cost-effective, being sufficient in certain circumstances. It enables the determination of the priority of each risk, providing information on which risks to focus. These risks are then subject to a quantitative risk analysis – if required – or to the risk evaluation process (PMI, 2008).

This analysis is performed considering (1) the information on the Risk Register, (2) the information on the risk tolerance of stakeholders and scope of the project, and (3) other relevant information available (data on past projects, studies). It should be an iterative process, revised throughout the life cycle of the project to keep up-to-date with identified risks. Likewise, the quality of data (accuracy, reliability) should be assessed (PMI, 2008).

The analysis of each risk is usually conducted through a probability and impact matrix (P-I matrix) (PMI, 2008). The P-I matrix is explained in detail by several authors (Cooper et al., 2005), (PMI, 2008), (Vose, 2008). It expresses each risk as a combination of a probability level and impact level.

The P-I matrix enables the visualisation of the relative importance of all identified risks. It is possible to prioritise risks and have an overview of the overall project risk. The levels are part of a nominal or descriptive scale, defined for probability and impact. These scales have to be clear, consistent and in accordance with the nature of the project, the objectives, the type of risk and the risk criteria. It should be noticed that inadequate use of these matrices might lead to poor resolution, errors, suboptimal decision-making and ambiguity (Cox Jr., 2008).

The Risk Register must be updated after this analysis, adding information on (1) the risk priorities or relative ranking, (2) the risk categories, (3) the risk causes, (4) the particular sensitive project areas or project phases, (5) the risks requiring urgent response, (6) the risks requiring further analysis, and (7) the trends in results that became visible from repeated analysis (PMI, 2008).

4.2.2. Quantitative Risk Analysis

Quantitative risk analysis consists of quantifying the effect of identified risks on project objectives. It is a numerical and more detailed risk analysis that requires more information, data and effort (IEC, 2009). Therefore, it is performed on risks that might have a significant influence on project objectives, and that have been analysed and prioritised in the qualitative risk analysis (PMI, 2008).

This analysis is performed considering (1) the information on the Risk Register, (2) the risk tolerance of stakeholders and project criteria on schedule and costs, and (3) other relevant information available (data on past projects, studies). These aspects influence the approach taken and how the quantitative analysis is structured (PMI, 2008).

PMI (2008) identified three possible techniques to perform the analysis: (1) a sensitivity analysis, to examine the effect of each risk on project objectives separately and determine the most significant risks; (2) an expected monetary value (EMV) analysis, to determine the average outcome of the effects of project risks on the objectives; or (3) a modelling and simulation analysis, to determine the likelihood of possible outcomes due to the effect of risks on project objectives[9].

The Risk Register must be updated after this analysis, adding information on (1) the probabilistic analysis of the project, (2) probability of achieving cost and time objectives, and (3) the prioritised list of quantified risks. The analysis should be repeated to determine the effect of adopted risk responses on project overall level of risk, and to observe possible trends in results (PMI, 2008).

4.3. Risk Evaluation

Risk evaluation consists of comparing the levels of risk found during the risk analysis with established risk criteria in order to determine the significance of the risk (Cooper et al., 2005), (ISO, 2009). It assists decision-making on responses for each risk, taking into account project requirements and project risk tolerance (ISO, 2009).

The Risk Register and the established risk management context provide the input for the risk evaluation process (PMI, 2008). The nature of the decision-making that might occur in this stage and the established risk criteria should be revised given the understanding of risks that resulted from the Risk Analysis stage. Decisions might be as follows: (1) whether a risk needs treatment; (2) priorities (of risks) for treatment; (3) whether an activity should be undertaken; or (4) which of a number of paths should be followed (IEC, 2009, p. 16).

There are several references in the literature about available response strategies that might be chosen at this stage (ISO, 2009, pp. 12-13), (PMI, 2008), (Vose, 2008). Primary and backup strategies for a given risk (or risks) might be defined if necessary, and risks that might surge from the adopted strategies should be understood also. Possible strategies include: (1) risk avoidance, (2) risk transfer, (3) risk mitigation, (4) risk exploitation, (5) risk sharing, (6) risk enhancement, and (7) risk acceptance. Avoidance, transfer or mitigation of risks is usually adopted for negative risks, while exploitation,

[9] The Monte Carlo Simulation technique enables the modelling and simulation analysis. This technique is described in detail in this work (see Project Appraisal Risk Assessment).

sharing and enhancement of risks are usually adopted for positive risks. Risk acceptance can be used for positive and negative risks.

The standard IEC (2009) mentions two possible risk criteria for decision-making at this stage: (1) a criteria based on a level of risk over which risk acceptance must not occur, and (2) a criteria based on the level of risk and the costs and benefits of accepting the risk or not, a criteria that introduces the concept of ‘As Low As Reasonably Practicable’ (ALARP) i.e. risks that should be reduced but with a reasonable balance between the incurred costs and the obtained benefits. These criteria refer to negative risks.

The Risk Register must be updated after the evaluation, registering for each evaluated risk aspects such as (1) the selected risk responses, (2) the actions, budget and scheduled activities required for implementation, (3) the residual risk, or (4) the secondary risks. Depending on the priority of the risk the level of detail in the Risk Register can be higher or lower. Significant risks should be addressed in detail relative to all their attributes (PMI, 2008).

4.4. Project Appraisal Risk Assessment

The risk assessment process might be applied for project appraisal. In this context, the assessment consists of identifying, analysing and evaluating the costs and benefits associated with a project, their uncertainties and the risks that might affect them. Vose (2008) mentioned the application of risk analysis techniques to determine the uncertainty on project cost. The European Commission (2008) guide recommended some steps to perform a risk assessment of project performance in terms of appraisal indicators such as the NPV or the IRR. These included (1) a sensitivity analysis to the project variables, (2) an assignment of probabilistic distributions to the critical variables, (3) a risk analysis, (4) the assessment of acceptable levels of risk, and (5) risk prevention.

Projects can be seen as a set of items that are subject to (1) the uncertainty about their impact, and (2) the occurrence of events that can affect their impact. Traditional approaches to deal with the risk of the project are (1) to consider a risk premium in the discount rate, (2) to perform sensitivity analysis to some factors, or (3) to appraise the DPP (Soares et al., 1999).

Ocean energy projects are subject to a great amount of uncertainty due to their characteristics. These are projects from an industry lacking operational experience, and still in the early stages of development in terms of design, manufacturing or installation. Moreover, ocean energy projects tend to involve a large amount of invested capital. The decision of whether to proceed or not with a project should be taken with a clear understanding of the existing project uncertainties and risks, and their effects on project cost, feasibility and cost-competitiveness. Therefore, the determination of the uncertainty on the results of project appraisal indicators is critical for decision-making.

A fundamental step in this assessment is the quantitative risk analysis. This enables an overall project appraisal risk analysis, providing input for informed decision-making. According to Cooper et al. (2005), the analysis provides information about (1) the likelihood of different outcomes, (2) the risk of exceeding specified targets, and (3) the major risk drivers for the project.

The impact of the uncertainties on project objectives can be assessed by the Monte Carlo simulation (MCS). The MCS technique is a (statistical numerical) technique for quantitative modelling. It enables the analysis of the uncertainty propagation in complex models with a large number of uncertainty factors.

In a MCS each variable is modelled by a probability distribution, and part of a model that is structured to link all variables and measure their combined effect on the uncertainty distribution of the possible outcomes of the model (Vose, 2008). It is an iterative process, requiring a large number of iterations to assure or increase the accuracy of the simulation.

The simulation generates a number of possible outcomes, taking into account all possible values for each variable modelled. Each iteration involves the random sampling of values from each variable of the model, which can occur through two different processes: the Monte Carlo sampling or the Latin hypercube sampling (Vose, 2008). In the Monte Carlo sampling process the random sampling occurs across the full range of possible values for each variable. In the Latin hypercube sampling process the random sampling is proportional to the probability of occurrence of possible values for each variable, meaning that it enables the reproduction of the input distributions.

The strengths and weaknesses of this technique are described with detail in the literature (Vose, 2008). Main strengths of the technique include (1) the fact that probability distributions of the inputs of the model do not need to be approximated, (2) the possibility to model correlations and other interdependencies, (3) the possibility to progressively change the model and compare results with ease, and (4) the fact that the technique is recognised as valid. Main weaknesses of the technique include (1) the possible large duration of simulation, (2) the accuracy dependent of the number of iterations performed, (3) the inability to represent certain uncertainties, and (4) the challenges of modelling large and complex systems.

The MCS technique can be performed through the use of special software such as @Risk or Crystal Ball, which function with the assistance of a conventional spreadsheet software. Cooper et al. (2005, pp. 276-277) identified the main advantages of spreadsheets for modelling and simulation, such as their ease and flexibility of use. Vose (2008, p. 37) considered these software adequate for project cost risk analysis. Their use for project appraisal is also possible.

The Risk Register provides the information required to build the quantitative model and proceed with the MCS. Based on the relevant findings that result from the risk identification and qualitative risk analysis, the model can be defined in terms of (1) the probabilistic distributions of the parameters of the model, (2) the probabilities relative to the occurrence of uncertain events, and (3) the existing correlations or other relationships between parameters.

4.5. Discussion

Risk Assessment is a fundamental practice of risk management. It provides input for decision-making about (1) how to maximise positive risks and minimise negative risks, (2) whether to proceed with a project, activity or task, (3) which risk response strategies to prioritise, or (4) which option to select between different alternatives.

Considering project risk management, the risk assessment process is applicable to all phases of the project life cycle. It might be applied with different levels of detail, helping decision-making in each phase. How it is applied is dependent on the context and the methods and techniques used. The standard IEC evaluates several tools used for risk assessment in terms of their applicability to each of the risk assessment stages (IEC, 2009, p. 22).

Ocean energy projects should benefit from risk assessment. These are projects planned for a long time horizon, complex in their nature, and from an industry in an early stage of development. The application of a risk assessment method for project appraisal could improve decision-making. A comprehensive understanding of project risks will enhance risk response strategies, and project objectives will be fulfilled or exceeded. The Renewable UK (2013, p. 3) report mentioned this, suggesting risk assessment as a mean to (1) develop more realistic projections, (2) educate and engage stakeholders, and (3) understand how best to develop the industry.

There are references in the literature on how risk assessment could be applied to ocean energy projects. The Carbon Trust (2005, pp. 21-22) report suggested five-level descriptive scales for the qualitative risk analysis. The report also considered (1) possible risk categories and risk criteria for wave energy projects, and (2) several life cycle events that could be considered for the risk assessment of wave energy projects. Some of these life cycle events are as follows: (1) foundation failure, (2) mooring failure, (3) stability failure, (4) structural failure, (5) collision risks, or (6) electrical failures.

The Renewable UK (2013) report assessed several risks faced by the ocean energy industry in the United Kingdom, related with (1) securing finance, (2) technological challenges, (3) grid access and connection, and (4) consenting processes. For each of these categories the report developed a Risk Register. The Wave Energy Centre (2004, p. 43) report identified several risks associated with wave farm projects, particularly the (1) cost overruns or delays in different phases of the project life cycle or (2) the overestimating resource assessments. Frid, et al. (2012) assessed potential environmental risks resulting from tidal and wave energy projects, although constrained by the lack of data. The report from Instituto do Ambiente (Cruz & Sarmento, 2004, pp. 45-48) addressed these risks too.

5. Methodology

Mueller & Wallace (2008) considered survivability, reliability and affordability as the most significant objectives for ocean energy technologies. Affordability consists of developing projects at a cost that enables market access and financial returns (Mueller & Wallace, 2008, p. 4378). It is a decisive factor for any ocean energy project as it is related with project feasibility, profitability and cost-competitiveness. Typical project appraisal indicators of the ocean energy industry provide information about these aspects. However, being a relative recent industry, ocean energy projects are subject to a great number of uncertainties that difficult decision-making.

Project appraisal risk assessment is an appropriate method to improve decision-making of investors and inform other stakeholders if required. As mentioned (see Project Appraisal Risk Assessment), the goal of this process is to determine the uncertainty in the project appraisal indicators, and the main sources of uncertainty and risk drivers.

The method is illustrated on Figure 1. First, the context of the work must be established. It consists of defining (1) the scope of the project and (2) the scope of the risk assessment. Then, the risk identification and qualitative analysis occurs, enabling (1) the creation of a Risk Register with the project risks, (2) the analysis of their likelihood and impact, and (3) the definition of the risks that require further analysis. This is followed by a quantitative risk analysis of the most significant uncertainties and risks that occurs in two steps – first, a sensitivity analysis, and then a simulation through the MCS technique. The assessment is concluded with a risk evaluation.

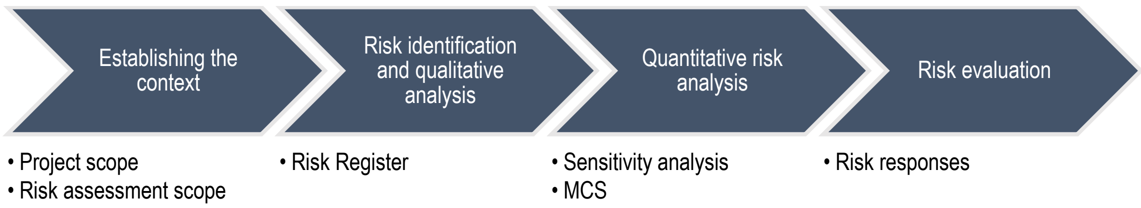


Figure 1: Project appraisal risk assessment methodology

The following information is critical: (1) data about site-specific resource characteristics; (2) data about the cost items of all life cycle phases; (3) data related with the project macro environment, such as the selling price of electricity, tax regime or legislation; and (4) data about the device characteristics and project execution procedures. These assessments must consider time, and assign costs, production and revenues to specific periods to perform the appraisal in terms of present value equivalent. Nonetheless, it might occur that some simplifications related with time are made.

The following chapters exemplify the application of this methodology. It proceeds with a project appraisal risk assessment for potential ocean energy projects installed at Portugal. The steps, assumptions and options are explained, and the results are interpreted and compared with the literature data. The evaluation is not performed in this exemplification as several distinct – and valid – responses could be used. This is ultimately up to the decision-makers.

6. Ocean Energy Project Context

It is important to establish the context of the ocean energy project appraisal risk assessment, i.e. to describe with detail the scope of the project and the scope of the risk assessment. Context is essential to proceed with – and understand – the assessment.

In this exemplification three different contexts are described: (1) the external context, which describes the project in terms of its macro environment; (2) the project context, which describes the project in terms of deliverables, stakeholders, exclusions, assumptions, work required, object and options; and (3) the risk assessment context, which describes the project appraisal risk assessment in terms of objectives, risk categories and risk criteria.

6.1. External Context

Portugal established a 320km^2 offshore area under its jurisdiction to conceive and implement ocean energy projects – the Portuguese Pilot Zone. It is located in São Pedro de Moel, a coastal location in the district of Leiria, over 100km north of Lisbon. Legal and regulatory requirements to develop an ocean energy project in this area were established in the decree-law 5/2008 (see Figure 2). The development of these projects in Portugal outside the Portuguese Pilot Zone is possible but legal and regulatory requirements are not clear, and there are uncertainties related with grid connection, grid capacity and the regulation of power supply[10].

