A Structured Innovation Approach for Application to the Wave Energy Sector.

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Abstract

As part of sector-wide rethink on the development process of wave energy converters (WECs), public-sector development programmes are implementing funding stage-gates that are based on performance validation. The aim of such programmes is to produce a commercially ready technology. However, a key limitation is the assumption that participating concepts cover enough of the parameter space and that a potential 'winner' is amongst them. Structured innovation approaches are used in other industrial sectors to analyse many alternatives concepts and as an initial step to avoid narrowing the design focus too early.

This research investigated the development of such an approach for application to wave energy. A 'concept generation and evaluation tool' was developed which can be used to scan the parameter space and identify concepts that have the potential to achieve a target return on investment for a given location and available resource. An initial review of structured innovation tools and metrics led to the conclusion that a techno-economic value based approach was the best way to identify promising concepts. The development of the tool was then broken down into three objectives.

The first objective was to develop a flexible method for providing resource and site characteristics. This was required to easily compare concepts in a number of different deployment scenarios and to provide results which were not location specific. Two 'Resource Estimating Relationships' (RER) were found through least squares fitting to reference data. These can be used to generate key resource characteristics from a small subset of high-level parameters. The first RER estimates a probability distribution of sea states based on site power level and geographic region. The second RER then estimates vessel delay durations to represent the average time spent waiting for a weather window in summer and winter.

To demonstrate this method, results were provided for an analysis of two WEC types, one operating in heave and one operating in surge, and for high and low energy sites in six regions. The results showed significant regional differences in the evolution of wave climate with increasing power level and consequently, differences in the amount

of energy captured by each WEC. This suggests that a deployment scenario may be profitable for one WEC type but not for another. In addition, there were significant variations in other key cost drivers, including the extreme sea state and vessel delay durations.

The second objective was to develop a techno-economic model that can be used at the concept creation phase of technology development. Few attempts have been made at early stage techno-economic assessment and existing methods had to be tailored for this application. This included finding parametric expressions to model cost and the development of a simple stochastic model to estimate reliability.

To demonstrate the functionality of the model, results were provided for an analysis of the relationship between site power level and WEC scale. Levelised cost of energy (LCoE) values of 0.69 £/kWh and 0.20 £/kWh were found for the heave and surge WECs respectively and were achieved by optimising power level and the principal WEC dimension. However, these values are higher than is currently considered to be competitive and the results suggested that further technological improvement is required. The results also suggested that an optimal site power level, in the range of 30 kW/m to 60 kW/m, exists in each of the six regions analysed.

The third, and final, objective was to develop a scoring method for indicating likelihood of development success. A 'commercial attractiveness' score is based on the value of LCoE as provided by the techno-economic model. In addition, a 'technical achievability' metric was developed to indicate whether technological improvements are realisable within a specified development period.

The final set of results show how thresholds for each score can be used to identify promising concepts and deployment scenario combinations, this being the main aim of the research. The results highlight that certain structural material and PTO technologies are more likely to provide a cost-competitive WEC and that careful consideration is needed for selecting deployment locations and WEC scales depending on the WEC type. Overall, the work presented in this thesis shows how a tool can be developed for facilitating structured innovation in the wave energy sector.

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Acronyms

ACE Average Climate Capture Width per Characteristic Capital Expenditure

AEP Annual Energy Production

BOP Balance of Plant

CA Commercial Attractiveness

CapEx Capital Expenditure

CBA Cost Benefit Analysis

CER Cost Estimating Relationship

CMA Conditional Modelling Approach

CSA Cross Sectional Area

DoE US Department of Energy

FMEA Failure Mode and Effects Analysis

GRP Glass Reinforced Plastic

GWS Global Wave Statistics

LCoE Levelised Cost of Energy

MLL Most Loaded Line

O&M Operations and Maintenance

OE Ocean Energy

OpEx Operational Expenditure

OWC Oscillating Water Column

OWSC Oscillating Wave Surge Converters

PCP Pre-Commercial Procurement

PDF Probability Density Function

PTO Power Take-Off

PV Present Value

QFD Quality Function Deployment

R&D Research and Development

RER Resource Estimating Relationship

RM3 Reference Model 3

RSSE Root of the Sum of the Square Error

TA Technical Achievability

TPL Technology Performance Level

TRIZ Theory of Inventive Problem Solving

TRL Technology Readiness Level

TTF Time to Failure

WEC Wave Energy Converter

WES Wave Energy Scotland

Nomenclature

Costs

$C_{\mathbf{C}}$	Cabling total cost
$C_{\mathbf{I}}$	Installation total cost
$C_{\mathbf{K}}$	Station keeping total cost
$C_{\mathbf{O\&M}}$	O&M cost per year
$C_{\mathbf{P}}$	PTO total cost
$C_{\mathbf{S}}$	Structure total cost
$C_{\mathbf{cap}}$	Capital Expenditure (CapEx)
$C_{\mathbf{mob}}$	Vessel mobilisation fee
$C_{\mathbf{op}}$	Operational Expenditure (OpEx)
$c_{\mathbf{PTO}}$	PTO cost per kW
$c_{\mathbf{bal}}$	Ballast cost per kg
$c_{\mathbf{cab}}$	Cable cost per m
$c_{\mathbf{day}}$	Vessel working day rate
$c_{\mathbf{exp}}$	Export cable cost per m
$c_{\mathbf{int}}$	Inter-WEC cable cost per m
$c_{\mathbf{mat}}$	Material cost per kg
$c_{\mathbf{mor}}$	Mooring line cost per kg

Operations & Maintenance

$H_{\mathbf{max}}$	Maximum H_{s} for vessel
$N_{\mathbf{c}}$	No. of corrective operations
$N_{\mathbf{p}}$	No. of preventative operations
κ	Percentage power loss due to operation
λ	Failure rate
$t_{\mathbf{d}}$	Delay time
$t_{\mathbf{i}}$	Installation duration
$t_{\mathbf{o}}$	Total operation duration
$t_{\mathbf{r}}$	Repair duration
$t_{\mathbf{t}}$	Transit duration
$t_{\mathbf{ww}}$	Weather window duration

Other

α	Learning elasticity
$\mathbf{LCoE}_{\mathbf{target}}$	Target LCoE value
r	Discount rate
$t_{\mathbf{life}}$	Project lifetime

Power Production

A	Availability
E	Annual Energy Production (AEP)
P	Produced power
$P_{\mathbf{WEC}}$	Rated power
$P_{\mathbf{array}}$	Array capacity
$\bar{P}$	Occurrence-weighted mean power
$\boldsymbol{P}$	Produced power matrix

η	Total conversion efficiency
$\eta_{\mathbf{cab}}$	Transmission efficiency of the cables
$\eta_{\mathbf{max}}$	Base conversion efficiency
ε	Absorption efficiency
k	Part-load performance parameter
$r_{\mathbf{max}}$	Survival ratio

Site characteristics

A^*	Accessibility
$F_{\mathbf{H}}$	Horizontal environmental force
J	Incident power flux
$H_{\mathbf{s}_{50}}$	50-year extreme H_s
$\bar{P}_{\mathbf{site}}$	Site power level
$\mathbf{\Theta}$	Sea-state occurrence matrix
d	Distance to shore
h	Water depth
$H_{\mathbf{s}}$	Significant wave height
$T_{\mathbf{e}}$	Energy period
$T_{\mathbf{z}}$	Zero-crossing period

WEC Dimensions

$L_{\mathbf{a}}$	Active width
$M_{\mathbf{bal}}$	Mass of ballast
$M_{\mathbf{mat}}$	Mass of material
$N_{\mathbf{WEC}}$	Number of WECs in array
$N_{\mathbf{mor}}$	Number of mooring lines
V	Total volume of the main structure
$\phi_{\mathbf{mat}}$	Material volume parameter
$\rho_{\mathbf{mat}}$	Primary material density
$l_{\mathbf{int}}$	Inter-WEC cable length
$l_{\mathbf{mor}}$	Mooring suspended length
$m_{\mathbf{mor}}$	Mooring mass per unit length

1. Introduction

The transition from high carbon to low carbon technology is one of the major challenges facing the world today. A recent and widely publicised report (IPCC, 2018), looked at the difference in impact of a 1.5 °C rise in global temperatures compared to a 2 °C, a highly probable scenario by the year 2050 based on current human activity. The report states that by limiting temperature rise, the impact on communities of factors including sea-level rise, ocean acidification and extreme weather events, can be greatly reduced. However, this requires immediate action, including the development and deployment of renewable energy as an alternative to fossil-fuel based generation.

Within this context, Ocean Energy (OE) is an exciting prospect as a clean and abundant (section 1.1.1) source of energy and yet the development of OE has taken much longer than expected and most forms of OE technology are at a pre-commercial stage[1].

In the UK, the Marine Energy Action Plan, which was set out by UK Government in 2010, estimated that wave energy and tidal stream technologies could achieve 2 GW installed capacity by 2020 (DECC, 2010). However, current UK operating capacity is around 10 MW of 25 MW globally (UoE, 2018; OES, 2017).

Nevertheless, the UK has a large proportion of world's extractable resource and OE remains an attractive option. As well as the potential to make a significant contribution to the UK's energy needs, the development of OE will create jobs and numerous export

[1]Large scale tidal-barrage generation has existed since the 1960s (Tethys, 2019).

opportunities (SI Ocean, 2014). It also remains a popular option as a source of energy from the viewpoint of the consumer, as according to the government's public attitudes tracker (DECC, 2016).

Table 1.1: Levelised Cost of Energy (LCoE) for utility-scale renewable power generation.

Year:	2010 (£/kWh)*	2017 (£/kWh)*
Biomass	0.06	0.06
Geothermal	0.04	0.06
Hydro	0.03	0.04
Solar photovoltaic	0.29	0.08
Concentrating solar	0.27	0.18
Offshore wind	0.14	0.11
Onshore wind	0.06	0.05

Source: IRENA (2017). *converted to $£_{2019}$

One of the reasons for the lack of uptake, has been the inability of developers to demonstrate OE as a cost-effective alternative to other low carbon technologies. Table 1.1 provides LCoE values for seven forms of renewable energy taken from a report by IRENA (2017). LCoE is the ratio of total lifetime costs to total energy output, discounted across the lifetime of the project. It represents the break-even price for the produced electricity. For comparison, a 2018 report on OE estimates a current LCoE of 0.30 £/kWh for tidal stream technologies with wave energy technology presumed to have an LCoE of >0.30 £/kWh (ORE Catapult, 2018).

Market support for renewable technologies in the UK is awarded through a process of competitive auctions (OES, 2017; BEIS, 2017). Therefore, the main challenge for the OE sector is to achieve an attractive LCoE through a combination of lower costs, better performance and improved reliability. It is worth noting from table 1.1, that the LCoE of solar photovoltaics has decreased rapidly since 2017. For offshore wind, prices a low as 0.04 £/kWh have been agreed with the UK government for generation beyond 2021 (BEIS, 2017). These reductions have largely come as a result of government supporting a rapid increase in deployment (ORE Catapult, 2016).

Currently, the majority of installed OE capacity in the UK is tidal-stream technology and the recent installation of two tidal-stream arrays in Scotland are important milestones for the sector providing reason for optimism (UoE, 2018). However, tidal-stream is limited to locations with enhanced tidal driven water flow, such as a channel between islands. Wave energy offers a more geographically widespread form of generation, but whilst tidal energy has progressed, achieved design consensus and is now seeking commercial tariffs for supplying the UK grid, wave energy remains in a prototyping stage with many competing designs in development.

Furthermore, high-profile cases of WEC developers who achieved full-scale, open water testing and then entered administration (e.g. Pelamis in 2014 and Aquamarine in 2015 (Hannon, 2016)) have resulted in damaged sector confidence (ETI, 2017). Consequently, the need for a rethink on wave energy development is now recognised, if the sector is to achieve commercial viability, rebuild confidence and avoid past pitfalls.

This thesis looks at the application of a 'structured innovation' approach to WEC development. The approach calls for a more objective and informed system for the award of funding to developers. This differs from a 'state-of-the-art' approach that relies on the natural emergence of winning technologies from the pool of competition. By identifying both promising concepts and design problems early on in the development process, a structured innovation approach will help to reduce the time, cost and effort needed to achieve a commercial wave energy technology (Weber et al., 2015).

In particular, the work focused on the development of a tool that could provide an informed search of the techno-economic WEC parameter space at the earliest stage of innovation: concept creation. The concept generation and evaluation tool was developed for the needs of an organisation tasked with directing Research and Development (R&D), with the aim of stimulating innovation in areas identified as having the highest potential for achieving success. Therefore, to increase the understanding of the parameter space, much of the research focused on mapping the links between design parameters and likelihoods of success.

The remainder of this chapter is split as follows:

- ▷ Section 1.1 provides an introduction to wave energy, including an overview of the resource, technology and current activity.
- ▷ Section 1.2 provides an introduction to structured innovation and its role in the development of wave energy.
- ▷ Section 1.3 presents the research question and objectives for the research.
- ▷ Section 1.4 provides an overview of the thesis and chapters.

1.1 Introduction to Wave Energy

Although wave energy is often described as a nascent sector, the technology has been in development for several decades and perhaps a better description would be stalled. Salter's Duck, one of the earliest WECs, began development in the 1970s at a time of global oil shortages and insecurity (Salter, 1974). Since then various WECs have been researched and developed (see Borthwick, 2016). The world's first supply of wave generated electricity to a national grid occurred in 2006 with the testing of the Pelamis WEC at full-scale (ETI, 2013). Despite this, commercial roll-out has not been achieved and there is little consensus within the sector regarding the best designs or technologies.

The aim of this section is to provide an overview of wave energy, including the resource, technology, and current activity in the sector to provide the context for applying a structured innovation approach.

1.1.1 The Wave Energy Resource

Wave energy has several advantages over other forms of renewable energy generation, including a higher power density and persistence. Swell waves travel long distances with little loss of energy meaning that a large proportion of the resource is more consistent and forecastable than wind or solar (Barstow et al., 2007; Reikard et al., 2015).

Globally, it is estimated that there is a total theoretical wave energy potential of 32 000 TW h/a (Mork et al., 2010) although, as with all resources, the amount that can

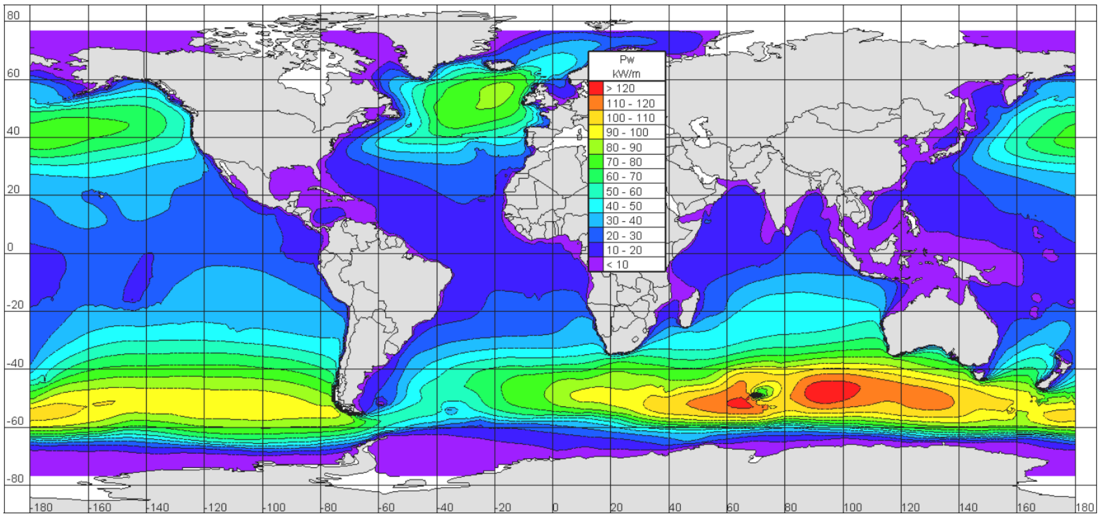


Figure 1.1: Global distribution of mean wave energy resource (Cornett, 2008).

be technically or economically extracted will be somewhat lower. Figure 1.1 shows how the wave resource is distributed according to wind circulation patterns, with a tendency to be stronger on western coastlines away from the equator. Western and Northern Europe coastlines have a high quality of resource, receiving a total of 2800 TW h/a (Mork et al., 2010) and the majority of wave energy development has occurred in these areas (OES, 2017). However, due to their length, the coastlines of Australasia, North America and South America offer potentially greater scales for wave energy deployment.

Locally, the amount of wave energy available depends on exposure to open ocean and the interaction area between the wind and ocean-surface. A good wave resource can be found at coastal locations orientated such that there is a sizeable distance to the next landmass in a direction that agrees with the prevailing wind, known as the 'fetch'. Other characteristics such as the bathymetry and the geometry of the coastline also impact on the quality of the resource, especially in the nearshore environment where the directionality of the waves can be a problem for certain WEC types. On the other hand, there are benefits to more benign conditions, creating a trade-off. Sheltered locations are more accessible for operations and are protected from the most damaging waves (Folley et al., 2009).

Potential sites for WEC deployment are characterised in terms of the regularity of sea states: periods of time of a certain average wave height (normally the significant wave height (H_s [m]) and corresponding average wave period (e.g. the zero-crossing period (T_z [s]), or energy period (T_e [s]). In a typical irregular sea, the incident power flux, in kilowatts per meter of crest length, can roughly be approximated by the formula:

$$J = 0.5 \cdot H_\mathrm{s}^2 \cdot T_\mathrm{e} \qquad \text{[kW/m]} \qquad (1.1)$$

Therefore, the most powerful sea states are those with the highest waves and longest periods. The power level of a site is the annual mean value of incident power calculated according the occurrence probability of sea states. Therefore, the contribution of a sea state to site power level is a combination of both its power and how frequently it occurs. It is suggested that power levels greater than 15 kW/m are required for wave energy to be economically viable (Pecher et al., 2017).

However, another important factor in determining the economically useful proportion of a resource is seasonal variability and the matching of production to demand. For example, locations of the west coast of Ireland have high annual power levels, but the winter averages can be as much as seven times the summer averages, which is more than the difference in energy demand (Dalton et al., 2009). Therefore, the best locations for wave energy extraction are likely to have a good balance of high average power and low seasonal variability.

1.1.2 Wave Energy Converters

In Falcão (2010) three main WEC types are defined according to working principle: Oscillating Water Columns (OWCs), oscillating bodies and overtopping devices. However, other WECs exist that do not fall into these categories and accounting for all the variations in WEC design as a limited set of categories is very difficult.

OWCs extract energy from the oscillating air pressure in an semi-enclosed chamber as a consequence of the oscillating sea surface. The resultant bi-directional flow of air is passed through turbines to generate power. Overtopping devices collect incoming waves and direct the flow of water through low-head turbines and back to the ocean. Long arms are needed to collect and concentrate a large wave field.

Typically, oscillating body types are split according to their principle direction of motion (fig. 1.2). Heaving devices extract energy from a vertical motion. This includes point-absorbers, which are smaller than a wavelength, and attenuators, which utilise the oscillatory motion between several long floats. Surge or pitch flap type devices move in a forward and back motion and are commonly referred to as Oscillating Wave Surge Converters (OWSC).

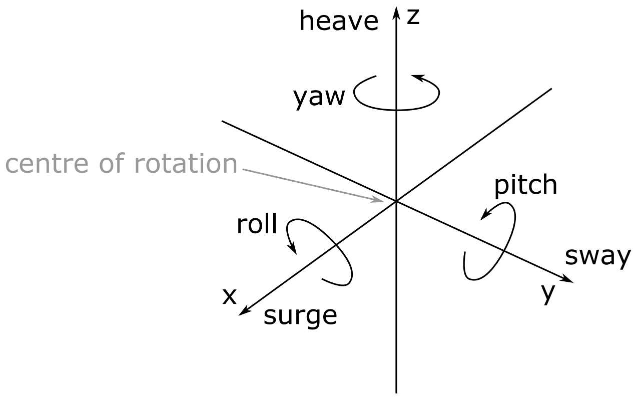


Figure 1.2: Axis of motion for an oscillating wave energy device.

The ability of a WEC to absorb the energy of an incoming wave depends on its hydrodynamic design and certain WECs utilise multiple degrees of freedom to try and improve energy capture (Yemm et al., 2012; Babarit, 2015). The absorption efficiency of a WEC is commonly calculated according to the formula (Babarit, 2015):

$$\varepsilon = \frac{P}{J \cdot L_{\mathrm{a}}} \tag{1.2}$$

Where:

- ▷ P is the power produced by the WEC [kW],
- ▷ J is the incident power flux,
- ▷ L_{a} is the active width, the main dimension of the WEC active in absorbing wave energy [m].

Absorption efficiency and active width are often referred to as the capture width ratio and characteristic dimension respectively (see Babarit, 2015), and are characteristic of WEC type. Typical values for ε are provided in table 1.2 for each of the four main WEC types.

The active width, defined as the "... width of all the components actively in the primary absorption process of the energy from the waves" (Pecher, 2012), is used to represent WEC scale when estimating WEC productivity. However, the total scale of the WEC can be much bigger than this when taking into account the other subsystems.

The dimension used as the active width varies according to WEC type. For an OWC this is the width of the chamber opening, for an overtopping device it includes the wave concentrating arms and for a axis-symmetric point absorber it is the diameter (Babarit, 2015). The characteristic dimension of other WEC types can be harder to define.

A design with good cost efficiency will have a combination of both a good absorption efficiency and an active width that accounts for most of the WEC body. For example, point absorbers are small, relatively simple, and the majority of the primary structure is involved in extracting wave energy in the heave motion. They consequently perform well on financial indicators such as absorbed energy per unit of mass, despite having lower values of absorption efficiency Babarit et al. (2012).

Table 1.2: Typical values of absorption efficiency for different WEC types (Babarit, 2015)

WEC type	ε (%)
OWCs	29
OWSCs	37
Heaving devices*	16
Overtopping devices	17

*Inc. point absorbers, attenuators
and submerged pressure differential devices

For oscillating bodies maximum energy will be extracted when the system is at resonance. Consequently, the optimal WEC and its optimal scale is strongly related to the most prevalent wave periods at a given site (Pecher et al., 2017). Furthermore, for some WEC types, the incoming wave direction is a critical factor in their positioning for maximum energy capture.

For a given WEC, sites with the most temporally consistent wave climate, in terms of wave period and wave direction, will produce the most power. For example, WECs that utilise wave surge are more suited to the nearshore environment, which has a more consistent directionality. These effects can be alleviated through control, for example control of the WECs stiffness in response to the incoming wave or of its yaw axis (fig. 1.2).

Distance to shore and suitability for different water depths also dictates the loading requirements of the WEC and the type of foundations or moorings that can be used. For each of the WEC types specified in table 1.2 there are examples of both bottom fixed and floating devices (Babarit et al., 2012). A further distinction can be made with fully submerged WECs, which extract energy from changes in pressure as a result of waves passing overhead.

Figure 1.3 depicts the following six WEC types with certain variations (as indicated in brackets) and their relative proximities to shore:

A : OWC (shoreline)
B : OWSC (bottom fixed)
C : Point absorber (bottom-fixed, multi-body)
D : Submerged pressure differential (taut mooring)
E : Attenuator (slack mooring)
F : Overtopping device (slack mooring)

The interdependence between optimal WEC design and optimal site has implications for the future prospects of WEC technology as a global source of energy generation and for the scalability of the technology (Pecher et al., 2017). The need to tune scale to the wave climate means that economies of scale seen for other renewable energy sources

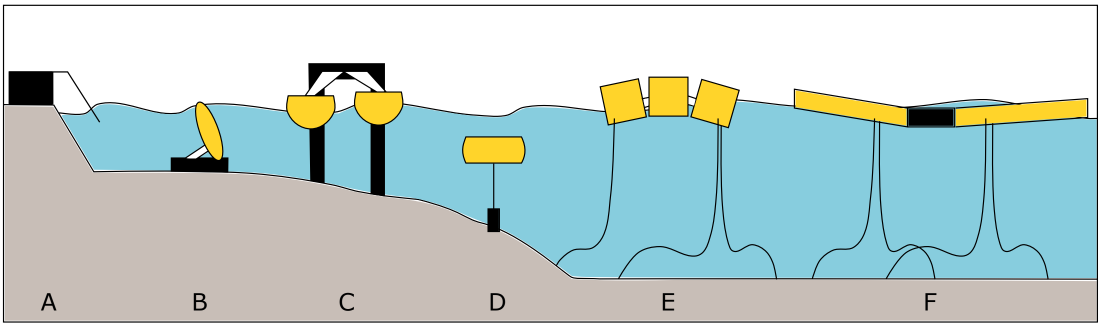


Figure 1.3: Six WEC types with typical water depth and distance to shore.

(e.g. offshore wind[2]), may not be applicable to wave energy. A potential solution is WEC technologies that are scalable by multiplication: multi-wave absorber WECs with a number of shared subsystems (Marquis et al., 2012; ARUP, 2018).

1.1.3 Subsystems

Despite the differences between WEC types they generally share the same subsystems, however the exact configuration and the type of technology is WEC dependent. Figure 1.4 provides a diagram of the subsystems which are generally required to generate electricity from wave energy.

The hydrodynamic subsystem describes components that interact directly with the waves to absorb energy. This is often referred to as the 'prime mover' and examples include the flap or heaving buoy components of oscillating body WEC (labelled in yellow in fig. 1.3). The Power Take-Off (PTO) subsystem is responsible for converting the absorbed energy to usable energy and includes the whole drivetrain involved in this process. The reaction subsystem is required to maintain the WEC position and to provide support. The control subsystem includes the sensors, processors and actuators used to adjust the WEC subsystems in response to the changing environment

[2]The aerodynamic efficiency of a wind turbine is primarily controlled by the profile of the blades rather than the scale of the rotor, allowing for larger scales to provide better economic returns.

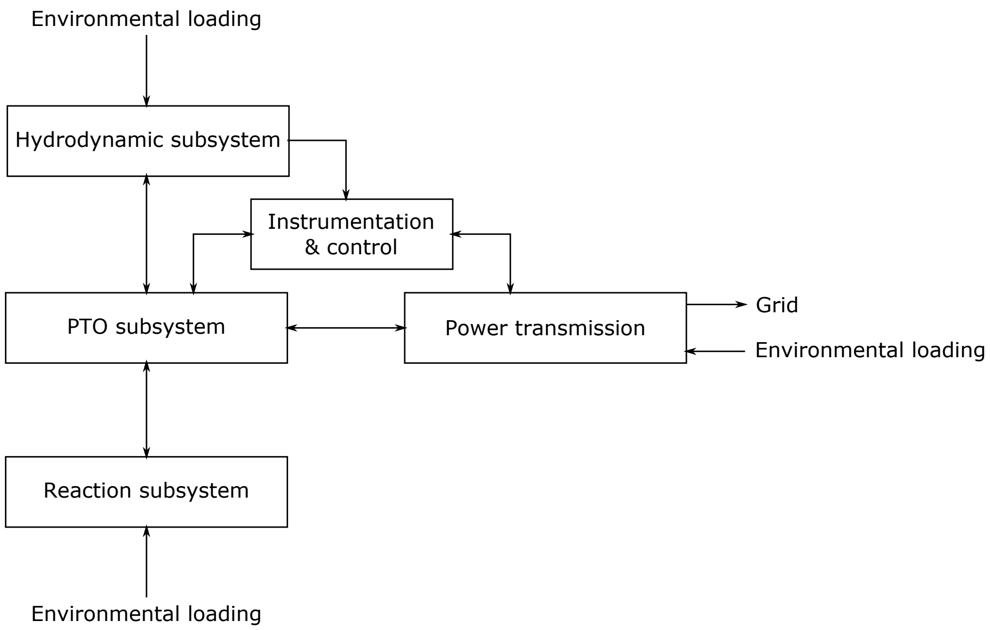


Figure 1.4: Typical WEC in terms of its subsystems for the generation of electricity. Environmental loading refers to forces acting on the WEC. Adapted from (Pecher et al., 2017).

as well as communication and data transfer instrumentation for providing real-time measurements to the operator.

For some WEC types there is a large variety of possible technology options and configurations, particularly with regards to the PTO. Hansen (2013) provides an analysis of 19 PTO variations for application to an oscillating body WEC. Configurations include both direct-drive generators and PTOs with various stages of energy transmission and storage (e.g. hydraulics, mechanical gears, magnetic gears) before conversion to electricity.

For economic modelling this translates to five 'dry' cost centres[3]: the structure and prime mover, PTO, station keeping (either foundations or moorings), power transmission and control. However, this definition varies from one set of guidelines to another (e.g. Sandia, 2014; Ramboll, 2010; Entec UK Ltd., 2006; Chozas et al., 2014), in partic-

[3]Where 'wet' cost centres include installation and Operations and Maintenance (O&M).

ular there is discrepancy in subsystems that are modelled as components of the WEC and those that are modelled as components of the array.

Other WEC concepts challenge this typical subsystem distinction. For example, there is active research in dielectric polymer technology that would enable the active structure to also be used as the PTO (Sant'Anna, 2017; Moretti et al., 2019).

1.1.4 Current Activity and Technology Readiness Levels

According to the website of the European Marine Energy Centre there were 227 wave energy developers active in February 2017 (EMEC, 2017). In fig. 1.5 these developers are grouped by WEC type (in terms of categories discussed) with the highest number for heaving-type point absorbers. These are often the focus of active development due to their relative simplicity and purported cost-efficiency (de Andrés et al., 2016). However, a significant proportion of the developers do not fall under the 'main' WEC types.

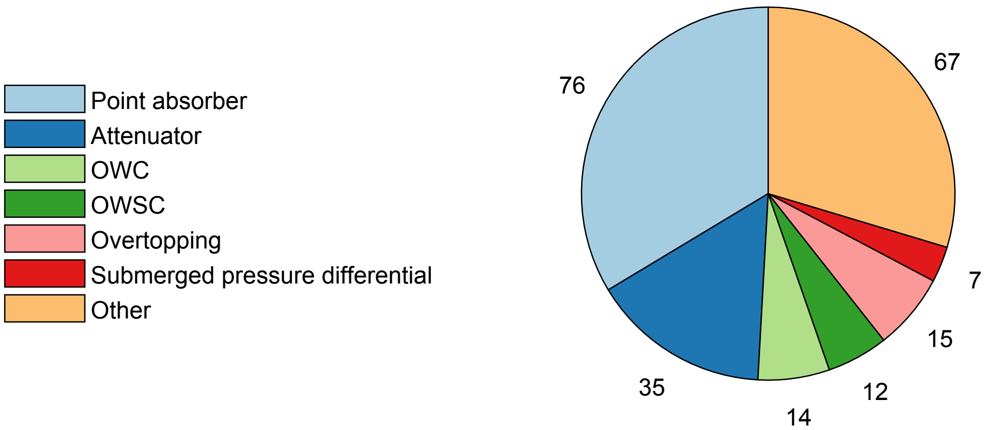


Figure 1.5: Active developers by WEC type. Source: (EMEC, 2017).

The status of these developers is typically described by the Technology Readiness Level (TRL)[4]. A TRL of one indicates the formulation of a concept and a TRL of nine

[4]Pioneered by the NASA in the 1980s and subsequently tailored for other industries including defence and energy sectors (EARTO, 2014)

indicates proven economic viability with the levels in between corresponding to scales of prototype and testing regimes.

Table 1.3 provides a general description of the TRL levels for wave energy, and there are several other examples which are more detailed (e.g. OES, 2010; Fitzgerald et al., 2012)). The majority of current developers are at a low TRL stage. However, the failure of previous developers, despite achieving high TRL, shows that it is a poor choice of metric for indicating success. Consequently, other activity includes a combined effort to develop metrics that can better indicate techno-economic performance (UMBRA, 2019; Sandia, 2017b; WES, 2016b).

Table 1.3: Brief summary of TRL levels (WES, 2015).

TRL	Description
1-3	Concept characterisation and feasibility assessment
4	Proof of concept/concept optimisation
5-6	Engineering development and small to medium scale prototype
7-8	Engineering definition and medium to large scale prototype

1.2 Structured Innovation

Despite a wealth of literature regarding technology development (e.g. UKERC, 2015; Gross et al., 2018; Geels, 2005; Robinson et al., 2013), there is a lack of clarity regarding the term 'innovation' and in particular, whether it has a defined beginning and end point within the technology development process.

The earliest phases of innovation are referred to in the literature by various names including the 'embryonic' stage (Gross et al., 2018) or 'formative' phase (Bento et al., 2018). The majority of these studies suggest common triggers and drivers for technology uptake and are based on retrospective analysis. They do not, however, go as far as to provide a blueprint for the successful harnessing of innovation and most focus on market formation and diffusion into the wider energy market.

Instead, the current status of wave energy covers two phases prior to this: concept creation and development and demonstration. According to Pahl et al. (2013), structured innovation covers these two phases and so is particularly relevant to wave energy. It refers to a systematic approach for stimulating innovation, identifying promising concepts and developing those concepts into a commercial product.

The aims of structured innovation are threefold:

- ▷ to accelerate development,
- ▷ to produce viable solutions and
- ▷ to derisk the development process.

Structured innovation methods are used to steer development and to make the developer conscious of defined end goals at every development stage, rather than treating them implicitly.

These methods have been widely discussed in the literature, including functional decomposition, TRIZ theory and value-centric approaches (see chapter 2). However, much of the available literature is abstract in its reasoning (Pahl et al., 2013; Chakrabarti, 2013, e.g.) and tends to lack real examples despite the purported power of such methods (Spreafico et al., 2016). This is likely due to the majority of companies keeping their tailored approaches to technology development in house.

1.2.1 Development Phases

As discussed, for an emerging energy technology, the innovation cycle can be split into the following four phases:

- ▷ Concept creation,
- ▷ Development and demonstration,
- ▷ Market formation,
- ▷ Growth and diffusion.

Activity within the wave energy sector is currently limited to the first two phases. In fig. 1.6, these are described in terms of the number of design options and level of investment required.

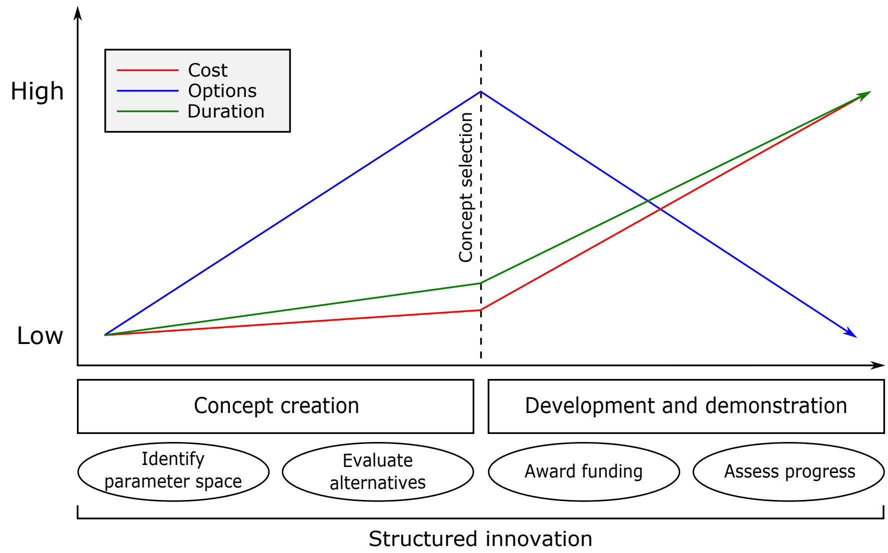


Figure 1.6: The first two phases of innovation. Adapted from OES (2010) and Pahl et al. (2013). 'Cost' refers to amount of spend on development stages and 'duration' the length of development stages.

During the concept creation phase the number of alternative solutions or design options increases. Structured innovation methods can be used to evaluate those alternatives and to understand their techno-economic potential. Furthermore, the mapping of the parameter space and the establishing of limits can help to ensure that no potential good solutions are overlooked.