The Portuguese Pilot Zone main benefits are (1) the fact that it is planned to have the infrastructures required for appropriate gird connection and grid capacity (up to 250MW); (2) the fact that it is located in a non-conditioned area with low traffic density, favourable to the implementation of ocean energy projects; and (3) the fact that it is a documented and characterised area for which most of the relevant assessments are available. The marine energy project owner must pay an annual rent throughout the project service life relative to the exploitation consent, which might extend up to 35 years. Likewise, a fee must be paid to obtain the installation consent. It is legally required to establish an insurance contract for liability to develop a project in this area.

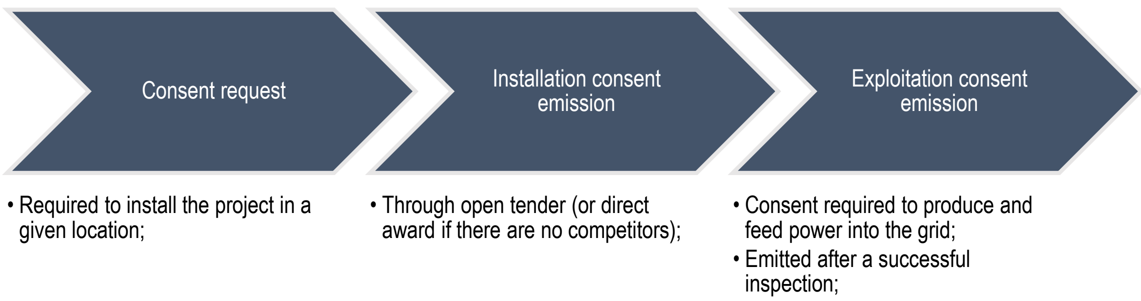


Figure 2: Legal procedures to implement an ocean energy project in the Portuguese Pilot Zone

The Portuguese market tariffs for ocean energy projects are fixed by the Portuguese government. These tariffs – also called feed in tariffs (FIT) – correspond to the selling price applied to the power

[10] The available legislation refers to the use of territorial waters and the production of electricity from renewable sources, established before the legislation created for the Portuguese Pilot Zone.

output produced by a project. Different FIT are applied depending if the goal is (1) to test a device concept at an early stage of development, (2) to test a mature device concept (pre-commercial tariff), or (3) to produce power output for commercial purposes (commercial tariff). However, these FIT are now under discussion and were not disclosed for the Portuguese Pilot Zone by the managing entity. For purpose of the exemplification, a value of 0,26 €/kWh is assumed. This was the value applied to the Pelamis wave farm project installed in Aguçadoura, Portugal (Fernandes, 2008).

In terms of taxation, the entities resident or established in the Portuguese territory are subjected to different tax rates, depending on aspects such as location, activity or taxation income. Here, a general tax rate of 25% is considered for the purpose of this exemplification.

6.2. Project Context

Project context is defined considering the following: (1) the deliverables of the project; (2) stakeholders; (3) exclusions; (4) assumptions; (5) device; (6) work required; and (7) the main options considered for the project.

In this thesis, the major deliverable of an ocean energy project is the produced power output that results from harnessing the ocean energy at a given location through one or more OECs. It is a deliverable expected to last the entire service life of the device/devices. It requires the construction, installation, operation and maintenance of a device or array of devices, depending on the project characteristics[11].

Main stakeholders in these projects include: (1) the project developer, responsible for the project execution; (2) the project owner, who invested in the project; (3) the funders, who support the project owner through funding; (4) the insurers, who assume project risks under agreement; (5) the entities, who authorise and supervise certain project procedures; (6) the utilities, who integrate the produced output in the grid; and (7) the government, who makes policies.

The general assumptions and exclusions considered in this assessment are as follows:

- Most cost drivers considered here are taken from the literature, based on cost percentages of the Capital cost or the O&M cost, and might not correspond to their real cost for a project involving the device considered in this assessment. However, the value of these cost items is considered as such for the purpose of this exemplification.
- The installation consent fee is not considered in this assessment due to the lack of information available in the literature and the fact that such information could not be disclosed by the managing entity.
- Insurance is considered as an annual cost.
- Funding is considered in terms of (1) total amount, as percentage of the Capital cost of the project, (2) interest rate, and (3) repayment period. It is assumed that a high percentage of the Capital cost (70 – 80%) is obtained through funding, the interest rate is in between 4 –

[11] Decommissioning is a requirement – either legal or by option – for project closure, not to produce power output.

8%, and the repayment period is the same as the service life period. Further definitions about the total amount and the interest rate occur throughout this assessment.

- The resource data is taken from Hogben et al. (1986) and it is presented on Table 5. It refers to a much larger area of the Atlantic Ocean in which the Portuguese coast is included. It is considered here as an approximate assessment of the resource characteristics on Portugal, for the purpose of this exemplification.
- It is assumed a linear depreciation through a period of 20 years of the device/devices considered in the project, a value quoted in the literature (Archetti, Passoni, & Bozzi, 2011). Salvage value is considered as null at the end of the device life.
- A discount rate in between 10 – 15% is considered in this assessment, a range of values taken from the literature (Entec UK Ltd, 2006). Further definitions about the discount rate occur throughout this assessment.
- A reinvestment rate equal to the discount rate is considered in this assessment.
- Considerations on the matching of power output supplied into the grid from OECs and the demand are excluded from this assessment.
- Possible structural changes in the network due to the project (i.e. changes to support the additional generation capacity), if needed, are excluded from this assessment. It is assumed that these changes are from the responsibility of the entities managing the distribution and the transportation of the electricity in the grid.

Table 5: Sea state probability matrix considered for the project appraisal risk assessment[12]

		Wave Period										
		3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5
Wave Height	0,5	0,000053	0,002124	0,012532	0,021782	0,014432	0,004587	0,000858	0,000110	0,000011	0,000001	0,000000
	1,5	0,000001	0,000404	0,011000	0,052578	0,077910	0,050775	0,018425	0,004390	0,000772	0,000109	0,000013
	2,5	0,000000	0,000060	0,003472	0,030724	0,077361	0,080193	0,043878	0,015070	0,003682	0,000700	0,000110
	3,5	0,000000	0,000010	0,000933	0,012415	0,044682	0,063727	0,046481	0,020711	0,006406	0,001510	0,000290
	4,5	0,000000	0,000002	0,000242	0,004366	0,020522	0,037215	0,033739	0,018333	0,006796	0,001891	0,000424
	5,5	0,000000	0,000000	0,000064	0,001463	0,008509	0,018693	0,020173	0,012854	0,005514	0,001755	0,000445
	6,5	0,000000	0,000000	0,000017	0,000490	0,003404	0,008774	0,010946	0,007964	0,003860	0,001374	0,000387
	7,5	0,000000	0,000000	0,000005	0,000169	0,001366	0,004035	0,005699	0,004645	0,002500	0,000980	0,000302
	8,5	0,000000	0,000000	0,000002	0,000061	0,000562	0,001869	0,002941	0,002648	0,001562	0,000666	0,000222
	9,5	0,000000	0,000000	0,000001	0,000023	0,000239	0,000884	0,001532	0,001506	0,000963	0,000443	0,000158
	10,5	0,000000	0,000000	0,000000	0,000009	0,000106	0,000429	0,000811	0,000863	0,000594	0,000292	0,000111
	11,5	0,000000	0,000000	0,000000	0,000004	0,000048	0,000214	0,000438	0,000500	0,000368	0,000192	0,000077
	12,5	0,000000	0,000000	0,000000	0,000002	0,000023	0,000109	0,000240	0,000293	0,000229	0,000127	0,000054
	13,5	0,000000	0,000000	0,000000	0,000001	0,000011	0,000057	0,000134	0,000174	0,000143	0,000084	0,000037
	14,5	0,000000	0,000000	0,000000	0,000001	0,000011	0,000066	0,000176	0,000259	0,000242	0,000159	0,000079

The Pelamis is a WEC developed by Scottish company Pelamis Wave Power Ltd. It is an offshore oscillating body device, composed by a set of cylindrical steel sections linked by hinged joints. It is designed so that it is semi-submerged and its sections oscillate relative to each other as the device interacts with the waves. The energy associated with these motions is harnessed by hydraulic motors within each section of the device (Yemm et al., 2012). So far six projects have been developed involving this device, being one of the few OECs that have reached full scale grid connection (Krohn et al., 2012). According to Yemm et al. (2012), the main characteristics of the device are as follows:

[12] The sea state probability matrix – along with the device power matrix – is explained later in this work (see Description of the Model)

- High power absorption efficiency in sea states characterised by small wave height and progressively limiting power absorption efficiency with increasing wave height (see Table 6).
- Technologically mature components from other industries.
- PTO and conversion systems designed for redundancy in case of fault.
- High degree of modularity.
- Onshore manufacturing and mooring installation requiring minor activities.
- Quick and easy device connection and disconnection from the infrastructure.
- Onshore maintenance, requiring a vessel to tow the device/devices.

The duration of maintenance and overhaul activities is assumed due to the lack of concrete data in the literature. Yemm et al. (2012) quoted the time of device connection and disconnection but few references state realistic values for the overall duration of these activities. Hence, planned maintenance is assumed to take one week, unplanned maintenance two weeks, and overhaul activities three weeks. Spares used these activities are assumed to be procured with anticipation.

Table 6: Device power matrix (O'Connor et al., 2013)

		Wave Period										
		3	4	5	6	7	8	9	10	11	12	13
	0.5	0	0	0	0	0	0	0	0	0	0	0
	1.5	0	0	32	65	83	86	78	65	53	42	33
W	2.5	0	0	89	180	231	238	216	181	146	116	92
a	3.5	0	0	0	354	438	424	377	326	260	215	180
v	4.5	0	0	0	544	642	628	562	473	382	338	266
e	5.5	0	0	0	0	750	750	737	658	530	446	355
	6.5	0	0	0	0	750	750	750	750	658	579	481
H	7.5	0	0	0	0	0	750	750	750	750	686	593
e	8.5	0	0	0	0	0	0	0	750	750	750	750
i	9.5	0	0	0	0	0	0	0	0	0	750	750
g	10.5	0	0	0	0	0	0	0	0	0	0	0
h	11.5	0	0	0	0	0	0	0	0	0	0	0
t	12.5	0	0	0	0	0	0	0	0	0	0	0
	13.5	0	0	0	0	0	0	0	0	0	0	0
	14.5	0	0	0	0	0	0	0	0	0	0	0

The work required throughout the project life cycle is illustrated through a work breakdown structure (WBS) (see Figure 3). In this exemplification, a broad view on project activities will be preferred instead of a detailed one. These activities might require equipment, personnel and logistics, which are assumed to be considered in the costs presented in this assessment. The Installation phase is assumed to occur at a season in which inadequate environmental conditions to perform the activities are less likely (usually the summer). Project cost estimates are taken or calculated based on the literature data (see Table 7).

Construction phase	Design	
	Manufacturing	
Installation phase	Power transmission system	
	Foundations/Mooring	
	Deployment and Commissioning	
O&M phase	Monitoring	
	Maintenance	
Decommissioning phase	Device removal	
	Foundations/Mooring removal	
	Asset management	

Figure 3: WBS of the project for the assessment

Table 7: Base cost estimates for the project appraisal risk assessment

Cost item	Work/Activity	Base estimate	Source
WEC (WEC IC)	Design; Manufacturing	3.000.000 €	(Raventos, Sarmento, Neumann, & Matos, 2010)
Power transmission system	Power transmission system	1.500.000 €	(Dalton, Alcorn, & Lewis, 2010), (Archetti, Passoni, & Bozzi, 2011)
Mooring	Mooring	300.000 €	(O'Connor et al., 2013)
Deployment and commissioning	Deployment and commissioning	60.000 €	(O'Connor et al., 2013)
Monitoring	Monitoring	48.114 €	(Carbon Trust, 2006), (O'Connor et al., 2013)
Planned maintenance	Maintenance	155.124 €	(Carbon Trust, 2006), (O'Connor et al., 2013)
Unplanned maintenance	Maintenance	254.302 €	(Carbon Trust, 2006), (O'Connor et al., 2013)
Spares	Maintenance	60.000 €	(Dalton, Alcorn, & Lewis, 2010)
Insurance	O&M	60.000 €	(O'Connor et al., 2013)
Annual rent	O&M	2.187 €	(Carbon Trust, 2006), (O'Connor et al., 2013)
Overhaul	Maintenance	300.000 €	(O'Connor et al., 2013)
Decommissioning	Decommissioning	300.000 €	(Dalton, Alcorn, & Lewis, 2010)

In the context of this exemplification different scenarios are considered in the assessment. Ocean energy projects with one, four, eight and thirty-two Pelamis units are assessed to verify the influence of project scale. It is assumed that the cost estimates for each device in a multiple-unit project remain the same. Further scenarios might be considered throughout the assessment if relevant.

6.3. Risk Assessment Context

The risk assessment context is based on the methodology presented in this work (see Methodology). This exemplification proceeds with a project appraisal risk assessment that is mainly based on literature data. It intends to be as extensive as reasonable given the available information. The following objectives are considered for this risk assessment:

- What is the likelihood of each scenario for which affordability is assured?
- What are the main sources of uncertainty and risk in these projects?

These objectives are selected for the purpose of this exemplification. The appraisal indicators considered are the (1) NPV, (2) the MIRR, (3) the DPP and (4) the LCoE. The MIRR is selected instead of the IRR due to the fact that it is a more adequate indicator for projects with unconventional cash flows, which might be the case.

Following the methodology described in this thesis, it is important to define (1) the risk categories and (2) the risk criteria.

Here, the risk categories considered for an ocean energy project are illustrated through a risk breakdown structure (RBS) (see Figure 4). It is possible to identify the major risk areas and causes considered in these projects. Risks are either (1) due to external causes, i.e. occurrences not related with the project that have impact on it; or (2) due to project execution, i.e. occurrences that result from executing the project and have impact on it. These main categories are broken down into more specific subcategories.

External	Market
	Legal
	Environment
Execution	Dimension
	Management
	Technology
	Quality
	Funding
	Insurance

Figure 4: RBS for the project appraisal risk assessment

Risk criteria is defined in accordance with the objectives established and available resources. Table 8 and Table 9 present the impact and likelihood descriptive scales. These scales are used to perform the qualitative risk analysis. Considering the objective of this assessment, cost is the only impact considered. The scale is defined in terms of how the objectives might be affected. It should be noted that other impacts could be assessed also, but in that case careful is advised to prevent inconsistencies in the analysis (see Qualitative Risk Analysis). The likelihood scale is adapted from Cooper et al. (2005).

Table 8: Impact descriptive scale for the project appraisal risk assessment

Class	Rating	Description
A	Catastrophic or Outstanding	Critical cost increase/decrease. Might compromise/facilitate project affordability
B	Major	Large cost increase/decrease
C	Moderate	Significant, manageable cost increase/decrease
D	Minor	Minor, manageable cost increase/decrease
E	Negligible	Insignificant cost increase/decrease

Table 9: Likelihood descriptive scale for the project appraisal risk assessment

Class	Rating	Frequency
A	Almost certain	Several occurrences per year
B	Likely	Occasional occurrence per year
C	Possible	Once in 5 years
D	Unlikely	Occasional occurrences in a lifetime. A similar event has occurred in the sector
E	Rare	Once in a lifetime. A similar event has occurred in the industry

The levels of risks are three: high, medium and low. High and medium level risks are considered as risks that require further analysis. If a negative risk is high or medium level after the quantitative analysis (1) an adequate response must be selected to reduce the level 'As Low As Reasonably Practicable' (ALARP), or (2) project execution might be reconsidered. If a positive risk is high or medium level after the quantitative analysis it should be (1) accepted, (2) shared, (3) enhanced or (4) explored (see Risk Evaluation). Low level risks require minimal action. These are assumptions considered for the purpose of this exemplification. The P-I table according to the levels of risk is presented in Table 10 (impact classes are vertical, likelihood classes horizontal).

Table 10: Levels of risks considered for the assessment

Likelihood **Impact**	**A**	**B**	**C**	**D**	**E**
A	High	High	High	Medium	Medium
B	High	High	Medium	Medium	Medium
C	High	Medium	Medium	Medium	Low
D	Medium	Medium	Medium	Low	Low
E	Medium	Medium	Low	Low	Low

7. Ocean Energy Project Risk Identification and Qualitative Analysis

Project risk is the effect of risk on project objectives. An adequate risk assessment requires comprehensive risk identification but there are constraints such as available time, available resources or existing data. The project risks identified must be understood in order to evaluate them according to the risk criteria and determine the adequate responses. These are part of the methodology defined in this thesis, and are exemplified in the following sections.

7.1. Ocean Energy Project Risk Identification

In this assessment, considering the objectives defined, the risk identification process is focused on typical risks in these projects, based on (1) evidence from the literature, and (2) analysis of the WBS. Risks are numbered with a risk ID for referencing purposes.

This section proceeds as follows. First, the identified risks in the Construction phase of ocean energy projects are presented. Then, the identified risks in the Installation phase are presented. This is followed by a presentation of the identified risks in the O&M phase. The section ends with the presentation of the identified risks in the Decommissioning phase.

7.1.1. Construction phase Risk Register

In ocean energy projects the Construction phase includes the design and manufacturing of the device (see Construction Phase). Here, it is considered that all major aspects of the design are clearly defined except for the resource and installation characteristics. The project proceeds with the manufacturing stage once the installation consent is given. The major deliverable of this phase is the device (or devices).

Possible risks in the Construction phase are presented in Table 11. This Risk Register identifies (1) the event (i.e. the risk), (2) root cause (or causes), (3) the type of risk it is, and (4) the associated risk category.

Two risks are considered in this phase: (1) the risk of conflicting uses on project required area/areas and (2) the risk of cost reduction due to scale. It might occur that the required offshore area/areas for project location and power transmission system installation have been or might be used for other purposes such as fishing activities, military activities or maritime traffic (Wave Energy Centre, 2004). The risk of conflicting uses on project required area/areas is a negative risk that belongs to the Environment risk category. Cost reduction due to scale might occur as the scale or volume of production of devices increases due to the effect of economies of scale. It is a positive risk that belongs to the Dimension risk category.

Table 11: Construction phase Risk Register

ID	Event	Root Cause	Risk Category	Type of Risk
C1	Conflicting uses on project required area/areas	Area/areas used for other activities	Environment	Negative
C2	Cost reduction due to scale	Economies of scale	Dimension	Positive

7.1.2. Installation phase Risk Register

In ocean energy projects the Installation phase includes the set of operations and processes needed to place the device at the planned location (see Installation Phase). Here, in terms of work required, it consists of (1) installing the power transmission system, (2) installing the foundation/mooring system, and (3) deploy and commission the device. The major deliverable of this phase is an installed and grid connected device (or devices) available to start its service life.

Possible risks in the Installation phase are presented in Table 12. This Risk Register identifies (1) the event (i.e. the risk), (2) root cause (or causes), (3) the type of risk it is, and (4) the associated risk category.

Ocean energy projects are planned for an extended service life. The risk of short term exploitation consent due to current legislation or decision making entities has a negative impact on cost. This risk is categorised into the Legal risk category.

Inadequate weather window is related with offshore operations. This event occurs as long as specific sea state conditions (i.e. wave height) verify, and it impedes the execution of offshore operations during its occurrence. It is a negative risk that belongs to the Environment risk category.

Asset damage is another risk in this phase. It consists of damage caused to the device, grid connection cables or other project asset located offshore. This might occur due to collisions or entanglements involving animals, vessels or other offshore activities. It is a risk with negative impact on cost that is categorised into the Quality risk category.

Cost reduction due to scale is an event that might occur in this phase. As the number of units to be installed increases there might be significant savings in cost due to specific design modifications and more efficient utilisation of vessels (SI Ocean, 2013). This is a positive risk, categorised into the Dimension risk category.

Table 12: Installation phase Risk Register

ID	Event	Root Cause	Risk Category	Type of Risk
I1	Short term exploitation consent	Legislation	Legal	Negative
I2	Inadequate weather window	Sea state conditions	Environment	Negative
I3	Asset damage	Collisions, entanglements	Quality	Negative
I4	Cost reduction due to scale	Economies of scale	Dimension	Positive

7.1.3. O&M phase Risk Register

In ocean energy projects the O&M phase includes the regular functioning of the device/devices and maintenance activities (see Operation and Maintenance Phase). In terms of work required, it consists of monitoring the device/devices and performing maintenance activities. Major deliverable of this phase is the power output produced. This is the major deliverable of the project also.

Possible risks in the O&M phase are presented in Table 13. This Risk Register identifies (1) the event (i.e. the risk), (2) root cause (or causes), (3) the type of risk it is, and (4) the associated risk category.

The following events might occur in this phase and are quite similar to those introduced in the Installation phase: (1) the risk of inadequate weather window, (2) the risk of asset damage, and (3) the risk of cost reduction due to scale. The type of risk and their root causes remain the same. In the O&M phase, the risk of inadequate weather window impedes the occurrence of maintenance activities only.

In the O&M phase there is a risk of an unplanned maintenance, i.e. the risk of non-scheduled, maintenance activities due to a fault (or faults) that compromises the Operation stage or even the project, requiring immediate intervention. Here, the following faults are considered as possible root causes: (1) power output losses, (2) mooring malfunction, (3) material failure, (4) hydraulic system malfunction, and (5) interface failure – i.e. failure in the monitoring and control systems. This is a risk with negative impact on cost, categorised into the Quality risk category. In the Maintenance stage there is also the risk of maintenance delay due to sourcing, caused by the unavailability of spares – which are sourced – in good time. This is a negative risk, categorised into the Technology risk category.

Considering performance, there is a risk of lower than expected performance of the device/devices due to poor resource assessment or changing resource characteristics. This is a negative risk that belongs to the Environment risk category.

Table 13: O&M phase Risk Register

ID	Event	Root Cause	Risk Category	Type of Risk
OM1	Inadequate weather window	Sea state conditions	Environment	Negative
OM2	Asset damage	Collisions, entanglements	Quality	Negative
OM3	Cost reduction due to scale	Economies of scale	Dimension	Positive
OM4	Unplanned maintenance	Fault requiring immediate intervention	Quality	Negative
OM5	Maintenance delays due to sourcing	Unavailable spares	Technology	Negative
OM6	Lower than expected performance	Poor resource assessment or changing resource characteristics	Environment	Negative

7.1.4. Decommissioning phase Risk Register

In ocean energy projects the Decommissioning phase corresponds to project closure (see Decommissioning Phase). Here, in terms of work required, it consists of (1) removing the device (or devices) from where it has been installed, (2) removing the foundation/mooring system, and (3) managing these assets (i.e. re-use, recycle or dispose).

Possible risks in the Decommissioning phase are presented in Table 14. This Risk Register identifies (1) the event (i.e. the risk), (2) root cause (or causes), (3) the type of risk it is, and (4) the associated risk category.

The following events might occur in this phase and are similar to those introduced in the Installation phase: (1) the risk of inadequate weather window, (2) the risk of asset damage, and (3) the risk of cost reduction due to scale. These life cycle phases consist of similar operations but with reversed goals, hence the similarity of the events.

Table 14: Decommissioning phase Risk Register

ID	Event	Root Cause	Risk Category	Type of Risk
D1	Inadequate weather window	Sea state conditions	Environment	Negative
D2	Asset damage	Collisions, entanglements	Quality	Negative
D3	Cost reduction due to scale	Economies of scale	Dimension	Positive

7.2. Ocean Energy Project Qualitative Risk Analysis

The qualitative risk analysis made in this exemplification consist of a preliminary analysis – without great detail but accurate. This enables the determination of the priority risks that require further and more detailed analysis.

This section proceeds as follows. The risks identified in this assessment are analysed in terms of likelihood and impact through the descriptive scales defined in the risk assessment context. The analysis is done for each life cycle phase at a time, and conclusions are drawn about priority risks of the project.

7.2.1. Construction phase Qualitative Risk Analysis

The Construction phase Risk Register consists of two risks: (1) the risk of conflicting uses on project required area/areas and (2) the risk of cost reduction due to scale. Here, both risks are analysed in terms of impact and likelihood as follows:

- Conflicting uses on project required area/areas might delay project execution. It might be required to use other areas, with additional design costs. If these area/areas are still used throughout the project there is a higher risk of unwanted events such as asset damage, and insurance cost might be higher too. These impacts might be significant but manageable, hence this risk is considered as moderate (or class C) according to the impact descriptive scale. In this assessment, considering the location of the project (see External Context), this risk is considered as rare (or class E) according to the likelihood descriptive scale.
- Cost reduction due to scale has a positive impact on the construction cost. Stallard et al. (2009) quoted a reduction of about 5 – 20% per doubled capacity considered. This risk is considered as outstanding (or class A) according to the impact descriptive scale. In terms of likelihood, there are several references in the literature to the occurrence of this risk (Stallard

et al., 2009), (SI Ocean, 2013), hence it is considered in this assessment as likely (or class B).

7.2.2. Installation phase Qualitative Risk Analysis

The Installation phase Risk Register consists of four risks: (1) the risk of a short term exploitation consent, (2) the risk of inadequate weather window, (3) the risk of asset damage, and (4) the risk of cost reduction due to scale or volume. Here, these risks are analysed in terms of impact and likelihood as follows:

- Short term exploitation consent implies a shorter than expected service life, with impact on the expected future revenues. This might affect project affordability. It is considered as catastrophic (or class A) according to the impact descriptive scale. In this assessment, considering the legislation (see External Context), this risk is considered as unlikely (or class D) according to the likelihood descriptive scale.
- Inadequate weather window has an impact on the duration of the installation activities. This event might increase the installation cost due to the personnel, vessels and infrastructure required for an extended period. It is considered as moderate (or class C) according to the impact descriptive scale. In terms of likelihood, considering the project scope (see Project Context), this risk is assumed as unlikely (or class D).
- Asset damage has a negative impact on project cost. Collisions or entanglements might compromise the regular functioning of the device or power transmission system, and even the safety of any person, activity or asset in a given area. Here, considering the project scope and WEC characteristics, asset damage might occur due to collisions involving vessels but not due to entanglements. This risk is considered as catastrophic (or class A) according to the impact descriptive scale. In terms of likelihood, it is considered as rare (or class E) due to three aspects: (1) the low marine traffic density registered in the Portuguese Pilot Zone area, (2) the lack of references in the literature or registrations of the occurrence of this event in the past, and (3) the signalling, monitoring and control strategies required to execute this projects.
- Cost reduction due to scale has a positive impact on the installation cost. Stallard et al. (2009) quoted a reduction of about 5 – 20% per doubled capacity considered. This risk is similar to the risk of cost reduction due to scale in the Construction phase in terms of impact and likelihood, considering that (1) construction cost and installation cost are of similar magnitude, (2) the occurrence of both risks is referred frequently in the literature (Stallard, Harrison, Ricci, & Villate, 2009), (SI Ocean, 2013), and (3) the reduction is of similar magnitude. Therefore, it is considered as outstanding (or class A) according to the impact descriptive scale, and as likely (or class B) according to the likelihood descriptive scale.

7.2.3. O&M phase Qualitative Risk Analysis

The O&M phase Risk Register consists of six risks: (1) the risk of inadequate weather window, (2) the risk of asset damage, (3) the risk of cost reduction due to scale, (4) the risk of unplanned maintenance,

(5) the risk of maintenance delays due to sourcing, and (6) the risk of lower than expected performance. Here, these risks are analysed in terms of impact and likelihood as follows:

- Inadequate weather window has an impact on the duration of the maintenance stage. This event might increase maintenance costs due to the personnel, vessels and infrastructure required for an extended period, and implies revenue losses due to reduced availability and power output produced. It is considered as minor (or class D) according to the impact descriptive scale. In terms of likelihood, considering the project scope and maintenance strategy (see Project Context), this risk is considered as likely (or class B).
- Asset damage has a negative impact on project cost. This risk is similar to the risk of asset damage in the Installation phase. It implies not only additional costs to recover and repair the device/devices but also revenue losses due to reduced availability and power output produced. Asset damage is considered as catastrophic (or class A) according to the impact descriptive scale, and as rare (or class E) according to the likelihood descriptive scale.
- Cost reduction due to scale has a positive impact on operating costs. Stallard et al. (2009) quoted a reduction of up to 30% per doubled capacity considered in terms of maintenance, monitoring, spares and insurance costs. This risk is considered as major (or class B) according to the impact descriptive scale. It is considered as likely (or class B) according to the likelihood descriptive scale, given the existing references in the literature to its occurrence (Stallard et al., 2009), (SI Ocean, 2013).
- Unplanned maintenance has a negative impact on project cost. The implications of this event are (1) increased operating costs due to non-scheduled maintenance activities and (2) revenue losses due to reduced availability and power output produced. Here, considering the estimated duration of this event, this risk is considered as moderate (or class C) according to the impact descriptive scale. Previsic (2010) mentioned a frequency of one unplanned maintenance every four years, hence this risk is considered as possible (or class C) according to the likelihood descriptive scale.
- Maintenance delays due to sourcing have a negative impact on project cost. The implications of this risk might be (1) increased cost of maintenance and spares and (2) revenue losses due to reduced availability and power output produced. It is considered as minor (or class D) according to the impact descriptive scale. In terms of likelihood, considering the project scope (see Project Context), it is assumed that this risk is unlikely (or class D).
- Lower than expected performance has a negative impact on project cost. If resource characteristics change or the resource assessment is inaccurate, the produced power output and revenues obtained might be lower than expected, compromising the affordability of the project. It is considered as catastrophic (or class A) according to the impact descriptive scale. In terms of likelihood, considering the resource characteristics (see Wave Energy and Project Context), this risk is considered as possible (or class C).