One criticism of applying structured innovation is the increase in the amount of time required for concept creation (Pahl et al., 2013). However, the purpose is to reduce the overall development time through the avoidance of design dead ends and the need to repeat the search for solutions.

During the development and deployment phase there is an increase in TRL. The structured innovation approach centres on assessing progress and ensuring development is providing the required levels of techno-economic performance. Robust testing and validation is used to narrow down the number of design options and to identify and prompt design changes as early as possible.

The development of concepts into prototypes of increasing scale means that the cost and duration of development increases rapidly, as does the level of risk. Therefore, confident decision making, in terms of both design and the award of funding, becomes increasingly important.

1.2.2 Other Sectors

Structured innovation approaches are used in other industrial sectors that have high degree of innovation, such as the defence, aeronautics and automotive sectors (DoD, 2007; Spitz et al., 2001; Weber, 2009).

For example, the Architecture Framework employed by the Department of Defence in the US (or DoDAF), includes a Capability Based Assessment to define needs, gaps and solutions and is used for decision making on procurement of new technologies or R&D (DoD, 2007). It is comprised of three major parts: a functional area analysis, which describes a mission area, a functional needs analysis, which assesses how well a mission is currently performed, and a functional solutions analysis, which identifies possible solutions to mission shortcomings.

As part of this, the solution space is searched and documented in an 'Analysis of Alternatives' that is not accepted if it overly narrows the focus. In other words, there is a requirement that the broadest possible range of solutions are analysed. This includes identifying approaches with large uncertainty that have potentially large pay-offs. Also assessed is viability, based on whether a solution is compatible with policy and realisable given the development time frame.

Within the automotive sector a lot of design effort is incremental improvements including those required to conform to some new or tighter requirements for emissions or safety (Spitz et al., 2001; Moody et al., 1997). Design approaches vary between country of manufacture and typically, the focus is on reducing the time taken to get a product to market (Spitz et al., 2001; Womack et al., 1990; Weber, 2009).

However, one of the key elements identified of 'lean' development of new technology is a high design change rate early on in the process (Moody et al., 1997; Womack et al., 1990). A tree search is used to make more solutions available. Although this is a more costly approach it allows for the emergence of superior solutions and avoids locking onto one design too early.

Another common purpose of structured innovation is to align innovation with customer needs. Eres et al. (2014) and Papageorgiou et al. (2016) discuss conceptual design for different aeronautical applications and how customer needs can be used to quantitatively assess the parameter space. The decomposition of customer needs into measurable technical parameters is a key element of systems engineering (see chapter 2). Those parameters can be used to set benchmarks for techno-economic performance during development to ensure that customer needs are satisfied to a sufficient level (Weber, 2009; Stevens et al., 1998).

1.2.3 Structured Innovation for Wave Energy

Analysis shows that the development of new technology in the energy sector is characterised by a non-linear progression through research, development, demonstration and deployment, with significant feedback and learning from failure (Gallagher et al., 2012). However, for wave energy the resources required for continuing to learn and improve from repeated failures do not exist, and a lack of collaboration means there is still a need to achieve design consensus (Hannon, 2016).

A possible reason for the failure of previous wave energy development is an inability to fully explore the parameter space and search for solutions. Figure 1.7 shows the distribution of funding for previous wave energy development, where the vast majority of investment went to a small number of developers. It is argued that the need to secure intellectual property and rapidly upscale to attract funding, led to a fixation on technologies which ultimately were sub-optimal when tested in the ocean at full scale

Weber et al. (2015). The funding environment limited the possibility for design changes and meant that important operational factors were considered too late.

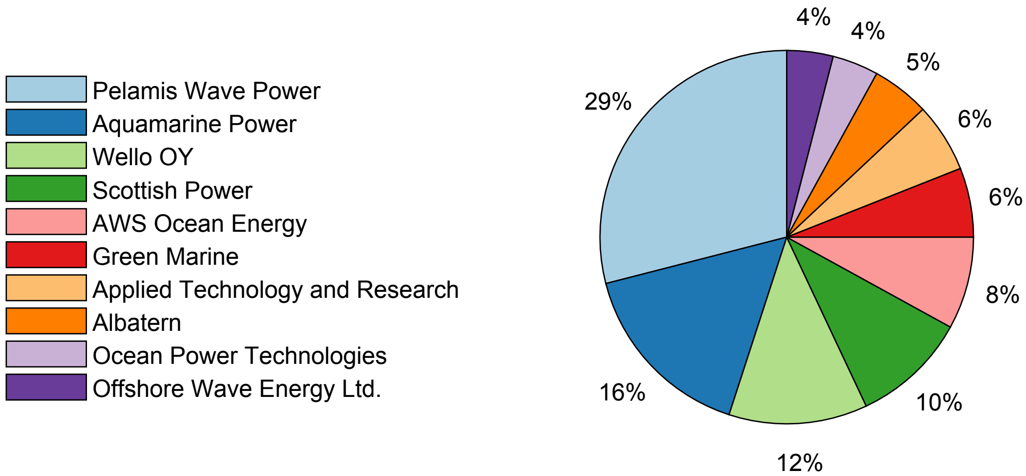


Figure 1.7: Distribution of demonstration grants awarded in the UK between 2000 and 2015 (Hannon, 2016).

So far, structured innovation approaches have been attempted for public-sector funding programmes aimed at development and demonstration. Two examples are the Wave Energy Prize, which was launched by the US Department of Energy (DoE) in April 2015, and the current Wave Energy Scotland (WES) funding programme. These are examples of 'Pre-Commercial Procurement', a type of innovation policy that is described further in appendix A.

The Wave Energy Prize was designed to increase interest in WECs and increase diversity amongst developers (U.S. DOE, 2015). The competition was run over 18-months and provided wave tank test time and support funding. The final monetary prize was dependent on achievement of certain cost and performance thresholds (see section 2.2.4) for a $1/20^{\text{th}}$ scale model and was awarded in November 2016. Nine teams entered the competition, with WEC concepts that included three point absorber and three submerged pressure differential type devices.

The WES programme uses a stage gate approach to award funding to developers. Progression from one stage to another is achieved through the fulfilment of certain requirements and the validation of cost and performance. There are parallel funding

Table 1.4: Guide to the PTO stage-gate programme from WES (2015).

Stage	Activity	Duration	Funding
1:	Feasibility assessment.	0.5 a	0.1 M£
2:	Proof of concept.	1 a	0.5 M£
3:	Validation of small-scale prototype.	2 a	2.5 M£
4:	Validation of large-scale prototype.	2 a	4.0 M£

paths for both whole WECs and individual subsystems. In table 1.4 the stages of the PTO programme are described in terms of their indicative TRL, duration and available level of funding. The first ocean testing of a WES funded WEC was conducted in 2018 (UoE, 2018).

The end goal of these programmes is to provide design consensus by producing a WEC that has the proven potential for commercialisation[5]. Although these approaches are markedly different from previous wave energy development, they rely on the availability of good WEC designs to achieve this end goal. Therefore, a major limitation is the assumption that at least one technology or concept exists amongst the entrants with the potential to provide the required level of techno-economic performance.

Therefore, structured innovation tools are also needed for the initial concept creation phase (fig. 1.6). These can be used to provide a thorough and objective search of the parameter space and to identify technologies with the highest likelihood of success from a wider pool of options, ensuring that potential winners are not overlooked.

[5]WES defines commercialisation as deployment of 1 GW cumulative generating capacity (WES, 2015).

1.3 Research Question

Previous iterations of wave energy innovation have not managed to achieve commercialisation and winning technologies have yet to emerge. Although technologies have previously progressed as far as full-scale open sea testing they could not prove economic viability and the sector now lacks design consensus. Resultantly, a rethink of the development process is required.

For stakeholders, including public-sector organisations, this rethink includes structured innovation as a more hands-on approach to R&D. However, the sector has limited time and resources and, consequently, there is a need to identify promising solutions at the earliest stage possible and to eliminate those that cannot demonstrate potential for success.

Whilst having plenty of crossover with other sectors that have established methods for structured innovation, wave energy has it own unique technical challenges and barriers to progress. Therefore, the top-level research question for this work was:

> *Can a structured innovation tool be developed for the wave energy sector?*

As discussed, current activity within the sector includes structured approaches for development and demonstration but not for the initial concept creation phase. The main aim was to create a tool that can be used to scan the parameter space and identify any concepts that have the potential to achieve a target return on investment for a given location and available resource (fig. 1.8). This can then be used to help converge sector development by ruling out areas of the parameter space which are unlikely to achieve success. The proposed 'concept generation and evaluation tool' is outlined in chapter 3.

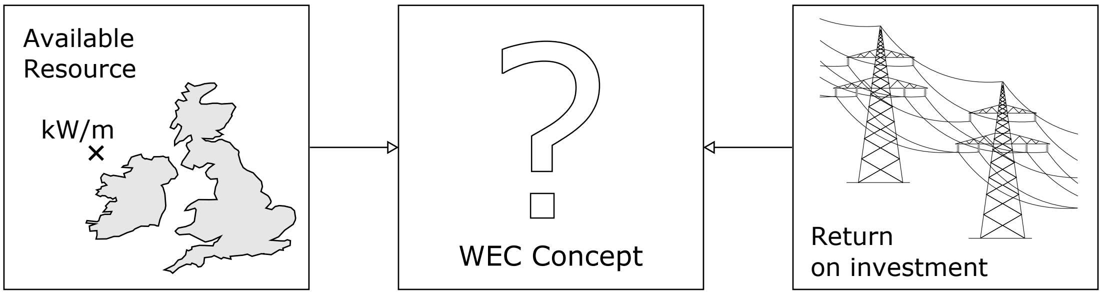


Figure 1.8: The main aim was to create a tool that can be used to scan the parameter space and identify any concepts that could achieve a target return on investment for a given location and available resource.

1.3.1 Objectives

To identify the best approach for the concept generation and evaluation tool a thorough review of existing structured innovation tools was conducted. This is presented in chapter 2. It was decided that a techno-economic value based approach was the best way to identify concepts with a high likelihood of development success.

However, creating a tool for low-TRL techno-economic assessment presented a number of challenges. Therefore, the research question was broken down into the following three objectives and these were the main focus of the research:

▷ *To develop a flexible method for providing resource and site characteristics.*

As discussed in section 1.1, there is close relationship between financial returns and the context for WEC deployment. In particular, the resource available at a site will dictate the profitability of a certain WEC concept. Therefore, techno-economic assessment that includes site characteristics is specific to that chosen site. This is problematic at low TRL because these characteristics will be unknown. On the other hand, concepts need to be selected using benchmarks of good performance in a wide variety of contexts. A method was developed for providing generic and easily manipulable resource data along with other deployment parameters, such as array scale, water depth and distance from shore, to define a flexible deployment context.

▷ *To develop a techno-economic model that can be used at low TRL.*

Low TRL techno-economic assessment is non trivial, there have been few attempts to tailor traditional approaches for concept evaluation and to cater for the high number of design variations and unknowns (see section 2.2). A techno-economic model was developed that could be used to assess a reduced number of inputs and that contained the most fundamental relationships between parameters. At the same time, the existing diverse range of WEC concepts meant that methods were also required to provide the flexibility for assessing the widest possible parameter space. Therefore, development of the model was a balance between reducing complexity and allowing for design variety.

▷ *To develop a scoring method for indicating likelihood of development success.*

Quantifying techno-economic potential and likelihood of success to evaluate concepts and technologies is a sector wide challenge that has been the focus of several workshops and bodies of work (WES, 2016b; WES, 2016c; Sandia, 2017a). Traditionally used measures of success have proven to be insufficient when used by investors and funding bodies to identify the best technologies. A scoring method was developed that can be used to indicate the attractiveness of current technology and the achievability of improvements required to reach the end development goal (target return on investment). This acknowledges that current technology has been unable to provide the required cost of energy and that time and resources are limited for achieving that goal.

When combined together, the various components of the tool provides a means to search the parameter space by explicitly linking changes in input parameter value to the scores used to indicate likelihood of success. The tool can then be used identify areas of the parameter space that should be investigated further and areas of the parameter space that should be ruled out.

1.4 Thesis Overview

The remainder of the thesis is divided into six chapters. The following descriptions provide an overview of the chapter content.

Chapter 2: Review: Tools and Metrics for Structured Innovation.
This chapter provides the review of the literature that was conducted to ascertain the best approach for creating the concept generation and evaluation tool. The chapter is split into two parts. Firstly, tools are reviewed that are employed in more established sectors to guide the innovation process. Secondly, metrics are reviewed that have been used to evaluate alternative wave energy technologies. The chapter ends with a summary and conclusions.

Chapter 3: Methodology
This chapter presents the top-level description of the proposed concept generation and evaluation tool. The chapter describes the main tool components and processes: generation of the input scenario, evaluation of the scenario in the techno-economic model, calculation of the 'commercial attractiveness' and 'technical achievability' scores and the setting of thresholds used to identify promising concepts.

Chapter 4: Resource Module
This chapter described the development of the resource module and the methods used to find two 'Resource Estimating Relationships' (RER). The RERs are used by the module to generate required resource characteristics from a small subset of high-level parameters. The method provides flexible and generic resource data to use in the calculation of LCoE.

The chapter starts with a review of literature regarding the inter-dependence of WEC design and available resource, and concludes with results from an investigation into the impact of increasing site power level on key drivers of cost and performance.

Chapter 5: Performance, Initial Cost and Reliability Modules
This chapter describes the development of the performance, initial cost and reliability modules of the LCoE model. An overview is given of the WEC evaluation process

and how methods were adapted to provide flexibility at low TRL. In the performance module a generic power matrix is built in several steps, in the initial cost module, parametric models are used to evaluate each cost centre and in the reliability module a simple stochastic module is used to model preventative and corrective maintenance activity.

The chapter starts with a review of literature regarding methods for low TRL cost estimation and concludes with results from an investigation into the impact of increasing site power level and WEC scale on LCoE. A sensitivity analysis of the input deployment parameters is also provided.

Chapter 6: Results and Discussion: Promising Scenarios

This chapter explores the final part of the concept generation and evaluation tool: evaluating scores and using thresholds to identify promising WEC concepts. Results are presented from two investigations. The first explores parameters relating to technology improvement including cost and efficiency. The second explores whether combinations of WEC and deployment parameters can deliver a WEC that has the potential to be cost-competitive. This concludes with a discussion on the degree to which the aims have been met for developing the concept generation and evaluation tool.

Chapter 7: Conclusions and Further Work

This chapter provides a summary of the main conclusions and an overview of potential areas for further work.

2. Review: Tools and Metrics for Structured Innovation

The focus for the PhD was the development of a concept generation and evaluation tool that can be used scan the parameter space and identify promising concepts worthy of further development. This chapter provides an overview of tools and metrics that were reviewed to identify the best approach for the tool.

For the wave energy sector, more efficient navigation of the design space is key to achieving commercialisation and structured innovation can help to direct stakeholders by prompting objective and informed design decisions (see section 1.2). The absence of structure, in particular the absence of robust performance assessment at the earliest stages of development, has led to a wide variety of designs and a lack of sector consensus (Weber, 2012). Identifying concepts with the best potential and prompting changes before design fundamentals are cemented, reduces the risk associated with developing a technology.

However, quantifying and evaluating 'likelihood of success' is not easy. Traditionally used metrics have proven to be insufficient when used by investors to identify the best technologies and finding an alternative approach has been the the focus of several workshops and bodies of work (WES, 2016b; WES, 2016c; Sandia, 2017a).

One challenge is that consideration is needed of the full set of factors that influence economic ability, which are often referred to as the 'ilities' (fig. 2.1). These factors should influence design decisions throughout the development process to ensure a commercially ready technology (WES, 2016c), however, some are easier to interpret than others in early design. For example, 'manafacturability' could inform the choice of scale or type of material, whereas 'acceptability', is more challenging to incorporate until there is a better understanding of deployment context.

A further complexity is that consideration of these factors can lead to multiple and contradictory criteria for good WEC design. Consequently, a metric to indicate 'likelihood of success' should consider the net value of a design (e.g. section 2.1.1).

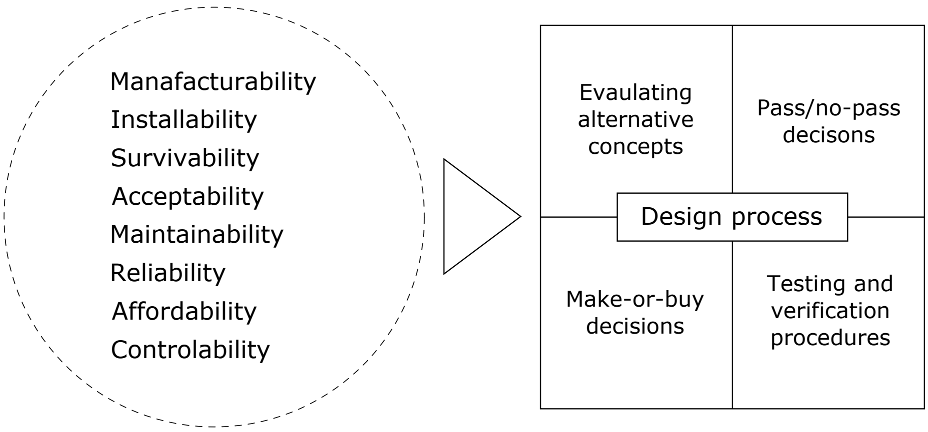


Figure 2.1: The 'ilities' that influence wave energy design (based on (WES, 2016c)).

The rest of this chapter is split into the following four sections.

- ▷ In section 2.1, an overview is provided of structured innovation tools that are used in other sectors to help deal with the complexity of finding solutions and managing design decisions.
- ▷ In section 2.2, metrics are reviewed that have been used to evaluate WEC designs and that could be used as part of a value-centric approach.
- ▷ Section 2.3 follows with a summary of the reviewed tools and metrics and a discussion on their applicability to the concept generation and evaluation tool.
- ▷ Section 2.4 ends the chapter with the conclusions that were used to dictate the approach that was chosen.

2.1 Tools

This section describes three common tools used for managing complexity in engineering design: The systems engineering approach, Theory of Inventive Problem Solving (TRIZ) and value-centric design.

2.1.1 Systems Engineering

Systems engineering is used to deal with the complexity of designing a subsystem according to the requirements of the overall system (Stevens et al., 1998). Independent optimisation of a subsystem according to its primary function can result in a system that is sub-optimal overall. For example, whilst a WEC fundamentally needs to capture lot of energy it also need to survive in the sea. Optimisation to increase energy capture will also result in the transfer of higher loads and increase the likelihood of failure. Managing both these factors will help to create the optimal WEC overall.

Central to the systems engineering approach is the decomposition of stakeholder needs into functional requirements and sub-requirements. Design development is then driven by the fulfilment of the requirements. As stakeholder needs are often high-level and wide ranging, a holistic and interdisciplinary approach is required for this decomposition. For a system where there is competition between requirements, a net satisfaction, adequate for all stakeholders is the end goal of the development process.

According to Moody et al. (1997) the typical components of systems engineering are:

- ▷ Understanding of stakeholder needs and stating the problem,
- ▷ Discovering system and subsystem requirements,
- ▷ Defining quantitative measures and validating thresholds,
- ▷ Prescribing testing regimes.

As part of this decomposition a complete analysis of all the processes across the lifetime of the system is needed. An example of the systems engineering approach applied to wave energy is given in table 2.1. This is from work conducted in the US as part of a

Table 2.1: Required capabilities of a commercial grid-scale WEC array (Sandia, 2017a).

C#: Capability   C#.#: Sub-Capability
C1: Have market-competitive cost of energy.
C1.1: Have as low capital expenditure as possible.
C1.2: Have as low operational expenditure as possible.
C1.3: Generate large amounts of electricity.
C1.4: Have high availability.
C1.5: Have a low financing rate.
C1.6: Have a low insurance rate.
C2: Provide a secure investment opportunity.
C2.1: Low uncertainty on costs and revenues.
C2.2: Survivable.
C3: Be reliable for grid operations.
C3.1: Be forecastable.
C3.2: Have high correlation of power production to demand.
C3.3: Be useful to the grid.
C3.4: Be grid compliant.
C4: Benefit society.
C4.1: Be beneficial to local communities.
C4.2: Be a low greenhouse gas emission energy source.
C4.3: Be a low polluting energy source.
C4.4: Have minimal impact on taxpayers.
C4.5: Contribute significantly to energy security.
C5: Be acceptable to permitting and certification.
C5.1: Be environmentally acceptable.
C5.2: Be acceptable to other users of the area.
C6: Be safe.
C7: Be globally deployable.

partnership between the National Renewable Energy Laboratory and Sandia National Laboratories (Sandia, 2017a). The work provides a decomposition of 'capabilities' that are desired for a grid-scale WEC array.

This provides a capabilities framework that could potentially be used to rule out concepts at an early stage. However, in practice many of the capabilities are not demonstrable until the higher TRL levels when both the technology and application are better understood. The process appears more suited to decisions on already ready technologies and optimisation rather than early design decisions and concept generation. In other words, the technology has to be proven against a few of these capabilities (e.g. low cost and high energy capture) before others can be applied. Furthermore, the translation of these capabilities into measurable technical parameters, which can be used to validate a technology, is subjective.

2.1.2 TRIZ

TRIZ or the 'Theory of Inventive Problem Solving' offers a set of tools for generating solutions to a problem that were developed through an analysis of patents (Haines-Gadd, 2016). The theory is based on the principle that there is uniformity in the fundamental problems faced by a designers across many disciplines and as a result every problem can be solved using a limited number of solutions.

Figure 2.2 illustrates the TRIZ methodology. The first step is to translate the specific problem into more general engineering problems that the TRIZ tools can be applied to.

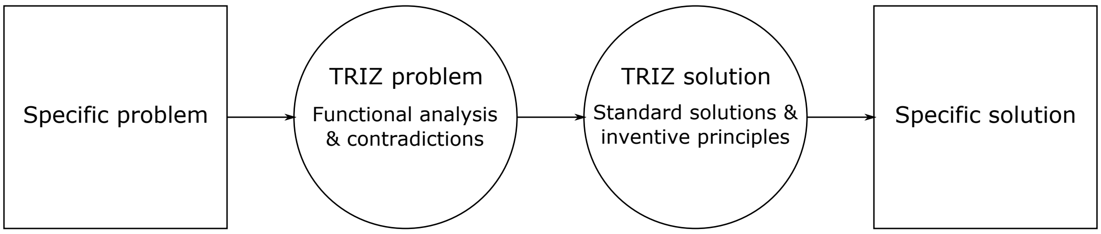


Figure 2.2: The TRIZ methodology for finding solutions (Haines-Gadd, 2016)

The contradiction matrix is one of the first tools used as part of methodology and also the most popular (Spreafico et al., 2016). A contradiction is where an improvement in one feature of a design leads to a worsening of another. The rows and columns of the matrix both relate to the same list of 39 technical parameters. Each cell is used represent a possible contradiction between those parameters where the rows are the improving technical parameters and the columns are the worsening technical parameters as a consequence. Contained with each cell is several possible solutions that are taken from a list of 40 inventive principles.

The previous example given of a contradiction in wave energy design was between energy capture and survivability. The parameters of the contradiction matrix are more general, for example surface area and stiffness. A large surface area of the primary moving competent is needed to increase the WEC-wave interaction to capture more energy. However, this is typically at the expense of structural stiffness. The contradiction matrix points to four typical solutions: *'dynamics'*, *'spherical'*, *'composites'* and *'local quality'*.

The next step is to translate the TRIZ solutions into specific solutions for the WEC. Suggestions for which are shown in table 2.2 and are based on examples given in Haines-Gadd (2016).

Table 2.2: TRIZ solutions for the surface area versus strength contradiction and translation into possible WEC solutions.

Contradiction: surface area versus strength

TRIZ solutions	Possible specific solutions
Dynamics	Use of flexible rather than rigid materials or the use of multiple hulls and the relative motion between them to increase the effective surface area.
Spherical	Use of curvature in the hull design to increase surface area whilst keeping structural integrity.
Composites	Composite materials are employed in the wind industry to construct very large wind turbine blades that are both stiff and light.
Local quality	Hull shapes with large surface areas on only some planes, such as cones, or the use of stronger materials or reinforcements in the weakest parts of the hull.

The TRIZ tools offer a shortcut to finding innovative new solutions by utilising proven knowledge. However, these solutions are abstract and open to interpretation. Skill is required to translate them into actual engineering design, along with a high level of knowledge of the technology in question. To remove subjectivity, TRIZ can be performed by a team of people.

Although many solutions can be generated in this way the thought process is not easily replicated as a model. It also does not provide a means to actually evaluate design merit and not all of the solutions generated will be feasible as commercial product (Spreafico et al., 2016). Therefore, TRIZ (on its own) is perhaps too broad for identifying promising concepts at the early design stages, becoming more useful with further definition of the design problem (especially for a problem as complex as cost-competitive wave energy extraction).

Instead, TRIZ tends to be employed for finding solutions to specific design problems and to help optimise with respect to a specific requirement (for example, one of the capabilities listed in table 2.1). Spreafico et al. (2016) provides an expansive review of the literature on TRIZ implementation. The study finds that in only 12 % of cases was TRIZ used for innovating. In the remaining cases it was used for the improvement of a specific quality of an existing design. 2 % cases were specifically for cost reduction.

The TRIZ methodology refers to increasing system 'ideality', defined as the ratio of benefits to costs and harms (Haines-Gadd, 2016), as the aim of the process. However, the quantification of this will vary according to the system in question. For this purpose, TRIZ is sometimes combined with more value focused methodologies such as Quality Function Deployment (QFD) and Failure Mode and Effects Analysis (FMEA) (Yamashina et al., 2002; Regazzoni et al., 2011).

2.1.3 Value-Centric Design

Value-centric design is where design decisions are made on the basis of adding measurable value. In other words, added value is at the heart of the development process rather than being considered implicit. The use of a common quantitative scale means that the design space is more easily mapped and this offers an efficient means for understanding the net benefit (or cost) of making design changes. Generally, the metric chosen to represent value is a relative measure and not necessarily intended to provide an absolute quantification.

The biggest challenge is choosing a method for quantifying value that resonates with stakeholders and conforms to their own interpretation. It is therefore complimentary to a systems engineering approach, as value can be used to represent the overall satisfaction of stakeholder needs. An added benefit is that, where there are several needs and requirements, stakeholder preference and prioritisation can easily be included into the value calculation.

A quantitative approach can help to deal with contradictions arising from these requirements by representing them as trade-offs in the calculation of a net design value. For example, the increased profit on an investment might unavoidably mean there is also an increased risk. Therefore, the value of that investment to a stakeholder depends on the ratio of preference for profit and preference for risk. Consequently, models of value can be a good way of simplifying multi-objective decision making and for finding design optimums.

This differs from the TRIZ thinking that suggests contradictions can be avoided by implementing existing inventive principles. However, as discussed, not all TRIZ solutions are feasible, and some contradictions have to be accepted as inherent to the design problem.

Figure 2.3 has been taken from Papageorgiou et al. (2016), and describes how a value model could be used to efficiently generate and improve concepts during a creative phase and a decision phase. The creative phase involves experimentation with design variables to create a concept. The value model is then used to inform the decision phase by assessing the concept on a set of desirable attributes.

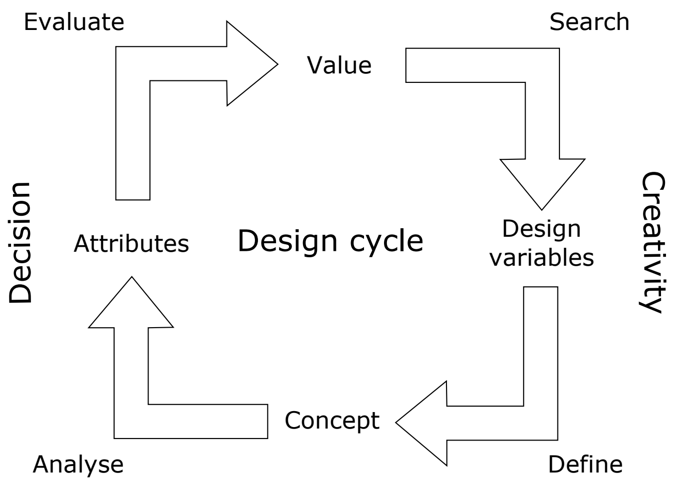


Figure 2.3: The value-centric design cycle (Papageorgiou et al., 2016).

For representing value, all metrics will have inherent limitations and disadvantages. Ross et al. (2010) discusses the use of cost-based metrics and qualitative-preference based metrics (Multi-Attribute Utility Theory) in the design of spacecraft for two different functions: telecommunication and deep space exploration. Spacecraft design is a special case in that budgets tend to be very large and little or no revenue can be expected. Resultantly, non-monetary attributes make up a greater proportion of the benefits that are assessed. For example, this includes proxies such as number of published articles as a product of data collection to represent the productivity of the space mission. Therefore, the cost based metrics are shown to be poor indicators of value due to the challenge of monetising certain attributes.

Whichever the approach, key to understanding the implication of a change in design is consistency in the calculation of value and the credibility of any assumptions that are used.

2.2 Metrics

Each of the three reviewed tools requires a quantification of design value to indicate success. For systems engineering this is the net fulfilment of stakeholder needs, for TRIZ the aim is to improve 'ideality' and for a value-centric approach such metrics are used to direct design choices.

The aim of finding concepts that add value is uncontroversial, however, the best choice of metrics to represent value is the topic of debate within the sector (e.g. WES, 2016b; WES, 2016c). A robust method for quantifying 'likelihood of success' would enable the objective identification of the best concepts at the initial development phase. This is particularly challenging due to existing pre-conceptions for the best WEC designs, and the non-agreement within the sector which has resulted in a wide variety of technology types.

In this section, five methods are discussed which could be used to evaluate concepts:

1. Technology Performance Levels (TPLs),

2. Value functions,
3. LCoE,
4. the ACE metric
5. and ratios of risk to reward.

Another approach that is commonly used in the energy sector, but which is not explored here, is Cost Benefit Analysis (CBA). CBA is similar to both TPL and value functions in that it includes non-monetary benefits and costs that are relevant to the full set of stakeholder needs and not just returns on investment (Ross et al., 2010). However, these are converted to monetary values and then discounted across the lifetime of the project similar to the calculation of LCoE. CBA is likely to be more suited to the later stages of project development and for policy based decision making as it can be used to include wider-view benefits such as job creation. A similar metric is used in Stallard et al. (2008) for assessing the efficacy of large-scale wave power schemes. The metric is a ratio of desired outputs to required inputs and the study focuses in particular on infrastructure inputs.

2.2.1 Technology Performance Levels

TPL are based on the systems engineering philosophy and were developed as a complementary metric to the TRL. The definition and difference between TRL and TPL is given in Table 2.3. The TPL scale allow for the requirements of a commercial, grid connected, WEC array to be included in the assessment of development progress.

Table 2.3: Definition of TRL and TPL from Weber (2012)

	TRL	TPL
Defines...	How ready a technology is.	How well a technology performs.
Relates to...	Commercial ability.	Economic ability.

The aim of the TPL scale is to ensure that techno-economic performance does not lag behind commercial readiness. In Weber (2012), development trajectories are described using a TPL-TRL matrix (fig. 2.4). The most cost and time efficient trajectories focus on performance improvements rather than upscaling and significant design changes are made at low TRL. Conversely, the least efficient trajectories focus on upscaling, resulting in a need for costly design changes at high TRL.

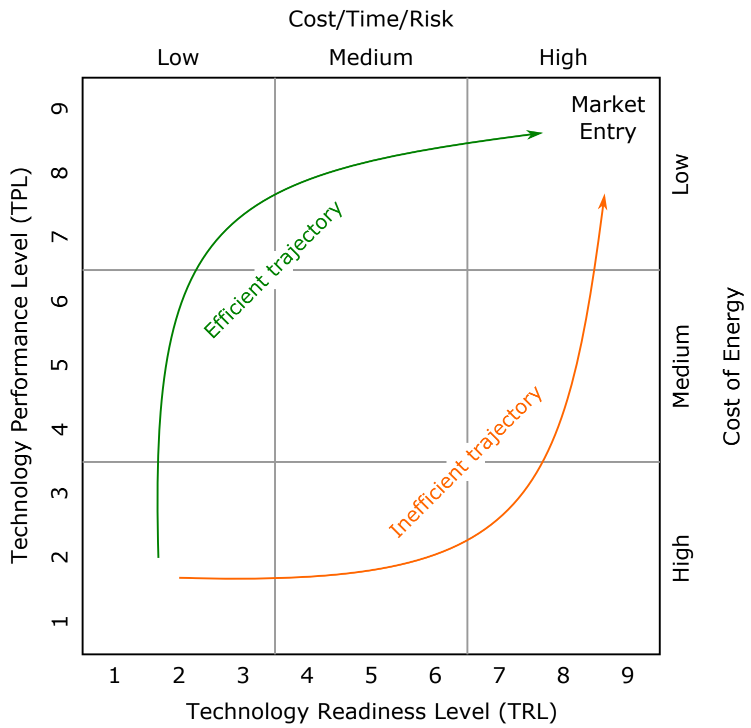


Figure 2.4: The TPL versus TRL matrix from (Weber, 2012). Increasing TPL before increasing TRL leads to a more investment-efficient trajectory for development.

Sandia National Laboratories have recently put forward a detailed methodology for TPL assessment (Sandia, 2017b). The TPL score is based on the fulfilment of the capabilities listed in table 2.1. According to the methodology, these capabilities are customer focused rather than technically focused so that achieving a high TPL score indicates that a technology is likely to be adopted by the targeted market.

Against each capability a WEC is scored as ‘high’, ‘medium’ or ‘low’ according to whether it meets certain criteria. This is then converted into a quantitative score and aggregated using a series of weightings that are based on the judgement of the authors. The criteria are a mixture of both qualitative and quantitative indicators tailored for different TRL levels.

Deficiencies of the metric are the large amount of information required and the difficulty in assessing the more holistic capabilities for which there is limited existing experience within the sector. For example, the capability C.4.1 ‘Be beneficial to local communities’ is scored at TRL 1-2 according to how many jobs a farm will contribute. This would not only be difficult to determine at low TRL, but is contextually dependent, requiring a good knowledge of specific deployment scenarios.

The weightings used for aggregating the total scores are particularly subjective. These indicate the relative importance of the capabilities and were chosen by the creators of the TPL. Furthermore, the lack of familiarity for developers might lead to an unwillingness to adopt TPL as a guide for developing their technology. The metric is more useful for a funding body wishing to compare WECs and some of the issues could be addressed through consistent and transparent evaluation by independent assessors.

2.2.2 The Value Function Method

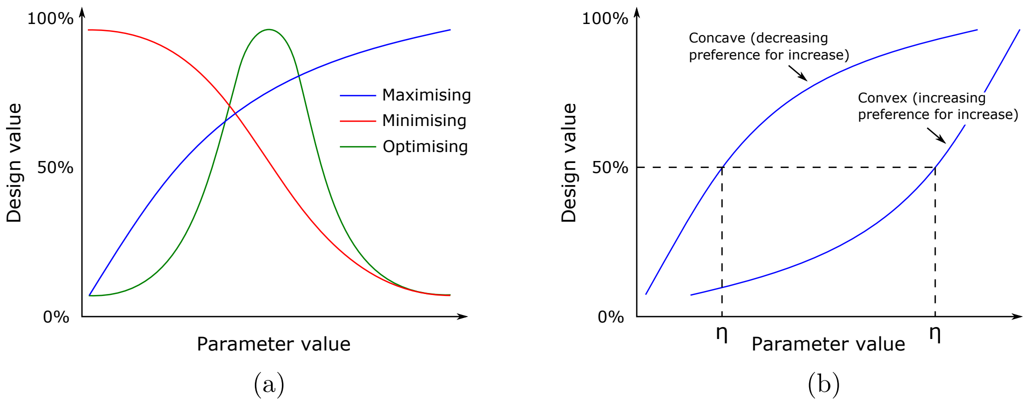


Figure 2.5: Net design value versus individual parameter value: types of value, describing how a change in a parameter value affects the net value of the overall design. η indicates the neutral parameter value equating to a net value of 50 %.