7.2.4. Decommissioning phase Qualitative Risk Analysis

The Decommissioning phase Risk Register consists of three risks: (1) the risk of inadequate weather window, (2) the risk of asset damage, and (3) the risk of cost reduction due to volume. Here, these risks are analysed in terms of impact and likelihood as follows:

- Inadequate weather window has an impact on the duration of the decommissioning activities. This event might increase the decommissioning cost due to the personnel, vessels and infrastructure required for an extended period. It is considered as moderate (or class C) according to the impact descriptive scale. In terms of likelihood, considering the project scope, this risk is assumed as likely (or class D).
- Asset damage has a negative impact on project cost. This risk is similar to the risk of asset damage in the Installation and O&M phases. However, the additional costs of repair might not be needed since the project service life has ended. Asset damage is considered as moderate (or class C) according to the impact descriptive scale, and as rare (or class E) according to the likelihood descriptive scale.
- Cost reduction due to scale has a positive impact on the decommissioning cost. Little information is available on the literature but a cost reduction equal or approximate to the estimated for the Installation phase might be assumed, considering how similar the offshore operations in these life cycle phases are. Therefore, it is assumed that the impact of this risk is about 5 – 20% cost reduction per doubled capacity considered, as Stallard et al. (2009) quoted. This risk is considered as major (or class B) according to the impact descriptive scale, and as likely (or class B) according to the likelihood descriptive scale.

7.2.5. Discussion

The early stage of development of the ocean energy technology and reduced operational experience determine the lack of data available or made public. Therefore, the analysis was made with some limitations and assumptions. Nonetheless, having this in consideration, conclusions might be taken about the significant risks.

Three levels of risk were established in the risk assessment context: high, medium and low. In this assessment, high and medium risks are considered as significant and subject to a more detailed analysis. Considering the analysis performed (see A – Project Life Cycle Risk Register), the significant risks are (1) the risks of cost reductions due to scale, (2) the risks of inadequate weather window, (3) the risk of lower than expected performance, (4) the risk of short term exploitation consent, (5) the risk of unplanned maintenance, and (6) the risks of asset damage in the Installation and O&M phases.

The risk of inadequate weather window, the risks of asset damage and the risk of short term exploitation consent will not be considered in the following steps of the assessment due to the lack of data available. However, it should be noted that a more detailed analysis of these risks is required, and effort should be made to produce data that might characterize them. This is out of the scope of this thesis.

8. Ocean Energy Project Quantitative Risk Analysis

The quantitative risk analysis stage enables the quantification of the effect of the risks and uncertainties of the project. This is essential to determine the impact of these factors on project objectives, and requires the development of a model. The stage is described in this exemplification as follows. First, the input and output variables of the model are described. This is followed by a description of the model and how all variables relate with each other. Then a sensitivity analysis is performed to determine the critical variables of the model, followed by the definition of the required probabilistic distributions and probabilities for these variables. The section ends with the analysis of the results from the simulation of the model described.

8.1. Input and Output Variables

The input and output variables of the model have been defined considering the established context (see Ocean Energy Project Context) and the conclusions from the assessment so far. Here, input variables are variables to which a value or set of values must be assigned to proceed with the analysis. Output variables are the variables of interest in this ocean energy project appraisal risk assessment, calculated with data from the input variables of the model.

Two categories of input variables are considered here: (1) variables related with the external context; and (2) variables related with the project context (see Figure 5). Therefore, variables in a given category relate to the characteristics, requirements or events of the specific context. The input variables of the model are as follows:

- The input variable related with external characteristics is the FIT.
- The input variables related with external requirements are (1) the exploitation consent annual rent, and (2) the annual tax rate.
- The input variables related with project characteristics are (1) the sea state probability matrix of the project location; (2) the device power matrix; (3) the device life time; (4) the number of units of the project; (5) the terms of funding, i.e. the amount, interest rate and repayment period; (6) the reinvestment rate; and (7) the financial and power output discount rate.
- The input variables related with project requirements are (1) the WEC IC; (2) the costs of installing the power transmission and mooring systems, and the cost of device/devices deployment and commissioning; (3) the costs of monitoring, maintenance (planned and unplanned), spares, insurance and overhaul that occur in the O&M phase; (4) the durations of the maintenance and overhaul activities in the O&M phase; and (5) the cost of decommissioning.
- The input variables related with project events are (1) the risks of cost reduction due to scale, that might occur in all the project life cycle phases; and (2) the risk of unplanned maintenance, that might occur in the O&M phase.

External	Characteristics	
	Requirements	
	Events	
Project	Characteristics	
	Requirements	
	Events	

Figure 5: Categories of the input variables of the model

The output variables of the simulation model are four: (1) the NPV, (2) the MIRR, (3) the DPP, and (4) the LCoE. These are the project appraisal indicators that evaluate affordability.

8.2. Description of the Model

The model consists of input variables that relate with each other through different formulas to originate the output variables. During the process other parameters of interest are originated, and these might be analysed also.

This assessment comprises all project life cycles phases, but it is centred on the project service life since in normal conditions this period is far longer than the other periods – service life might be between 15-25 years, while decommissioning, construction and installation might take months (Previsic, 2010). Therefore, time is not considered for the Construction, Installation and Decommissioning phases – the occurrence and completion of these phases is acknowledged at the beginning and at the end of the project service life.

It is important to represent the entire project service life in terms of equal year intervals or periods. The model must be able to characterise each period in terms of costs incurred, events occurred, device (or devices) productivity and revenues obtained. There are three different periods, regardless of the project service life time: (1) the beginning period, in which the O&M might begin; (2) the intermediate periods, which consists of all periods that correspond exclusively to the O&M phase; and (3) the end period, in which the project service life ends, followed by project closure.

The output variables of the model require the calculation of (1) the net cash flow per period and (2) the net cost per period. Net cash flow CF of a period i corresponds to the difference between cash inflows and cash outflows of the same period (see equation 7), whereas net cost C of a period i corresponds to the sum of the Capital costs and O&M costs minus the Salvage value of that period (see equation 8). As mentioned in the project scope (see Project Context), Salvage value is considered as null in this assessment.

$$CF_i = Cash\ Inflows_i - Cash\ Outflows_i \tag{7}$$

$$C_i = Capital\ cost_i + O\&M\ cost_i - Salvage\ value_i \tag{8}$$

The different classes of periods and how they are defined determine the parameters considered to calculate the net cash flow and the net cost. Table 15 and Table 16 present these parameters for the net cash flow and net cost respectively.

Capital costs can be described as the sum of the construction, installation and decommissioning costs, which occur in different periods. However, in this assessment the construction and installation costs are considered in the beginning period of the project service life as if they occur in the same period. These costs correspond to the project initial Capital cost. The decommissioning cost is considered in the end period of the project service life. Initial Capital cost and decommissioning cost are considered to calculate the net cash flow and net cost.

Depreciation, borrowed funds, debt repayments and net income are considered to calculate the net cash flow. Depreciation is calculated based on the initial Capital cost and the device life time. A straight-line depreciation method with no Salvage value is assumed, meaning that an equal amount is depreciated each period after the beginning until the end of the device life time. Funding occurs in the beginning period and borrowed funds correspond to a percentage of the Initial Capital cost, with a given interest rate and term. Debt repayments occur throughout the following periods until the term. Net income is related with the project service life and it is obtained from the income statement, considering project revenues and operating expenses, depreciation, interest and income tax payments of a given period (see B – Income Statement of the Model).

Table 15: Parameters considered calculating the net cash flow

Beginning period	**Intermediate periods**	**End period**
$-Initial\ Capital\ Cost$	$\pm Net\ Income$	$\pm Net\ Income$
$+Borrowed\ Funds$	$+Depreciation$	$+Depreciation$
	$-Debt\ Repayment$	$-Debt\ Repayment$
		$-Decommisioning\ Cost$
$= CF$	$= CF$	$= CF$

Operating expenses are considered to calculate the net cost. These correspond to the costs incurred in the O&M phase – input variables of the model – and are obtained from the intermediate periods and the end period in the income statement.

Table 16: Parameters considered calculating the net cost

Beginning period	Intermediate periods	End period
$+Initial\ Capital\ Cost$	$+Operating\ Expenses$	$+Operating\ Expenses$
		$+Decommisioning\ Cost$
$= C$	$= C$	$= C$

To obtain the output variables of the model it is also important to calculate the produced power output per period. This is related with the O&M phase, therefore it is only relevant in the intermediate periods and in the end period. It is obtained with some calculations through the following input variables: (1) the device power matrix, (2) the sea state probability matrix of the project location, and (3) the durations of maintenance – planned or not – and overhaul activities.

The device power matrix indicates the produced power output for a given sea state (i.e. wave height and period), whereas the sea state probability matrix indicates the likelihood of a given sea state. If the likelihood of all sea states included in the probability matrix is equal to or approximately 1, it is possible to calculate the expected power output by multiplying both matrixes (see equation 9). These matrixes must be of equal dimension, and the sea states represented must be equal too – if not, an interpolation of any of the matrices to equal their sea states is required. This occurred with the data used in this exemplification for the assessment, and the sea state probability matrix was interpolated so that the sea states in both matrices were equal and power calculations valid (see C – Interpolated Sea State Probability Matrix).

$$Expected\ Power\ = Sea\ state\ probability\ matrix\ \times Device\ power\ matrix \tag{9}$$

The produced power output in a given period is related with the number of hours that the device/devices operated without fault in that period – i.e. the availability of the device. Availability in a period i is equal to the amount of time of the period i minus the time spent in that period (1) on planned or unplanned maintenance and (2) on overhaul activity. Periods are defined in the simulation model as a year interval, meaning that the amount of time of any period is 8760 hours. Maintenance and overhaul activities comprise the maintenance stage (see equation 10). It is considered that the maintenance stage starts with (1) a planned set of actions to interrupt power output production or (2) the occurrence of a fault that leads to the interruption of power output production. The availability is then multiplied by the expected power output to obtain the produced power output in a given period i (see equation 11).

$$Availability_i = 8760 - Maintenance\ stage\ duration_i \tag{10}$$

$$Produced\ power\ output_i = Availability_i \times Expected\ power_i \tag{11}$$

In this exemplification, ocean energy project revenues are due to the produced power output only. The revenue in a period i is obtained by multiplying the produced power output and the FIT applied to the project (see equation 12).

$$Revenue_i = Produced\ power\ output_i \times FIT \tag{12}$$

A constant prices model is considered in this assessment, meaning that cash flows, costs and benefits of all periods are relative to a reference date, and inflation is not taken into account. Cost items considered in this assessment are defined as percentages of WEC IC or Capital cost, and therefore the values obtained do not need adjustments to any reference year. WEC IC and feed in tariffs are taken from the literature, but do not need any adjustments too. The assessment is made considering the reference date of 2010, the equivalent to the beginning period of the model.

The model enables two different analysis: (1) a deterministic analysis, in which no uncertainties are considered in the input variables; and (2) the MCS, in which a set of input variables is modelled as uncertain and the output variables are analysed in accordance with the simulation statistics. This is part of the methodology defined (see Methodology).

8.3. Sensitivity Analysis of the Input Variables

The model is built to perform the quantitative risk analysis, as defined in the methodology. First, it is important to analyse the relevance of all input variables considered. It might occur that some input variables have minimal impact on the output variables, and therefore might not need to be modelled as uncertain or included in the model. This restricts to the most significant input variables (1) their description in terms of probabilistic distributions in the case of variables relative to external or project characteristics or requirements; and (2) their inclusion in the model in the case of variables relative to external or project events that would be modelled as risks.

To determine the most significant input variables of the model a sensitivity analysis is performed. The analysis consists of varying each input variable at a time and verify the impact on the output variables of the model. This is different from the MCS since the uncertainty is not considered and the values for the input variables refer to the base scenario. Sensitivity analysis is based on the concept of elasticity, i.e. the variation in the output variables per variation in a given input variable.

The following input variables were analysed: (1) all input variables related with project requirements, (2) the exploitation consent annual rent, (3) the amount obtained through funding and interest rate, (4) the discount rates and reinvestment rate, and (5) the expected power. The impact of the input variables related with project events on the output variables is evaluated from the analysis of the input variables affected by their occurrence, hence the fact that the risks of cost reduction were not analysed. The risk of unplanned maintenance, due to the fact that it might occur at any period except the beginning period and for more than one occasion, was not analysed also but considered for the simulation analysis.

The initial results from the deterministic analysis for the single-unit project are presented in Table 17. These are the results considering the values and estimates from the base scenario. To perform the sensitivity analysis, +1% and +10% variations relative to those values were considered for each input variable analysed, and the impact of each variation on the output variables was registered in percentage variation relative to the initial result. These variations did not affect the initial result of the DPP indicator due to the fact that no variation considered made the project reach the break-even. Therefore, the conclusions were based on the analysis of the variations in the NPV, MIRR and LCoE indicators.

Table 17: Initial results from the single-unit project (deterministic analysis)

Output variable	1 unit project
NPV	- 1.062M €
MIRR	3,08%
DPP	n.a
LCoE	0,352 €/kWh

Figure 6 presents the impact of different, specific variations in the value of the input variables in the NPV. It is clear that some variables have minimal impact on the NPV, causing minimal NPV variation. The cost of mooring installation, deployment and commissioning, monitoring, annual rent, overhaul and decommissioning are not significant input variables. Likewise, planned maintenance and overhaul hours, and the financial discount rate have minimal impact on the NPV. For this indicator, the most significant input variables are the following: (1) WEC IC, (2) power transmission system cost, (3) Installation cost, (4) Capital cost, (5) planned maintenance cost, (6) spares cost, (7) insurance cost, (8) funding, (9) interest rate, and (10) expected power.

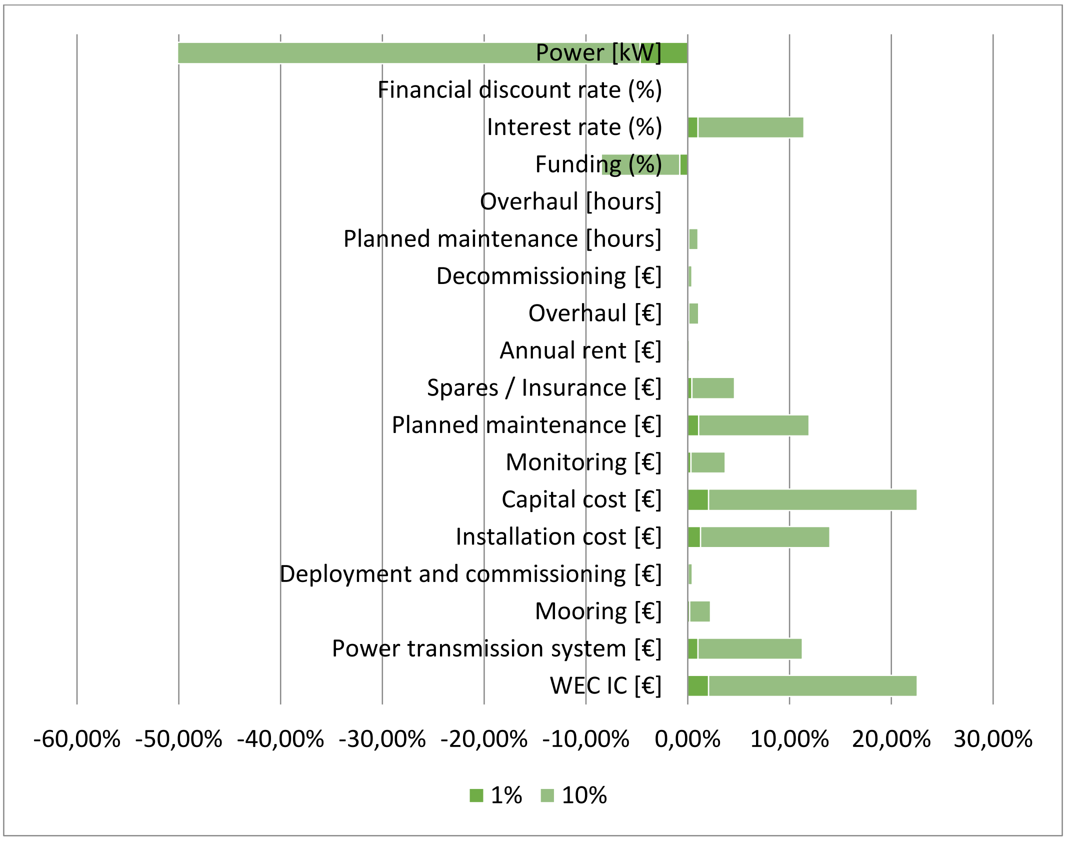


Figure 6: Sensitivity analysis for the NPV (single-unit scenario)

Figure 7 presents the impact of different specific variations in the value of the input variables in the MIRR. The variations obtained are higher than those verified for the NPV, regardless of the input variable. Nonetheless, conclusions on the least and most significant variables are quite similar to those taken from the analysis of the NPV variation. The reinvestment rate, input variable used exclusively for the MIRR, has not a relative impact on this indicator.

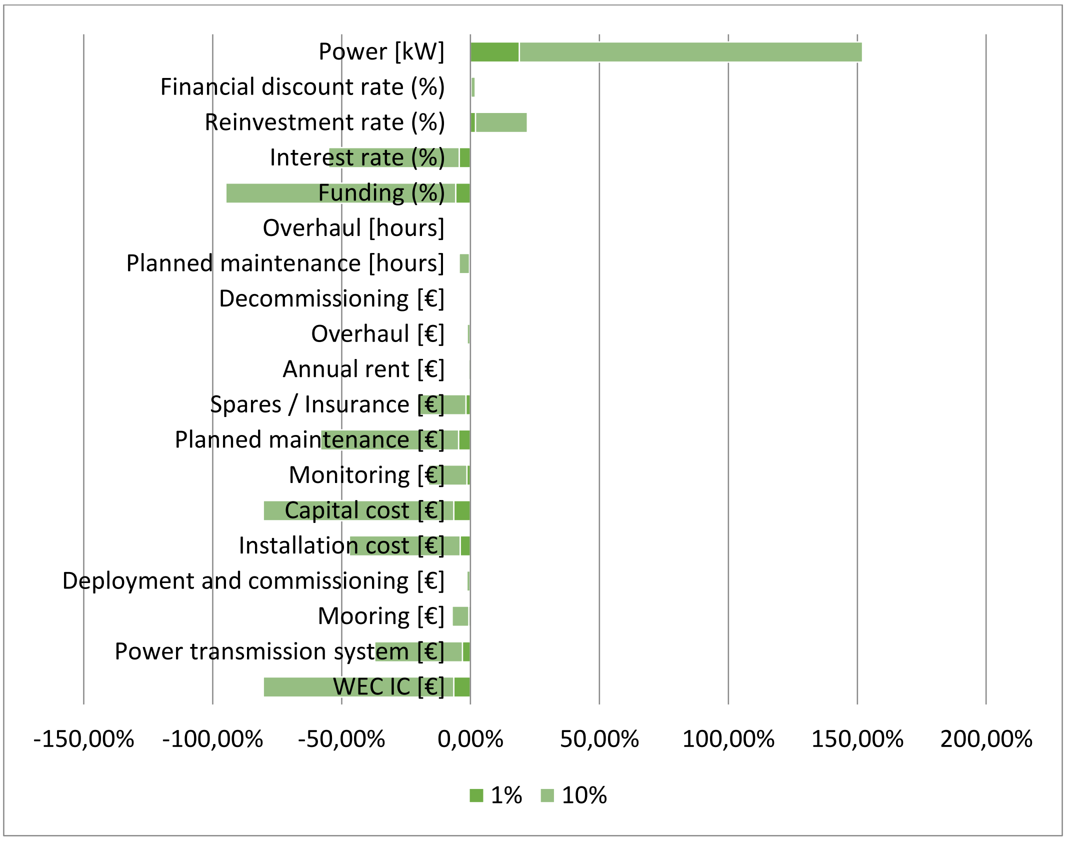


Figure 7: Sensitivity analysis for the MIRR (single-unit scenario)

Figure 8 presents the impact of different, specific variations in the value of the input variables in the LCoE. From the output variables considered in this sensitivity analysis, the LCoE is the least variable from variations in the input variables. It has elasticity lower than the unity for all input variables except the expected power. However, conclusions on which input variables have greater impact are similar to those taken from the analysis of the NPV and MIRR variations. The power output discount rate, used for this indicator only, has significant impact on the LCoE.

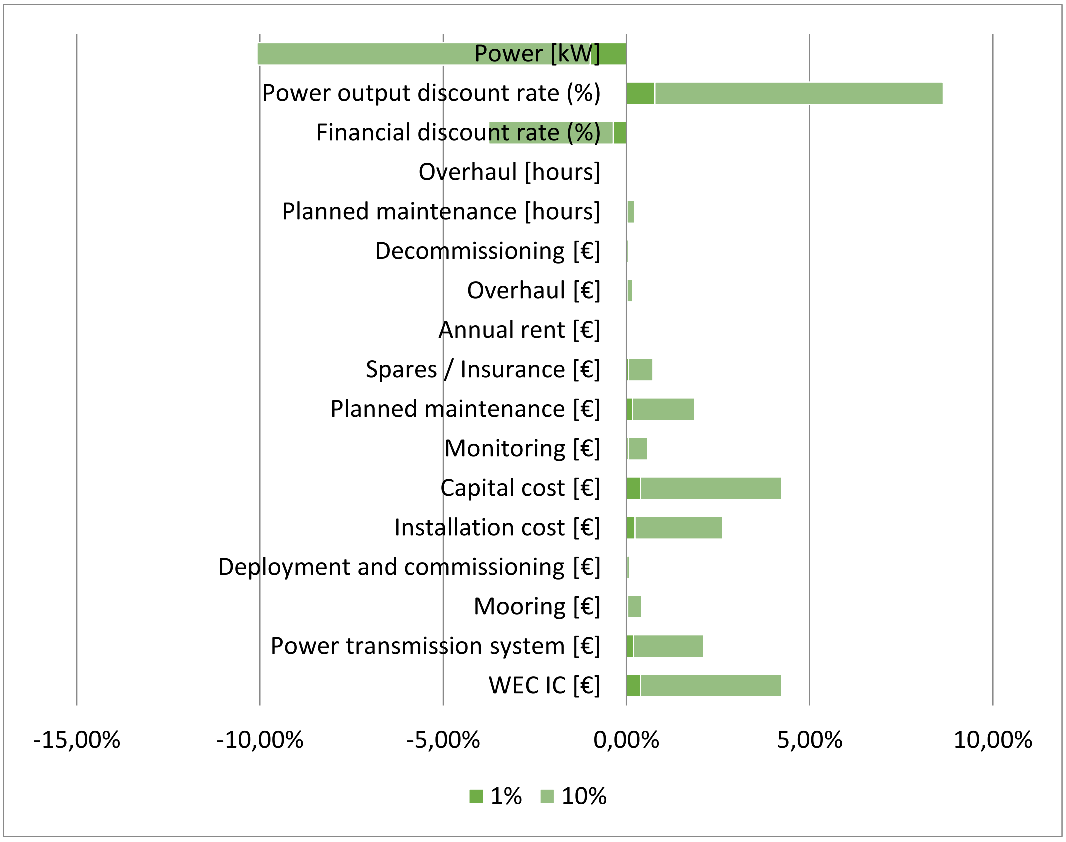


Figure 8: Sensitivity analysis for the LCoE (single-unit scenario)

The selection of the significant input variables must be such that distortions or redundancy are avoided (European Commission, 2008). Here, the results demonstrate that WEC IC, power transmission system cost, Installation cost and Capital cost are significant input variables. However, power transmission system cost is included in the Installation cost, and both are included in the Capital cost along with the WEC IC. Therefore, to avoid double counting – and considering that risks have been identified and included in the quantitative risk analysis relative to the Construction and Installation phases – the WEC IC and the Installation cost are selected as significant input variables and modelled as uncertain. The expected power, power output discount rate, interest rate, funding amount, and the cost of spares, insurance and planned maintenance are selected as significant input variables also.

The least significant input variables are not excluded from the model but modelled as certain. The exception is the costs of mooring and deployment and commissioning, which are included in the Installation cost, input variable that is modelled as uncertain.

The fact that the decommissioning cost has minimal impact in the output variables analysed indicates that risks with impact in this variable are likely to have a minimal impact in the output variables also. This is the case of the risk of cost reduction due to scale in the Decommissioning phase. Therefore, this risk is not included in the following steps of this assessment. Likewise, unplanned maintenance hours are not considered as uncertain in the following steps of this assessment since the sensitivity analysis demonstrated that the duration of planned maintenance and overhaul have little impact on the output variables.

8.4. Probabilistic Distributions of the Model

The significant input variables of the model must be described in terms of discrete or continuous probabilistic distributions. This is important to model the uncertainty associated with these variables, enabling the analysis of the uncertainty propagation and effect on the output variables of the model.

Discrete probabilistic distributions are used to define the input variables relative to the occurrence of events: (1) the risk of unplanned maintenance in the O&M phase, (2) the risk of cost reduction due to scale in the Construction phase, (3) the risk of cost reduction due to scale in the Installation phase, and (4) the risk of cost reduction due to scale in the O&M phase. These variables – or risks in this case – either occur or not, and therefore are modelled as a Bernoulli trial with a given probability of occurrence as follows:

- The probability of occurrence of an unplanned maintenance is 0,195 and it is calculated considering the findings from the qualitative risk analysis and the Poisson distribution. This risk is modelled as a series of Bernoulli trials, i.e. a binomial distribution, to enable multiple occurrences in the multiple-unit projects simulated.
- The probability of occurrence of cost reduction in the Construction, Installation or O&M phases is assumed to be 0,7. This value is selected from a range of values that Cooper et al. (2005, p. 53) identified as adequate to describe the probability of a likely (class B) event.

The impact of the occurrence of these risks is modelled through continuous probabilistic distributions as follows:

- The impact (cost) of the occurrence of an unplanned maintenance is modelled through a triangular distribution. It is assumed that the cost of unplanned maintenance estimated for the base scenario is the most likely estimate.
- The impact of the occurrence of cost reduction in the Construction, Installation or O&M phases is modelled through uniform distributions. Estimates for the cost reductions have been referenced in this assessment (see Ocean Energy Project Qualitative Risk Analysis).

The following input variables are modelled through triangular distributions: (1) the WEC IC, (2) the Installation cost, (3) the cost of planned maintenance, (4) the cost of spares, and (5) the insurance cost. These variables, along with the cost of unplanned maintenance, comprise the cost items that are modelled as uncertain. It is assumed that the base estimates for cost (see Project Context) correspond to the most likely estimates.

The triangular distribution was selected to represent the cost items – cost of unplanned maintenance included – for the following reasons: (1) the limited data available about these costs; (2) the fact that the distribution can be described by three estimates; and (3) the fact that it is applicable since the relationship between the cost input variables is known. This option implies that the pessimistic and optimistic estimates considered in the assessment are equivalent to the worst and best case scenarios respectively, meaning that the range of possible values for each cost input variable is limited to these estimates.

Previsic & Epler (2012) mentioned a cost estimating table developed by EPRI with information on the likely range of uncertainty in cost estimates applicable to ocean energy projects, based on the maturity of the technology and the detail of the cost estimate. Stallard et al. (2009) quoted the uncertainty of some project developers on their cost estimates, with some developers assuming an uncertainty of up to 50% on some of their cost estimates. The Pelamis is a technologically mature WEC. Six full scale devices have been built and tested at sea, producing power output that is fed into the grid. However, the operational experience with wave farms is reduced. Therefore, the uncertainty on estimates for multiple-unit marine energy projects should be equal or higher to the uncertainty on estimates for single-unit projects.

Table 18 describes the costs in the model characterised by a continuous distribution. Here, as mentioned, the uncertainty considered for the cost estimates varies if the project is (1) a single-unit project or (2) a multiple-unit project.

For a single-unit project scenario, an uncertainty of ±20% is considered for the WEC IC and the cost of spares. The Installation cost estimate is considered with an uncertainty of ±15%. The cost estimates of maintenance – planned and unplanned – and insurance are considered with an uncertainty in between−25% to +30%. For a multiple-unit project scenario, an uncertainty of −25% to +30% is considered for all cost items except the cost of spares, for which an uncertainty of ±20% is considered.

Table 18: Cost estimates for the MCS

Parameter	Single-unit Project			Multiple-unit Project		
	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic
WEC IC	+20%	Base estimate	−20%	+30%	Base estimate	−25%
Installation cost	+15%	Base estimate	−15%	+30%	Base estimate	−25%
Planned Maintenance	+30%	Base estimate	−25%	+30%	Base estimate	−25%
Unplanned Maintenance	+30%	Base estimate	−25%	+30%	Base estimate	−25%
Spares	+20%	Base estimate	−20%	+20%	Base estimate	−20%
Insurance	+30%	Base estimate	−25%	+30%	Base estimate	−25%

The following input variables are modelled through uniform distributions: (1) the funding amount, (2) the interest rate, and (3) the power output discount rate. The minima and maxima estimates for these variables and for the cost reductions are presented in Table 19. For each of these variables no information available in the literature indicated a particular value as more likely to occur, hence the selection of the uniform distribution. Estimates are assumed equal regardless of the number of units of a project.

Table 19: Other estimates for the MCS

Input variable	Minima	Maxima
Funding (% of initial Capital cost)	70	80
Interest rate	0,04	0,08
Power output discount rate	0,08	0,11
Cost reduction due to scale (Construction phase)	0,05	0,20
Cost reduction due to scale (Installation phase)	0,05	0,20
Cost reduction due to scale (O&M phase)	0,00	0,30

The average power is modelled through a normal distribution with mean equal to the expected power (value used in the deterministic analysis) and standard deviation calculated considering all values of the device power matrix, their probability of occurrence, and the mean. The distribution was truncated between the values 0 and 750, which correspond to the possible values of the average power of the device.

8.5. Simulation Analysis and Results

Once the model is built, the significant input variables identified and the adequate probabilistic distributions used to describe those variables, the simulation might occur.