The value of a design can be measured in terms of how well it satisfies certain design requirement and value functions can be used to investigate how added value can be achieved. They are used to describe the relationship between design parameters and design requirements and are based on the perception of stakeholders rather than empirically derived.

Figure 2.5a shows three different types of value function. A value function is maximising if an incremental increase in parameter value increases the satisfaction of the design requirement, minimising if an incremental decrease in parameter value increases the satisfaction of the design requirement or optimising it there is an optimal parameter value in terms of satisfying the design requirement.

For example, a requirement for a good WEC design is to capture lots of energy and a parameter to describe a WEC could be its scale. Increasing the scale, increases the satisfaction of the energy capture requirement and resultantly the design value (maximising). However, certain parameters might have one type of relationship with one requirement and a different type of relationship with another. For example, if another requirement is low cost, for which an increase in scale has a negative effect (minimising), then any change in design value will depend on the relative importance of the one requirement over the other.

Combining multiple value functions creates a value model that can be used to provide a net design-value score. Typically, magnitude or weighting of each value function is dependent on the preference of stakeholders. For instance, if the satisfaction of a requirement is perceived to be more important than the satisfaction of another, then the contribution of that requirement to the net design value score will be greater.

This score is a relative measure, and a neutral set of parameter values is required in its calculation. These neutral values could be used to represent current technology and the value model is typically designed such that the neutral values provide a net value score of 50 %. Therefore, any changes to design parameters that result in a score of >50 % indicate an improvement on current technology. Appendix B provides a simple example of a value model for application to WEC design, which is based on the example for an aircraft given by Eres et al. (2014).

More complex functions can be used to provide further dexterity (e.g. Papageorgiou et al., 2016; Downen et al., 2005). For instance, value functions can be used to model preferences that change with parameter value. In fig. 2.5b two shapes of maximising function are shown, concave and convex. For a maximising convex function, there is an increasing preference from stakeholders for increasing the value of the parameter in order to increase the satisfaction of a certain requirement. At the same time there is an increasing willingness to do so at the expense of other requirements. Concave functions are used to model the opposite relationship.

Value functions and models offer a means to turn qualitative perceptions of design value into a quantitative score and can be used to explore the parameter space. Whilst the score allows a relative comparison, it is dimensionless and does not allow for any statistical analysis. Furthermore, its abstract meaning can be difficult to interpret if the method for its calculation is not understood.

Other disadvantages of the approach include the need for extensive interaction with stakeholders and a reliance on the quality of the responses to this interaction (Papageorgiou et al., 2016). However, established methods for aggregating stakeholder preferences can be used to reduce subjectivity. In Papageorgiou et al. (2016), an Analytic Hierarchy Process is used to rank stakeholder needs and to provides a score for the consistency of their responses. The study uses value functions to create a model for identifying the best architectures for a surveillance drone from a multi-stakeholder and multi-objective perspective.

2.2.3 Levelised Cost of Energy

LCoE is the ratio of lifetime expenditures to lifetime outputs when converted to their present value. It has been the most widely used metric for reporting the economic performance of WECs in common with the reporting with other energy generating technologies (e.g. IRENA, 2017). Another function of the LCoE is for indicating the selling price of electricity required for a project to break even.

The LCoE is calculated by adjusting lifetime costs and energy outputs to Present Value (PV). For a renewable energy technology, where their are no associated fuel costs, the following formula is used:

$$\text{LCoE} = \frac{\text{PV(Costs)}}{\text{PV(Output)}} = \frac{\sum_t^{t_\text{life}} (C_\text{cap}(t) + C_\text{op}(t))/(1+r)^t}{\sum_t^{t_\text{life}} E(t)/(1+r)^t} \qquad [£/\text{kWh}] \quad (2.1)$$

Where:

- ▷ C_cap is the Capital Expenditure (CapEx) in year t [£],
- ▷ C_op is the Operational Expenditure (OpEx) in year t [£],
- ▷ E is the Annual Energy Production (AEP) in year t [kW h],
- ▷ r is the discount rate,
- ▷ t_life is the project lifetime [a].

Reliability of using LCoE for the assessment of economic performance relies on consistent assumptions and a confidence that the uncertainty does not effect the meaning of the results. Key assumptions include the project lifetime and the discount rate, which is used to adjust costs and outputs to their present value equivalent by taking into account depreciation.

The magnitude of the discount rate is based on the perceived risk of the project and therefore requires a prediction of the future target market. Values in the literature range from 5 % (Dalton et al., 2009) to 15 % (de Andrés et al., 2017a). Generally, lower discount rates have been used when considering commercial deployment for large multi-megawatt farms whilst higher discount rates have been used for modelling so called 'first-of-their-kind' projects, reflecting the level of project risk. Some authors suggest that a discount rate of 10 % is representative of the transition between this initial and commercial deployment (Farrell et al., 2014; Guanche et al., 2014). Project lifetimes are typically modelled as 15 (e.g. O'Connor et al., 2013b) to 25 years (e.g de Andrés et al., 2017b).

A disadvantage of metrics which use discounting, such as LCoE, is the issue of truncation (Ross et al., 2010). The choice of discount rate and project lifetime affects the weighting of future events in the calculation of LCoE. For example, the lower the discount rate and the longer the lifetime, the more important factors that affect AEP and OpEx reliability become. Information from operational experience is typically unavailable at low TRL so a higher discount rate can be used to lessen this uncertainty. On the other hand, final LCoE values are very sensitive to discount rate. According to (Allan et al., 2010) a 10 % increase in discount rate results in a >0.10 £/kWh increase in LCoE.

The large amount of information that is required for calculating LCoE reliably, means that many studies advise caution for using any absolute values and instead focus on comparative LCoE analysis. For the 20 plus techno-economic studies that were reviewed as part of this work, analysis focused on six main variables, which included WEC scale and resource level (fig. 2.6).

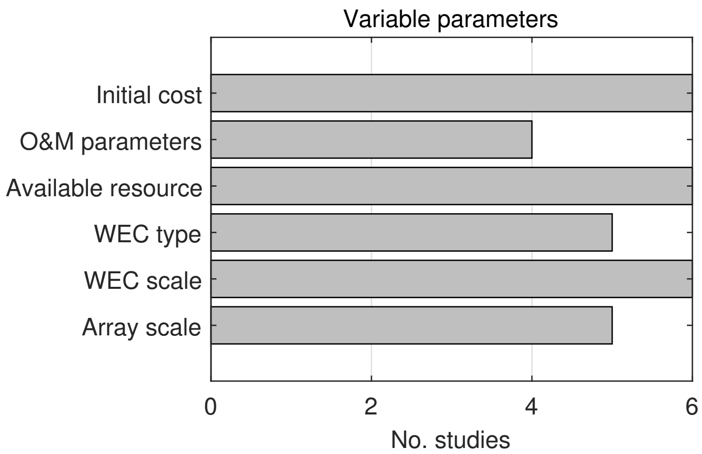


Figure 2.6: Reviewed techno-economic studies grouped according to topic area/main variable parameters. References given in appendix C.

Table 2.4 shows some of the LCoE values presented in the literature for certain WEC types, locations and array scales. Many of the studies before 2015 predicted LCoE values for the commercial deployment of the Pelamis WEC that was considered the leader in wave energy technology at the time. Estimates vary from 0.05 €/kWh to 0.69 €/kWh with a high degree of variability that could influence future investment decisions. A lack of consistency in the cost modelling method accounts for much of this variability and some common assumptions have a large impact on final LCoE (Topper et al., 2019).

In particular, LCoE is very sensitive to the learning rate parameter, which is used to account for cost reduction as a result of technological change and economies of scale

Table 2.4: Summary of LCoE estimates from the literature. Ranges represent the minimum and maximum values reported. Taken from Farrell et al. (2014) with additional sources added. Conversion to Euros is in year of publication.

Study	LCoE €/kWh	Array Scale	Location
Topper et al. (2019)	0.69	100 WECs[1]	California
ARUP (2018)	0.19	100 WECs[2]	Scotland
de Andrés et al. (2016)	0.30 - 0.68	20 MW[3]	Scotland
Farrell et al. (2014)	0.29	100 WECs[4]	Ireland
Sandia (2014)	0.62	100 WECs[2]	California
O'Connor et al. (2013b)	0.21 - 0.26	100 WECs[4]	Ireland
O'Connor et al. (2013a)	0.21	100 WECs[4]	Ireland
Teillant et al. (2012)	0.21	100 WECs[5]	Ireland
Carbon Trust (2011)	0.43 - 0.55	10 MW[5]	UK
Archetti et al. (2011)	0.64	28 WECs[4]	Italy
Allan et al. (2010)	0.22	Unspecified[4]	Scotland
Dalton et al. (2009) [2004/2008]	0.05/0.15	100 WECs[4]	Ireland
Dunnett et al. (2009)	0.16 - 0.28	15-27 WECs[4]	Canada
EPRI (2005)	0.06 - 0.12	44 WECs[4]	California
Previsic (2004)	0.07 - 0.14	213 WECs[4]	California

[1] Reference Model 3 (RM3) WEC
[2] Heave buoy type
[3] CorPower WEC
[4] Pelamis WEC
[5] Unspecified

(explained further in appendix D). Consequently, it is a key parameter for providing attractive returns on investment (e.g. Farrell et al., 2014; Guanche et al., 2014).

Finally, the dependence of the LCoE results on site data and deployment scenario, can be considered both an advantage and disadvantage. The inclusion of these parameters means that predictions are more realistic and it allows for the comparison of locations and WECs in those locations (see chapter 4). However, the studies listed in table 2.4 show that the LCoE result is very sensitive to these parameters and consequently the absolute values are not directly comparable.

At low-TRL a number of different locations and deployment scenarios need to be investigated, assuming multiple sets of data are available. This will then provide insight into WEC design versatility and the impact of resource on WEC attractiveness.

2.2.4 The ACE metric

The Average Climate Capture Width per Characteristic Capital Expenditure (ACE) metric was a LCoE proxy metric, specifically for evaluating WEC prototypes at low TRL. It was developed for the Wave Energy Prize (see section 1.2).

It was calculated as the equally-weighted ratio of performance to cost and contained the most fundamental components of LCoE (Jenne et al., 2017). Performance was defined by an average value for adsorption efficiency (specifically the capture width) and cost was defined by a 'characteristic capital expenditure', an approximation of the primary structure cost. Therefore, the main assumption was that WEC design value is primarily driven by hydrodynamic performance and structural cost.

The approach to calculating the characteristic capital expenditure was the most novel aspect of the metric, given by the formula:

$$C_{\text{total}} = \Sigma_i \cdot A_i \cdot l_i \cdot \rho_{\text{mat}_i} \cdot c_{\text{mat}_i} \qquad [£] \quad (2.2)$$

Where for component i:

- ▷ A is the representative surface area [m^2],
- ▷ L is the representative structural thickness [m],
- ▷ ρ_{mat} is the material density [kg/m^3],
- ▷ c_{mat} is the cost of the fabricated material [£/kg].

This was designed to provide an equitable measure of cost at low TRL to account for the variation in detail of cost analysis by developers. The key parameters, representative surface area and representative structural thickness, were based on simplified profiles of the main components involved directly in energy capture. The latter was not a physical measurable thickness but used to provide a volume of material when combined with the former. It was calculated from numerical simulations or based on loading observations made during tank testing. These parameters provided the flexibility for easily assessing different WEC geometries and materials.

Criticisms of the ACE metric include the subjective nature by which cost parameters are determined and that it does not include many of the important factors which affect cost of energy. Using the ACE metric places a greater importance on CapEx, represented solely by structure costs, in comparison to using LCoE.

The over simplicity also means that it has a limited functionality for searching the design space, with a focus mainly on WEC scale and material type. The focus of the ACE metric on the primary structure means that the best performing concept is a single component floating sphere that is structurally strong, requires a low mass and also has a large area interacting with the waves.

Furthermore, the calculation of the ACE metric is unfamiliar to developers, and it is difficult to understand the scale of absolute ACE scores. Using a number assumptions it is possible to determine equivalent LCoE. Following the methodology outlined in (de Andrés et al., 2017b), the equivalent ACE score for a WEC in a 10 MW array with an LCoE of 0.15 £/kWh is approximately 8.7 m/M£[1]. The eligibility criteria at the end of the Wave Energy Prize (to be considered for continued funding) was a minimum ACE threshold of 3 m/M$. If using the same assumptions before, the equivalent LCoE is approximately 0.33 £/kWh[2].

Other Proxy Metrics

A number of simpler performance to cost proxies are described in the numerical benchmarking study conducted by Babarit (2017). Annual absorbed power (AAP) per characteristic mass, AAP per surface area and AAP per power take-off force are used to compare eight WEC types. Each metric produces a different 'winning' WEC type, highlighting the difficulty in choosing a single variable to represent cost.

The exact relationship between each of these metrics and the LCoE is dependent on resource (de Andrés et al., 2016). Metrics that use mass as a proxy for cost (such as the ACE metric) provide a better indication of LCoE than metrics that use surface

[1]Assuming an annual O&M cost of 5 % CapEx, primary structure accounting for 42 % of CapEx and other losses amount to a 70 % reduction in annual energy production.

[2]When converted to $£_{2019}$.

area (de Andrés et al., 2016). Partly, this is because a good hydrodynamic efficiency does not mean a good cost efficiency.

2.2.5 Risk to Reward Ratios

The overall design value can be a function of both the potential reward offered by a concept and risk associated with achieving it. Table 2.5 is taken from a cost estimating handbook for shipbuilding (NAVSEA, 2005) and defines several types of risk. The challenge for quantitatively representing risk is deciding which types of risk to include and how to measure them. In general, representations of risk aim to quantify the likelihood of events occurring as predicted, along with the severity of any potential consequences. However, the most applicable types of risk and the level of detail that is included will depend on TRL.

Table 2.5: Types of risk (NAVSEA, 2005).

Risk type	Definition
Cost risk	Uncertainty resulting from the use of a particular cost estimating methodology.
Technical performance risk	Uncertainty in the system performance, associated with system requirements, planning or operations.
Project schedule risk	Uncertainty in the project completion or schedule and the subsequent impact on costs and level of benefits.
Integration complexity risk	Risks associated with integration, including software requirements, data dependencies and the number of interfaces.
Market risk	Risks associated with the stability of the market.

Studies of wave energy have typically concentrated on cost risk and the uncertainty surrounding techno-economic assessment (e.g. Topper et al., 2019; Guanche et al., 2014; Farrell et al., 2014; Teillant et al., 2012). In this case risk is described by the likelihood of achieving the predicted economic performance. Stochastic modelling and Monte-Carlo methods can be used to evaluate a range of possible outcomes and to provide an understanding of how input-parameter uncertainty effects financial returns (e.g. Topper et al., 2019; Guanche et al., 2014; Teillant et al., 2012). One method for quantifying this is to use the 'Value at Risk' metric (Farrell et al., 2014), which can be used to calculate the price premium needed for wave energy to guarantee a return on investment.

An important risk to consider for the development of a new technology is the risk of achieving the development goals within a given time-frame (a form of project schedule risk). For example the time frame set by a funding programme aiming to deliver a commercial technology. However, only a few studies have used this type of risk to identify technologies worthy of further investigation.

Hutcheson et al. (2016) proposes a lengthy but methodical approach for this that uses a ratio of risk to reward. The risk is based on design difficulty and requirement for resources and reward is the LCoE. The approach is based on work by Moody et al. (1997) that categorised innovative engineering designs according to how easy they were to achieve.

Design difficulty is scored against a number of questions including: how well established is the technology? and how efficiently does the technology perform its prime function? A criticism is therefore that it mixes both achievability and current ability to provide good economic performance. A score of one to three is applied to each technology for each question and then summed together. This approach is highly subjective; in this case, much of the justification for the scores focuses on whether technologies are tried and tested and the availability of 'off-the-shelf' components.

A simpler and more qualitative example was the approach used in the materials landscaping study conducted by WES (WES, 2016a). A matrix of impact and risk was used to decide which technologies warranted further investigation. The impact score described the potential for the technology to reduce cost of energy and the risk score described the level of R&D needed for its incorporation into a wave energy device.

2.3 Discussion

This chapter provided an overview of tools and metrics that were reviewed to help identify the best approach for the concept generation and evaluation tool. In the first part of this review, three tools were discussed which can be use to manage innovation complexity. A summary of the three tools, along with the challenges of their implementation, is given in table 2.6.

Systems engineering provides a framework of functional requirements that can be used to validate technologies and direct development to help ensure a commercially viable system. However, it is difficult to interpret many of these requirements in initial WEC design and to use them to generate new concepts.

The TRIZ methodology offers a pre-made set of tools, but is best suited to finding solutions to specific problems. It requires a working knowledge of the process to generate workable WEC concepts and a hands-on approach that is difficult to replicate in a model. Furthermore, determining whether generated concepts offer improvement in system 'ideality' is a secondary process. This does not offer a direct route for mapping the parameter space and so cannot easily be used to improve understanding of design changes and their consequences.

A value-centric approach can help to ensure development is on track to achieve certain end goals. The development of a common value scale can then also be used for mapping the parameter space to identify promising concepts. This may be based on the functional requirements decomposition as part of the systems engineering approach (Sandia, 2017a, e.g.). However, mapping the wide variety of systems requirement to a common scale is difficult and, as discussed, many commercial requirements will be intangible at low TRL.

Potentially, such tools could help the sector to avoid some of the failures that were identified from previous wave energy development. Namely, the lack of consideration for the full set of operational requirements, the inability to look beyond preconceived design and simultaneously, a failure to achieve design consensus.

Table 2.6: Summary of the reviewed design methodologies.

Methodology	Used to...	Challenges
Systems Engineering	Create a strategy for incorporating stakeholder needs into development.	Defining a coherent strategy for multi-stakeholder and multi-requirement systems.
	Define requirements of a cost-competitive system and use them to inform sub-system design.	Prioritising requirements objectively and dealing with contradictions.
		Defining measurable technical parameters and validation thresholds appropriate for each TRL.
TRIZ	Encourages thinking based on generalised problem solving that is beyond preconceived design ideas.	Translating TRIZ concepts to workable engineering designs.
	Turn contradictions between technical requirements into improved solutions.	Understanding (and buying in to) the unfamiliar and abstract methodology.
		Measuring system ‘ideality’ and verifying improvement.
Value-Centric	Simplify multi-stakeholder and multi-requirements problems to a common scale of design value.	Finding a suitable method for quantifying design value that meets stakeholder expectations.
	Understand impact of design changes on net value and efficient searches of parameter space.	Aggregating mixtures of monetary cost and benefits and non-monetary cost and benefits.
		Assumption that mapping to a common scale is possible for all factors that influence design value.

In the second part of the review, metrics were discussed which could be used to quantify design value. Tables 2.7 and 2.8 summarises the main advantages of TPL, value functions, LCoE and the ACE metric. Important considerations are the acceptance by stakeholders, suitability for low TRL assessment and ability to indicate likelihood of success. A sufficient metric for assessing technology development risk was not found and so is not included.

The TPL is an attempt to map the full set of system capabilities to a common quantitative scale. It is offered as an alternative to the TRL focused development approach, which prioritises commercialisation over performance. Scores are assigned for each capability and the level of assessment is tailored for each TRL. However, several of the capabilities are intangible at low TRL and the methodology requires extensive detail and a high number of assumptions. The TPL is controlled by the thresholds set for capability and the weightings used to aggregate the individual scores. Therefore, it represents a perceived design value that is indirect from any input design parameters and difficult to replicate in a model.

The value function method was shown as an example of how similar quantitative assessments can be turned into a quantitative value model. A value model allows for a conceptual design space search by providing direct links between design parameters and net value. However, to accurately model stakeholder preference it requires extensive interaction with stakeholders. Furthermore, its abstract representation of value is less likely to be accepted as a means to inform WEC design.

The LCoE has been the most widely used metric for reporting the economic performance of WECs and is familiar to stakeholders. Economic studies of wave energy (table 2.4) have provided an indication of the key drivers that need to be included in the LCoE calculation. Most of these studies analyse the potential of commercial scale wave energy arrays based on available WEC data. An advantage of LCoE is the inclusion of lifecycle parameters that impact on profitability. For instance, this includes operational parameters that can be dependent on the choice of technology and WEC design.

On the other hand, the lack of experience within the wave energy sector makes it difficult to predict future events that are needed in the LCoE calculation. Proxy metrics,

Table 2.7: Advantages and disadvantages of TPL and value functions for a value-centric approach to design and development of WECs.

	Advantages	Disadvantages
TPL	Considers all system attributes that influence commercialisation.	Not all system requirements are tangible at low TRL.
	Helps to reduce performance risk through early identification of system weaknesses.	Requires independent and consistent assessment to reduce subjectivity.
	Represents the aggregation of multiple stakeholder needs.	Lack of transparency regarding choice of weightings and thresholds needed to score each capability.
		Untested on real world applications.
		Difficult to quantify the relationship between design parameters and final TRL score.

	Advantages	Disadvantages
Value function method	Used to combine multiple stakeholder preferences into a quantitative model.	Based on perceived value not the direct measurement of value.
	Established methods exist for aggregating stakeholder preferences.	Complexity of model is limited to the amount of information given by stakeholder elicitation.
	Can include monetary and non-monetary benefits.	Provides a dimensionless and non-ratio score that does not allow for statistical analysis and might not resonate with stakeholders.

Table 2.8: Advantages and disadvantages of the LCoE and ACE metrics for a value-centric approach to design and development of WECs.

	Advantages	Disadvantages
LCoE	Widely used and accepted.	Assumes revenue is only source of value to stakeholders.
	Allows for statistical analysis.	Does not consider non-monetary factors and costs beyond scope of the technology.
	Inclusion of resource and deployment parameters allows for the assessment of design versatility.	Issue of truncation: weighting of future events sensitive to the choice of discount rate and lifetime.
	Includes full-lifecycle costs and performance.	Absolute values are specific to the location and array scale.
	Target value can be established based on current market for renewables.	High uncertainty at low TRL due to lack of experience in sector.
	Advantages	**Disadvantages**
ACE	Retains the LCoE arithmetic whilst removing unknown lifecycle parameters	Assumes that hydrodynamic performance and structural cost are the only important factors in determining cost of energy.
	Equivalent LCoE values can be calculated assuming a certain location and deployment scenario.	Uses representative quantities to approximate cost which are subjective in their calculation.
		As a simplified version of LCoE the analysis of sensitivity to input parameters does not provide much insight.

such as the ACE metric, have been proposed in order to utilise the LCoE arithmetic whilst avoiding lifecycle uncertainties. The ACE metric offer a means for a low-TRL comparison of high-level design details but requires some significant assumptions. In particular, the preferential selection of key variables and their assumed independence from other variables may result in non-meaningful or biased solutions.

For these reasons, it was decided to use a value-centric approach for the concept generation and evaluation tool that was based around LCoE, which remains the most useful metric for indicating likelihood of success.

Whilst it has been argued that purely economic drivers of cost of energy are only a subset of the considerations needed to achieve commercialisation (Weber, 2012), the main focus for the sector should be reducing projected cost of energy. Furthermore, the existing renewables market provides a cost of energy benchmark which can be used as an end development goal. Where the sector has previously used financial metrics these were typically considered implicit to technology development rather than central to design decisions.

The review highlighted a number of challenges for using LCoE in assessing WEC concepts. In particular, few attempts have been made to use LCoE at the initial design stage due to the high uncertainty. However, it was believed that as an output of a consistent techno-economic model, LCoE can be used to compare concepts whilst not necessarily provide accurate absolute values. The work presented in chapter 5 includes methods that were developed with the aim of providing LCoE at low TRL.

Another challenge was deciding which parameters are used to define concepts and as inputs to the calculation of LCoE. The decision requires an assumption that input parameters are mutually independent from another and so can take any value regardless of the value of the other input parameters. This is a typical problem of any metric unless there are constraints. Therefore, a further focus for tool development was on understanding the dependencies between parameters (e.g. a large scale of device requires heavier mooring lines) so that these could be included in the model and so that unlikely input parameter combinations could be avoided (see section 3.1).

Finally, it was decided that as a means to scan the parameter space, LCoE was not particularly insightful on its own. For example, it could simply tell us that the best concepts have low cost and produce a high amount of energy. Therefore, two metrics were required: The LCoE to represent 'commercial attractiveness' and a further metric to represent the feasibility of certain input parameter values being achieved, or the 'technical achievability'. This provides a measure of the risk associated with achieving technology development goals as discussed in section 2.2.5 and its calculation is outlined in section 3.3. It is proposed that the combination of the two metrics can be used to indicate likelihood of concept success.

2.4 Chapter Conclusions

This chapter provided an overview of tools and metrics that were reviewed to help identify the best approach for the concept generation and evaluation tool. Firstly, three tools were discussed that can be used to manage innovation complexity: systems engineering, TRIZ and value-centric design. Secondly metrics were discussed that could be used to quantify design value: TPL, value functions, LCoE and the ACE metric. The key messages from this chapter are as follows:

Although systems engineering is useful for defining functional requirements and ensuring technology development is directed towards stakeholder needs, many of the wider view requirements are difficult to interpret in WEC design at low TRL. The TRIZ methodology, whilst useful as an exercise to encourage 'outside the box' thinking, would be difficult to replicate as a model for independently generating concepts. Instead, it was decided that a value-centric approach was best for the structured innovation tool, to provide a comparison of concepts based on LCoE.

The review highlighted a number of disadvantages for using LCoE, however, it remains the most useful and familiar metric for indicating likelihood of success. In particular, the main focus for the sector is to reduce the projected cost of energy and a LCoE benchmark can be used as an end development goal.

On the other hand, because LCoE has typically been considered implicit to technology development rather than central to design decisions, few attempts have been made to use LCoE at the initial design stage. Therefore, novel methods will be needed to calculate key components of the LCoE equation from the limited amount of information available. Furthermore, as is common within the literature, certainty in absolute values can be avoided to some extent by using LCoE as a comparative indicator whilst ensuring the weighting given to each component is at least reasonable.

Finally, it was also decided that a second metric was required to constrain the value of parameters so that generated concepts would be feasible. The combination of the two proposed metrics can be used to indicate likelihood of concept success: LCoE to represent ‘commercial attractiveness’ and a ‘technical achievability’ metric to provide a measure of technology development risk.

The next chapter provides the methodology for the concept generation and evaluation tool and shows how this approach was implemented, including the method for calculating the commercial attractiveness and technical achievability scores.

3. Methodology

The goal of the research was to develop a structured innovation tool for the concept creation phase of innovation. Components of the proposed 'concept generation and evaluation' tool were built on the Matlab programming software. This chapter provides a top-level overview of the tool and an indication of how the components relate to the three objectives identified with the research question:

- ▷ To develop a flexible method for providing resource and site characteristics.
- ▷ To develop a techno-economic model that can be used at low TRL.
- ▷ To develop a scoring method for indicating likelihood of development success.

Figure 3.1 shows the main components of the tool and stages of the concept generation and evaluation process.

The first stage is the generation of an input scenario. The input scenario contains the value of each deployment parameter and the value of each WEC parameter, which is then input into the techno-economic model. Deployment parameters describe the deployment context and the WEC parameters describe the WEC concept to be evaluated.

The primary function of the tool is achieved by allowing it to run through many iterations, which results in a ranking of each concept and deployment context combination. However, even for a relatively simple set of parameters, scoring every combination can

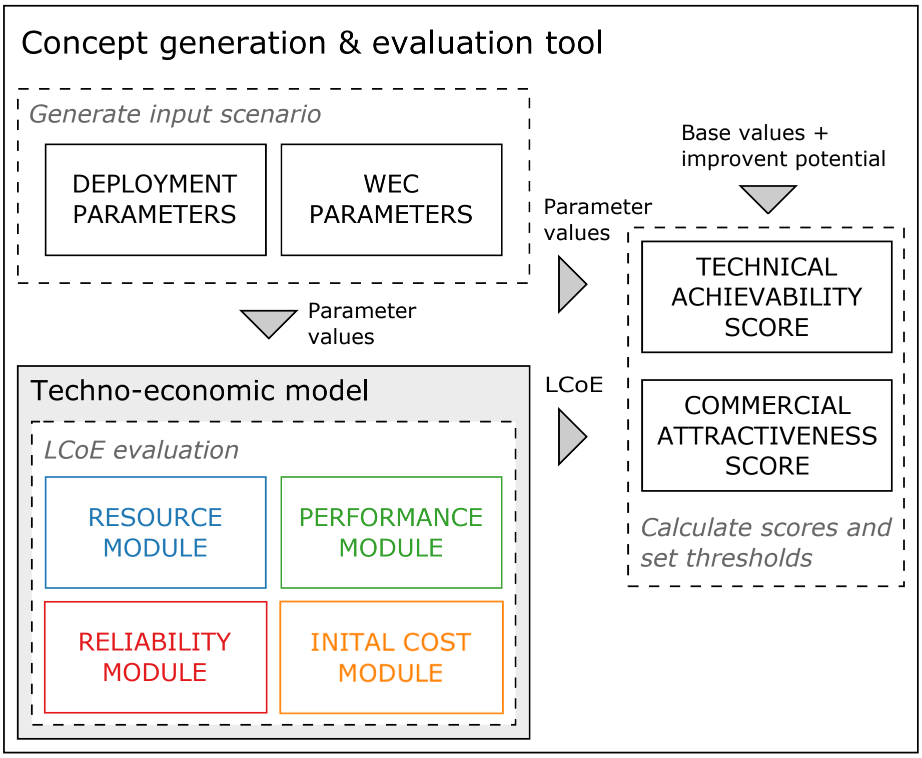


Figure 3.1: The main components and processes of the proposed concept generation and evaluation tool.

become very time consuming if the the number of possible options is very large[1]. For this research, subsets of input parameters were investigated to manage the number of results. The decision on which parameters to include was based around the key components of the LCoE equation (see section 3.3.1).

The second stage is the evaluation of a likely LCoE for the input scenario in the techno-economic model. The development of the model is split into two parts in this thesis. Firstly, development of a resource module that is used to estimate key resource characteristics based on the high-level input deployment parameters. Secondly, the development of performance, initial cost and reliability modules that are used to evaluate power production, capital costs and O&M costs respectively.

[1]For instance, if the number of options for each parameter was the same then the number of possible combinations would be equal to no. options$^{\text{no. parameters}}$

The modules are made up of parametric expressions that were either established through modelling, taken directly from the literature or based on regression of actual data with the aim of creating a continuous map of input values to LCoE.

The final stage is the calculation of two scores for 'Commercial Attractiveness (CA)' and 'Technical Achievability (TA)' and the setting of thresholds to identify promising concepts. The CA score is based on the LCoE value output from the techno-economic model. LCoE was identified as the most appropriate metric for describing the parameter space at this time despite its deficiencies (as discussed in chapter 2).

The TA score is calculated from the difference between the input parameter values and values representative of current technology. The magnitude of the score also depends on the 'improvement potential' level of the technology type. The assessment of improvement potential is subjective but a description of each level is given here which refers to both technology maturity and the amount of active R&D. The TA score is used to indicate feasibility or likelihood of achieving the input scenario.

The following sections of this chapter describe these components in more detail:

- ▷ Section 3.1 provides the deployment and WEC parameters that make up the input scenario.
- ▷ Section 3.2 provides an overview of the four modules, including their main input and outputs.
- ▷ Finally, section 3.3 explains how the two scores are calculated and how thresholds are used to determine the parts of the parameter space worthy of further investigation.

3.1 Input Scenario

Deployment parameters and WEC parameters are used to form the input scenario. The parameters and the range of possible values that they can take, define the limits of the parameter space that can be explored.

There are two types of parameter value: numeric and descriptive. As much as possible, parameters were included that can take a numeric value to allow for investigation beyond current technology and to create a more continuous parameter space. For example, the parameter *maximum conversion efficiency* can be defined by a range from 0 % to 100 %.

Parameters that take a descriptive value are associated to information stored in lookup tables, which is then used to calculate LCoE. For example, the input parameter *primary material* has options such as 'steel' and 'concrete' which are associated to certain densities used to calculate the mass of the WEC structure.

It is assumed that all the input parameters are mutually independent (they can take any value regardless of the value of the other parameters), an assumption that is not always valid and one that is a common disadvantage of techno-economic analysis using conventional monetary based metrics (see section 2.2.3). Much of the work focused on including the most important dependencies to limit the possibility for unrealistic or non-practicable results. This was not always possible and this is discussed alongside results presented in this thesis.

3.1.1 Deployment Parameters

Deployment parameters describe the deployment context for the evaluation of the WEC concept and are given in table 3.1. These are a key feature of the tool and were determined to be the minimum needed to allow for versatility implications of WEC design to be investigated. The deployment parameters include site and resource characteristics along with array scale and vessel information. A target LCoE value, which is representative of a price of electricity, is also context dependent and used in the calculation of the CA score.

Other parameters needed in the calculation of LCoE are assumed to be dependent on the input scenario. For example, water depth and distance to shore are assumed to be related to one another and are estimated from the input site power level (appendix F).

Table 3.1: The variable deployment parameters that describe the deployment context for the WEC.Base values are used for parameters in *italics*. These are kept constant for the analysis presented in this thesis.

Deployment parameters:	Description
▷ Target LCoE	A cost competitive LCoE used to calculate the CA score.
▷ Regional zone	Area of ocean for which distinctions are made on the occurrence distribution of sea states (input to resource module).
▷ Site power level	Annual average mean power per meter of wave crest at a site. Used to generate occurrence distribution of sea states (resource module).
▷ Maximum vessel H_s	The maximum H_s in which O&M or installation vessels can operate which defines a suitable weather window (resource module).
▷ Array capacity	The total installed capacity of the WEC array or farm (initial cost module).
▷ *Vessel speed*	Average speed at which an O&M or installation vessel travel to and from WEC location (initial cost and reliability modules).

3.1.2 WEC Parameters

The WEC parameters describe the WEC concept and are given in table 3.2. As discussed in section 1.3, one of the main challenges for the development of the tool was to allow for the wide variety of possible WEC concepts whilst using a minimal number of input parameters to reduce complexity.

Certain parameters, such as the absorption efficiency, maximum conversion efficiency, part-load performance and geometry can be treated independently of existing WEC technology (‘technology agnostic’) to investigate their impact on CA. They can also be selected for pre-defined technology types, e.g. PTO type: hydraulic, linear, mechanical etc. However, for the calculation of TA, technology types need to be defined (section 3.3).

‘WEC type’ refers to operating principle, e.g. heave, surge etc. (see section 1.1), which typically infers a certain geometry and absorption efficiency, although, as mentioned, the tool does allow for these to be treated independently. The treatment of certain parameters as independent, which may in reality be dependent, also allows for the creation of ‘what-if’ scenarios, providing a challenge for developers innovating in the areas of the parameters space which are indicated as being attractive.

For the analysis presented in this thesis, a base set of values is used for failure rates, repair durations, installation durations and the majority of unit cost values, which are kept constant. Further work is required to establish their relationship (if any) with the other inputs. However, the impact of reducing material cost and PTO cost is explored in chapter 6. Other parameters are treated as dependent variables and are estimated within the model. This includes parameters for which values are found by optimising for cost of energy (assumed to be the primary governing factor in development decisions) whilst meeting the requirements placed on the subsystem by the input scenario. For example, the power rating of the WEC is based on the available resource and absorption performance, the mooring line weight is selected to minimise cost according to a required strength and the specifications of the cables are selected to minimise cost according to the required current carrying capability.

Table 3.2: The variable WEC parameters that describe the WEC concept. Split according to to the module in which they are first used. Base values are used for parameters in *italics*. These are kept constant for the analysis presented in this thesis.

WEC parameters	Description
▷ Active width	Representing the scale of the WEC and the WEC dimension involved in energy capture (input to initial cost and performance modules).
▷ Absorption efficiency	The ratio of power incident on the WEC to the power passed to the PTO, variable with sea state and characteristic of WEC type (performance module).
▷ Max. conversion efficiency	The constant component of the PTO efficiency and characteristic of PTO type (performance module).
▷ Part-load performance	The variable (with sea state) component of the PTO efficiency and characteristic of PTO type (performance module).
▷ Operating limit ratio	The ratio of the WEC rated power to the cut-off or survival power (performance module).
▷ Geometry	The aspect ratios which define the length of the other dimension to the active width (initial cost module).
▷ Primary material	The material used to build the WEC structure (initial cost module).
▷ Number of mooring lines	The number of catenary mooring lines, with a range from three to six (initial cost module).
▷ *Unit costs*	Prices/rates for quantities calculated from input scenario (initial cost and reliability modules).
▷ *Installation duration*	Average duration for installation of each WEC (initial cost module).
▷ *Failure rates*	The average number of O&M trips to a WEC per year (reliability module).
▷ *Repair durations*	Average duration of time spent at WEC for each O&M trip (reliability module).

3.2 The Techno-Economic Model

The techno-economic model is split into four modules for resource, performance, initial cost and reliability and the outputs of each module are used to calculate LCoE (see section 3.3). The inputs and outputs of the modules are given in figs. 3.2 to 3.5 where the arrow direction and colour (blue, green, orange, red for resource, performance, initial cost and reliability modules respectively) are used to indicate the source or destination:

- ▷ Input arrows coming from above indicate the input scenario parameters.
- ▷ Input arrows coming from below indicate other module output.
- ▷ Output arrows leaving from below indicate inputs to the other modules.
- ▷ Output arrows leaving to the right indicate the components used to calculate LCoE.

The resource module (fig. 3.2) uses the site power level to estimate key resource characteristics: wave climate (described by a occurrence probability matrix), extreme conditions and mean delay durations for O&M vessels waiting at port. Two 'Resource Estimating Relationships' are used to estimate these characteristics that are dependent on the region, maximum H_s, operation duration and season. The resource module also provides an estimate of water depth and distance to shore based on the site power level. The full methodology for resource the module is given in chapter 4.

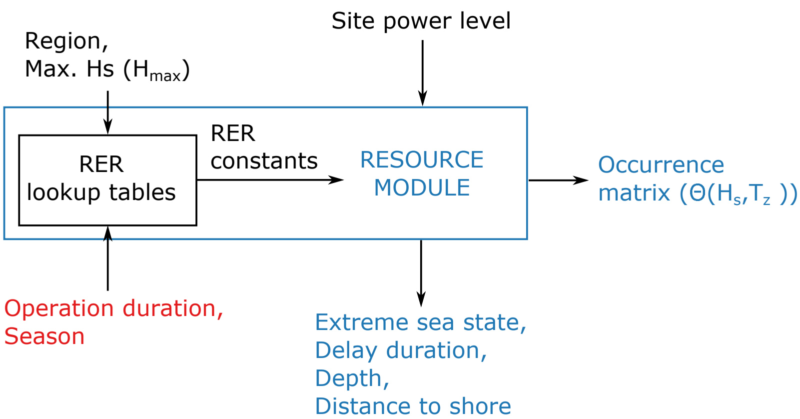


Figure 3.2: The resource module with inputs and outputs.

The performance module (fig. 3.3) builds a power matrix based on the input parameters that describe ability to absorb and then convert wave energy to electricity. The WEC power rating is calculated based on the annual average amount of power absorbed by the WEC and the operating limit is then calculated from rated power using the operating limit ratio. The full methodology for the performance module is given in chapter 5.

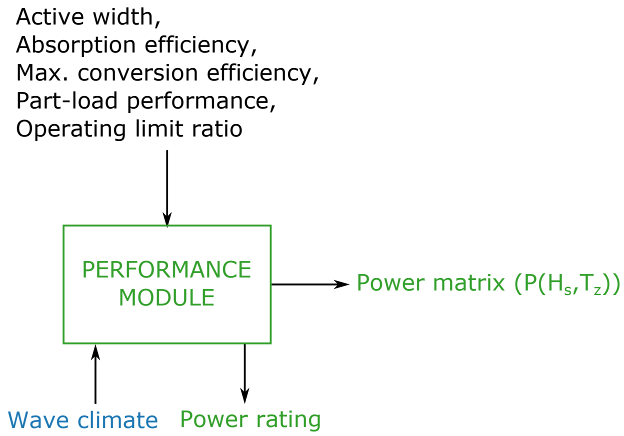


Figure 3.3: The performance module with inputs and outputs.

The initial cost module (fig. 3.4) calculates costs for five cost centres: structure, PTO, station keeping, cabling and installation. The cost centres were chosen to replicate other techno-economic studies (e.g. Entec UK Ltd., 2006; Guanche et al., 2014; Ramboll, 2010; de Andrés et al., 2017b). The process for each cost centre is to calculate the fundamental quantities needed for their cost estimation and then to apply unit costs. For example, the mass of the structure is calculated from the volume of the WEC using a mass per volume constant selected according to material type and the extreme sea state. A total cost is then calculated by applying the material cost in units of (£/kg).

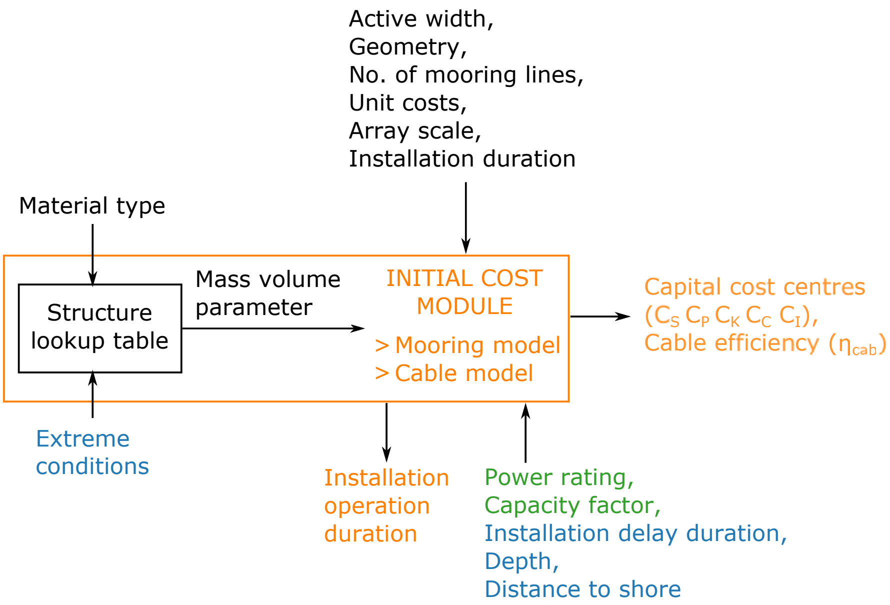


Figure 3.4: The initial cost module with inputs and outputs.

As previously discussed, the mooring weight and cable specifications are treated as dependent parameters that are optimised according to the input scenario. In optimising the cable specifications, the cable model calculates a cost of power loss due to the transmission efficiency of the cables. The transmission efficiency is then also output from the module and used to calculate AEP. The full methodology for the initial cost module is given in chapter 5.

The reliability module (fig. 3.5) creates an O&M schedule using a relatively simple 'time to failure' model (described in appendix J) that finds the number of preventative (scheduled for summer) and corrective (unscheduled) maintenance events for each year of deployment lifetime. Weather window delay durations are provided by the resource module according to the duration of the operation and the season. Vessel rates are then applied to the delay and operation durations to give total vessel costs. The module also uses these durations to calculate WEC downtime and a value for the availability of the WEC to produce power. The full methodology for the reliability module is given in chapter 5.

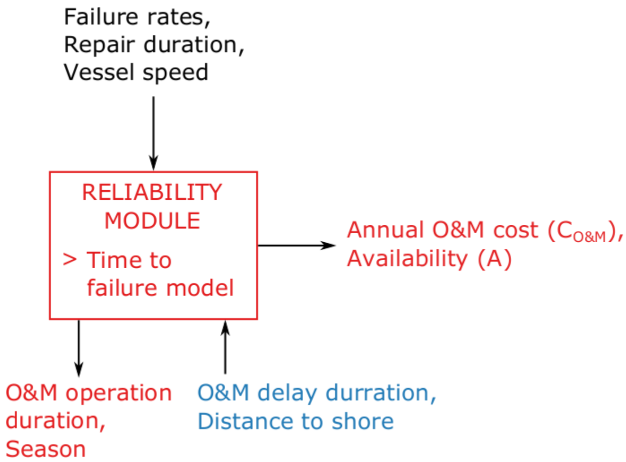


Figure 3.5: The reliability module with inputs and outputs.

3.3 Scores and Thresholds

Typical financial indicators for wave energy have a high uncertainty associated with them and caution is often advised for analysing absolute results (OES, 2015; Guanche et al., 2014). Instead, the aim for the tool output was a relative comparison of WEC concepts in a number of deployment scenarios. Two scores are proposed and are described in the following sections along with thresholds that were used to analyse the results given in chapter 6.

3.3.1 Commercial Attractiveness Score

The CA score is based on an LCoE estimate for the input scenario. In chapter 2 this was identified as the most appropriate metric for describing the parameter space and a particular focus was placed on adapting the LCoE calculation for low TRL.

The outputs indicated in figs. 3.2 to 3.5 are used to calculate the CA score according to the following equation:

$$\mathrm{CA} = \frac{\mathrm{LCoE}_{\mathrm{scenario}}}{\mathrm{LCoE}_{\mathrm{target}}} = \frac{1}{\mathrm{LCoE}_{\mathrm{target}}} \cdot \left[\frac{C_{\mathrm{S}} + C_{\mathrm{P}} + C_{\mathrm{K}} + C_{\mathrm{I}} + C_{\mathrm{C}} + \mathrm{PV}\left(C_{\mathrm{O\&M}}\right)}{\mathrm{PV}\left(A \cdot \eta_{\mathrm{cab}} \cdot \sum_{T_{\mathrm{z}}} \sum_{H_{\mathrm{s}}} \boldsymbol{P} \cdot \boldsymbol{\Theta} \cdot 8766\right)} \right] \tag{3.1}$$

Where:

- ▷ $\mathrm{LCoE}_{\mathrm{target}}$ is a target LCoE value [£/kWh],
- ▷ C are the cost centres,
- ▷ A is the availability,
- ▷ η_{cab} is the total cable efficiency,
- ▷ $\boldsymbol{P}$ is the produced power matrix,
- ▷ $\boldsymbol{\Theta}$ is the sea state occurrence matrix.

For the analysis presented in this thesis, PV adjustments were made using a project lifetime of 20 years with a discount rate of 10 % and all the initial cost centres were assumed to occur in year 0. These values are chosen for consistency with other studies of wave energy LCoE (see section 2.2.3).

The target value of LCoE is used to make the CA score unitless and is chosen to represent cost-competitiveness (the end goal of development). A previous work by de Andrés et al. (2017b), which explored the use of a reverse LCoE calculation, established cost benchmarks based on a cost of electricity of 0.15 £/kWh. At the time this target was identified as being cost competitive with offshore wind which, as an emerging technology with similar operational demands, was seen as the main competitor of wave energy (MacGillivray et al., 2014).

The LCoE of offshore wind has since reduced significantly; strike prices agreed with the UK government for generation planned beyond 2021 range from 0.040 £/kWh to

0.092 £/kWh (NAO, 2017; BEIS, 2017). However, these reductions are driven by increased deployment (ORE Catapult, 2016), and the value of 0.15 £/kWh is retained here to represent the target value required for initial deployment.

3.3.2 Technical Achievability Score

The techno-economic model allows for the value of each input parameter to be changed and the resultant impact on the CA score to be investigated. The technical achievability score was developed to constrain certain parameter values so that 'what-if' input scenarios are actually feasible.

The score can be calculated for the parameters which relate to technology type such as unit cost and efficiency. It can also be thought of as an indication of the level of risk associated with developing a concept in order to achieve the end development goal.

The formulation of the score is based on the experience curve, which is used to describe the rate of decreasing unit cost as a function of some measure of experience (see appendix D). For an energy generating technology this is typically the cumulative deployed capacity or cumulative R&D spend (Grübler et al., 1999). The experience curve implies that cost reduction occurs as a result of increased learning and two learning rates are often observed: learning-by-research and learning-by-doing (Rubin et al., 2015).

The earliest stages of development are characterised by the learning-by-research rate and for the TA score it is assumed that this can also be applied to increases in efficiency as well as decreases in cost. An individual score is calculated for certain cost and efficiency parameters (see chapter 6) using the re-arranged experience curve formula:

$$f(c_{\text{TA}}) = \left(\frac{c_0}{c_{\text{TA}}}\right)^{1/\alpha} \tag{3.2}$$

Where:

- ▷ c_0 is the current value of the parameter,
- ▷ c_{TA} is the improved value of the parameter,

▷ α is the learning elasticity, which is positive for cost and negative for efficiency.

The total concept TA score is then found by summing the individual scores. For improvements in efficiency, the learning rates were reduced by a factor of ten to make the scores comparable to scores for reduction in cost. The justification for this is that it is likely to be more difficult to achieve a unit improvement in efficiency than a unit reduction in cost, and a unit change in efficiency also has a larger impact on LCoE. Further work is needed to validate this approach.

The learning elasticity can be calculated from learning rate according to appendix D and is used here to describe how easily a technology can be expected to be improved. An alternative definition of the TA score is that it represents the length of time, or amount of R&D spend, it would to take to achieve a certain level of improvement. Using the re-arranged experience curve formula, where rate of change is described by a power law, means that it is easy to filter out concepts that are unlikely to achieve big improvements.

Learning rates have been widely used in the literature to show that cost-competitive wave energy is possible (see chapter 2). However, there is a high uncertainty in selecting the appropriate value of learning rate and this can have a large impact on results. Analysis of energy generating technologies shows that learning rates have typically ranged from 0 % to 25 %, although higher rates are possible (Neij, 2008; Grübler et al., 1999; Klaassen et al., 2005; Rubin et al., 2015).

Technologies are often categorised according to the learning rate observed in recent cost trends and this is typically associated to the level of technological maturity (Grübler et al., 1999). For example in Jamasb (2007), mature, reviving, evolving and emerging categories are used. In general there is a reduction in learning rate, and potential for cost reduction, as a technology moves from immature to mature. However, for learning-by-research existing knowledge has to be considered (Klaassen et al., 2005). For instance, very immature technology can have a lower learning rate as it takes time for understanding to be established (Jamasb, 2007).

Although less common, learning rates have been used to categorise technologies at a subsystem level in order to indicate the most likely areas for cost reduction (Carbon Trust, 2011; de Andrés et al., 2017b). In Carbon Trust (2011), learning rates of between 7 % to 12 % were predicted for the structure, PTO and station keeping subsystems.

Three values of learning rate were used in the analysis of concepts presented in chapter 6 to represent cases of high, medium and low potential for improvement. These are given in table 3.3, along with the equivalent learning elasticity values and a description of the technology type to which they were applied.

Table 3.3: Learning rate levels used in the scoring of TA and indicating the potential for a technology to be improved through the development process. A positive value of learning elasticity is used if improvement relates to a reduction in parameter value and a negative value is used if improvement relates to an increase in parameter value.

Improvement potential	Learning rate	Learning elasticity	Description
Low	5 %	(−) 0.07	Mature technologies that have featured in previous wave energy development or in similar applications but are the subject of little active R&D. Technology that would likely require a high investment to achieve unit improvement.
Medium	10 %	(−) 0.15	Emerging technologies that are mostly new to wave energy development and similar applications or reviving technologies that are the subject of active R&D. Technology that would likely require a medium investment to achieve unit improvement.
High	15 %	(−) 0.23	Evolving technologies that may have featured in previous wave energy development or in similar applications but are the subject of extensive active R&D. Technology that would likely require a low investment to achieve unit improvement.

3.3.3 Selection Thresholds

As discussed, the CA score is a normalised LCoE where the normalisation factor is a target, cost-competitive value of LCoE and the eventual end goal for technology development. Therefore, concepts that have a CA score of greater than one are not cost-competitive and need to be improved. The achievability of improvements is then indicated by the TA score. Thresholds for the two scores can be used to judge whether concepts should be considered for development or ruled out.

For the analysis presented in chapter 6, two thresholds were used to represent 'very achievable' improvement and 'achievable' improvement, which are given in table 3.4. Above the achievable threshold the level of improvement is considered to be not achievable.

The thresholds used here are chosen for the purpose of demonstrating the tools functionality and are based on an analysis of the number of results which satisfy them. They are used in combination with the CA score to identify the top scenarios relative to the others.

It would be useful to relate these thresholds to similar improvements that have been seen in other sectors. An empirical method for selecting thresholds could be based on the length of time allowable for technology development, for instance this could be the duration of a funding programme. Such a method, and a means for validating the TA score, is the subject of further work.

Table 3.4: Suggested thresholds for the TA score.

Thresholds	TA score
Very achievable:	$TA \leq 10^1$
Achievable:	$10^1 < TA \leq 10^2$
Not achievable:	$TA > 10^2$

Figures 3.6 and 3.7 demonstrate how the thresholds can be used to indicate the corresponding values of CA for two technology types. Based on current values, technology

1 and technology 2 would provide a CA score of 1.4 and 1.15 respectively and need to be improved to be cost-competitive.

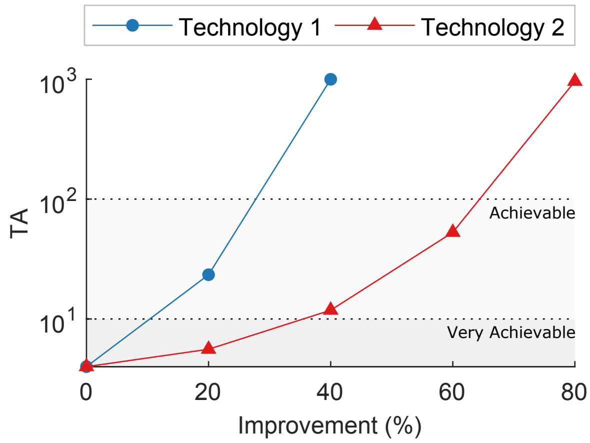


Figure 3.6: Example plot showing TA score versus improvement in the value of some parameter. The TA score corresponds to the CA score given in fig. 3.7. Two technologies are shown with different improvement potential. The very achievable and achievable limits are shown as dotted lines.

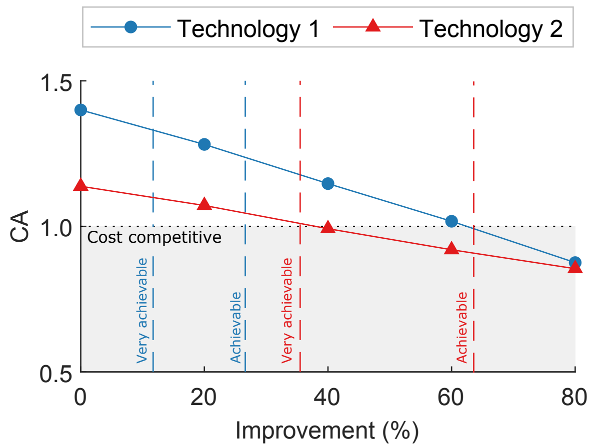


Figure 3.7: Example plot showing CA score versus improvement in the value of some parameter. The CA score corresponds to the TA score given in fig. 3.6. Two technologies are shown with different values of current CA and different sensitivity to improvement. The very achievable and achievable limits are shown as dotted lines.

In fig. 3.6, the TA score of both technologies is plotted against percentage improvement with the two thresholds indicated as dotted lines. Technology 1 has a lower improvement potential and lower learning rate. The very achievable and achievable limits are then 12 % improvement and 27 % improvement respectively. In fig. 3.7 it can be seen that neither level of improvement provides a cost-competitive CA score. Technology 2 has a higher improvement potential and higher learning rate. In this case, the very achievable and achievable limits are 36 % improvement and 64 % improvement respectively and a cost-competitive CA score is within the achievable improvement limit.

3.4 Summary

This chapter provided an overview of the proposed concept generation and evaluation tool and its various components. The following two chapters, chapters 4 and 5, present the development of the techno-economic model, firstly, the resource module and secondly, the performance, initial cost and reliability modules. In each chapter a set of results is provided from an investigation into the impact of site power level and WEC scale on LCoE. This is to demonstrate the functionality of the techno-economic model. In chapter 6 two set of results are provided. Firstly, from an investigation into technology improvements and impact on the CA and TA score. Secondly, a ranking of multiple input scenarios according to the two scores. This demonstrates how the concept generation and evaluation too can be used to quickly compare many combinations of WEC and deployment parameters, that being its main function.

4. Resource Module

This chapter describes the development of a resource module that allows for the techno-economic evaluation of WEC concepts in the context of available resource. A method was required for providing non-site specific resource characteristics that could be easily manipulated, so that concepts could be evaluated in a number of different scenarios. This was the first objective identified with the research question (section 1.3).

This chapter is split as follows.

- ▷ In section 4.1, studies are reviewed that investigate the economic interdependence of the resource and WEC. This is to highlight the importance of considering the resource in the assessment of concepts.
- ▷ In section 4.2, an overview is provided of the methods used to represent resource in the techno-economic assessment of wave energy. The aim is to highlight the lack of a sufficient approach for low-TRL assessment.
- ▷ In section 4.3 the methodology is presented that was used to find two parametric expressions that are used by the resource module to estimate key resource characteristics.
- ▷ In section 4.4 results are presented from an investigation into the impact of increasing site resource level on important LCoE drivers for two example WECs. Results are also provided for a comparison between the module output and actual site data.

▷ In section 4.5 the results are discussed and the chapter ends with concluding remarks in section 4.6.

4.1 Resource-WEC interdependence and impact on LCoE

Techno-economic studies have shown that financial returns are sensitive to the annual variability of sea conditions (e.g. Guanche et al., 2014; Costello et al., 2012) and a key factor in determining concept attractiveness is the impact of wave conditions on performance.

According to eq. (1.1), wave energy flux increases with increasing wave height and period. However, the performance of the WEC, in terms of its efficiency for absorbing wave power, is also dependent on these characteristics. For example, the optimum absorption efficiency of a point absorber occurs when the system is at resonance; the velocity of the point absorber and the hydrodynamic wave excitation force are in-phase. Therefore, a good WEC design should have a natural frequency closely matching the most prevalent wave frequencies at the deployment site.

Several studies have examined this resource-WEC interdependence and impact on financial returns. Dalton et al. (2009) looked at locations in Ireland, Portugal and North America and found a return on investment for the highest energy sites only. In O'Connor et al. (2013b) the performance of two WECs were compared and showed that the optimal location is WEC dependent. The floating Pelamis device produced more energy at the higher resource sites. On the other hand, the WavesStar, a bottom fixed nearshore device, produced more energy at lower resource sites as it's more suited waves with shorter time period.

In the study by Frost et al. (2018), the floating Albatern-WaveNET device achieved lowest LCoE in the most sheltered locations with higher accessibility. The study placed a greater importance on maintainability and installability considerations and the results are shown to be very sensitive to month of installation. This is because there is a large difference in the waiting time for suitable weather windows between months and longer waiting times mean that installation vessels needed to be chartered for longer. For example, it was possible to install the WEC at almost all the sites throughout July, whereas for planned installation in February a project would not be viable due to the extreme sea conditions. Another important factor was found to be the WEC operating range, which had a large impact on LCoE if not well matched to the wave climate.

Other studies determined optimum WEC scale for certain locations, considering both improvements in performance and impacts on cost (O'Connor et al., 2013b; de Andrés et al., 2016; Hutcheson et al., 2016; ARUP, 2018). Results varied depending on type of WEC but also because of differences in the amount of detail included in the cost estimation. For example, de Andrés et al. (2016) found that the optimum scale of the floating CorPower device, is around 1 MW for optimum energy capture but that LCoE continues to decrease with decreasing size. In part, this is due to the assumption that CapEx and OpEx can be scaled consistently, resulting in costs that reduce faster than loss of energy production.

In O'Connor et al. (2013b) smaller WECs produced more energy overall as part of a farm but larger WECs produced better economic returns. The method used in the study for calculating cost includes a factor for modelling the cost reduction associated to volume manufacture. In Teillant et al. (2012) a more detailed O&M model is used and the results showed that arrays of >150 WECs are not profitable due to saturation of weather windows and available boats.

A problem for these studies is the specificity of the results to the data that was available to the authors. This has limited understanding to a reduced number of locations and specific WEC types, making it difficult to establish generalised links between WEC design, available resource and LCoE. The versatility of a WEC design has implications for its diffusion prospects as a global source of energy generation. At the same time, one of the deficiencies of previous WEC developments was the inability to identify fundamental weaknesses at the earliest stage possible (Weber, 2012). Therefore, improved methods are needed for considering the resource in low-TRL assessment of WEC concepts.

4.2 Resource in Techno-Economic Assessment

The majority of the techno-economic studies of wave energy are based on resource data for a limited number of sites. For low-TRL assessment this site specificity is at odds with the other characteristics describing the WEC.

According to the standard for assessment of WEC power production (BSI, 2012), the resource is represented by an occurrence matrix, where each element is the occurrence probability of the corresponding sea state, characterised by an average value for wave height and period. WEC performance is then represented by a power matrix, where each element is the average power produced by the WEC in each sea state. The sum product of the two matrices is then used to calculate AEP.

Several occurrences matrices are provided in LCoE tools (Chozas et al., 2014; Exceedence, 2018) so that calculations can be repeated for several resource cases. However, to fully understand WEC versatility a more wide ranging analysis is required.

Occurrence matrices can be approximated using a joint-Probability Density Function (PDF) that provides the probability distribution of the sea states in terms of their significant wave height and wave period values. This can be used to give information on extreme wave conditions used to determine design requirements.

Global Wave Statistics (GWS) (BMT, 2018) is a paid-for database of probability distributions for the world's oceans split into 104 areas. Although this provides a means to generate generic occurrence matrices, variation is then limited to that found between those broad ocean areas.

Some studies use an annual occurrence-weighted mean value for representing the available power at a site, avoiding the requirement for actual site data (Castro-Santos et al., 2015; de Andrés et al., 2017b). It does not then provide an indication of the annual variability of the resource, which can have a large impact on AEP ($\approx \pm 50\,\%$ according to Pecher et al. (2017)).

Alternatively, Burger et al. (2005) presented a method that uses the annual mean power value to estimate a joint-PDF. The study found linear expressions to relate the parameters of the function to the value for annual mean power, providing an occurrence matrix that is easily scalable for resource level. The model is shown to be comparable to using the data provided by the GWS for accuracy of calculating AEP.

Another important factor that impacts on LCoE is the site accessibility. Sites with low accessibility will experience greater delays for installation and O&M operations and this will incur increased cost and increased time when the WEC is unable to produce energy. There are several factors that contribute to accessibility, including the distance to port and the readiness of local vessels. Even if vessels are available it may not be possible to perform operations due to the wave conditions at the WEC site. The wave climate dictates the average time spent waiting for weather windows of sufficient length (or 'persistence') and long wait times are considered a potential barrier to progress in regions with a high wave resource (O'Connor et al., 2013c; Guanche et al., 2015).

Site accessibility due to wave conditions can be calculated from the occurrence matrix as the probability that waves will not exceed vessel operating limits. However, translating this into estimates for delay durations, which can be used to adjust vessel costs and WEC availability, is problematic without data on the persistence of weather windows.

A limited number of solutions exist in the literature. In Chozas et al. (2014) a 100 % availability was assumed so that all failure events occur in calm conditions outside of WEC operating range and within vessel operating limits. In O'Connor et al. (2013b) availability was calculated directly from accessibility using a curve representative of WEC type. However, this required assumptions for WEC reliability and offers little flexibility for investigating the impact of reliability on availability. A new method is presented later in this chapter that addresses these problems (section 4.3.3).

4.3 Module Methodology

This section provides an overview of the method used to develop two parametric expressions, or Resource Estimating Relationships (RERs). These are used in the resource module to calculate key resource characteristics from a limited number of inputs (see fig. 3.2). The characteristics output by the module are as follows:

- ▷ The occurrence matrix describing the annual variability of sea-states. This is used to calculate AEP.
- ▷ An extreme sea state of a specified return period. This is used to determine the costs of the WEC structure and mooring system.
- ▷ A mean delay duration representing the amount of time a O&M vessel has to wait in port for a sufficient weather window. This is used in the calculation of vessel costs and WEC downtime.

To determine these characteristics, two RER were required and these were derived through least-squares regression of known datapoints. This method was based on the approach outlined in Burger et al. (2005).

RER-1 was used to generate a joint-PDF (referred to as just PDF from now on) from site power level, defined as the occurrence-weighted annual mean power. The PDF provides an occurrence matrix, extreme sea state and a value for accessibility. RER-2 was used to estimate a mean delay duration from accessibility. The function of each RER is shown in Figure 4.1.

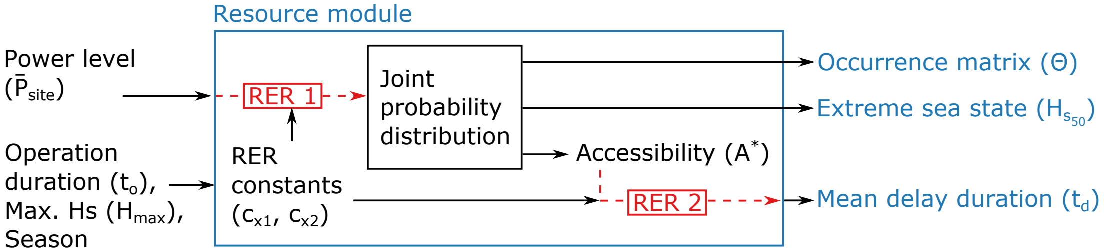


Figure 4.1: The resource estimating relationships.

The following steps were used to determine each RER:

1. Calculate reference values from the reference site data.
2. Perform regression of a target expression for each RER to the reference values using least squares fitting.
3. Calculate the regression coefficient to evaluate the goodness-of-fit and populate lookup tables with the RER values which provide best fit.

4.3.1 Reference Data

Numerically generated hourly significant wave height (H_s [m]) and zero-crossing period (T_z [s]) data was provided for 10 years at 50 locations. The hindcast model is described in more detail in Kalogeri et al. (2017) and the 50 locations, off the European Atlantic coast and from the North Sea, are shown in fig. 4.2 (blue dots).

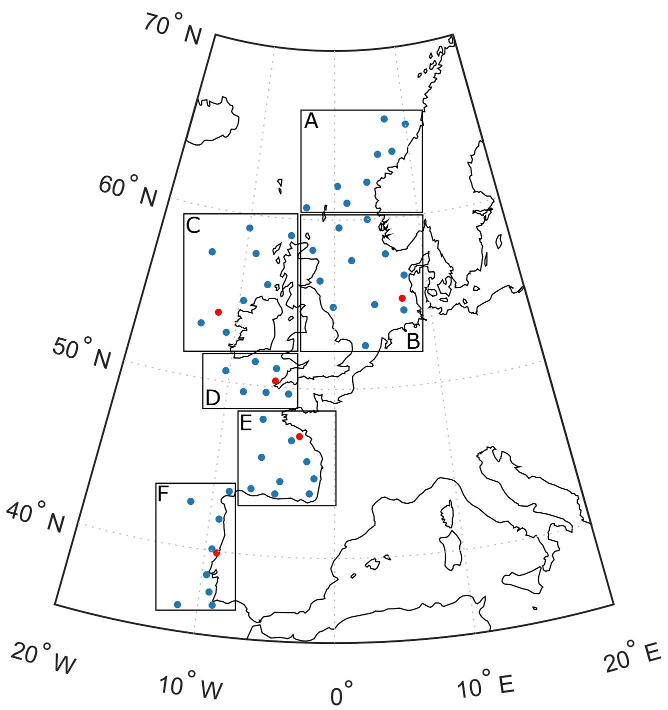


Figure 4.2: Reference data sites. Blue dots from numerical simulation (Kalogeri et al., 2017). Red dots from real data (Chozas et al., 2014).

For finding RER-1, the reference sites were split into six zones to improve goodness-of-fit. These are labelled A to F in fig. 4.2 and were chosen to replicate the distinct ocean areas given in the GWS database (BMT, 2018). Table 4.1 gives the number of sites in each of the six zones along with the range in site power level that they represent. It should be noted that for the analysis presented in this thesis, no restriction was placed on power level regardless of the specified zone. This means that results are not always for realistic scenarios (higher power level are possible in the North Atlantic compared to the North Sea, for example).

Also shown on fig. 4.2 are five reference sites taken from the Aalborg University LCoE calculation tool (Chozas et al., 2014). These were used to compare output of the resource module (see section 4.4).

Table 4.1: Sites in each zone.

	Sites	$\bar{P}_{\text{site}}$ (kW/m)
All zones	50	7.72 - 88.60
Zone A	8	42.99 - 69.75
Zone B	11	7.72 - 38.75
Zone C	8	56.52 - 88.60
Zone D	6	30.42 - 69.33
Zone E	9	28.14 - 53.24
Zone F	8	28.38 - 50.78

4.3.2 Reference Characteristics

Reference power levels, PDF parameters, accessibility values and mean delay durations were calculated for each of the 50 sites using standard approaches outlined in the literature (BSI, 2012; DNV, 2010; Tecnalia, 2017).

For each site, data was binned with intervals of 0.5 m for H_s and 0.87 s for T_z to provide an occurrence matrix[1]. This meant that the total number of bins varied depending on the range of values in the data.

Power Level

Power level is calculated by summing the average power of each available sea state (J), weighted for their occurrence probability given in the occurrence matrix ($\boldsymbol{\Theta}$):

$$\bar{P}_{\text{site}} = \sum_{H_s} \sum_{T_z} \boldsymbol{J}\left(H_s, T_z\right) \cdot \boldsymbol{\Theta}\left(H_s, T_z\right) \cdot \text{hrs}_{\text{yr}} \qquad [\text{kW/m}] \quad (4.1)$$

A Brettschneider spectrum was assumed, such that the following relationship was used for converting the wave period (Cahill et al., 2014):

$$T_e = 1.15 \cdot T_z \qquad [\text{s}] \quad (4.2)$$

Joint Probability Distribution

In Burger et al. (2005), the Ochi PDF is used (see Ochi, 1978), however, it was decided to use the Conditional Modelling Approach (CMA) as this is the recommended practice for characterising long term resource variability (DNV, 2010). According to the CMA, the occurrences of H_s and T_z can be modelled as a marginal distribution and a series of conditional density functions.

Firstly, H_s is modelled by the three-parameter Weibull PDF:

$$f\left(H_s\right) = \frac{\beta}{\alpha} \cdot \left(\frac{H_s - \gamma}{\alpha}\right)^{\beta-1} \cdot \exp\left\{-\left(\frac{H_s - \gamma}{\alpha}\right)^{\beta}\right\} \quad (4.3)$$

[1] Recommended practice for marine energy production, 0.87 s $T_z \approx$ 1.0 s T_e (BSI, 2012).

Where:

▷ α, β and γ are the scale, shape and location parameters respectively.

Secondly, T_z conditional on H_s is modelled by a lognormal distribution:

$$f\left(T_z|H_s\right) = \frac{1}{\sigma \cdot T_z \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left\{-\frac{\left(\ln T_z - \mu\right)^2}{2 \cdot \sigma^2}\right\} \tag{4.4}$$

Where:

▷ σ and μ are the location and scale parameters respectively.

Finally, the value of σ and μ can be modelled as functions of H_s according to the formula:

$$\begin{aligned} \mu &= a_1 + a_2 \cdot {H_s}^{a_3} \\ \sigma &= b_1 + b_2 \cdot e^{b_3 \cdot H_s} \end{aligned} \tag{4.5}$$

Where:

▷ a_1, a_2, a_3, b_1, b_2, b_3 are constants that are characteristic of location.