The initial results for the deterministic model for the four scenarios of interest in this assessment are presented in Table 20. These results do not consider the occurrence of the risks modelled in this assessment, and are based on the estimates of the base scenario. Conclusions are as follows:

- The NPV is negative for all scenarios. As an increasing number of units were considered the NPV decreased. These projects are not affordable and should not be executed in these conditions.
- The MIRR is around 3% for all scenarios, a rate lower than the financial discount rate considered for these projects (10%), hence these projects are not attractive and should not be executed in these conditions. This is consistent with the NPV results.

- The DPP could not be calculated since the NPV is negative in all scenarios, meaning that the project did not reach the break-even within its service life. The output variable is formulated to return “n.a” (i.e. non applicable) in these situations.
- The LCoE is around 0,35 €/kWh for all scenarios, with a marginal decrease (10^{-3}) from the single-unit project to the eight-unit project and a marginal increase from the eight-unit project to the thirty-two-unit project. The feed in tariff is 0,26 €/kWh, meaning that these projects are not cost-competitive since the cost of energy is higher than the selling price.

Table 20: Initial results for all scenarios (deterministic analysis)

Output variable	1 unit project	4 unit project	8 unit project	32 unit project
NPV	- 1.062M €	- 4.208M €	- 8.118M €	- 33.564M €
MIRR	3,08%	3,12%	3,25%	3.13%
DPP	n.a	n.a	n.a	n.a
LCoE	0,352 €/kWh	0,351 €/kWh	0,349 €/kWh	0,351 €/kWh

None of the scenarios is affordable in the deterministic analysis but a marginal improvement occurred from the single-unit project to the eight-unit project, considering the MIRR and the LCoE. The base estimates and deterministic results are shown here to enable a comparison with the results from the simulation, which is performed using the @Risk software. In this assessment, 10.000 iterations are considered for the simulation of each scenario to reduce the error in the mean to a minimum percentage. The Latin hypercube sampling was selected as the random sampling process of the simulation.

The simulation statistics of the NPV are presented in Table 21 (histograms can be found on NPV histograms). No errors occurred in the simulation performed, as it should be. An analysis of the mean indicates that the NPV has increased with the increase of the project scale – with the exception of the four-unit scenario. The eight-unit and thirty-two-unit projects have positive mean NPV. The probability of a project that might be worth pursuing, i.e. with NPV ≥ 0, has increased with project scale also. The key input variables in each scenario for the occurrence of a non-negative NPV were (1) the device average power and interest rate for the single-unit project, and (2) the O&M cost reduction due to scale for the multiple-unit projects. These results are completely different from the deterministic analysis.

Table 21: Simulation statistics of the NPV for all scenarios

Scenario	Mean	Std. Deviation	Confidence Interval (95%)	$P(NPV \geq 0)$	Key inputs for $P(NPV \geq 0)$
1 unit	- 1.266M €	0,789M €	[- 1.251M €; - 1.281M €]	5.4%	Device power; Interest rate
4 unit	- 1.381M €	3.563M €	[- 1.451M €; - 1.311M €]	35.8%	O&M cost reduction
8 unit	0,123M €	7.670M €	[- 0.027M €; 0.273M €]	51.2%	O&M cost reduction
32 unit	18.044M €	35.621M €	[- 17.346M €; 18.742M €]	69.3%	O&M cost reduction

Regression coefficients are presented in Figure 9. These coefficients represent the impact of a given input in a given output variable, normalised by their respective standard deviations. Positive coefficients mean that the input and output variable have the same behaviour, i.e. an increase (or decrease) in the input causes an increase (decrease) in the output, whereas negative coefficients mean that the input and output variable have opposite behaviour, i.e. an increase (or decrease) in the input causes a decrease (increase) in the output.

For all scenarios, the device power is a quite influential input variable, with the average power from the initial service life periods being more important. Cost reductions have significant impact in multiple-unit projects, which appears to increase with the number of units involved. O&M cost reductions have the most significant impact, followed by the Construction cost reductions and the Installation cost reductions. The WEC IC and interest rate also have significant impact in all scenarios but become less influential as the project scale increases. The same behaviour appears to occur with the planned maintenance cost, which is an influential input variable in the single-unit project but becomes less relevant in larger scale projects.

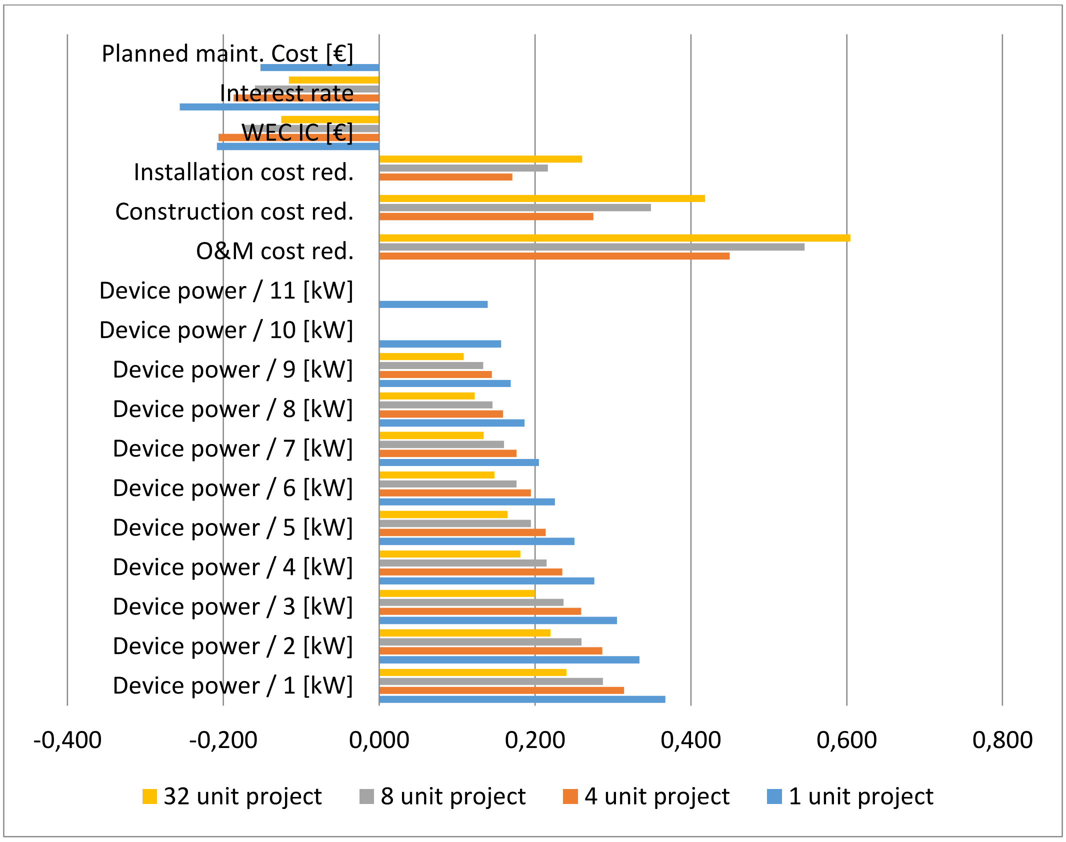


Figure 9: Regression coefficients of the NPV for all scenarios (MCS)

Simulation statistics for the MIRR are presented in Table 22 (histograms can be found on MIRR histograms). No errors occurred in the simulation performed, as it should be. An analysis of the mean indicates that the MIRR has increased with the increase of the project scale. Considering the financial discount rate used in this assessment, the thirty-two-unit project is an attractive project given the mean MIRR of 12,06%. The probability of a MIRR equal or higher than the financial discount rate is the same as the probability of a NPV ≥ 0. Therefore, these probabilities are the same as those seen for the NPV, and the key input variables are the same also. The positive trend verified in these results is more noticeable and less irregular than the trend verified in the deterministic analysis.

Table 22: Simulation statistics of the MIRR for all scenarios

Scenario	Mean	Std. Deviation
1 unit	5,64%	2,91%
4 unit	8,69%	3,20%
8 unit	9,97%	3,46%
32 unit	12,06%	4.11%

Regression coefficients are presented in Figure 10. Conclusions are similar to those for the NPV regression coefficients, although their values are different. Device power has significant impact in the MIRR for all scenarios but cost reductions become more influential as the project scale increases. O&M cost reductions have the most significant impact of all cost reductions, followed by Construction cost reductions and Installation cost reductions. WEC IC and interest rate have more influence in smaller scale projects but are still relevant in all scenarios.

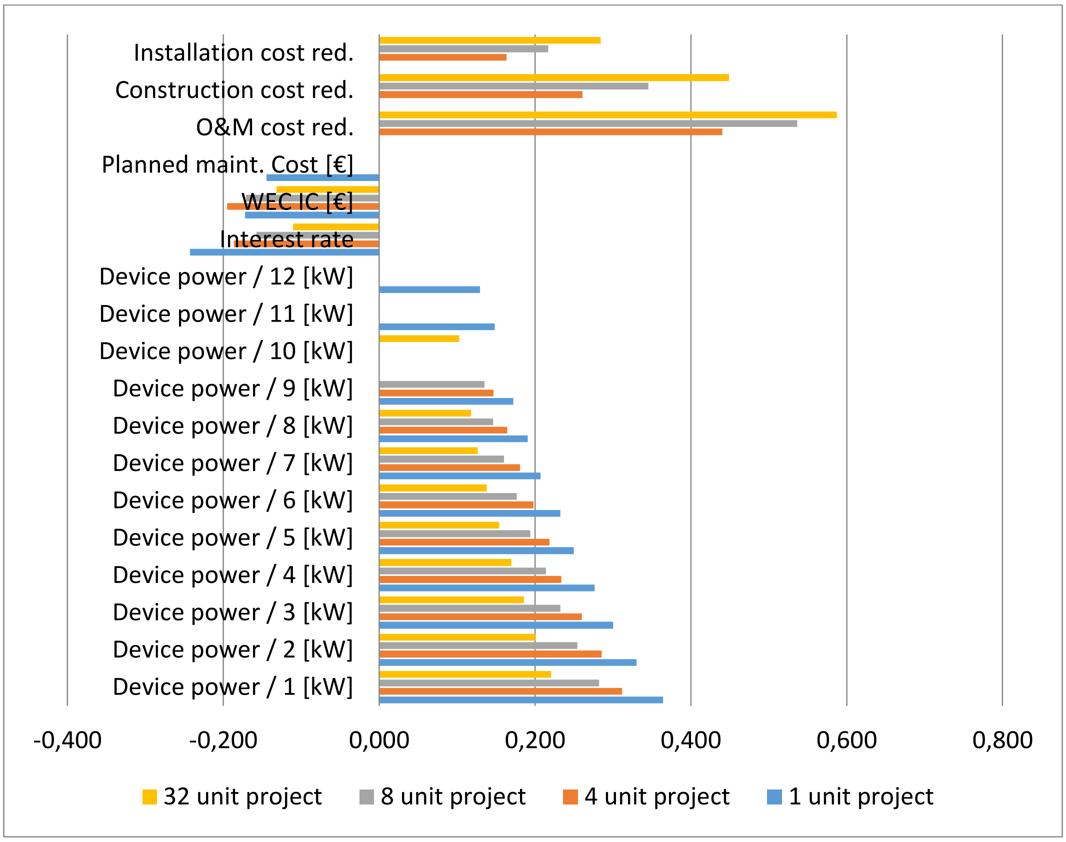


Figure 10: Regression coefficients of the MIRR for all scenarios (MCS)

The simulation originated some errors for the DPP. This is due to the fact that if the project cannot reach the break-even within its service life the DPP is formulated to return an "n.a" response, as mentioned before, meaning that the project has no DPP. Therefore, errors correspond to iterations in which the project being simulated had these characteristics. The number of errors is a good indicator of the probability that the project will not reach the break-even. Conclusions are as follows:

- The single-unit project simulated had a mean DPP of approximately 12,7 years and a standard deviation of approximately 5,76 years. The mode was 20 years, which corresponds to the most likely DPP in case the project has one. The simulation originated 8981 errors out of 10000 iterations, meaning that there is an 89,9% chance that the project does not reach the break-even.
- The four-unit project simulated had a mean DPP of approximately 9,2 years and a standard deviation of approximately 5,5 years. The mode was 4 years, and the simulation originated

5719 errors out of 10000 iterations, meaning that there is a 57,2% chance that the project does not reach the break-even.

- The eight-unit project simulated had a mean DPP of approximately 7,8 years and a standard deviation of approximately 5,2 years. The mode was 3 years, and the simulation originated 4268 errors out of 10000 iterations, meaning that there is a 42,7% chance that the project does not reach the break-even.
- The thirty-two-unit project simulated had a mean DPP of approximately 6,1 years with a standard deviation of approximately 4,7 years. The mode was 2 years, and the simulation originated 2672 errors out of 10000 iterations, meaning that there is a 26,7% chance that the project does not reach the break-even.

The probabilities obtained from the simulation about the project reaching the break-even and having a non-negative NPV would be equal if after the break-even period all annual net cash flows were positive. This was not the case in some of the outcomes of the simulation, hence the difference between these probabilities. Compared with the deterministic analysis, all scenarios have a probability of reaching the break-even.

Regression coefficients are presented in Figure 11. For all scenarios, device power is quite influential, with the initial periods being more important. Cost reductions have a significant impact in multiple-unit projects that increases with project scale. Capital costs and the interest rate also have significant impact in all scenarios but become less influential as the project scale increases.