This means that nine PDF parameters had to be evaluated for each of the 50 reference sites. These were found using the optimisation function 'fminsearch' within MATLAB, firstly by fitting eq. (4.3) to the reference distribution of H_s values and then by fitting eqs. (4.4) and (4.5) to the reference distributions of T_z values corresponding to each H_s bin. A new occurrence matrix was produced using the modelled values for the PDF parameters and goodness of fit was evaluated by taking the Root of the Sum of the Square Error (RSSE) for each cell. This is then a least squares method, where RSSE was calculated according to the formula:

$$\text{RSSE} = \sqrt{\sum_{H_s} \sum_{T_z} \left(\boldsymbol{\Theta}^* - \boldsymbol{\Theta}\right)^2} \tag{4.6}$$

Where:

▷ $\boldsymbol{\Theta}$ is the reference occurrence matrix,

▷ $\boldsymbol{\Theta}^*$ is the generated matrix.

Two further checks were used to check the validity of the resulting occurrence matrix. Firstly, to check that the sum of the occurrence matrix is equal to one (the definition of a PDF) and secondly, to check for the difference between the reference site power level and the power level calculated from the generated matrix. The RSSE was increased if these were not within an acceptable margin at each iteration of the optimisation.

The average of the RSSE across the 50 sites was 0.064 (indicating similar occurrence matrices), the total sum values were all >0.97, and the differences in power level values were all <1 %. These results compare well with the results presented in Burger et al. (2005). A two-parameter Weibull simplification, where $\gamma = 0$, can be used with fixed values for the parameters a_1 and b_1 (DNV, 2010). This simplification was found to have negligible impact on the overall goodness-of-fit.

Extreme Conditions

Offshore structures are designed to withstand extreme events that have a return period of typically 50 to 100 years. For the analysis presented here a 50-year return period was assumed.

The 50-year characteristic largest value of significant wave height was obtained using the parameters from eq. (4.3) according to the formula (Bitner-Gregersen et al., 2007):

$$H_{\mathrm{s}_{50}} = \gamma + \alpha \left(\log N\right)^{\frac{1}{\beta}} \qquad \text{[m]} \quad (4.7)$$

▷ N is the number of observation made during the return period.

A corresponding value for T_{z} was then found using the formula:

$$T_{\mathrm{z}|H_{\mathrm{s}_{50}}} = \exp\left(\mu + 0.5 \cdot \sigma^2\right) \qquad \text{[s]} \quad (4.8)$$

For hourly data, the value of N is equal to the return period multiplied by the the number of hours in a year ($50 \cdot 8766 = 438300$). The maximum height of the individual design wave can be approximated as $1.9 \cdot H_{\mathrm{s}_{50}}$ (DNV, 2010).

This was used as indicative of the extreme event to estimate costs. It should be noted that there will be a contour of sea states with equal return period which may cause extreme responses and loads on the WEC, not necessarily the sea state with the largest value of H_s. For example, sea states with waves at the resonant frequency of an oscillating WEC will likely place very large forces on the mooring system.

Accessibility

Accessibility is defined as the probability of non-exceedance for vessel operating limits. For this study, the only limit considered was a maximum operating wave height (H_max). Therefore, accessibility was calculated from the occurrence matrix through the equation:

$$A^* = \sum_{H_\mathrm{s}} \sum_{T_\mathrm{z}} \mathbf{\Theta} \left(H_\mathrm{s} < H_\mathrm{max}, T_\mathrm{z} \right) \tag{4.9}$$

Mean Delay Duration

A Boolean approach was used to count the number of weather windows in the reference data, their duration and the duration of time between them, whereby hours were assigned a one or zero depending on whether H_s was above or below H_max.

Weather windows were only counted if they were of a minimum duration (t_ww), representing the duration of time required for an operation to be completed. For long periods of $H_\mathrm{s} < H_\mathrm{max}$, multiple weather windows of t_ww were counted. For example, in any 24-hour period there are potentially 4 six-hour weather windows. The mean delay duration was then calculated as the total hours waiting divided by the number of waiting instances, as according to the definition given in the OPERA project (Tecnalia, 2017).

Values of delay duration were calculated for both winter (Oct-Mar) and summer (Apr-Sep) periods and then averaged across the 10 years of data. Results were found for five values of maximum significant wave height: 1 m, 1.5 m, 2 m, 2.5 m and 3 m, and four values of weather window duration: 12 h, 24 h, 36 h and 48 h.

4.3.3 Regression Analysis

The two RERs were evaluated through least-squares fitting of candidate regression expressions to the reference values calculated for the 50 reference sites.

For RER-1, a linear expression was used, as suggested in Burger et al. (2005) but for the different joint-density function. Therefore, for each parameter of the joint-density function two RER-1 parameters were obtained representing the slope and y-intercept. This was repeated for the six regional zones.

For RER-2, an appropriate regression expression had to be determined based on goodness-of-fit. Two options were considered each containing two RER-2 parameters. Regression was repeated for different values of maximum significant wave height (H_{max}), weather window duration (t_{ww}) and for two seasons: summer and winter.

Goodness-of-fit was indicated by the regression coefficient R^2, which has a value of one for a perfect fit and is calculated according to the formula:

$$R^2 = 1 - \frac{\sum_i (y_i - y_i^*)^2}{\sum_i (y_i - \bar{y}_i)^2} \tag{4.10}$$

Where:

- ▷ y is the reference data point,
- ▷ y^* is the modelled data point,
- ▷ $\bar{y}$ is the mean value of the reference data.

RER-1: Power Level and Joint-PDF Parameters

A linear relationship between site power level and the PDF parameters had already been proposed in Burger et al. (2005) and was considered appropriate. This meant that for each parameter the regression expression was of the form:

$$\alpha = c_{\alpha_1} \cdot \bar{P}_{\text{site}} + c_{\alpha_2} \tag{4.11}$$

Where:

- ▷ c_{α_1} is the RER-1 constant controlling the rate of change of the α value,

▷ c_{α_2} is the RER-1 constant controlling the magnitude of the α value.

The two RER-1 constants were found for each of the nine PDF parameters in each zone. Therefore, 18 constants per zone were evaluated in total.

Figure 4.3 shows the regression of α and β values for all 50 reference sites. In agreement with the prediction, a strong linear trend can be seen for α, which gave a regression coefficient of 0.97. On the other hand, significant difference can be seen between some β values (roughly 10-15 sites) and the linear trend. This resulted in a much lower regression coefficient of 0.15.

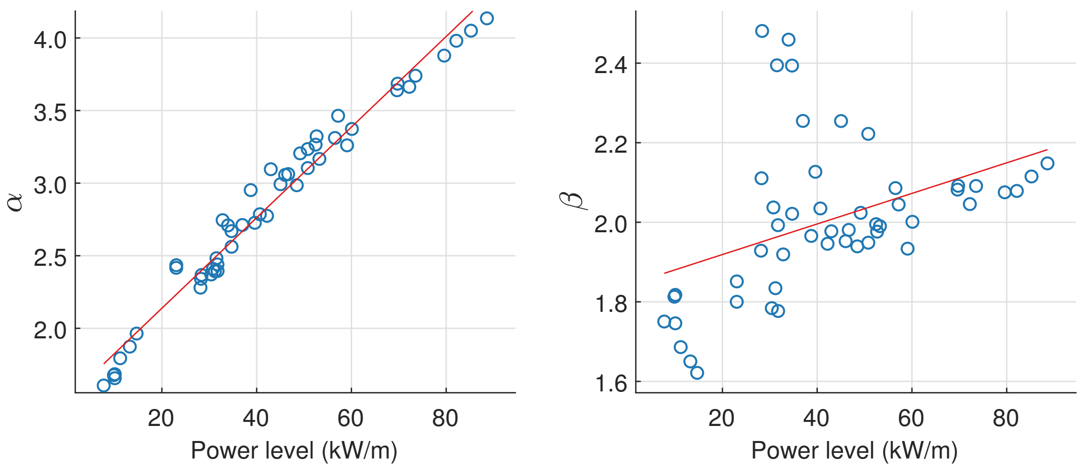


Figure 4.3: Linear regression performed on all 50 sites and results indicated by red lines. Left) Weibull scale parameter versus power level. Right) Weibull shape parameter versus power level.

Figure 4.4 shows the regression of β values when split into the six zones. It can be seen that this generally resulted in an improvement in fit. However, low values for the regression coefficient were still observed for some zones (table 4.2). This is because of the small variation in the values of β with changing power level across the reduced number of datapoints.

Similarly, a poor fit is seen for the other PDF parameters, even when the reference values were split into zones (table 4.2). For this reason it was decided to use the expression given in eq. (4.11) for α and β only, to model the Weibull distribution of H_s. Zone averaged values were then used for the parameters: a_1, a_2, a_3, b_1, b_2, b_3. These

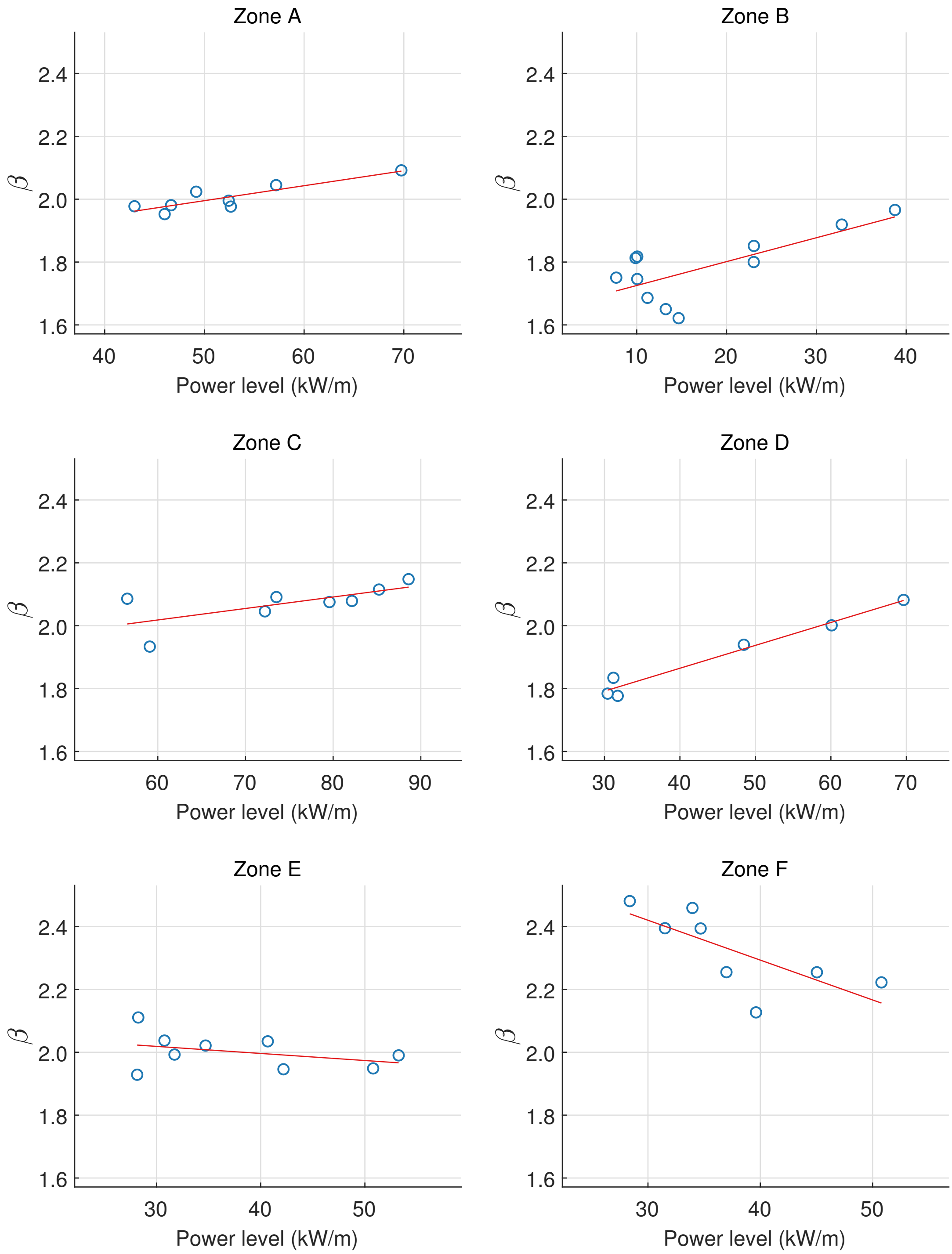


Figure 4.4: Linear regression performed on reference sites split into six zones. Result indicated by red line for β versus power level.

describe the conditional relationship between the lognormal T_z distribution and H_s and so this allows for the $T_z$probability values to be shifted with power level anyway. The final lookup table used by the resource modules is provided in appendix E.

Table 4.2: Regression coefficient (R^2) results for a linear approximation of the PDF parameters. Where $R^2 = 1$ is a perfect fit.

R^2	α	β	γ	a_1	a_2	a_3	b_1	b_2	b_3
All zones	0.97	0.15	-	0.14	0.24	0.01	0.26	0.02	0.00
Zone A	0.94	0.78	-	0.20	0.13	0.19	0.23	0.38	0.13
Zone B	0.98	0.54	-	0.28	0.01	0.36	0.01	0.00	0.05
Zone C	0.99	0.46	-	0.01	0.18	0.32	0.15	0.58	0.30
Zone D	1.00	0.97	-	0.40	0.18	0.01	0.04	0.62	0.00
Zone E	0.99	0.14	-	0.02	0.00	0.07	0.26	0.30	0.24
Zone F	0.96	0.54	-	0.17	0.15	0.34	0.16	0.17	0.00

RER-2: Accessibility and Mean Delay Duration

For RER-2 the appropriate expression had to be determined first with accessibility used as the independent variable. Figure 4.5 shows the mean delay durations in winter (averaged for the 10-year period) plotted against accessibility along with the average number of weather windows. For each maximum wave height and weather window duration, the delay duration rapidly decreases with increasing accessibility suggesting that the appropriate regression expression is either an inverse exponential or a negative power relationship.

Therefore two candidate expressions were evaluated, as given by:

$$t_{\mathrm{d}} = c_{t_1} \cdot A^{*-c_{t_2}} \quad \text{[d]} \quad (4.12)$$

$$t_{\mathrm{d}} = \exp\left(-c_{t_1} \cdot A^{*} + c_{t_2}\right) \quad \text{[d]} \quad (4.13)$$

Where:

- ▷ c_{t_1} is the RER-2 constant controlling the magnitude of the wait duration [d],
- ▷ c_{t_2} is the RER-2 constant controlling the rate of change of the wait duration.

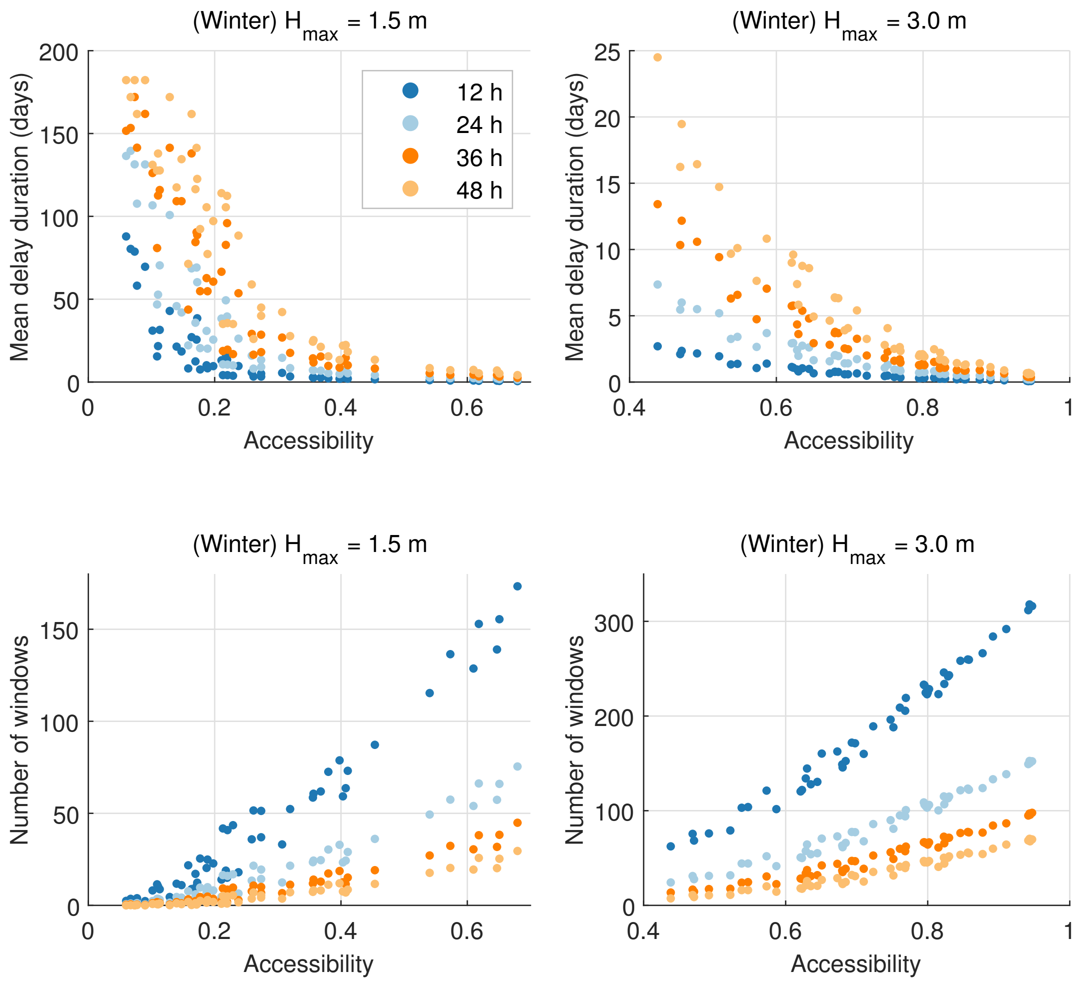


Figure 4.5: Winter delay durations and number of weather windows versus accessibility as calculated from the reference data. Legend indicates weather window duration. Left) $H_{\text{max}} = 1.5\,\text{m}$ Right) $H_{\text{max}} = 3\,\text{m}$. **Note the difference in values on the y-axis.**

The RER-2 constants, c_{t_1} and c_{t_2}, were evaluated for each $H_{\max}$ and t_{ww} combination. This was done by taking logarithms of each of the candidate equations so that linear regression could be performed. Regression was not performed below 10 % accessibility due to the high standard deviation associated to the averaged reference values. Consequently, for the lowest values of $H_{\max}$, there were less than 50 datapoints used, as given in table 4.3.

Table 4.3: Number of datapoints for fitting when $A^* > 10\,\%$ is applied.

$H_{\max}$ (m)	Datapoints
1.0	20
1.5	49
2.0	50
2.5	50
3.0	50

Figure 4.6 shows the two candidate expressions fitted to the reference data for $H_{\max}$ = 2 m. It can be seen that at low accessibility, eq. (4.12) tends to overestimate the delay duration whilst eq. (4.13) tends to underestimate. Regression coefficient values for $H_{\max}$ = 2 m are shown in table 4.4. In all cases this was >0.9 showing that both equations provide a good approximation. However, on average eq. (4.13) provided a slightly better fit and so was chosen to be used as the RER-2 expression. The final lookup tables of values for c_{t_1} and c_{t_2} are given in appendix E.

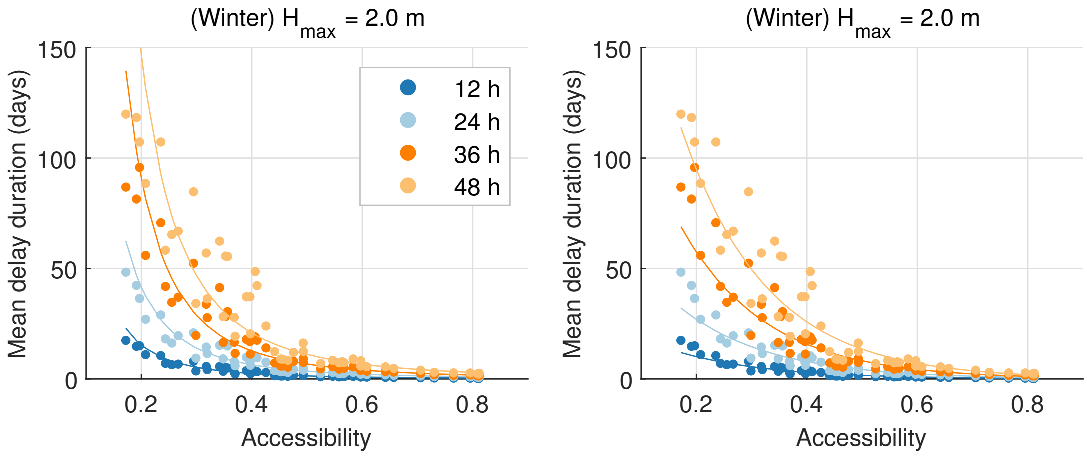


Figure 4.6: Winter delay duration versus accessibility for $H_{\max} = 2\,\mathrm{m}$, with the regression results indicated by the line. Left) Using eq. (4.12). Right) Using eq. (4.13).

Table 4.4: Regression coefficient (R^2) results for the two candidate expressions using the $H_{\max} = 2\,\mathrm{m}$ datapoints. Where $\mathrm{R}^2 = 1$ is a perfect fit.

Option 1: eq. (4.12)			Option 2: eq. (4.13)		
t_{ww}	Summer	Winter	t_{ww}	Summer	Winter
12 h	0.94	0.96	12 h	0.98	0.95
24 h	0.94	0.95	24 h	0.98	0.94
36 h	0.95	0.94	36 h	0.98	0.93
48 h	0.96	0.91	48 h	0.98	0.92

4.4 Results

The results section is split into two parts. Firstly, results are shown from a comparison made between the occurrence matrices generated using RER-1 and a number of other reference datasets. The purpose of these results was to verify the accuracy of the module. Secondly, results are shown from an investigation into the impacts of an increasing site power level on the outputs of the module. The purpose of these results was to examine the relationship between optimum location and optimum WEC and also to demonstrate the module functionality. In particular, its flexibility for providing generic characteristics for high and low energy sites.

Included in the results are values for annual incident energy and annual absorbed energy. Incident energy refers to the wave energy incident on the WECs active width (see section 1.1), absorbed energy is then the energy that is absorbed and then passed to the PTO subsystem. Absorbed energy was calculated for two WECs types, described by their absorption efficiency at different wave periods fig. 4.7. The curves are characteristic of a WEC operating in the surge direction and a WEC operating in the heave direction (fig. 1.2). In this case, both WECs have a 15 m active dimension. The computation of these curves is described in chapter 5.

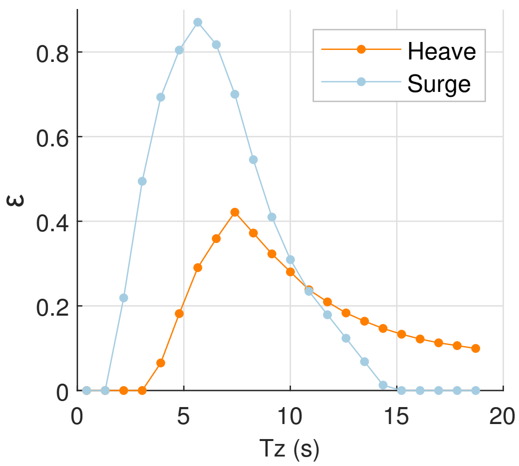


Figure 4.7: Absorption efficiency of a 15 m WEC operating in surge and a 15 m WEC operating in heave, used to calculate absorbed energy.

4.4.1 Comparison to Other Site Data

A comparison was made between the occurrence matrices generated using RER-1 and a number of other reference datasets. Table 4.5 provides the percentage difference between incident energy values calculated from a number of reference occurrence matrices and from occurrence matrices that were output from the resource module using the same zone and value of power level. Also given is the percentage difference in absorbed energy calculated for the heave WEC. Six of the reference matrices were made using the GWS database (BMT, 2018) for the areas corresponding to zones A to F. Another five reference matrices were taken from the Aalborg LCoE tool[2] (Chozas et al., 2014).

Table 4.5: Comparison of output using RER-1 with Global Wave Statistics (top) and occurrence matrices from the Aalborg LCoE tool (bottom).

Area	Zone	$\bar{P}_{\text{site}}$ (kW/m) ref./model[1]	Incident energy (% diff.)	Absorbed energy (% diff.)
GWS area 4	A	43.23/47.75	10 %	3 %
GWS area 11	B	27.94/28.16	1 %	2 %
GWS area 9	C	73.75/77.11	5 %	6 %
GWS area 10	D	33.78/36.07	7 %	14 %
GWS area 17	E	47.17/51.18	9 %	11 %
GWS area 16	F	69.19/75.36	9 %	16 %

Site	Zone	$\bar{P}_{\text{site}}$ (kW/m) ref./model[1]	Incident energy (% diff.)	Absorbed energy (% diff.)
Denmark: North Sea 2	B	11.13/10.83	12 %	7 %
Ireland: Belmullet	C	71.19/75.14	6 %	15 %
England: Wave Hub	D	16.07/21.38	33 %	16 %
France: Yeu Island	E	24.76/27.21	10 %	11 %
Portugal: Pilot Zone	F	19.66/21.44	9 %	0 %

[1] The model value is the power level calculated using RER-1.

[2]The LCoE tool provided no data for zone A.

Generally, the module performed better when replicating the GWS matrices than for the matrices taken from the LCoE tool. This is expected as the GWS is also based on the same type of joint-PDF. However, differences of >10 % in absorbed energy can be seen for zones D, E and F.

For the matrices provided in the Aalborg LCoE tool the largest difference between the amount of incident energy is for Wave Hub which is a lower energy site with water depth of around 50 m. The PDF and its parameter values were based on deep water reference sites meaning it will work less well in shallow water. Again, differences in annual absorbed energy were reduced in cases where the WEC was not well matched.

Also given in table 4.5 is the input power level and the power level calculated from the output occurrence matrix. Errors of up to 7 kW/m were exhibited for both the GWS and LCoE tool matrices. This error is a result of the linear assumption for RER-1, which did not provide a close fit to the reference data in some cases.

Examples of the reference and output matrices are shown in fig. 4.8 as overlaid contour plots. The plots suggest that most of the poor agreement is due to a shift of the most prevalent sea states to longer wave periods in the resource module output. It should be noted that the magnitude of the difference in the absorbed energy value depends on the efficiency curve of the WEC because this can have the effect of either enhancing or lessening the impact of this shift.

For example, fig. 4.9 shows the same Portugal Pilot Zone results but as matrices that have been summed across the significant wave heights to give the distribution of wave period only. The absorption efficiency of the heave WEC is also plotted to show how it corresponds to wave period prevalence. For the real data, the WEC is well matched to the most prevalent wave periods. However, in the resource module output the WEC is less well matched due to the shift to longer periods. Therefore, the difference in the annual absorbed energy values is reduced to 0 %.

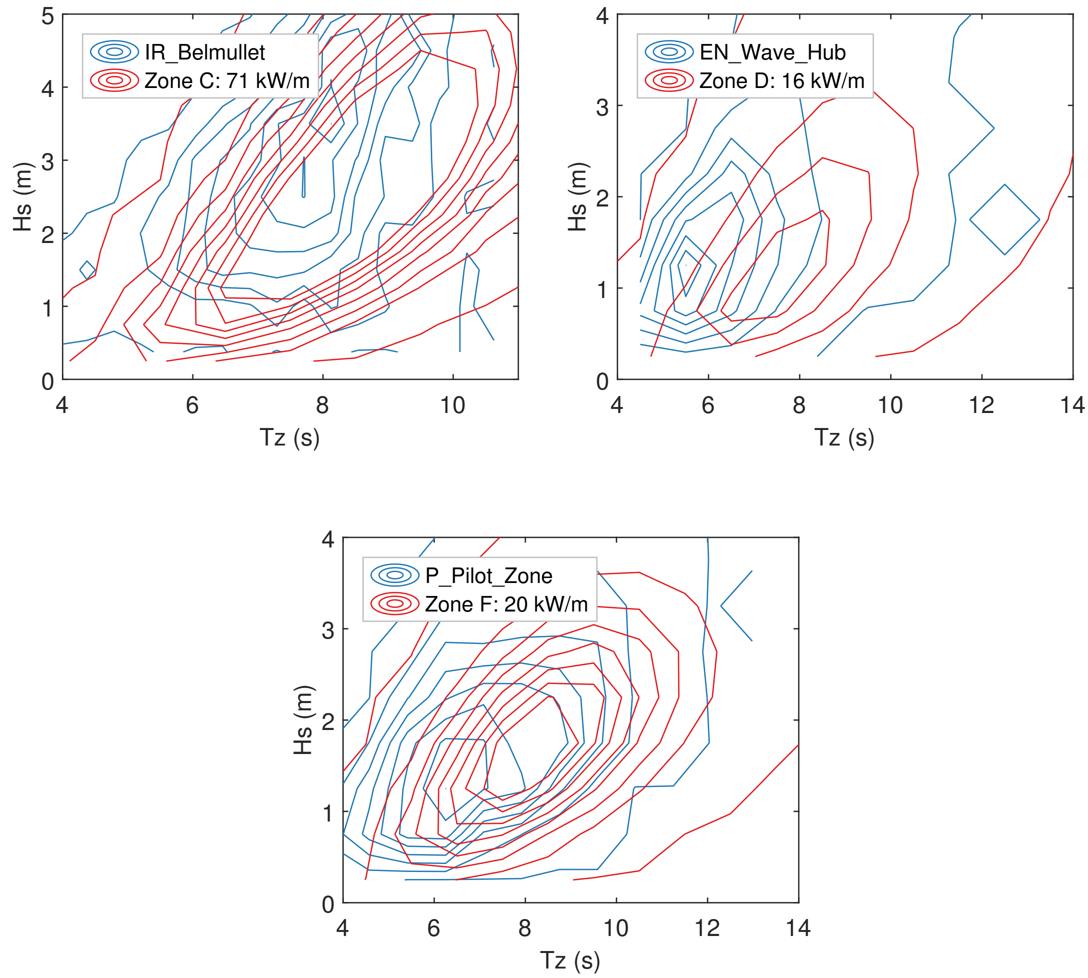
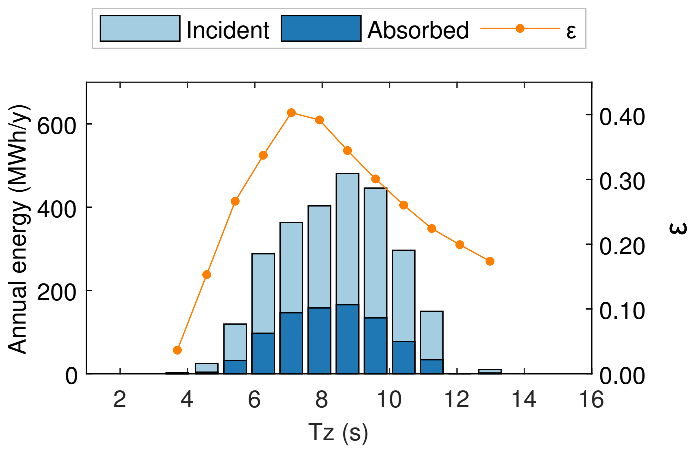
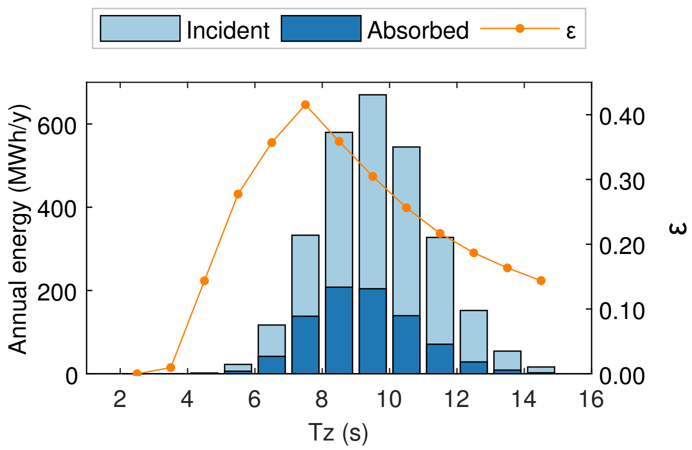


Figure 4.8: Actual occurrence matrices (blue contours) and occurrence matrices output from the resource module for matching zone and site power level (red contours).



(a) Portugal Pilot Zone.



(b) Resource module output.

Figure 4.9: Annual distributions of incident energy in terms of wave period for the Portugal Pilot Zone ($\bar{P}_{\text{site}} = 19\,\text{kW/m}$, zone F) and absorbed energy for the heave WEC, in comparison to the output from the resource module. Note that the slight differences in the efficiency curve is due to interpolation method used in the module.

4.4.2 Output from the Resource Module

The second set of results are from an investigation into the impacts of an increasing site power level on the outputs of the module. Figure 4.10 shows the evolution of the significant wave height distribution with increasing power level in zones C and F. The general trend is the same for both plots, with increasing power level there is a greater spread of occurrences and more occurrences of higher waves. Consequently, the spread of wave periods and the prevalence of longer wave periods also increases. However, the rate of this evolution is more pronounced in zone F with a bigger difference between a 30 kW/m site and 80 kW/m site.

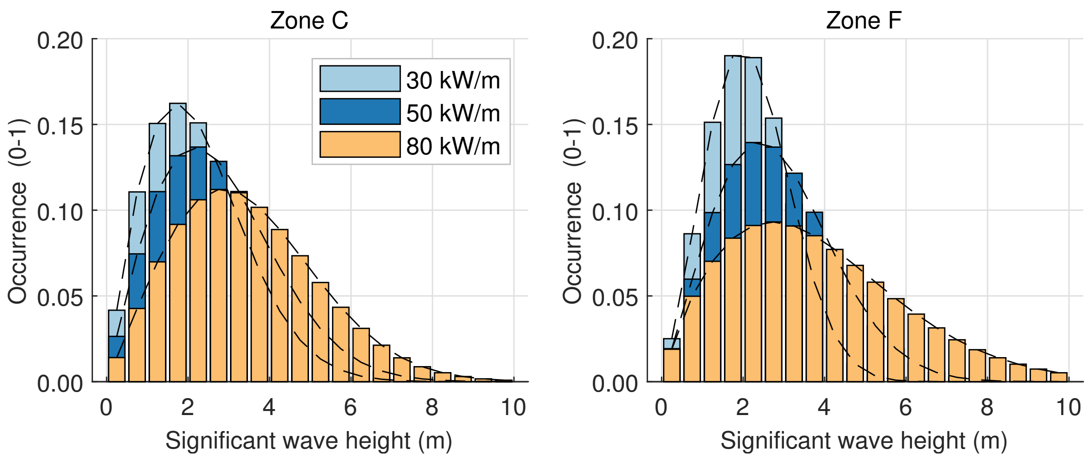


Figure 4.10: Weibull distribution of H_s for three power levels in zone C and zone F.

This also has implications for the 50-year extreme wave (fig. 4.11). In zone F there is an increasing rate of increasing in extreme significant wave height with increasing power level, whilst in zone C the rate of increase stays relatively constant, corresponding to the trends seen in fig. 4.10.

Also plotted in fig. 4.11 is the maximum significant wave height seen in the data for the 50 reference sites. Comparison of the data with the modelled results suggests that RER-1 produces a probability distribution that under predicts the 50-year wave. Most of the datasets exhibit a higher value of significant wave height within their 10-year record. This is likely due to errors in fitting the PDF and the accuracy of eq. (4.7) for approximating the 50-year wave.