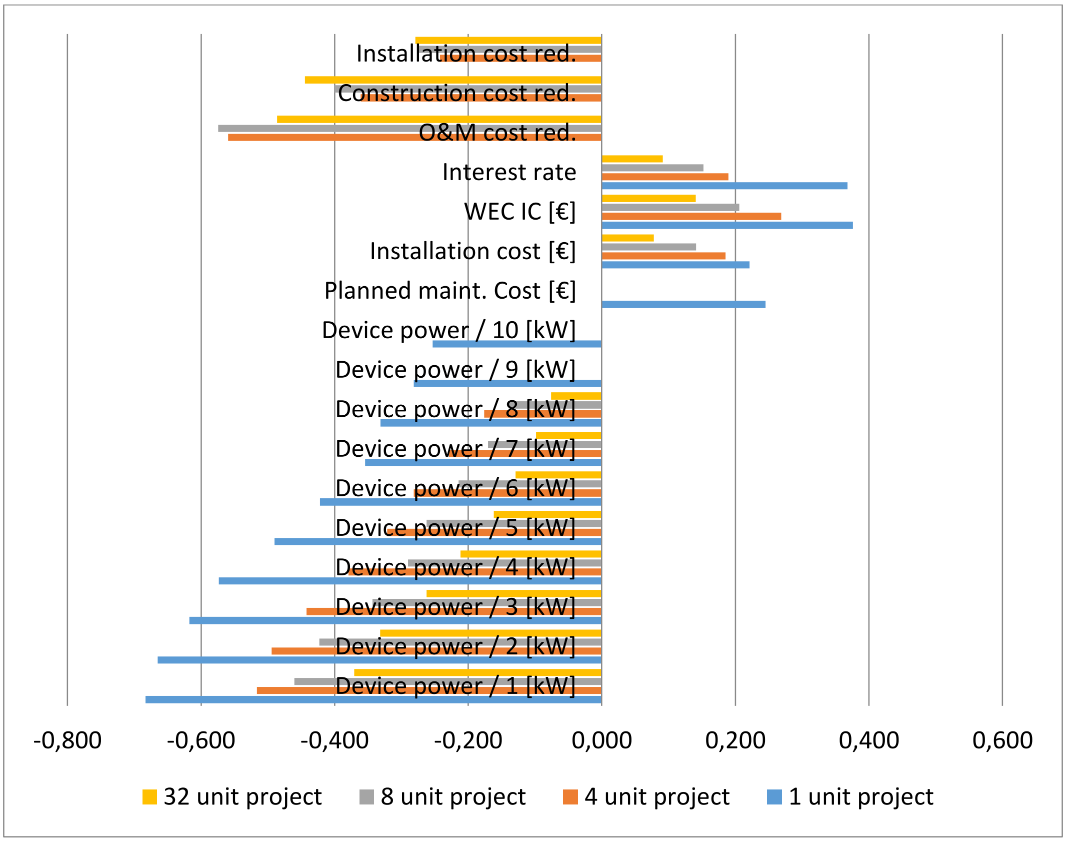


Figure 11: Regression coefficients of the DPP for all scenarios (MCS)

Simulation statistics for the LCoE are presented in Table 23 (histograms can be found on LCoE histograms). No errors occurred in the simulation performed, as it should be. An analysis of the mean indicates that the LCoE has decreased with the increase of the project scale. Considering the FIT in this assessment (0,26 €/kWh), the thirty-two-unit project is cost-competitive and the eight-unit project might be cost-competitive also, given their mean LCoE values. The standard deviation for each scenario suffers little variation, with the exception of the increase verified for the thirty-two-unit project. The probability of a cost-competitive project, i.e. a project with LCoE ≤ FIT, has increased with project scale. The key inputs for this condition in each scenario were (1) the power output discount rate and device power for the single-unit project, (2) the power output discount rate and O&M cost reduction for the four-unit project, and (3) the O&M cost reduction for the eight-unit and thirty-two-unit projects. The trend verified in these results is more noticeable and less irregular than the trend verified in the deterministic analysis.

Table 23: Simulation statistics of the LCoE for all scenarios

Scenario	Mean	Std. Deviation	Confidence Interval (95%)	$P(LCoE \leq FIT)$	Key inputs for $P(LCoE \leq FIT)$
1 unit	0,339 €/kWh	0,057 €/kWh	[0,338 €/kWh; 0,340 €/kWh]	5.4%	Output d. rate; Device power
4 unit	0,286 €/kWh	0,056 €/kWh	[0,285 €/kWh; 0,287 €/kWh]	35.2%	O&M cost reduction; Output d. rate
8 unit	0,265 €/kWh	0,058 €/kWh	[0,264 €/kWh; 0,266 €/kWh]	50.9%	O&M cost reduction
32 unit	0,232 €/kWh	0,065 €/kWh	[0,231 €/kWh; 0,233 €/kWh]	69.2%	O&M cost reduction

Regression coefficients are presented in Figure 12. Conclusions about device power and cost reductions are similar to those taken from the analysis of the regression coefficients for the NPV and MIRR. WEC IC and power output discount rate also have a significant impact in all scenarios, the latter being one of the most influential variables.

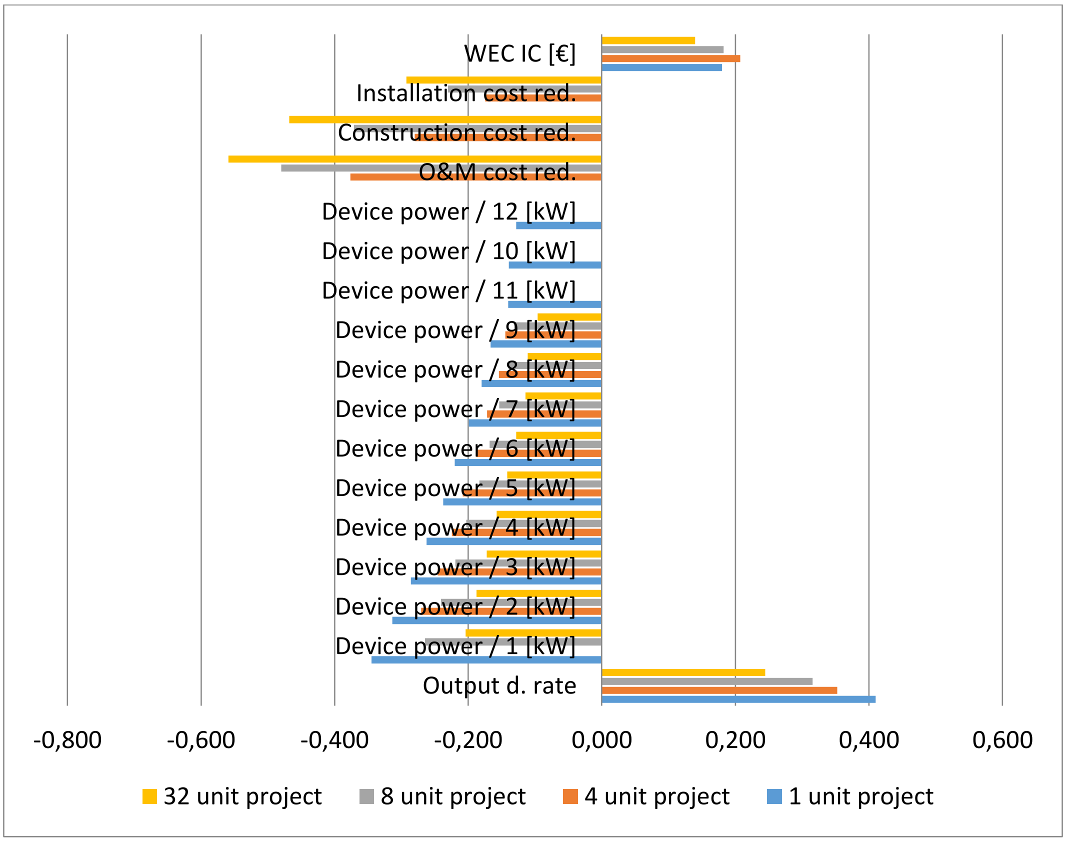


Figure 12: Regression coefficients of the LCoE for all scenarios (MCS)

8.6. Discussion

The quantitative risk analysis provided detailed information about the uncertainty of the project under assessment. The sensitivity analysis enabled the following conclusions:

- Overhaul and decommissioning costs have reduced impact in the output variables. This is related with the concept of time value of money, meaning that these costs are less significant due to the fact that their occurrence is occasional and several years after the beginning of the project service life.
- The financial discount rate has reduced impact in the output variables. This legitimates the appraisals in the literature that assume a discount rate applicable to these projects (SI Ocean, 2013), (O'Connor et al. 2013).
- Availability appears to have reduced impact in the output variables. Variations in the duration of the activities of the maintenance stage had little influence on the appraisal indicators. However, this should be interpreted with careful.

The process continued with a simulation analysis of the model using the MCS technique. Mean and standard deviations of the variables of interest of the assessment were registered for all scenarios considered. Moreover, confidence intervals could be calculated considering the characteristics of the analysis. The impact of variability in a given input variable on the output variables was measured through the regression coefficients, and the simulation software enables the determination of the key input variables for the occurrence of a given outcome. Conclusions are as follows:

- The main sources of risk appear to be the WEC IC, the interest rate, the device average power and the risks of cost reduction. Except for the risks of cost reduction, all these input variables have reduced but considerable influence on the output variables as the project scale increases. The impact on affordability of a particular device average power that might occur several years after the beginning of the project service life is still significant. Of all cost reductions considered, O&M cost reduction appears to be the most significant, being a critical input for the affordability of larger scale projects.
- It should be noticed that planned maintenance cost and power output discount rate also have a significant influence, although more specific. Planned maintenance cost has significant impact on a single-unit project but reduced impact on larger scale projects, whereas power output discount rate has significant impact on the LCoE, being a critical input for the cost-competitiveness of smaller scale projects.
- Results indicate that large scale projects have an increased chance of being affordable. This is due to the effect of cost reductions due to scale, which gain importance as project dimension increases. However, the occurrence and the magnitude of these reductions is uncertain.

The results of the assessment are as accurate as the accuracy of the estimates and assumptions considered. This is ultimately a trade-off between preciseness and resources. Nonetheless, considerable information might be obtained from a valid model built with acceptable choices. The analysis could be extended in several ways. The FIT could be modelled to determine its effect on project affordability or the adequate selling price given the project uncertainties. Learning curves could be considered also, to understand the effect of cost reductions throughout the service life due to accumulated experience. Other option could be the determination of correlations between the input variables. The methodology developed in this thesis is adequate and able to include these additional considerations.

9. Conclusion

In this thesis, a methodology is presented to appraise ocean energy projects. This method consists of a risk assessment applied to project appraisal indicators used in the industry, and it is exemplified here considering a case study with Portugal as the project location and the Pelamis wave energy converter as the project device.

The methodology comprises the following processes: (1) establishment of the context, (2) risk identification and qualitative analysis, (3) quantitative risk analysis, and (4) risk evaluation. The risks identified must be understood in order to evaluate them according to the risk criteria and determine the adequate responses. First, a qualitative risk analysis is performed to identify the risks that require further analysis. Then, a model is built considering all the significant variables, and a sensitivity analysis is performed to these variables to decide those that will be modelled as uncertain. The method proceeds with the MCS, enabling the analysis of uncertainty propagation and an overview of project risk. This understanding facilitates decision-making and the evaluation process.

The case-study exemplified in this work demonstrated that the method is applicable to different scenarios, the techniques useful and the results valid. It is possible to understand the uncertainties and risks of a project, and to obtain a detailed statistical description for the variables of interest and the probability of different outcomes in a given scenario. This is important for stakeholders, improving their understanding of the project and their decision-making. An adequate assessment of the sources of risk will enhance the development of projects in this industry and the development of the industry itself. Specific strategies might be implemented to target the critical variables and exceed the objectives.

The lack of data available in the literature limited the scope of the assessment, but access to this information will improve the accuracy of the results. This will occur as the ocean industry matures and stakeholders gain experience – estimates and other aspects relevant to the assessment will be refined and validated.

It should be noticed that conclusions taken from the assessment exemplified are coherent with the literature. The results indicated the importance of potential cost reductions due to scale, with reductions occurring in the O&M phase being the most influential on project affordability. This also confirms the significance of O&M costs to project affordability in a life cycle perspective, which is consistent with the conclusions from O'Connor et al. (2013). Other important aspect is the productivity, represented here through the yearly average power, which proved to have a quite significant impact on project affordability. This is mentioned by Guanche et al. (2014), and it is consistent with the idea that it is essential that a perfect match between device and resource characteristics occurs, hence the importance of resource assessment and efficient design. Device cost and interest rate are also variables with significant influence, an indicator that the cost of design and fabrication and the market conditions and perception of the industry are aspects that must be controlled and managed by project owners and developers.

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Annex

A – Project Life Cycle Risk Register

ID	Event	Life Cycle Phase	Root Cause	Category	Type of Risk	Impact	Likelihood	Level of Risk
C1	Conflicting uses on project required area/areas	Construction	Area/areas used for other activities	Environment	Negative	Moderate	Rare	Low
C2	Cost reduction due to scale or volume	Construction	Economies of scale	Dimension	Positive	Outstanding	Likely	High
I1	Short term exploitation consent	Installation	Legislation	Legal	Negative	Catastrophic	Unlikely	Medium
I2	Inadequate weather window	Installation	Sea state conditions	Environment	Negative	Moderate	Unlikely	Medium
I3	Asset damage	Installation	Collisions, entanglement s	Quality	Negative	Catastrophic	Rare	Medium
I4	Cost reduction due to volume	Installation	Economies of scale	Dimension	Positive	Outstanding	Likely	High
OM1	Inadequate weather window	O&M	Sea state conditions	Environment	Negative	Minor	Likely	Medium
OM2	Asset damage	O&M	Collisions, entanglement s	Quality	Negative	Catastrophic	Rare	Medium
OM3	Cost reduction due to volume	O&M	Economies of scale	Dimension	Positive	Major	Likely	High
OM4	Unplanned maintenance	O&M	Fault requiring immediate intervention	Quality	Negative	Moderate	Possible	Medium
OM5	Maintenance delays due to sourcing	O&M	Unavailable spares	Technology	Negative	Minor	Unlikely	Low
OM6	Lower than expected performance	O&M	Poor resource assessment or changing resource characteristic s	Environment	Negative	Catastrophic	Possible	High
D1	Inadequate weather window	Decommissio ning	Sea state conditions	Environment	Negative	Moderate	Likely	Medium
D2	Asset damage	Decommissio ning	Collisions, entanglement s	Quality	Negative	Moderate	Rare	Low
D3	Cost reduction due to volume	Decommissio ning	Economies of scale	Dimension	Positive	Major	Likely	High

B – Income Statement of the Model

Periods 0, 1 and 2 (values of the single unit scenario).