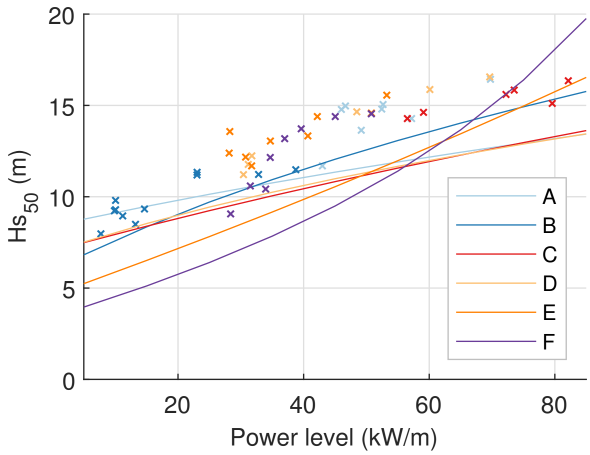


Figure 4.11: Extreme significant wave height versus site power level for each zone with a return period of 50 years. Crosses mark the maximum values from the 10-year data for each of the 50 reference sites.

The data plotted in fig. 4.12 shows the mean delay time for zone C in the summer and winter. There is a big difference between the two seasons and between the values of maximum wave height and weather window duration. Older vessel operating limits are around 1.5 m but newer vessels can operate in up to 3 m wave heights (O'Connor et al., 2013c). For a site with $\bar{P}_{\mathrm{site}} = 50\,\mathrm{kW/m}$, the average delay caused by waiting for a 24-hour window of H_{max} 1.5 m is four days in summer and 25 days in winter. For the same site, but with a H_{max} of 3 m, the mean delay time drops to <1 day and 2 days for the summer and winter respectively. Extremely long delays show that the operating limits of the vessel are not compatible with the characteristics of the site.

Figure 4.13 shows annual values of incident and absorbed energy for both the heave and surge WECs in higher (90 kW/m) and lower (20 kW/m) power level sites and in each of the six zones. The potential amount of annual absorbed energy at the high energy sites is as much as five times as at the low energy sites for the heave WEC and eight times for the surge WEC.

For the lower energy sites, the surge WEC performs better in all the zones with the greatest differences between the two WECs in zones A and B. This is as expected

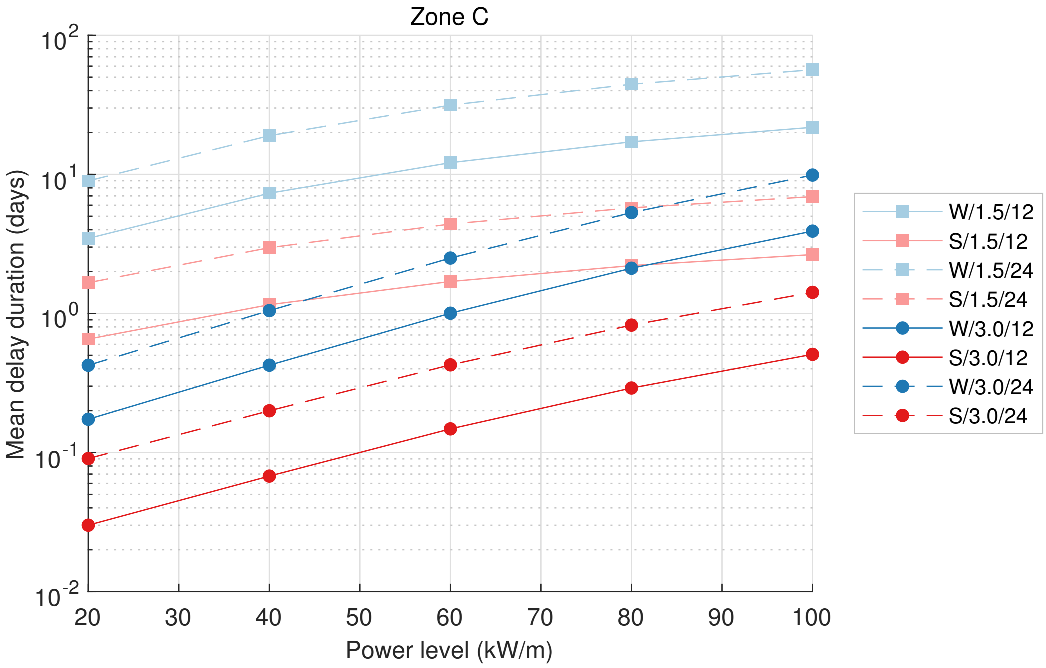


Figure 4.12: Mean delay durations versus site power level for zone C. Results shown for summer (s) and winter (w), for two values of weather window duration (12 h and 24 h) and for two values of maximum operating wave height (1.5 m and 3.0 m).

because the surge WEC has a much greater peak efficiency, which also corresponds to a shorter wave period (fig. 4.7).

For the higher energy sites, the surge WEC performs much better than the heave WEC in zone F where it performs best overall. On the other hand, the heave WEC performs better than the surge WEC in zone A. The performance is similar or the same in the other zones, despite the difference in peak efficiency.

The best performance of the heave WEC is the higher energy site in zone B, however, as previously mentioned, this scenario is unrealistic as zone B represents the North Sea where maximum values of power level in the reference data were much lower than 90 kW/m (table 4.1). Taking this into account, zone F is the best for higher energy sites and zone A is the best for lower energy sites, in terms of the annual energy capture of both WECs.

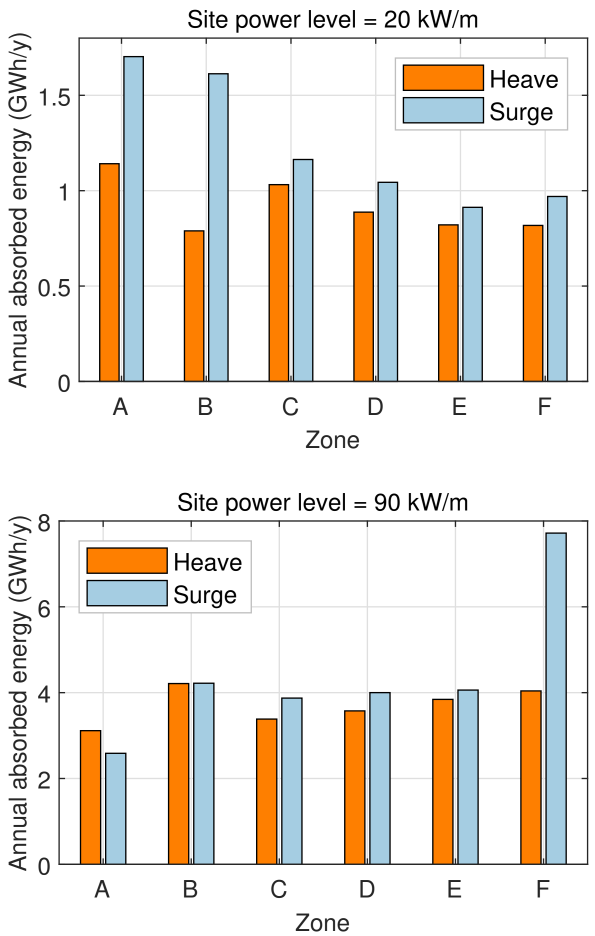


Figure 4.13: Annual absorbed energy for the heave WEC and surge WEC, in high and low power level sites in each of the six zones.

4.5 Discussion

The results demonstrate how the resource module method can be used to provide generic and adaptable resource and site characteristics from a limited number of inputs. This was the first objective identified with the research question (section 1.3) to allow for the low-TRL evaluation of WEC concepts in a deployment context.

The uncertainty in using RER-1 to generate the resource data was explored in the first set of results. The results suggest that RER-1 works similarly for locations in each zone. An error of ±15 % is seen for deep-water sites, based on the difference in the values of annual absorbed and annual incident energy between the RER-1 generated matrices and the matrices chosen for comparison. This seems reasonable given that the inter-annual variability between occurrence matrices representing a single year can be around 20 % (Dalton et al., 2012). However, for nearshore sites the error for RER-1 is likely to be increased, although it is not possible to estimate a value for this from these results.

This approach to providing generic resource data, which is used in the concept generation and evaluation tool, is sufficient for establishing the fundamental relationships that can be used to rule out certain WEC concepts in certain scenarios. A method for validating RER-2 is also required and is the subject of further work.

The second set of results looked at the output of the resource module and investigated the impact of changing site power level. There was a difference in the evolution of sea state distribution with increasing site power level between the different regions and this has potential implications for the profitability of wave energy projects and for the optimum siting of certain WEC types.

The potential impact on cost is shown by the results for extreme wave height and mean delay duration. The results suggest that there may be optimums for power level in terms of cost per unit of power output in certain scenarios and for certain technologies. However, the amount or energy captured increased by up to a factor of five between the low (20 kW/m) and high (90 kW/m) energy sites. Therefore, any optimum will depend on the sensitivity of lifetime expenditure to these factors.

In particular, the structure and station keeping cost centres are affected by the size of the extreme wave used to determine ultimate loads. The PTO cost is affected by extremes during normal operation, assuming that the absorption of the largest waves is avoided. An important consideration, is whether bulk production of a commercial WEC implies a design based on global conditions, or whether cost savings can be made by tailoring WEC designs for specific sites.

The results show that significant delays to installation and O&M operation could occur as a result of adverse weather conditions. Using RER-2 produces a big difference in delay duration of up to two orders of magnitude between the range of seasons, weather window durations and maximum significant wave heights that were tested.

This is likely to have a large impact on LCoE as vessels will have to be chartered for longer (Tecnalia, 2017; Frost et al., 2018). In addition, the delay also impacts on the length of downtime experienced by a WEC after failure, reducing the annual energy output. The sensitivity of LCoE to the maximum significant wave height parameter is presented in section 5.3.3.

Two other factors, that are important for estimating costs, are the water depth and distance to shore. Site power level is related to these parameters and they cannot realistically be treated as mutually independent from one another. Therefore, it was decided that these parameters would be estimated from each other to generate more realistic scenarios for cost calculation. The method for estimating depths and distances was based on the reference sites used in this chapter and is explained in appendix F. A sensitivity analysis of both parameters was conducted and is presented in section 5.3.3.

The results for annual absorbed energy suggested that a surge WEC was better than the heave WEC in low energy sites and the same or marginally better in high energy sites for most of the zones. However, the method for calculating energy capture neglects the effect of depth on the type of wave. WECs operating in surge are better suited for nearshore and shallower water depths for the reasons described in appendix F. In addition, they are more directionally dependent and this can limit energy capture in higher energy sites where there is likely a greater spread of incoming wave directions.

These results highlight the importance of matching WECs design to wave climate, with particular regards to the mode of extraction, and for considering the resource-WEC interdependence in concept evaluation. Potentially, this sensitivity of performance to wave climate could limit the widespread roll-out of one type of technology and consequently limit the cost reduction that is typically associated with increased deployment.

4.6 Chapter Conclusions

This chapter outlines the development of a resource module that generates generic and flexible resource data from a subset of single value inputs. This is part of the deployment context required to evaluate the versatility of WEC concepts and one of the objectives identified with the research question (section 1.3).

The results demonstrate how the chosen method can be used to compare different WEC types in different regions and in high and low energy sites. The key messages from the results and discussion are as follows:

- ▷ The accuracy of the resource module for providing values of annual incident energy and absorbed energy was found to be reasonable: ±15 % in comparison to real data and data generated through the GWS database.
- ▷ Using the resource module gives results showing that the difference in the wave climate between high and low energy sites is zone dependent and this impacts on factors that influence the optimal WEC design in terms of energy capture.
- ▷ Consequently, a scenario may be unprofitable for one WEC type but not for another. This limits the scope for widespread deployment of one WEC type and has likely implications for deployment driven cost-reduction.
- ▷ Results were provided that compared two WEC types. The surge type WEC performed better than the heave type WEC in low energy sites, whereas, performance

was mostly similar for both WECs in the high energy sites. However, surge type WECs are typically depth and distance from shore limited.

▷ The evolution of the sea state distribution with increasing site power level also impacts on cost factors such as the extreme significant wave height, where the rate of increase depends on the regional zone.

▷ The module provides estimates of delay duration as a result of adverse wave conditions. There are significant differences in the output delay durations between seasons, weather window durations and in particular, for vessels with different maximum significant wave heights. This could have a large impact on lifetime expenditures and LCoE.

▷ Other important cost drives are the water depth and distance to shore, factors that are not independent of each other or of the site power level. A method for estimating both parameters is suggest in appendix F.

▷ There is a difference in energy capture between low and high energy sites and the sensitivity of lifetime expenditure to these factors will dictate whether optimum site power levels exist.

The next chapter discusses how the outputs from the resource module are used in the WEC evaluation methodology to provide values of produced power, capital cost and operational cost. Results are presented that show the impact of changing site power level and WEC scale on LCoE, continuing the analysis presented here. A sensitivity analysis of the input deployment parameters is also provided.

5. Performance, Initial Cost and Reliability Modules

This chapter covers the development of performance, initial cost and reliability modules that are used to evaluate WEC concepts in the techno-economic model. The second objective identified with the research question (section 1.3) was to develop a model that can be used at low TRL and that allows for a continuous parameter space to be explored.

As outlined in section 3.2, the main component of the commercial attractiveness score is a value for LCoE. This was chosen as it is an already familiar metric within the sector and the arithmetic is widely employed in the literature, however, calculating LCoE at low TRL is non-trivial. Therefore, it was decided that the tool need only to provide a sufficient comparison of concepts despite the lack of certainty (relative rather than absolute values of LCoE) and that methods were required to reduce complexity with a focus on the most fundamental relationships that govern LCoE.

The rest of this chapter is split as follows.

- ▷ Section 5.1 provides a review of techno-economic assessment methods from the literature. The purpose of this section is to identify how assessment can be tailored for the lack of known information at an early design stage.

- ▷ Section 5.2 provides an overview of the WEC evaluation methodology used in the tool. This is divided into subsections corresponding to the three modules: performance, initial cost and reliability.
- ▷ Section 5.3 presents a selection of results that demonstrate the calculation of LCoE for two base case WECs. This is followed by results from an investigation into the impact of WEC scale and site power level on LCoE.
- ▷ In section 5.4 a discussion of the results is provided and the chapter ends with concluding remarks in section 5.5.

5.1 Early Stage Cost Assessment

At the earliest stages of design, cost estimation is crucial for guiding development and for indicating whether a design is worthy of further investment, yet the number of assumptions needed to estimate cost is at its highest. This paradox has led to the development of cost estimating methods despite design detail unknowns. Several of these methods are discussed here.

Ship yards use quick cost estimates when competing for ship building contracts (Caprace et al., 2012; NAVSEA, 2005; Ross, 2004). A top-down approach is based on a subset of primary ship characteristics that can be approximated at the start of the development process. This might include the hull surface area, power rating of the energy generating systems or the block weight, a representative quantity based on a simplified ship profile. Costs for new ships can be estimated by adjusting the known costs of a similar ship according to the difference in these characteristics (Son et al., 2011). The magnitude of the adjustment is calculated using a Cost Estimating Relationship (CER) (fig. 5.1) (Leal, 2008).

For example, to give manufacturing cost, the total number of man hours are estimated from the ships block weight using a linear CER with units of hours per tonne, in addition to a complexity factor (Leal, 2008; Caprace et al., 2009).

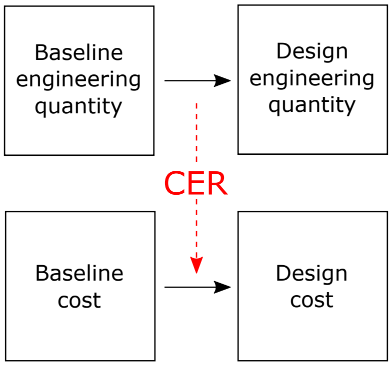


Figure 5.1: The top-down cost estimation approach.

For offshore wind, whole-lifecycle parametric models have been established (Fingersh et al., 2006; Shafiee et al., 2016; Ioannou et al., 2018). Due to the relative homogeneity of wind turbine design, cost estimates can be made on the basis of archetypal design parameters, such as hub height, rotor radius and rated power (Ioannou et al., 2018).

Fingersh et al. (2006) provided a more detailed cost model with expressions for individual turbine components, and separate calculations of manufacturing and material costs. However, for most studies the flexibility for turbine design parameters is limited. More typically, turbine cost is used as an independent, fixed input, with a focus instead on Balance of Plant (BOP) and operational parameters (Castro-Santos et al., 2014; Shafiee et al., 2016).

The parametric expressions used in these studies have been established through regression of known datapoints: either historical examples or results from numerical simulation (Rahmdel et al., 2016). The confidence in a cost value estimated using a parametric model is the combination of the confidence in the parametric expression and the confidence in the quantities used as independent variables.

Credible parametric expressions can be used as design guidelines for future development. Unfortunately however, wave energy does not have numerous historic examples on which to base these relationships. The few attempts lack the granularity required to freely explore the concept parameter space (e.g. Astariz et al., 2015). Until future development builds the required knowledge other methods for establishing low-TRL techno-economics are required.

A typical approach is proportional evaluation of cost centres. For example, OpEx is commonly calculated as a % of CapEx (O'Connor et al., 2013a; Dalton et al., 2009). Although the sector has experience of full-scale ocean deployment, these estimates are highly uncertain and often outdated[1] (Teillant et al., 2012).

There is also a lack of consistency. O&M, can be defined as a percentage of WEC CapEx, project CapEx or of total lifetime expenditure, with significant differences in the chosen value (e.g. 1 % to 8 % of project CapEx) (O'Connor et al., 2013a). This means that's results are easily manipulated. In O'Connor et al. (2013a) positive results were only achieved using an annual O&M cost of <3 % project CapEx[2].

Other studies use proportionality to calculate the cost of WEC subsystems. For example, de Andrés et al. (2017b) applied a percentage breakdown of cost centres to determine a budget for wave energy developers. The breakdown is based on values presented in the literature, including a report from Carbon Trust (2011), which provided the contribution of cost centres to LCoE at 10 MW of installed cumulative capacity (fig. 5.2). Although this can be a useful approach for highlighting areas of most importance for R&D, it is highly uncertain given the low TRL status of the technology and lack of design convergence. Other factors such as the price of raw materials (Dalton et al., 2009), and the rate for learning driven cost reduction (MacGillivray et al., 2014) add to this uncertainty.

Alternatively, variations in cost components have been calculated scientifically from changes in device scale by using Froude scaling (Chozas et al., 2014; O'Connor et al., 2013b; de Andrés et al., 2016). The Froude number is a dimensionless ratio of inertial to gravitational forces. By assuming that Froude number is kept constant, changes in force, velocity and power can be calculated from changes in device scale, which can then be used to calculate the changes in power capture and costs. Therefore, both this method, and the use of percentage based cost centres, require some base or reference value.

[1] Often older reports are used of of specific WEC types (e.g. Previsic, 2004)
[2] for a 75 MW farm with discount rate 6 % and 15-year lifetime

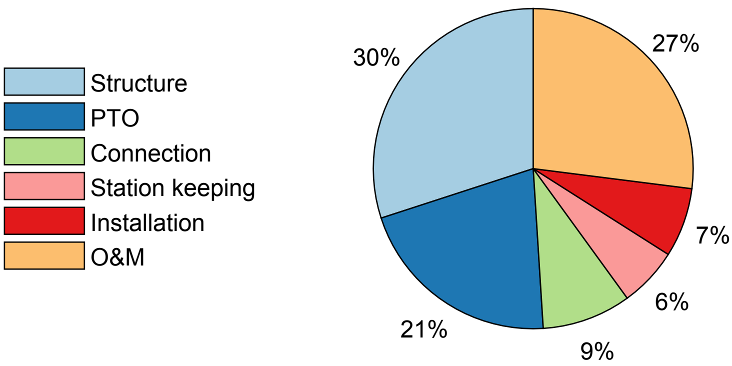


Figure 5.2: Breakdown of WEC cost centres as % of total expenditure (Carbon Trust, 2011).

In Teillant et al. (2012) the uncertainty surrounding certain values is included in the modelling of operations. Unknowns are generated stochastically with a variability of ±50 %. These include values for hourly vessel rates, material unit costs, equipment costs and repair durations. The model is then run many times over, providing a range of possible results for each iteration. Although, the sensitivity of the results is significant, general trends can still be established and used to identify important drivers of LCoE.

In Thies et al. (2009), component failure rates were adjusted depending on differences in environmental conditions and operating application. This is based on an approach used in naval applications (DoD, 1991) and is the method adopted in Rinaldi et al. (2018). Although these adjustments can be crude, Thies et al. (2009) argued that they are necessary for modelling WEC reliability due to the sheer lack of directly applicable data. The magnitude of the adjustment was based on a qualitative adjustment and tended to lead to a pessimistic outcome. A more quantitative approach could be used. For example, by comparing loading cycles and their frequency.

Thies et al. (2009) also suggested that an adjustment for the source data quality be used. This is similar to other studies that adjusted values for established technologies to account for the immaturity of new technologies. For example this is used for modelling failure events (Tecnalia, 2017) and for calculating availability based on site conditions (O'Connor et al., 2013b).

During the Wave Energy Prize (U.S. DOE, 2015), the challenge of assessing diverse WEC types at low TRL was addressed by using a simplified set of high-level parameters (see ACE metric, chapter 2). This included representative quantities which were evaluated by expert judgement. For example, a representative structural thickness parameter was used to scale material mass based on numerical model observations and tank testing (Jenne et al., 2017).

Although often notional, these methods can provide an understanding of the fundamental drivers of cost reduction. A parametric approach can help to reduce complexity and the level of information required and was employed in this work. When only limited data is available, interpolation or extrapolation of the data cannot be performed in confidence and crude adjustments are typically required. However, even at low TRL and with limited confidence, the mapping of the parameter space can help to identify potential trade-offs and design optimums. Important for the sector is transparency in the approach used, and the continued improvement of models as more datapoints become available.

5.2 Module Methodologies

The WEC evaluation is dealt with by three modules for performance, initial cost and reliability. Each of the modules deals with major components of the cost of energy and the outputs are used to calculate the commercial attractiveness score (section 3.2).

This section covers each of these modules in turn. A base case input scenario (see chapter 3) was used to generate results. The base deployment parameters are given in table 5.1 and the base WEC parameters are given in table 5.2. Figures for the base scenario are provided throughout the methodology as examples of the evaluation procedures.

The parameters describing the site and resource were chosen to be roughly representative of the Irish Atlantic Coast using the approximate relationships for depth and distance specified in appendix F. The corresponding occurrence matrix for the site, as output from the resource module, is given in fig. 5.3. The equation used to calculate LCoE is given in section 3.3. The sensitivity of LCoE to the deployment parameters, discount rate and project lifetime is tested in section 5.3.3.

Table 5.1: Base case deployment parameters.

Input parameter	Base value	Input parameter	Base value
Zone:	C	Power level ($\bar{P}_{site}$):	40 kW/m
Distance to shore (d):	26 km	Farm capacity (P_{array}):	10 MW
Water depth (h):	103 m	Max. vessel H_s (H_{max}):	2 m

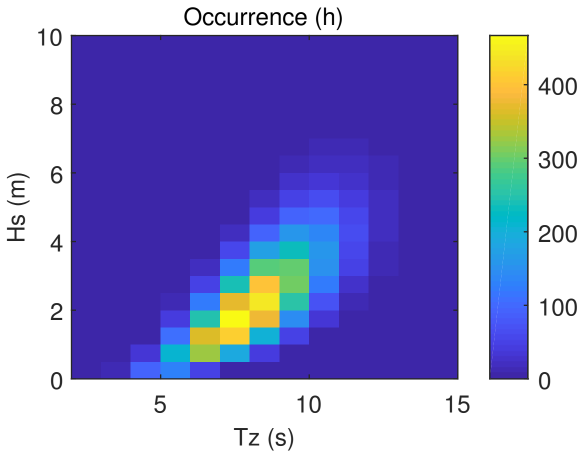


Figure 5.3: The occurrence matrix produced by the resource module for the inputs given table 5.1. Represents an annual available energy of 372 MW h/m

Table 5.2: Base WEC parameters.

Input parameter	Base value
Active width (L_a):	10 m
Geometry:	heave WEC (table 5.7)
Primary material:	steel
Absorption efficiency (ε):	heave WEC (fig. 5.16)
Rated power (P_{WEC}):	90 % absorbed power
Max. conversion efficiency (η):	80 %
Part-load performance (k):	1
Operating limit ratio (r_{max}):	1
No. mooring lines (N_{mor}):	3

5.2.1 Performance

In the model, WEC performance is represented by a power matrix where the value of each cell is the power produced in the corresponding sea state. This is the typical approach used in the calculation of WEC energy production (BSI, 2012). The power matrix is built in four steps which are described in detail later in this section. In summary they are as follows:

1. Calculate amount of absorbed power.

   To calculate the amount of absorbed power an adsorption efficiency (ε) is applied. This is modelled as a function of wave period and describes the ratio of incident wave power to the power passed to the PTO subsystem. Alternatively, it can be thought of as the absorbed-percentage width of the incoming wave front.

2. Calculate rated power.

   The PTO power rating (P_{WEC}) is selected to give an 90 % probability of absorbed power being below that value. Therefore, it is dependent on the distribution of sea states provided by the resource module.

3. Calculate amount of produced power.

   To calculate amount of power produced by the WEC, a mechanical-electrical conversion efficiency (η) is applied. This is a function of the ratio of absorbed power to rated power and of a part-load performance parameter k.

4. Apply operating limit.

   A typical feature for WEC design is an operating limit beyond which power production is stopped and damaging loads are avoided, determined by some control mechanism. In the model an operating limit ratio parameter ($r_{\max}$) is used to calculate this limit from the rated power.

The method is easily adaptable for different technology types and allows for the four main parameters (ε, η, P_{WEC} and $r_{\max}$) to be explored independently.

Figures 5.4 and 5.5 shows the reduction in useful power with each step for the base input parameters given in table 5.2. Levels of annual incident, annual absorbed and annual energy production are shown for each dimension of the power matrix. In this case, WEC scale is not well matched to available resource as peak efficiency does not align with the most prominent wave periods. The results is an occurrence weighted mean value of 26 % and 54 % for absorption and conversion efficiency respectively. In total, this is an 92 % reduction from the amount of energy available to the amount of energy produced before downtime and cable losses are applied.

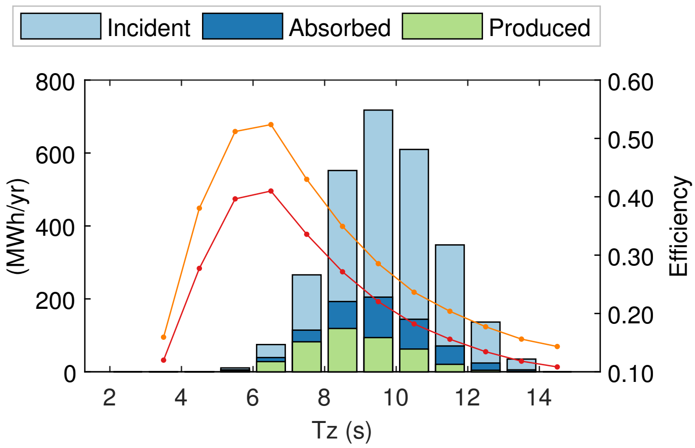
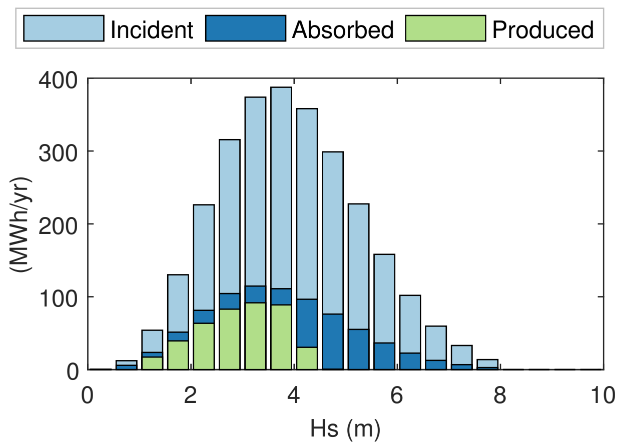


Figure 5.4: Power matrices averaged across H_s and showing the losses due to absorption efficiency (orange line) and conversion efficiency (red line).



Performance results	
Annual energy absorbed:	802 MW h
Annual energy produced:	350 MW h

Figure 5.5: Power matrices averaged across T_z and showing the effect of the operating limit on production.

Absorbed Power

The amount of power absorbed by the WEC is calculated as:

$$P_{\text{abs}} = J \cdot L_{\text{a}} \cdot \varepsilon \qquad \text{[kW]} \quad (5.1)$$

Where:
- ▷ J is the incident power flux [kW/m],
- ▷ L_{a} is the main active WEC width involved in wave energy capture [m].

Both absorption efficiency and active width parameters are characteristics of different WEC types (see section 1.1). Absorption efficiency of a WEC with a particular scale is primarily dictated by the prevalence of certain wave periods (Babarit et al., 2012).

Ricci et al. (2012) provides the relationship between absorption efficiency and wave period for five WEC types (fig. 5.6a), found using a simple hydrodynamic model and linear wave theory. The study used a non-dimensionalised wave period calculated according to the formula:

$$T^{*} = T_{\text{z}} \cdot \sqrt{\frac{g}{L_{\text{a}}}} \qquad (5.2)$$

Where:
- ▷ g is the acceleration due to gravity [m/s^2].

This allowed for performance to be scaled with WEC size assuming a constant geometry. The results indicate rules that could be used to characterise mode of operation as a more general way of specifying WEC type. For example, WECs operating primarily in surge tend to be less stiff than those operating in heave and therefore are more suited to higher frequency waves.

The other key factor that dictates optimum scale and overall performance is the width of the absorption efficiency curve, controlling how well a WEC performs over a range of periods. The peak value has a strong influence if it is well matched to the most prevalent wave conditions.

For comparison, fig. 5.6 also gives the performance of three WECs as calculated from values given in the literature. Figure 5.6a is for the Pelamis P2 device, an attenuator type WEC. This was calculated from a produced power matrix for the 2010 to 2014 period of testing at the European Marine Energy Centre in Scotland. A value for active width of 30 m was used following Babarit (2015)[3]

Figure 5.6c was calculated from the RM3, which is a heaving point absorber with an active width of 20 m (Sandia, 2014). Figure 5.6d was calculated from the performance of the Wave Dragon device in a select number of sea states with an active width of 53 m. Although the Wave Dragon is an overtopping type rather than an oscillating body, a similar dependence on wave period is observed.

Rated Power

A number of methods exist for scaling rated power. For example, in some techno-economic studies, Froude scaling is used to scale rated power with peak operational loads or other WEC dimensions (e.g. ARUP, 2018). This approach can be problematic as it implies that small changes in WEC scale should result in much larger increase in power rating (power rating scales with $S^{3.5}$ whilst length scales with S), which is not necessarily cost effective given WEC absorption efficiency.

Alternatively, an appropriate rated power can be selected based on the resulting capacity factor, calculated according to the formula:

$$\delta = \frac{\bar{P}}{P_{\mathrm{WEC}}} \tag{5.3}$$

Where:

- $\bar{P}$ is the occurrence weighted mean annual power limited by the value of P_{WEC} [kW].

In some cases, rated power is selected to give maximum capacity factor (Tecnalia, 2015). In other studies a value is chosen based on providing a capacity factor of 30 % (e.g. Sandia, 2014; Castro-Santos et al., 2015), which was a typical value for offshore wind turbines.

[3]assuming five hulls of 36 m by 4 m (Yemm et al., 2012).

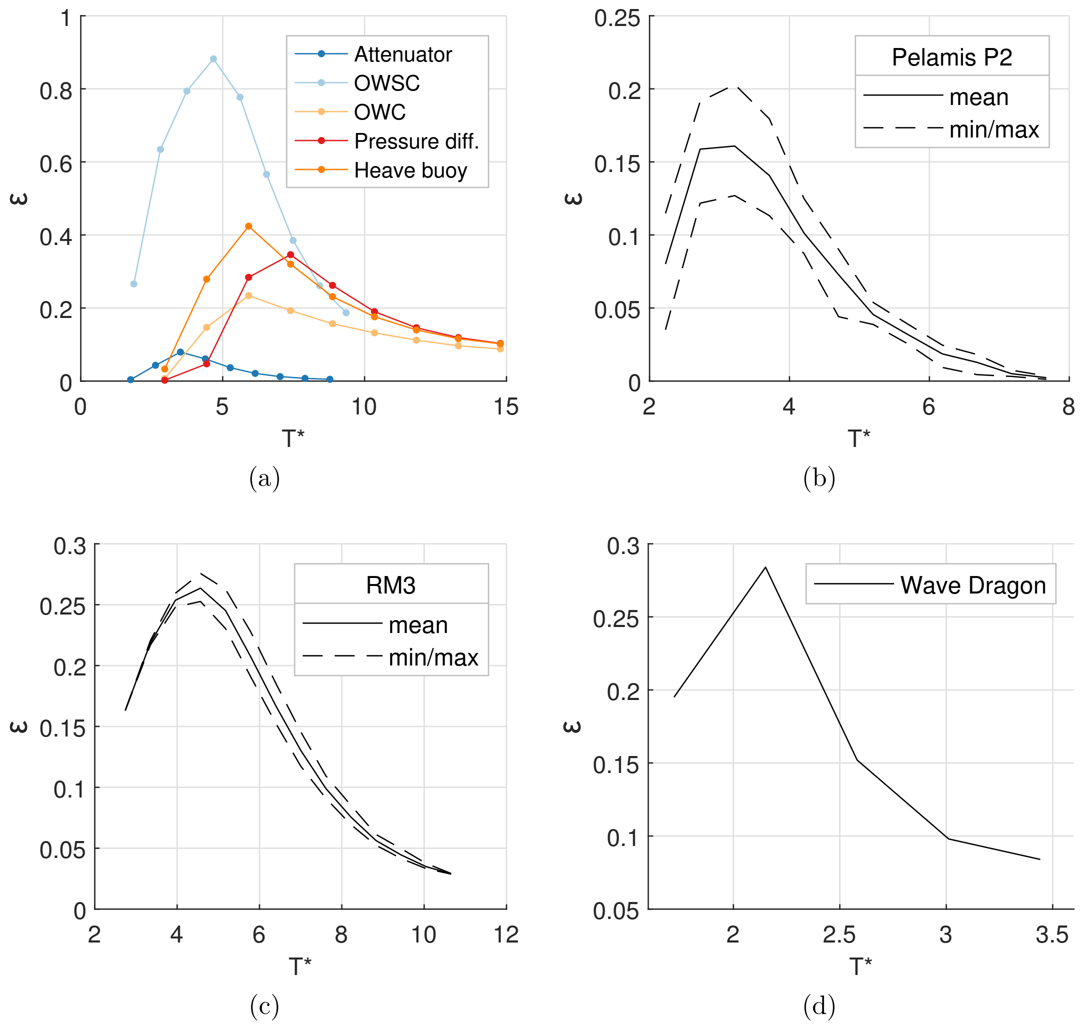


Figure 5.6:
a) Absorption efficiency for five types of WEC, from Ricci et al. (2012).
b) Absorption efficiency of the Pelamis P2 WEC, averaged across values of H_s and ignoring H_s <0.5 m (Pelamis, 2015).
c) Absorption efficiency of the RM3 WEC, averaged across values of H_s (Sandia, 2014).
d) Absorption efficiency of the Wave Dragon WEC (Kofoed et al., 2009).

The chosen method here was to select the value corresponding to 90 % of energy available or, in other words, to give an 90 % probability of absorbed power being below that value. Rated power is then dependent on the distribution of sea states as given in the occurrence matrix provided by the resource module. This typically provides a rated power that is greater than the value corresponding to maximum capacity factor. Experience suggests that rated powers that are close to the maximum level of available energy are required for good economic returns (Astariz et al., 2015). There is also a greater variation in results for different resource levels and locations using this method.

Figure 5.7 shows the relationship between rated power, probability of non-exceedance and capacity factor for the base case with values of operating limit ratio of $r_{\max} = 1$ and $r_{\max} = 1.5$. For the former, an 90 % probability of non-exceedance corresponds to a capacity factor of 25 %. For $r_{\max} = 1.5$, a capacity factor of 30 % is achieved, equating to an increase in AEP of 150 %.

This choice of method means that rated power is 200 kW in both cases. However, if the optimum capacity factor value was used then the rated power for the $r_{\max} = 1.5$ case would be lower and the impact on AEP would be reduced (when considering a single WEC).

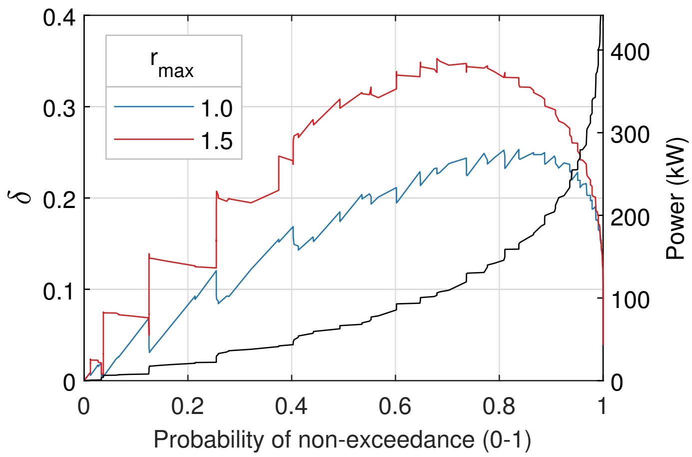


Figure 5.7: Selection of rated power by maximising capacity factor for two operating strategies governed by the $r_{\max}$ parameter. Other input parameters given in table 5.2.

Produced Power

The amount of power produced by the WEC after losses is calculated as:

$$P = P_{\text{abs}} \cdot \eta \qquad \text{[kW]} \qquad (5.4)$$

The single conversion efficiency parameter is used to represent the efficiency of the whole PTO component chain and is made up of two components. Firstly, a fixed maximum efficiency η_{max}, which is the conversion efficiency at rated power. Secondly, a variable component that reduces this efficiency at part-load, calculated as the ratio of absorbed power to rated power.

A formula for calculating the variable component is given by Hansen (2013) who compared different PTO configurations for application to the WaveStar device. This is used here[4] such that total conversion efficiency is calculated as:

$$\eta = \eta_{\text{max}} \cdot \tanh\left(11.18\sqrt{(1+k) \cdot \frac{P_{\text{abs}}}{P_{\text{WEC}}} - 0.05} - 2.5\right) \quad k = 0, 1, 2 \qquad (5.5)$$

Where:

- ▷ k is a part-load performance parameter that can take three values: 0, 1, 2.

The formula was established through analysis of typical wind turbine efficiency curves, with a reduction adjustment made to reflect the relative immaturity of wave energy technology. Figure 5.8 shows the effect of changing the value of k for $\eta_{\text{max}} = 0.8$. In each case, efficiency increases rapidly at low loads and reaches a maximum value quickly, from which point it is sustained as the load continues to increase.

For comparison, fig. 5.9 is for the Pelamis P2 (Yemm et al., 2012). It shows the part-load performance of the motor-generator that converted the power transmitted by hydraulics to electricity. The maximum efficiency was >90 % and the average efficiency was around 70 % at the test site. The part-load performance was relatively poor, indicated by the gradient of the curve at lower power output, and was similar to $k = 2$. It can be seen

[4] Modified to remove surplus terms.

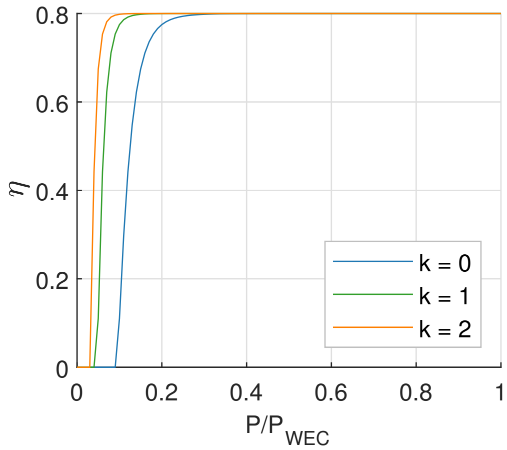


Figure 5.8: Typical load-dependent conversion efficiency.

that efficiency is not actually constant at higher loads and begins to decrease at higher power output.

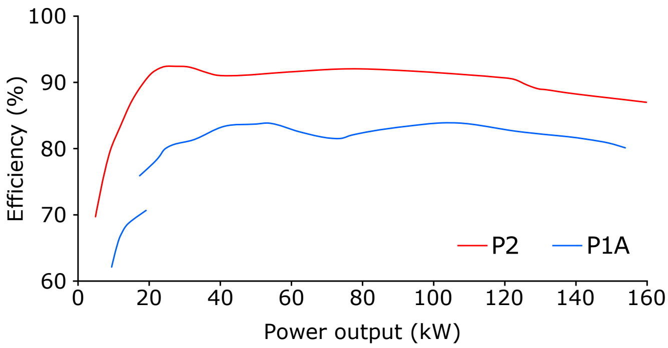


Figure 5.9: Part-load performance of the motor-generator sets in the Pelamis P2 device (Yemm et al., 2012).

Operating Limit

The final step is to adjust the power matrix by defining the behaviour above rated power. This is controlled by the parameter r_{max}, which is the ratio of a cut-out value for absorbed power to the power rating. Typically this cut-out value represents a operating limit beyond which a WEC is in survival mode where the aim of the limit is to avoid the largest loads.

The adjustment is made by applying the following limits:

▷ For $P_{\text{abs}} \geq P_{\text{WEC}}$ and $P_{\text{abs}} \leq P_{\text{WEC}} \cdot r_{\text{max}}$:

$P = P_{\text{WEC}}$

▷ For $P_{\text{abs}} \geq P_{\text{WEC}} \cdot r_{\text{max}}$:

$P = 0$

The affect of these limits is shown in fig. 5.10. This is the slice of a power matrix (power curve), produced by the model for a particular value of T_z. Between $H_s = B$ and $H_s = C$ the produced power is held constant. This implies that extra incident wave power is either avoided or dissipated through a control subsystem. The amount of time that a WEC is working and producing electricity will depend on the probability of occurrence of the working area defined by these values.

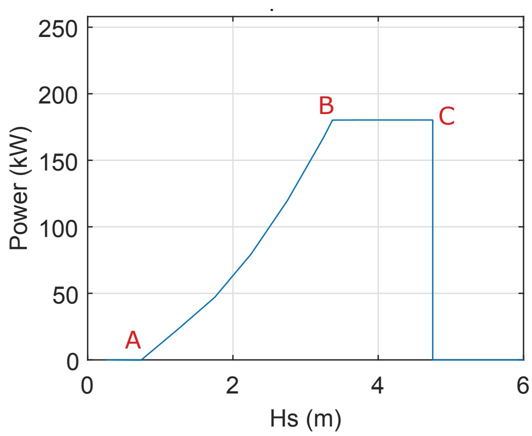


Figure 5.10: Power curve in terms of H_s for a single value of T_z. The labelled points are as follows:
A) Minimum cut-in value that is controlled by the part-load performance and calculated using eq. (5.5),
B) Rated power, P_{WEC},
C) Cut-out value (operating limit), equal to $P_{\text{WEC}} \cdot r_{\text{max}}$.

It is assumed that WEC operation is not limited by wave steepness. However, very steep sea states are represented in the supplied occurrence matrix by ≈ zero probability and have negligible impact on results.

5.2.2 Initial Cost

The initial cost module calculates five cost centres representing CapEx. These are: structure (C_{S}), PTO (C_{P}), station keeping (C_{K}), connection (C_{C}) and installation (C_{I}). The process of evaluating each cost centre is to first estimate the fundamental quantities that govern cost. Unit costs can then be applied to those quantities in order to give a total cost. The following sections describe the computation of each cost centre in more detail.

Structure

The cost of the main structure is based around the mass of the primary material and calculated according to the formula:

$$C_{\mathrm{S}} = M_{\mathrm{mat}} \cdot c_{\mathrm{mat}} + M_{\mathrm{bal}} \cdot c_{\mathrm{bal}} \qquad [£] \quad (5.6)$$

Where:

- ▷ M_{mat} is the mass of the primary material in the structure [kg],
- ▷ M_{bal} is the mass of ballast material [kg],
- ▷ c_{mat} is the primary material price [£/kg],
- ▷ c_{bal} is the ballast material price [£/kg].

For the analysis presented here the ballast material is assumed to be sand. The amount of ballast required is calculated to achieve a certain percentage volume displacement and is dependent on WEC type.

Developing an expression for a general calculation of M_{mat} was particularly challenging due to the number of influencing factors and the wide variety of possible geometries. Therefore, to simplify the problem, it was assumed that a rough value could be estimated by assuming that the amount of material required was proportional to volume and by ignoring differences in geometry whilst accepting a high degree of uncertainty.

M_{mat} is then calculated according to the formula:

$$M_{\mathrm{mat}} = \rho_{\mathrm{mat}} \cdot \phi_{\mathrm{mat}} \cdot V \qquad [\mathrm{kg}] \quad (5.7)$$

Where:

- ▷ V is the total volume of the main structure [m^3],
- ▷ ρ_{mat} is the material density [kg/m^3],
- ▷ ϕ_{mat} is the material volume parameter.

Therefore, the relationship between mass and volume is dependent on the material type and the parameter ϕ_{mat}, which represents the percentage of total volume that is occupied by the structure material. The value of ϕ_{mat} is assumed to be a function of the resource, characterised by an extreme value of H_{s}.

This approach is similar to the ACE metric calculation, which used a representative structural thickness to calculate structure mass. A dimensionless parameter is used here instead for two reasons. Firstly because, it is more acceptable than a non-physical thickness that is difficult to understand and secondly, because it makes it easier to compare existing data for a wide variety of structure geometries and scales.

Figure 5.11 shows the model that was used to generate results presented in this thesis. The corresponding values of the material volume parameter are given in table 5.3. The model was primarily based on a simple analysis of cylinder buckling, as described in appendix G. Also plotted are values taken from the literature that were calculated using the assumptions given in table 5.4. This includes the base of the Pelastar floating wind turbine, which has a relatively complex shape (Glosten, 2014). Using the model would give a mass for the Pelastar that is roughly 1 % less than the actual value.

Table 5.4: Assumed values used to calculate the ϕ_{mat} values given in fig. 5.11.

WEC	Material	Mass (t)	Vol. (m^3)	ρ_{mat} (kg/m^3)	Ref.
Pelastar[1]	Steel	1174	4033	7800	(Glosten, 2014)
RM3	Steel	674	2518	7800	(Sandia, 2014)
P1	Steel	380	1994	7800	(Previsic, 2004)
P1[2]	Steel	54.0	234[3]	7800	(Ocean Power Delivery, 2003)

[1] for $H_{\text{s}} = 8.2\,\text{m}$
[2] values for 7$^{\text{th}}$ scale prototype.
[3] based on 50 % displaced mass = 120 t.

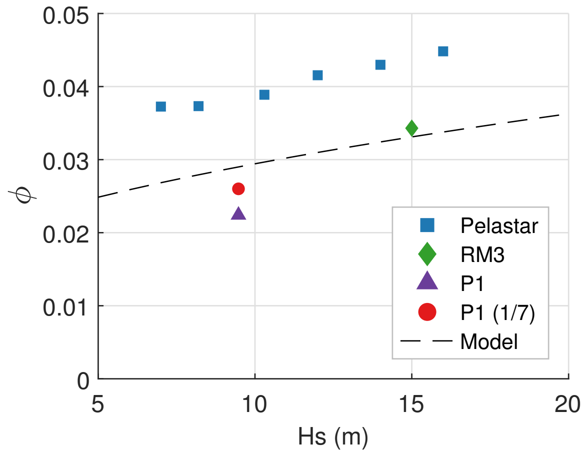


Figure 5.11: The material volume parameter as a function of resource, characterised by extreme H_s. Plotted with values for WECs that are taken from the literature (table 5.4). The design case for the Pelamis P1 devices is not clear but an 18 m extreme individual wave height is observed at the deployment location (EMEC, 2017)

.

Table 5.3: The structure mass model: ϕ_{mat} for values of extreme significant wave height.

$\phi_{mat} \backslash H_s$	5 m	10 m	15 m	20 m
Steel:	0.025	0.029	0.033	0.036

Further validation is needed to examine the relationship with extreme H_s. However, results in section 5.3 suggest that the structural cost is far more sensitive to WEC scale and that the relationship with extreme H_s has lesser importance. The value of ϕ_{mat} is also dependent on material type and this is explored further in section 6.1.

The main difficulty lies in establishing realistic geometries for the wide variety of WEC types. For example, Figure 5.12 shows the selection of the primary material volume for the base case. The geometry used here for a cylindrical heaving body (table 5.7) results in a comparatively high value of 23 m^3. This is because the outer volume is very large relative to active width. More typically designs aim to reduce the ratio of WEC volume to active width as this is considered roughly equivalent to cost per unit energy capture (Babarit et al., 2012).

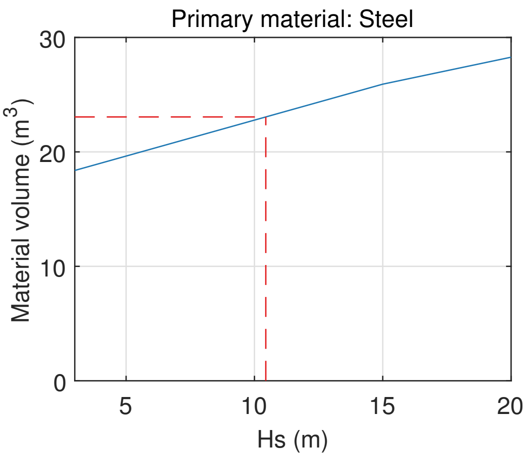


Figure 5.12: Required volume of structural material in the base case, selected according to the 50-yr extreme H_s - as indicated by red dotted line.

PTO

The cost of the PTO system is scaled linearly with WEC power rating according to the formula:

$$C_P = P_{WEC} \cdot c_{PTO} \qquad [£] \qquad (5.8)$$

Where:

- ▷ c_{PTO} is the PTO price [£/kW].

This includes both raw material costs and manufacturing cost components that can vary widely between PTO types. The physical size of the PTO will also depend on type (Hansen, 2013), and further work is needed to establish the relationships of PTO rating, mass and scale and to build these differences into the model.

Station Keeping

The model calculates a station keeping cost for a floating WEC according to the formula:

$$C_K = c_{mor} \cdot l_{mor} \cdot m_{mor} \cdot N_{mor} \qquad [£] \qquad (5.9)$$

Where:

- ▷ c_{mor} is the mooring line price [£/kg],
- ▷ l_{mor} is the length of each line [m],

- ▷ m_{mor} is the line mass per unit length [kg/m],
- ▷ N_{mor} is the number of lines.

A parametric model for catenary moorings was provided and used to calculate the total mass of the moorings. The model is described in detail by Touzón et al. (2018) and a brief summary is also provided in appendix H. Parameter values were provided for 3 to 6 mooring line configurations. A key feature of the model is that the parameters are non-dimensionalised for water depth, line weight and line length. Therefore, for any given water depth and line mass per unit length, a line length can be computed for the horizontal force F_{H} acting on the WEC.

In the analysis presented here, the horizontal force is calculated according to the formula:

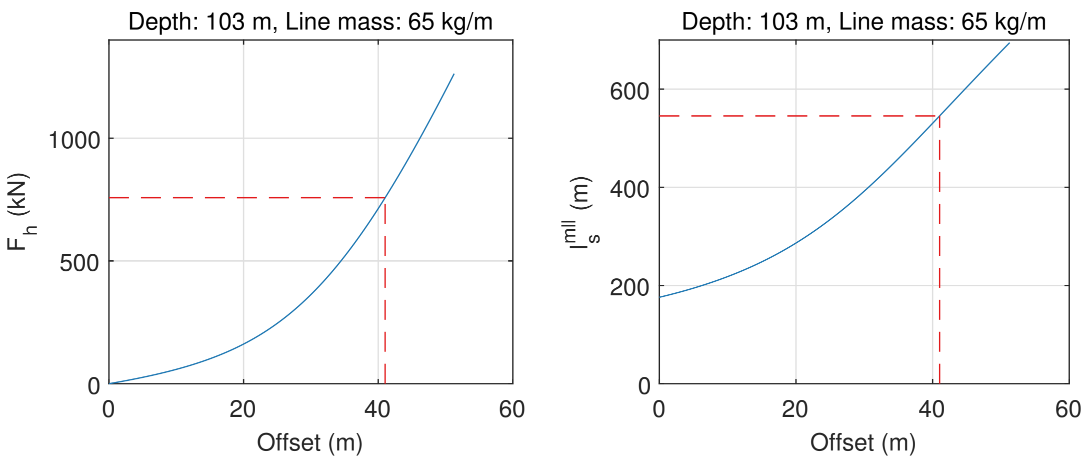
$$F_{\text{H}} = \frac{\rho_{\text{sea}} \cdot g \cdot {H_{\text{s}}}^2}{32} \cdot L_{\text{a}} \qquad [\text{N}] \quad (5.10)$$

which is the mean drift force in irregular waves, acting on the active width. This is a very simple approach that ignores wind and current forces, but one that provides a conservative[5] estimate (Pecher et al., 2017).

For simplicity all the mooring lines are assumed to be designed to the requirements of the most loaded line. The line mass per unit length is calculated from a standard mooring diameter that is selected by the model to provide the lowest total mass of the mooring system whilst meeting a design safety factor of at least 1.7 (DNV, 2015) and for a maximum offset of $0.5 \cdot d$.

The process is shown for the base case in fig. 5.13. Firstly, the horizontal force is equated to a value for WEC offset according to the specified depth and the optimised mass per unit length. Secondly, the suspended line length is found that corresponds to that offset (545 m).

[5] Based on the assumption that the object reflects all waves in the opposite direction to the incoming waves for all component waves.



(a) (b)

Figure 5.13: Process for finding the suspended length of the Most Loaded Line (MLL) mooring line for the base case. a) red dotted line shows how the horizontal force is equated to a value for WEC offset. b) red dotted line shows how a suspended line length is found that corresponds to that offset. See appendix H for more detail

Connection

For evaluating connection cost, a WEC array is modelled where the number of individual WECs is calculated to provide a fixed array capacity. The aim of this approach is to capture the impact of WEC scale on connection costs by including cable size and length in the evaluation. It should be noted that array optimisation is not a function of the model and the cable configuration is based on a likely layout scenario.

The WEC spacing is calculated as the horizontal seafloor footprint of the suspended catenary mooring lines (see appendix H). In reality a number of factors could be used to determine spacing, including O&M requirements and the effect of hydrodynamic interaction on energy yields. In several studies, the spacing is simply given as a multiple of WEC diameter, typically around 10 times the diameter (Astariz et al., 2015). This provides sufficient space for maintenance operations and avoids hydrodynamic interference (Borgarino et al., 2012; Babarit et al., 2012).

The assumed layout for the base case, in terms of the distances used to calculate cable lengths, is given in fig. 5.14. This case results in an array of 50 WECs spaced 278 m apart. This is more than 20 times the diameter of the WEC due to the its small scale and relatively deep water.

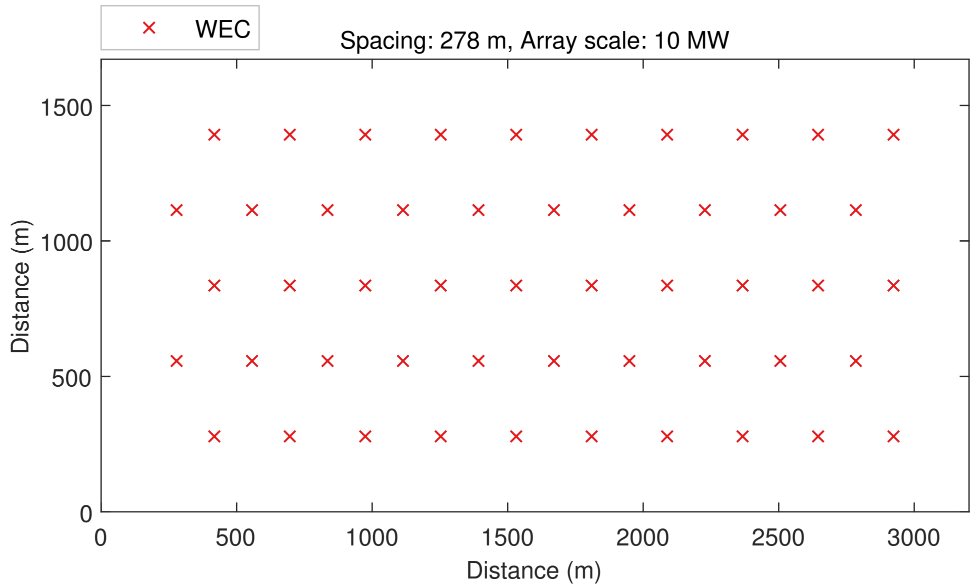


Figure 5.14: Representative array used to estimate cable lengths for the base case.

Two types of cable are considered, the export cable and the inter-WEC cables. The total connection cost (per WEC) is calculated according to the formula:

$$C_{\text{C}} = \frac{d \cdot c_{\text{exp}}}{N_{\text{WEC}}} + c_{\text{int}} \cdot l_{\text{int}} \qquad [£] \quad (5.11)$$

Where:

- ▷ N_{WEC} is the number of WECs in the array,
- ▷ c_{exp} is the export cable price [£/m],
- ▷ c_{int} is the inter-WEC cable price [£/m],
- ▷ d is the distance to shore [m],
- ▷ l_{int} is the length of the inter-WEC cable [m].

Between each WEC the length of internal cabling is calculated as the spacing plus twice the depth. This is based on the example of a radially laid out wind farm (Sharkey et al., 2011).

The values for c_{exp} and c_{int} are dependent on the Cross Sectional Area (CSA) and voltage rating of the cables. A base price is used for a 10 kV cable with CSA = 95 mm^2, which is then adjusted accordingly using the normalised values provided in appendix I and taken from Sharkey (2013).

The model selects appropriate values for CSA and voltage from the possible options in two stages. Firstly, cables are removed that do not meet the current carrying requirements of the WEC or WECs operating at rated power. Secondly, the cable is selected from the remaining options that provides the minimum increase in LCoE.

The increase in LCoE is calculated from both the cable cost and the power loss caused by the cables resistance. This approach is based on the methodology presented in Beels et al. (2011) and the cable model is described in more detail in appendix I. Once the appropriate cable has been selected, an average transmission efficiency is calculated from the total power loss and this is then used in the calculation of AEP (eq. (3.1)). Using the base case input values results in a transmission efficiency of 89 %.

Installation

The installation cost is calculated according to the formula:

$$C_{\text{I}} = C_{\text{mob}} + c_{\text{day}} \cdot (t_{\text{i}} + t_{\text{t}} + t_{\text{d}}) \qquad [£] \quad (5.12)$$

Where:
- ▷ C_{mob} is a fixed vessel mobilisation fee [£],
- ▷ c_{day} is the vessel day rate [£/d],
- ▷ t_{i} is the installation duration for the WEC [d],
- ▷ t_{t} is the travel duration for accessing the WEC [d],
- ▷ t_{d} is the delay duration due to adverse weather conditions [d].

The total duration of an installation operation is therefore variable with distance to shore and site accessability. The value for t_{d} is supplied from the resource module (chapter 4). For installations it is assumed all operations are scheduled and a summer delay is applied. Other duration values are given in table 5.6, these were used for the analysis presented in this thesis.

5.2.3 Reliability

The reliability module calculates the frequency of maintenance operations and their duration. This is then used to estimate annual O&M vessel costs for the calculation of OpEx and annual availability. The latter is applied as a percentage reduction in energy production.

Maintenance operations are modelled using a probabilistic Time to Failure (TTF) model of the project lifetime. The TTF model is described in appendix J. This is a simplified version of the method outlined in Tecnalia (2017). For each input scenario the TTF model is run 30 times and average values are used in the LCoE calculation.

An advantage of this method is that it is easily tailorable for different granularities of failure modes and effects assessment. A simple set of failure modes is used here, as the lack of reliable data, or rules of thumbs, mean that there would be little advantage in providing a more detailed assessment.

Types of Maintenance Operation

The input to the model is either a single failure rate or several component failure rates, where failure refers to any trip by a vessel to the WEC, along with their associated uncertainties. The output is a number of preventative maintenance operations and corrective maintenance operations for each year of operation.

The model assumes that preventative maintenance repairs expected degradation so that actual failure is avoided. Corrective maintenance is required when a subsystem failure occurs earlier than expected. Whereas preventative maintenance can be scheduled to match with favourable sea conditions, corrective maintenance is unscheduled, resulting in a longer wait for an appropriate weather window. This incurs both a cost and availability penalty.

An inspection rate can also be input, indicated by an uncertainty of zero such that this adds to the number of scheduled operations only. The model assumes constant failure rates throughout the lifetime of the project and that failures occur independently of each other.

Failure Modes

For the analysis presented here, only three failure modes are considered: PTO failures, other failures and inspections. Base failure rate values are provided in table 5.5, including a biannual inspection rate, and are based on several studies, the majority of which involve hydraulic PTO setups (Tecnalia, 2017; Rinaldi et al., 2018; Thies et al., 2009; Sandia, 2014; Teillant et al., 2012; Astariz et al., 2015).

A 100 % power loss was assumed in each case along with the repair durations given in table 5.6. A typical vessel speed of 12 km/h was used to calculate the travel duration from the distance to shore (Tecnalia, 2017). A separate failure rate is used for the PTO because this is typically the main contributor to annual failures. An uncertainty of ±10 % was applied to the PTO failure rate as hydraulic technology is generally considered to be mature but the wave energy application remains novel.

The total O&M operation duration includes a repair duration, travel duration and delay duration ($t_o = t_r + t_t + t_d$). Base duration values are given in table 5.6.

PTO failures arise in particular from electrical components, however the mechanical components such as gearboxes result in a greater repair duration (Tavner, 2017). This is likely to be the subsystem with the most scope for reducing O&M costs with big difference in failure rates and repair durations between different PTO configurations. More reliable data is needed to model these differences and this is discussed further in section 6.2.

O&M Cost

As with the calculation of installation cost, O&M cost is based on the cost of the vessels and is calculated by applying a day rate to the total operation duration. For preventative maintenance a summer delay duration is applied, whereas for corrective maintenance a winter delay duration is applied.

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Table 5.5: Assumed failure rate values for the analysis presented in this thesis (source provided in text). Lifetime $N_\mathrm{p}/N_\mathrm{c}$ is the number of preventative/corrective operations across the project lifetime as output from the model in the base case.

Type	λ (fail/year)	Uncertainty	Power loss (κ)	Lifetime N_p/ N_c[1]
PTO	2.50	±10 %	100 %	25/21
Other failures	0.70	±1 %	100 %	11/2
Inspection	2	-	100 %	40/0

[1] Average values for the base case after 30 runs.

Table 5.6: Assumed operation duration values for analysis presented in this thesis, where d is the distance to shore.

Duration	Value (h)
Installation (t_i)	12
Travel (t_t)	$12 \cdot d$
Repair (t_r)	6/24 (inspection/repair)

For multiple component failure rates the total O&M cost per year i is calculated according to the formula:

$$C_{\mathrm{O\&M}i} = \sum_{\lambda} N_{\mathrm{p}_i} \cdot (C_\mathrm{mob} + c_\mathrm{day} \cdot t_\mathrm{o}) + N_{\mathrm{c}_i} \cdot (C_\mathrm{mob} + c_\mathrm{day} \cdot t_\mathrm{o}) \qquad [£/\mathrm{a}] \quad (5.13)$$

Where:

▷ λ is the component failure rate [1/a],

▷ $N_{\mathrm{p}i}$ is the number of preventative operations in year i,

▷ t_o is the duration of the operation [d],

▷ $N_{\mathrm{c}i}$ is the number of corrective operations in year i, *Availability*

The annual availability is calculated as the percentage uptime and is used to adjust the AEP accordingly. It is calculated using the formula:

$$A = 1 - \left(\sum_{\lambda} (N_{\mathrm{p}} \cdot t_{\mathrm{o}} + N_{\mathrm{c}} \cdot t_{\mathrm{o}}) \cdot \kappa \right) / 365.25 \tag{5.14}$$

Where:
- ▷ κ is the percentage WEC power loss associated to the maintenance operation [%].

Figure 5.15 gives the annual availability results for the base case. Using the assumptions described above, the weather window delay time is 1 day in summer and 10 days in winter resulting in an average availability of around 95 %.

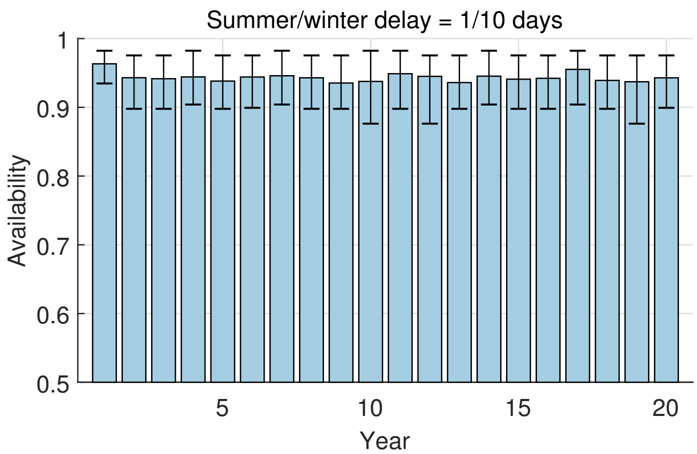

Figure 5.15: Mean annual availability for the base case after 30 runs with a lifetime average of around 95 %. Minimum and maximum values indicated by the error bars.

5.3 Results

Three sets of results are presented. Firstly, results comparing the base case heave WEC with a base case surge WEC. Secondly, results from an investigation into the impact of changing site power level and WEC scale on LCoE, continuing the investigation started in section 4.4. Thirdly, results from a sensitivity analysis of the base case deployment parameters.

The purpose of presenting these results is twofold. Firstly, to investigate whether optimums in site power level and WEC scale exist and whether they are affected by the value of other parameters. Secondly, to demonstrate the functionality of the techno-economic model developed for the concept generation and evaluation tool.

The price values, which were used to calculate actual expenditure, are given in Appendix K. These are averages of values taken from a range of sources, adjusted to sterling for 2019. Unless otherwise stated, values for the other input parameters were for the base case given in tables 5.1 and 5.2 at the start of the methodology.

5.3.1 Base Case Results

LCoE values were calculated for both the heave and surge WECs. The two WECs were characterised by their absorption efficiency, given in fig. 5.16, and their geometry, given in table 5.7. The surge WEC has a higher peak efficiency and works best at shorter wave periods. The heave WEC has a lower peak efficiency but a wider bandwidth and works best at longer wave periods.

Figure 5.17 shows the contribution of cost centres to lifetime expenditure for the heave WEC with the corresponding absolute cost values given in table 5.8. O&M contributes a large proportion to lifetime expenditure, 55 %, owing to the small scale of the other subsystems. This is equivalent to an annual OpEx cost of 14.5 % of CapEx. Other studies have suggested that figures of around 25 % of total expenditure and 5 % annually of CapEx are typical (O'Connor et al., 2013a). The discrepancy is due to the rates used

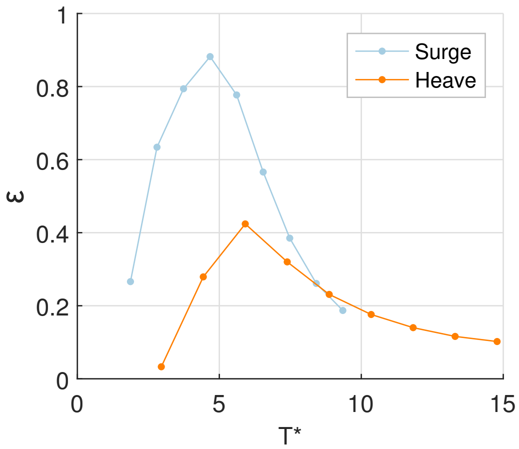

Figure 5.16: Efficiency versus normalised wave period for the heave and surge WECs, used to calculate absorbed energy.

Table 5.7: Geometry of the heave and surge WECs used to model costs. **bold** indicates the dimension used as the active width with a base value as specified. Draught is given as percentage of volume.

WEC	Shape	Geometry	Draught	Base L_a
Heave	cylinder	(**d**:l)[1] 1:1	50 %	10 m
Surge	flap	(h:**b**:t)[2] 0.5:1:0.05	100 %	25 m

[1] l: length, d: diameter
[2] h: height, b: breadth, t: thickness

to cost vessel hire. Here the same costs have been used regardless of scale due to the lack of information regarding this relationship. This will penalise the smaller WECs, when the number of failures per MW capacity is much higher.

Removing O&M cost and adjusting the other cost centres shows that the proportions are mostly reasonable in comparison with the literature (fig. 5.2), although this probably suggests that the installation cost is undervalued, again due to difficulty in accurately scaling vessel costs.

Figure 5.18 shows the contribution of cost centres to lifetime expenditure for the surge WEC with the corresponding absolute values given in table 5.8. The biggest difference with the heave WEC is that the PTO and connection cost centres account for a much larger proportion of total expenditure (66 % and 15 % respectively once O&M is

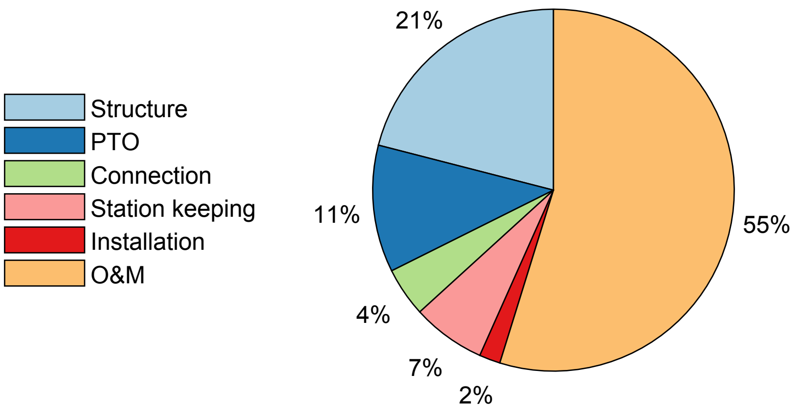

Figure 5.17: Contribution of cost centres to LCoE for the heave WEC ($\bar{P}_{\text{site}} = 40\,\text{kW/m}$ and $L_{\text{a}} = 10\,\text{m}$).

Table 5.8: Absolute values of each cost centre for the base case heave and surge WECs. O&M cost is per year.

Cost centres (M£):	C_{S}	C_{P}	C_{C}	C_{K}	C_{I}	$C_{\text{O\&M}}$
Heave:	0.56	0.30	0.12	0.18	0.05	0.18
Surge:	0.49	2.51	0.58	0.08	0.07	0.18

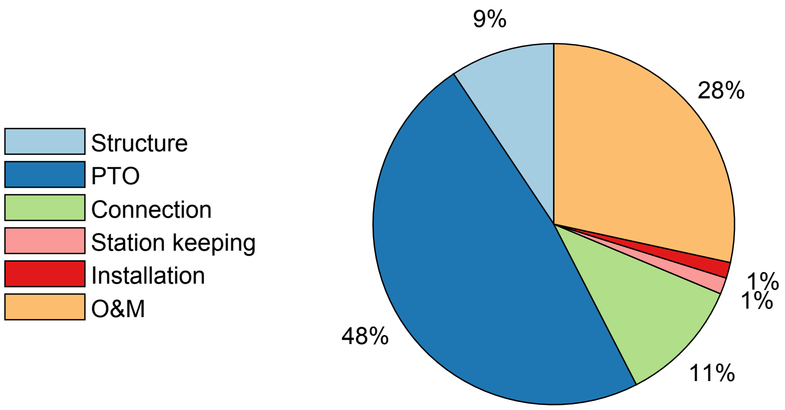

Figure 5.18: Contribution of cost centres to LCoE for the surge WEC ($\bar{P}_{\text{site}} = 40\,\text{kW/m}$ and $L_{\text{a}} = 25\,\text{m}$).

removed). This is because of the much larger amount of energy absorbed by the WEC and passed to the PTO.