	Period	0	1	2
(1)	Year [hours]	0	8760	8760
(2)	Yearly Planned Maintenance [hours]	0	168	168
(3)	Yearly Unplanned Maintenance [hours]	0		
(4)	Overhaul [hours]	0	0	0
(5)	Availability [hours]	0	8592	8592
(6)	**Availability (%)**	-	0,980821918	0,980821918
(7)	Power [kW]	303,73	303,73	303,73
(8)	Yearly Produced Output [kWh]	0	2609605,78	2609605,78
(9)	Feed in Tariff [€/kWh]	0,26	0,26	0,26
(10)	**Revenue [€]**	-	678.497,50	678.497,50
(11)	Monitoring [€]	-	48.114,00	48.114,00
(12)	Yearly Planned Maintenance [€]	-	155.124,00	155.124,00
(13)	Yearly Unplanned Maintenance [€]	-		
(14)	Spares [€]	-	60.000,00	60.000,00
(15)	Insurance [€]	-	60.000,00	60.000,00
(16)	Annual Rent [€]	-	2.187,00	2.187,00
(17)	Overhaul [€]	-	n.a	n.a
(18)	**Operating Expenses [€]**	-	325.425,00	325.425,00
(19)	**EBITDA [€]**	-	353.072,50	353.072,50
(20)	Depreciation [€]	-	243.000,00	243.000,00
(21)	**EBIT [€]**	-	110.072,50	110.072,50
(22)	Interest [€]	-	204.120,00	198.571,09
(23)	**EBT [€]**	-	- 94.047,50	- 88.498,59
(24)	Annual Tax (%)	25%	25%	25%
(25)	Income Tax [€]	-	-	-
(26)	**Net Income [€]**	-	- 94.047,50	- 88.498,59
(27)	Net Income + Depreciation [€]	-	148.952,50	154.501,41
(28)	Total Investment [€]	4.860.000,00		
(29)	Borrowed Funds [€]	3.402.000,00		
(30)	Debt Repayment [€]		92.481,86	98.030,77
(31)	**Annual Cash Inflow [€]**	3.402.000,00	148.952,50	154.501,41
(32)	**Annual Cash Outflow [€]**	4.860.000,00	92.481,86	98.030,77
(33)	**Annual Net Cash Flow [€]**	- 1.458.000,00	56.470,64	56.470,64

$$Year\ [hours] = 365 \times 24 \times nº\ of\ device\ units$$

$$Yearly\ planned\ maintenance\ [hours] = Plannne\ maintenance\ duration \times nº\ of\ device\ units$$

$$Yearly\ unplanned\ maintenance\ [hours] = Unplanned\ maintenance\ duration \times nº\ of\ device\ units$$

$$Overhaul\ [hours] = Overhaul\ duration \times nº\ of\ device\ units$$

$$Availability\ [hours] = (1) - (2) - (3) - (4)$$

$$Availability\ (\%) = {}^{(5)}\!\big/_{(1)}$$

$$Yearly\ produced\ output\ [kWh] = (5) \times (7)$$

$$Revenue\ [€] = (8) \times (9)$$

$$Monitoring\ [€] = Monitoring\ cost \times nº\ of\ device\ units$$

$$Yearly\ planned\ maintenance\ [€] = Planned\ maintenance\ cost \times nº\ of\ device\ units$$

$$Yearly\ unplanned\ maintenance\ [€] = Unplanned\ maintenance\ cost \times nº\ of\ device\ units$$

$$Spares\ [€] = Cost\ of\ spares \times nº\ of\ device\ units$$

$$Insurance\ [€] = Insurance\ cost \times nº\ of\ device\ units$$

$$Annual\ rent\ [€] = Annual\ rent\ cost \times nº\ of\ device\ units$$

$$Overhaul\ [€] = IF(Period = 10, Overhaul\ cost \times nº\ of\ device\ units, 0)$$

$$Operating\ expenses\ [€] = \sum_{i=(11)}^{(17)} i$$

$$EBITDA\ [€] = (10) - (18)$$

$$Depreciation\ [€] = {}^{Total\ investment\ [€]}\!\big/_{Device\ life\ [years]}$$

$$EBIT\ [€] = (19) - (20)$$

$$Interest\ [€] = -IPMT(Interest\ rate, Period, Term, Borrowed\ funds)$$

$$EBT\ [€] = (21) - (22)$$

$$Income\ tax\ [€] = IF(EBT > 0, (23) \times (24), 0)$$

$$Net\ income\ [€] = (23) - (25)$$

$$Total\ investment\ [€] = WEC\ IC + Installation\ phase\ cost$$

$$Debt\ repayment\ [€] = -PPMT(Interest\ rate, Period, Term, Borrowed\ funds)$$

$$Annual\ cash\ inflows\ [€] = IF(Net\ income\ [€] > 0, Net\ income[€], 0) + Borrowed\ funds\ [€]$$

$$\begin{aligned} Annual\ cash\ outflows\ [€] \\ &= IF(Net\ income[€] > 0, Net\ income\ [€], 0) + Total\ investment\ [€] \\ &+ Debt\ repayment\ [€] \end{aligned}$$

$$Annual\ net\ cash\ flow\ [€] = (31) - (32)$$

IF, IPMT and PPMT are functions from the Microsoft Excel software. For multiple-unit projects, Operating expenses and Total investment are subject to the risks of cost reduction in (1) the O&M phase and (2) the Construction and Installation phase respectively. The risk of unplanned maintenance determines the Unplanned maintenance cost and the number of device units.

C – Interpolated Sea State Probability Matrix

Original Matrix

		Wave Period										
		3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5
	0,5	0,000053	0,002124	0,012532	0,021782	0,014432	0,004587	0,000858	0,000110	0,000011	0,000001	0,000000
	1,5	0,000001	0,000404	0,011000	0,052578	0,077910	0,050775	0,018425	0,004390	0,000772	0,000109	0,000013
W	2,5	0,000000	0,000060	0,003472	0,030724	0,077361	0,080193	0,043878	0,015070	0,003682	0,000700	0,000110
a	3,5	0,000000	0,000010	0,000933	0,012415	0,044682	0,063727	0,046481	0,020711	0,006406	0,001510	0,000290
v	4,5	0,000000	0,000002	0,000242	0,004366	0,020522	0,037215	0,033739	0,018333	0,006796	0,001891	0,000424
e	5,5	0,000000	0,000000	0,000064	0,001463	0,008509	0,018693	0,020173	0,012854	0,005514	0,001755	0,000445
	6,5	0,000000	0,000000	0,000017	0,000490	0,003404	0,008774	0,010946	0,007964	0,003860	0,001374	0,000387
H	7,5	0,000000	0,000000	0,000005	0,000169	0,001366	0,004035	0,005699	0,004645	0,002500	0,000980	0,000302
e	8,5	0,000000	0,000000	0,000002	0,000061	0,000562	0,001869	0,002941	0,002648	0,001562	0,000666	0,000222
i	9,5	0,000000	0,000000	0,000001	0,000023	0,000239	0,000884	0,001532	0,001506	0,000963	0,000443	0,000158
g	10,5	0,000000	0,000000	0,000000	0,000009	0,000106	0,000429	0,000811	0,000863	0,000594	0,000292	0,000111
h	11,5	0,000000	0,000000	0,000000	0,000004	0,000048	0,000214	0,000438	0,000500	0,000368	0,000192	0,000077
t	12,5	0,000000	0,000000	0,000000	0,000002	0,000023	0,000109	0,000240	0,000293	0,000229	0,000127	0,000054
	13,5	0,000000	0,000000	0,000000	0,000001	0,000011	0,000057	0,000134	0,000174	0,000143	0,000084	0,000037
	14,5	0,000000	0,000000	0,000000	0,000001	0,000011	0,000066	0,000176	0,000259	0,000242	0,000159	0,000079

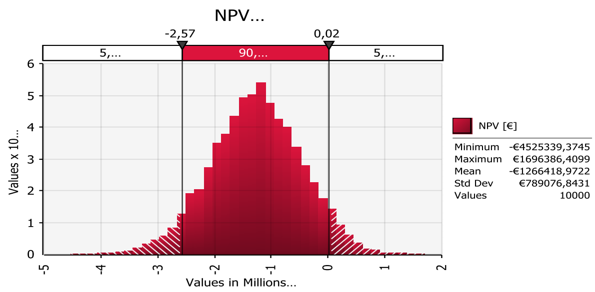
Interpolated Matrix

		Wave Period									
		4	5	6	7	8	9	10	11	12	13
	0.5	0,001089	0,007328	0,017157	0,018107	0,009510	0,002723	0,000484	0,000061	0,000006	0,000001
	1.5	0,000203	0,005702	0,031789	0,065244	0,064343	0,034600	0,011408	0,002581	0,000441	0,000061
W	2.5	0,000030	0,001766	0,017098	0,054043	0,078777	0,062036	0,029474	0,009376	0,002191	0,000405
a	3.5	0,000005	0,000472	0,006674	0,028549	0,054205	0,055104	0,033596	0,013559	0,003958	0,000900
v	4.5	0,000001	0,000122	0,002304	0,012444	0,028869	0,035477	0,026036	0,012565	0,004344	0,001158
e	5.5	0,000000	0,000032	0,000764	0,004986	0,013601	0,019433	0,016514	0,009184	0,003635	0,001100
	6.5	0,000000	0,000009	0,000254	0,001947	0,006089	0,009860	0,009455	0,005912	0,002617	0,000881
H	7.5	0,000000	0,000003	0,000087	0,000768	0,002701	0,004867	0,005172	0,003573	0,001740	0,000641
e	8.5	0,000000	0,000001	0,000032	0,000312	0,001216	0,002405	0,002795	0,002105	0,001114	0,000444
i	9.5	0,000000	0,000001	0,000012	0,000131	0,000562	0,001208	0,001519	0,001235	0,000703	0,000301
g	10.5	0,000000	0,000000	0,000005	0,000058	0,000268	0,000620	0,000837	0,000729	0,000443	0,000202
h	11.5	0,000000	0,000000	0,000002	0,000026	0,000131	0,000326	0,000469	0,000434	0,000280	0,000135
t	12.5	0,000000	0,000000	0,000001	0,000013	0,000066	0,000175	0,000267	0,000261	0,000178	0,000091
	13.5	0,000000	0,000000	0,000001	0,000006	0,000034	0,000096	0,000154	0,000159	0,000114	0,000061
	14.5	0,000000	0,000000	0,000001	0,000006	0,000039	0,000121	0,000218	0,000251	0,000201	0,000119

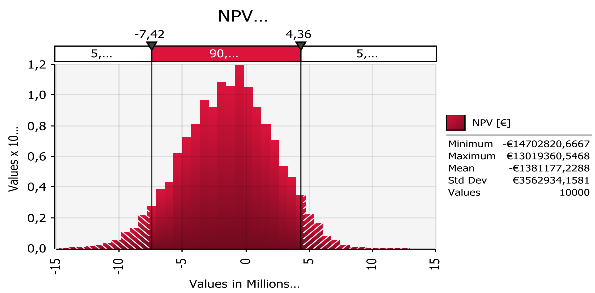
D – Histograms of the Output Variables of the Simulation

NPV histograms

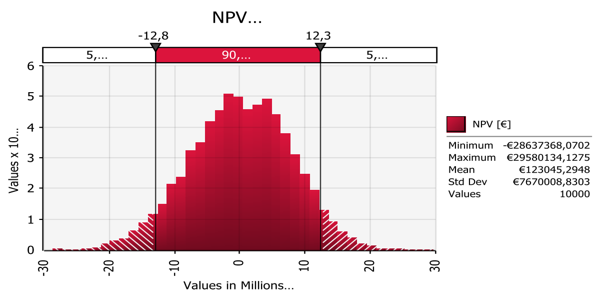
1 unit project



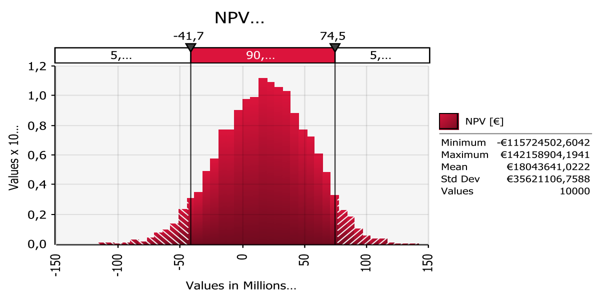
4 unit project



8 unit project

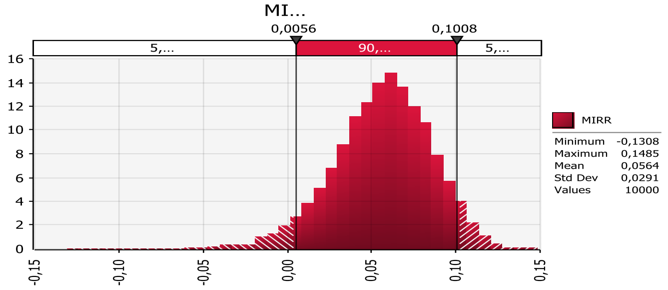


32 unit project

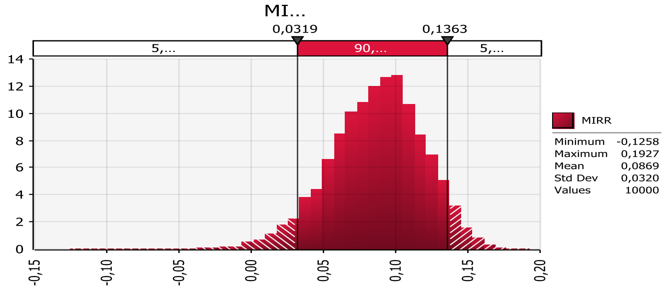


MIRR histograms

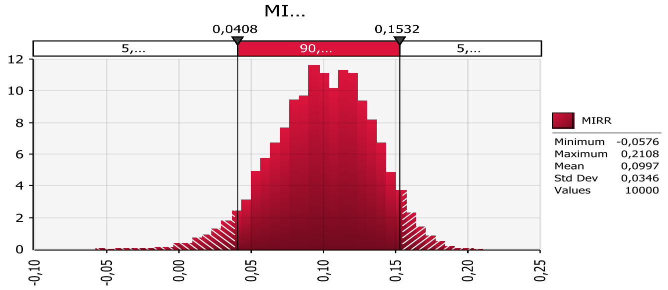
1 unit project



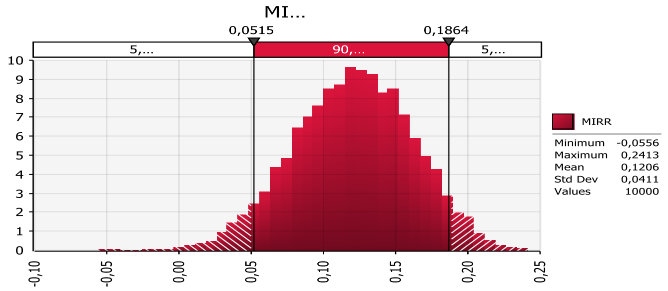
4 unit project



8 unit project

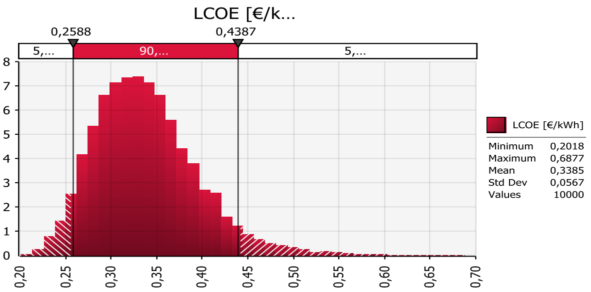


32 unit project

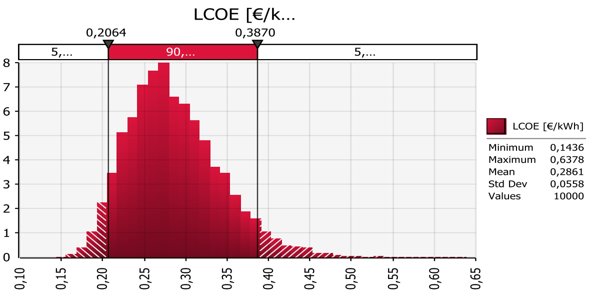


LCoE histograms

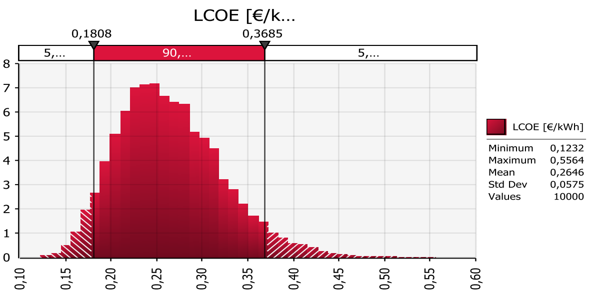
1 unit project



4 unit project



8 unit project



32 unit project