As a result, the annual OpEx cost as a percentage of CapEx is lower than for the heave WEC (5 %) and closer to values published in the literature (O'Connor et al., 2013a). However, the implications of the higher energy capture on reliability is not captured in the model and this is discussed in section 5.4.

The LCoE values for the two WECs are given in table 5.9 along with values for power rating and CapEx per kW. The power rating of the heave WEC is much smaller owing to the poor absorption efficiency and the CapEx per kW is much higher due to the poor use of WEC volume.

For comparison, the 'commercial' cost of the Pelamis P1 WEC was estimated as 1880 £/kW (750 kW at 1.41 M£) in (Dalton et al., 2009) although this appears to have been optimistic. General values for wave energy were given as between 4000 £/kW to 7000 £/kW for 2010 and targeted as 1500 £/kW to 2000 £/kW by 2050 in ETI (2010). Meanwhile, a range of 1500 £/kW to 8500 £/kW was given for the WEC types analysed in ARUP (2018).

Table 5.9: LCoE results for the base case heave and surge WECs.

	L_a (m)	P_WEC (kW)	CapEx (£/kW)	LCoE (£/kWh)
Heave:	10	200	6050	0.89
Surge:	25	1670	2234	0.22

5.3.2 Changing Power Level and WEC Scale

The following results looks at the impact of changing site power level and active width on the LCoE of the base case heave WEC and the base case surge WEC.

Heave WEC

Figure 5.19 shows how AEP changes with power level and WEC scale. For a single WEC, the AEP increases with power level as more energy is available. In addition, the total losses reduce with increasing power level for the heave WEC. This is because of the shape of the adsorption efficiency curve, which is unsymmetrical and retains a reasonable efficiency over longer wave periods. Consequently, increasing power level results in an increasing annual average absorption efficiency. The results show an optimum active width that shifts from around 30 m at 20 kW/m to around 45 m at 80 kW/m. The highest values of AEP for the single heave WEC are >3.5 GW h with an active width of >50 m at >100 kW/m.

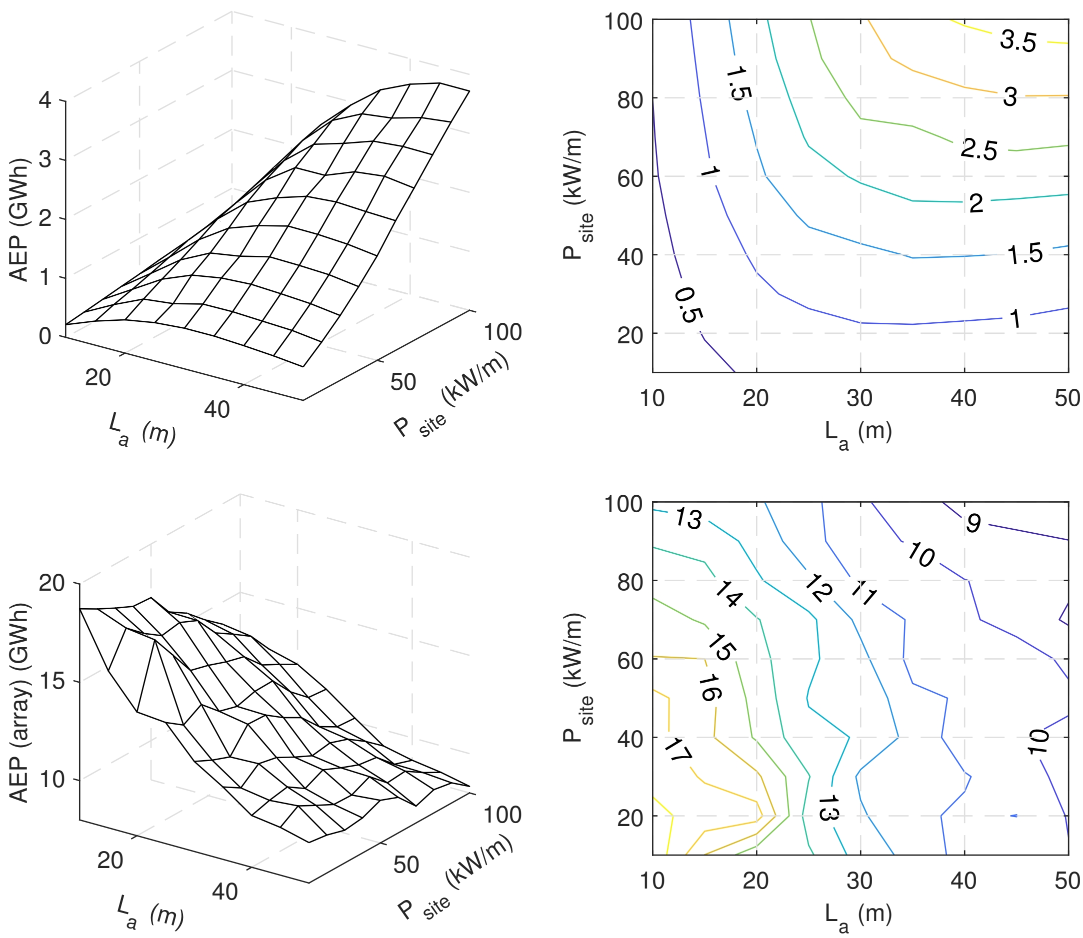

Figure 5.19: AEP versus site power level and WEC scale as a surface plot and corresponding contour plot. Contours represent values of AEP (GW h). Top) the single heave WEC. Bottom) the 10 MW array.

Also shown is the total AEP for an array of heave WECs. In this case total AEP decreases with increasing WEC scale. The reason being that the number of WECs making up the array is found by dividing the total array capacity by the individual WEC rating. For higher power levels and larger individual scales, the number of WECs is generally reduced[6], which also reduces the sum total active width and total energy capture. At the same time the total losses (due to operating limits, absorption efficiency, and conversion efficiency and cable losses), increase with increasing scale.

Although these results may seem counter intuitive, it is a typical characteristic of WEC design, whereby upscaling may be better achieved through the multiplication of smaller wave absorbing bodies as opposed to increasing the scale of a single body (see section 1.1).

Similarly, the total AEP for the array reduces with increasing power level. However, this is at a lesser rate due to the balance of reduction in the energy absorbed through fewer WECs and an overall increase in efficiency.

Figure 5.20 is a bar chart of total lifetime expenditure adjusted for present value (LCoE numerator) versus site power level for the individual 10 m WEC. It also shows how the cost centre proportions change with increasing site power level. For the individual WEC the total expenditure increases with power level. All the costs centres show an increase, although the majority of the total increase is caused by increasing vessel delay durations that are costed using a flat daily rate. The increase in the structure costs is comparatively very small.

Also plotted, is the total lifetime energy production of the single WEC adjusted for present value (LCoE denominator). Between the lowest and highest values of power level, the expenditure increases by a factor of more than two and at a relatively constant rate. From 10 kW/m to 60 kW/m the energy production increases by a factor of eight, but from 60 kW/m to 100 kW/m the increase is by a factor of less than two. Therefore, there is an optimum power level in terms of LCoE at 60 kW/m.

[6]In the lowest power level cases, the power rating of the individual WECs is small despite the size of the active width.

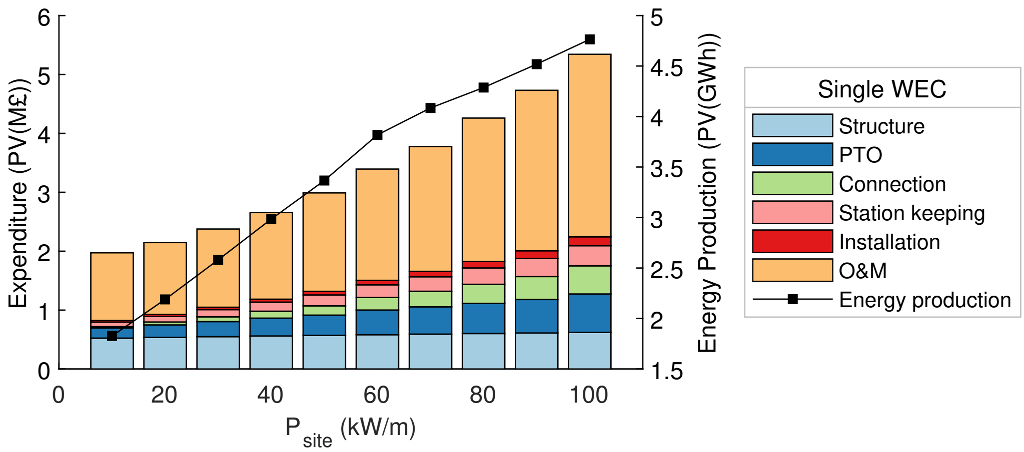

Figure 5.20: Left axis) total lifetime expenditure versus site power level for the heave WEC (L_a = 10 m) with cost centre breakdown. O&M cost converted to present value. Right axis) total lifetime AEP converted to present value.

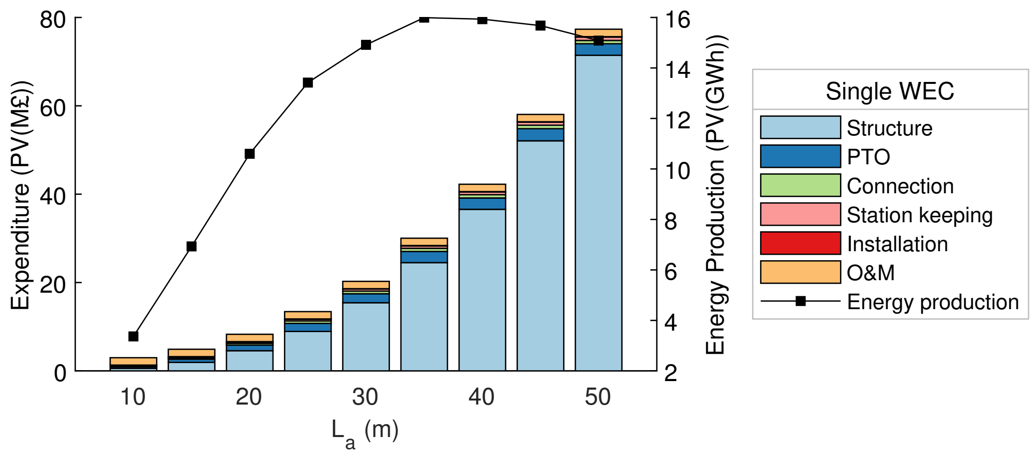

Figure 5.21: Left axis) lifetime expenditure versus WEC scale for the heave WEC ($\bar{P}_{site}$ = 40 kW/m) with cost centre breakdown. O&M cost converted to present value. Right axis) lifetime AEP converted to present value.

Figure 5.21 is the equivalent bar chart for total lifetime expenditure versus active width with a site power level of 40 kW/m. The structure cost increases rapidly with increasing active width. In this case, the 1:1 geometry for cylinder length to diameter means that the total volume, on which the structure cost is based, is high in relation to the active width. The optimum active width for lifetime energy production is 35 m. However, the optimum active width for LCoE is less than this (25 m to 30 m), when the positive difference between energy production and expenditure is greatest. The reduction in energy production beyond 35 m means that this is the maximum active width value for achieving minimum LCoE even with any improvement in volume efficiency.

Figure 5.22 shows how the heave-WEC LCoE changes with active width and site power level as a surface plot and corresponding contour plot. The lowest LCoE values of <1 £/kWh are achieved at an optimum scale of around 15 m. This is different to the optimum for AEP (fig. 5.19) due to the impact of increasing costs with scale. For a 25 m WEC the LCoE roughly halves in value from low to high site power levels.

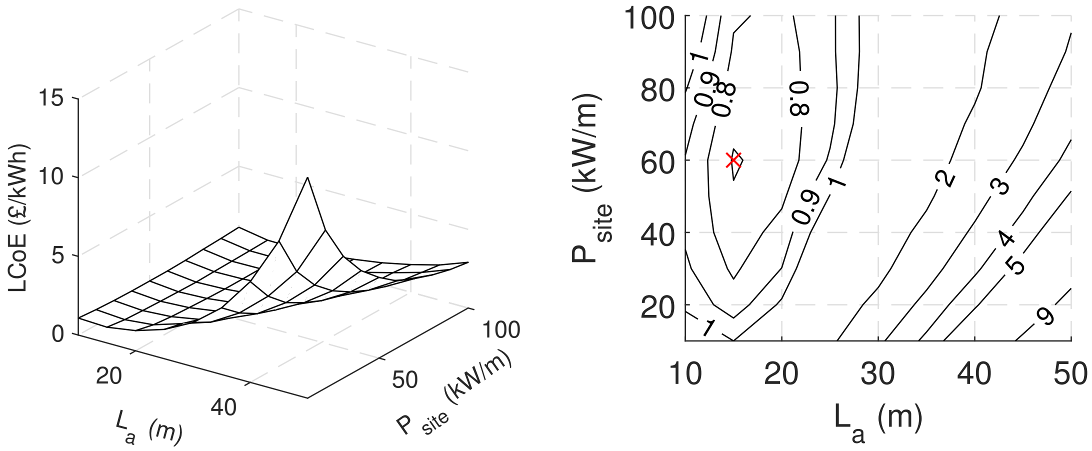

Figure 5.22: LCoE versus site power level and WEC scale for the heave WEC, as a surface plot and corresponding contour plot. Contours represent values of LCoE (£/kWh).

Figure 5.23 shows how the heave-WEC LCoE changes with power level and scale in each of six zones modelled in the resource module. For the plot of increasing power level, roughly the same trend is seen in each case, suggesting an optimum of 40 kW/m to 60 kW/m for the heave WEC. The lowest values of LCoE achieved for each zone by varying power level and active width are given in table 5.10. The optimum scale is the same in every location and was shown to remain similar across different power levels (fig. 5.22). This suggests the modelled heave type WEC is a versatile design, but one that cannot provide good economic returns without significant improvement.

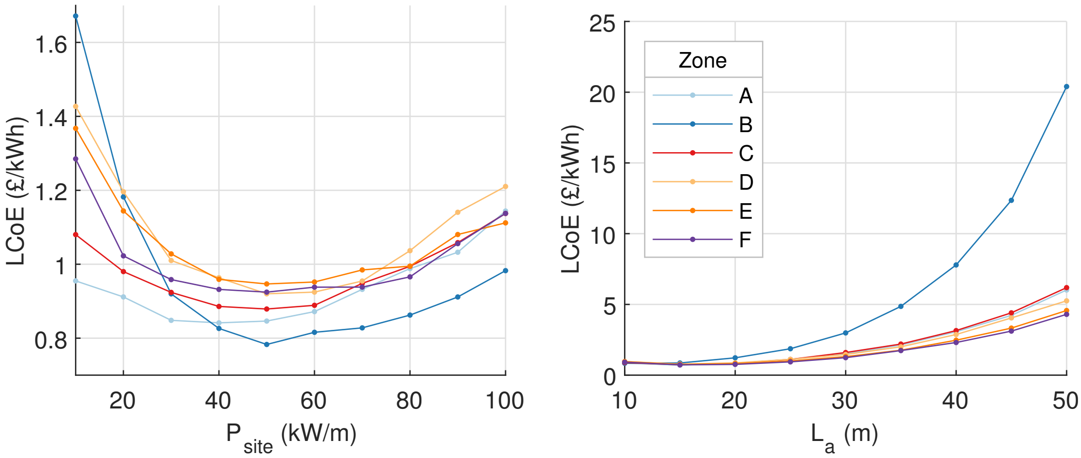

Figure 5.23: Left) LCoE versus site power level ($L_a = 10\,\mathrm{m}$) for the heave WEC in each zone and Right) LCoE versus WEC scale ($\bar{P}_{site} = 40\,\mathrm{kW/m}$) for the heave WEC in each zone.

Table 5.10 also provides the corresponding power rating values in each zone. These are similar apart from in zone B, where the optimum WEC has a rating that is double the rating in other zones. This mean that the absorption efficiency of the heave WEC is better suited to the zone B resource in theory and able to absorb more of the available energy. Consequently, Zone B, which represents the North Sea, provides the lowest value of LCoE. However, this also means that zone B is the most sensitive to changes in power level and scale. Furthermore, the maximum power level in the zone B reference data was <40 kW/m and that much higher values are most likely not possible due to the limited depth range.

Table 5.10: Best LCoE results for the heave WEC in each of the six zones with the corresponding values of power level, active width and power rating.

Zone	Min. LCoE (£/kWh)	$\bar{P}_{\text{site}}$ (kW/m)	L_{a} (m)	P_{WEC} (kW)
A	0.70	40	15	620
B	0.74	90	15	1140
C	0.69	60	15	580
D	0.71	60	15	560
E	0.72	60	15	560
F	0.70	50	15	470

Surge WEC

The second set of results are for the surge WEC. Figure 5.24 shows how AEP changes with power level and WEC scale. The results for the single WEC show that AEP increases with power level as more energy is available, the same result as for the heave WEC. However, unlike for the heave case, the results suggest that the optimum active width is greater than the range of values that were modelled. This is due to the higher value of peak efficiency which means that the decoupling between WEC and resource needs to be greater in order for the occurrence-weighted average energy capture to decrease.

The highest values of AEP for the single surge WEC are >11 GW h, more than three times the highest values for the heave WEC, at the scale of >50 m and power levels of >100 kW/m.

As for the heave WEC, total array AEP decreases with individual WEC scale and power level due to the lower power capture associated with a decreased number of WECs. The staccato appearance of the results is caused by the limited granularity of the occurrence and power matrices. This results in capacity factor and power rating jumps, an effect that is more observable for the surge WEC due to the higher absorption efficiency.

Figures 5.17 and 5.18 showed that the main difference of the surge WEC with the cost centre breakdown of the heave WECs, is the larger proportion of PTO and cable costs. These difference are also seen in the bar charts given in figs. 5.25 and 5.26 of total lifetime expenditure versus site power level for the 25 m WEC and versus active width

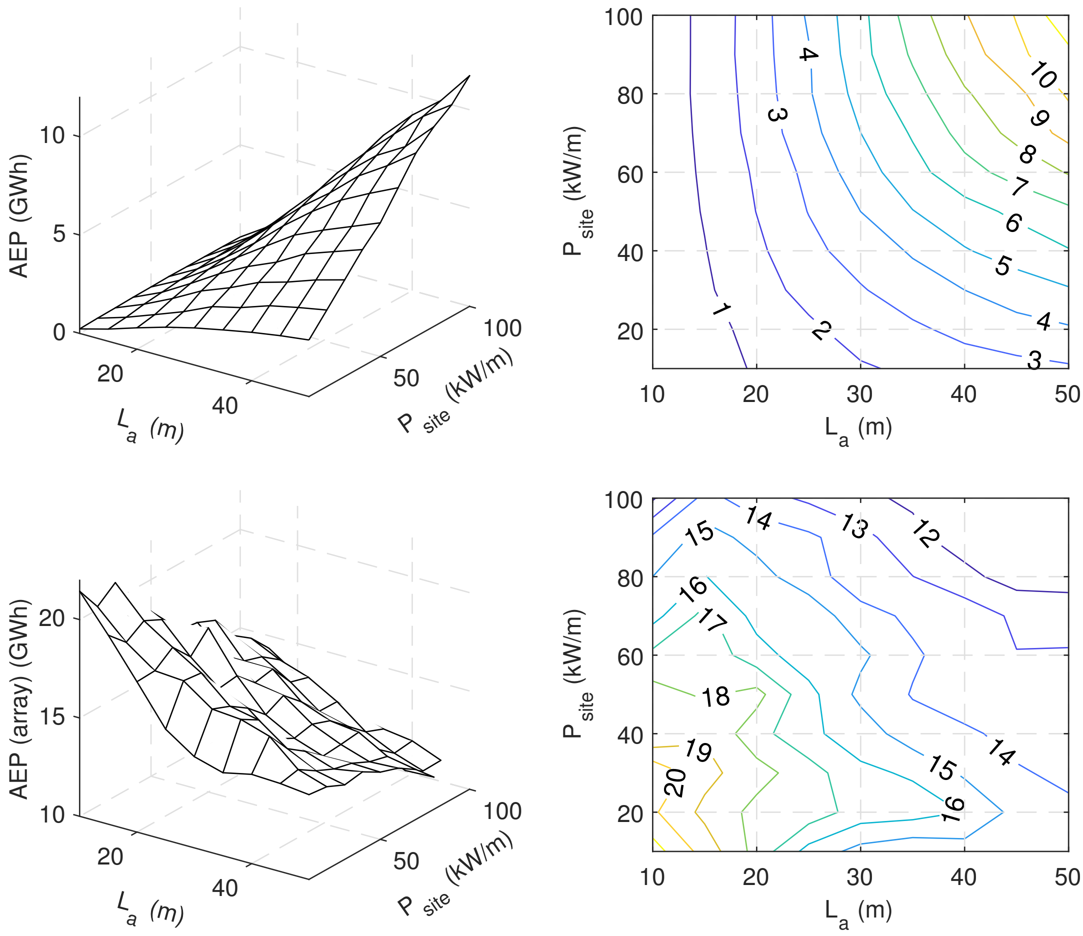

Figure 5.24: AEP versus site power level and WEC scale as a surface plot and corresponding contour plot. Contours represent values of AEP (GW h). Top) the single surge WEC. Bottom) the 10 MW array.

for a site power level of 40 kW/m array respectively. An optimum power level in terms of LCoE is seen at 70 kW/m when the positive difference between energy production and expenditure is greatest. Beyond this, expenditure increases more rapidly than energy production. Similarly an optimum active width is seen at 35 m.

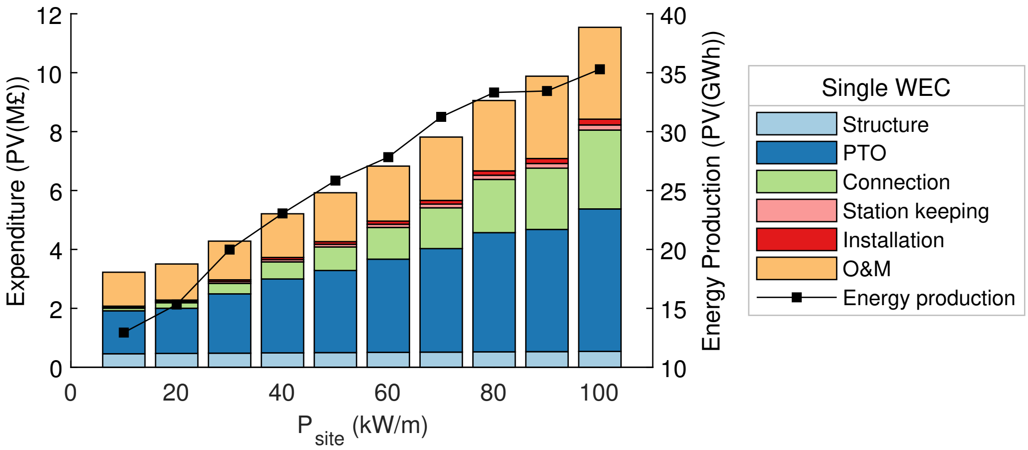

Figure 5.25: Left axis) lifetime expenditure versus site power level for the surge WEC (L_a = 25 m) with cost centre breakdown. O&M cost converted to present value. Right axis) lifetime AEP converted to present value.

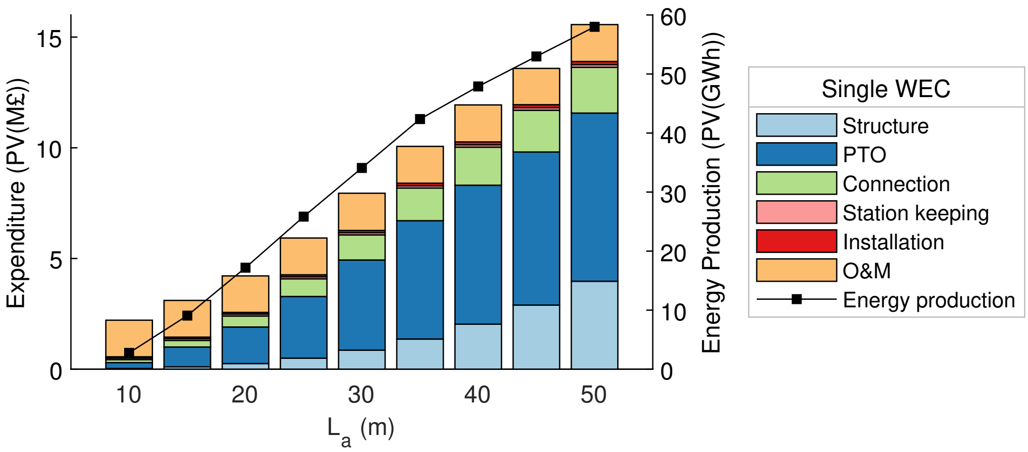

Figure 5.26: Left axis) lifetime expenditure versus WEC scale for the surge WEC ($\bar{P}_{\text{site}}$ = 40 kW/m) with cost centre breakdown. O&M cost converted to present value. Right axis) lifetime AEP converted to present value.

For increasing active width (fig. 5.26), the PTO cost increases at a faster rate than the structure cost owing to the better volume efficiency of the surge WEC. At the smaller scale, the expenditure value is similar to the heave WEC, but at larger scale it is more than five times lower.

Figure 5.27 shows the surge-WEC LCoE results as a surface plot and corresponding contour plot. The lowest LCoE values of <0.3 £/kWh are achieved at optimum scales of 25 m to 35 m at power levels of around 40 kW/m. Below 20 m LCoE is very sensitive to scale, which relates to the narrow shape of the absorption efficiency curve.

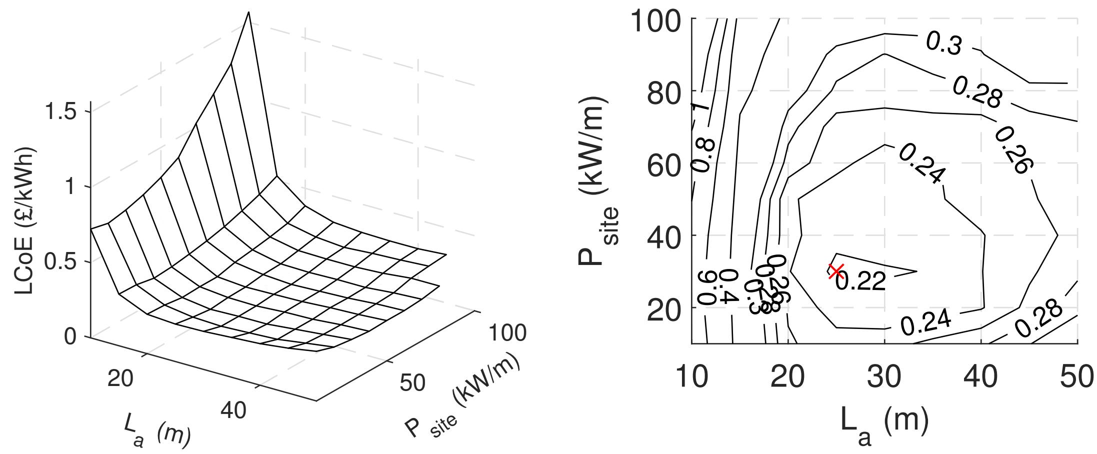

Figure 5.27: LCoE versus site power level and WEC scale for the surge WEC, as a surface plot and corresponding contour plot. Contours represent values of LCoE (£/kWh).

LCoE values of <0.3 £/kWh are seen from 15 m to >50 m and for power levels <100 kW/m. However, consideration needs to be given to other practical limits, such as limits on the amount of power that can be passed to the PTO, as discussed in section 4.5.

Figure 5.28 shows how the surge-WEC LCoE changes with power level and scale in each of six zones modelled in the resource module. In this case, the resource modelled for zone B provides the worse LCoE and zone F the best. However, it should be noted that, due to a lack of available data, the relationships between depth, distance and power level were chosen based solely on zone C, and in reality there are significant differences between each zone.

The optimum power levels (30 kW/m to 50 kW/m) are lower than for the heave WEC and the surge LCoE is more sensitive to power level changes in general. As well as

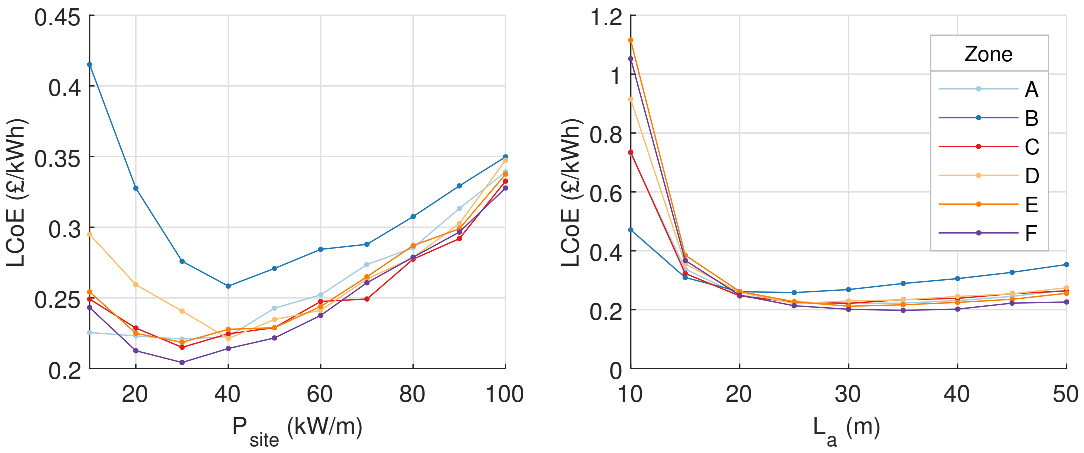

Figure 5.28: Left) LCoE versus site power level ($L_a = 25\,\mathrm{m}$) for the surge WEC in each zone and Right) LCoE versus WEC scale ($\bar{P}_{\mathrm{site}} = 40\,\mathrm{kW/m}$) for the surge WEC in each zone.

the increased cost of the PTO this is due to the higher power carrying requirements of the export cable and resultantly the higher costs associated with being further offshore. Therefore, the surge WEC results will also be more sensitive to the relationship between power level and distance to shore (see section 5.3.3).

The lowest values of LCoE given for each zone are provided in table 5.11 along with the corresponding values of power level and active width. The relationship with scale is similar in each location, however, the optimum varies by $\pm 10\,\mathrm{m}$. These results suggests that a 'one-size-fits-all' surge type WEC is less versatile than the corresponding heave WEC.

Table 5.11: Best LCoE results for the surge WEC in each of the six zones with the corresponding values of power level, active width and power rating.

Zone	Min. LCoE (£/kWh)	$\bar{P}_{\mathrm{site}}$ (kW/m)	L_a (m)	P_{WEC} (kW)
A	0.21	30	30	1970
B	0.26	50	30	2980
C	0.22	30	25	1340
D	0.22	40	25	1390
E	0.21	40	30	1970
F	0.20	40	35	1350

5.3.3 Sensitivity Analysis

A sensitivity analysis was conducted to test whether the base values given to the deployment parameters had a large influence on results, along with the values used for the discount rate and project lifetime, used in the LCoE equation (section 2.2.3). These parameters are listed in table 5.12, with their base value and ±50 % values. Whether the 50 % (or 150 %) value represents a best or worse case in terms of LCoE depends on the parameter.

Table 5.12: Sensitivity analysis inputs: ±50 % values for the deployment parameters, discount rate and project lifetime. Best/worst case depends on whether they have a decreasing or increasing impact on LCoE respectively.

Parameter	Worst case	Base case	Best case
Discount rate (r)	15 %	10 %	5 %
Lifetime (t_{life})	10 a	20 a	30 a
Water depth (h)	155 m	103 m	52 m
Distance to shore (d)	38 km	26 km	13 km
Array capacity (P_{array})	5 MW	10 MW	15 MW
Vessel max. H_{s} (H_{max})	1 m	2 m	3 m

Figure 5.29 shows the change in heave-WEC LCoE for each parameter when using the worst case (red bar) and best case (blue bar) values and whilst using the base case for the other parameters. The most sensitive parameter is the maximum wave height for vessel operation, which impacts heavily on the accessibility of the site (see chapter 4, fig. 4.12). This is especially in the worse case where a decrease of 1 m adds more than 0.7 £/kWh (+80 %) to the LCoE. For the heave WEC, this is unsurprising given the large proportion of lifetime expenditure attributed to O&M.

Figure 5.30 shows the same plot but for the surge WEC. Despite a much lower contribution of O&M to lifetime expenditure for the surge WEC, the impact of reducing maximum wave height is still very significant. In this case, a decrease of 1 m adds more than 0.11 £/kWh (+50 %) to the LCoE.

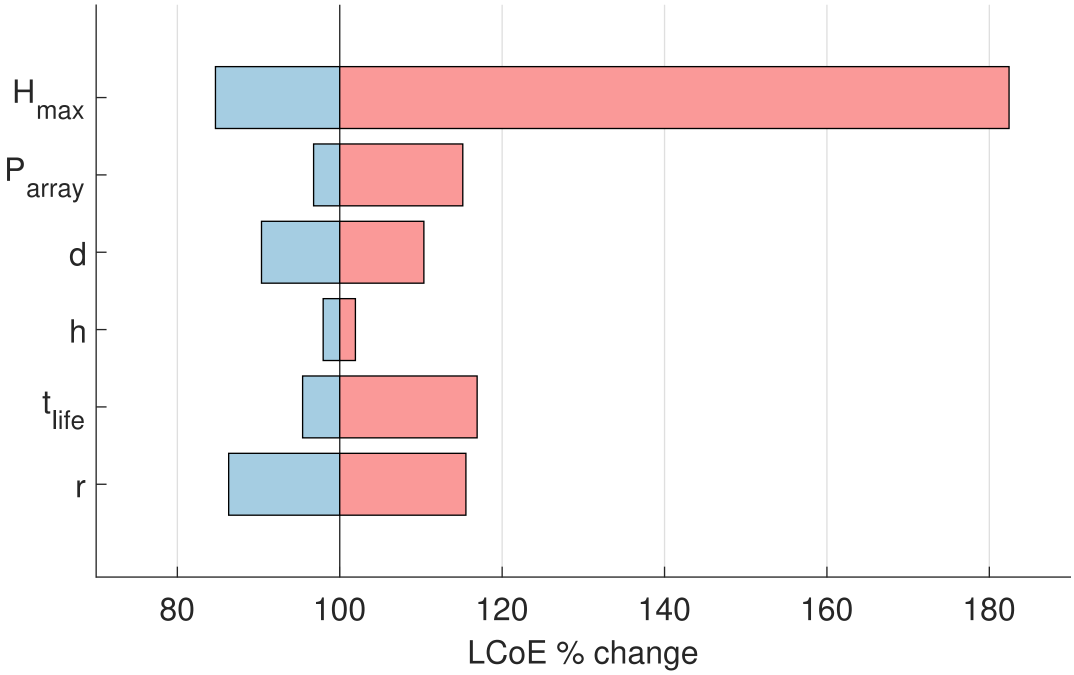

Figure 5.29: Change in heave-WEC LCoE for the ±50 % parameter values given in table 5.12. The 100 % base case value is 0.89 £/kWh. Blue bar indicates best case LCoE reduction. Red bar indicates worst case LCoE increase.

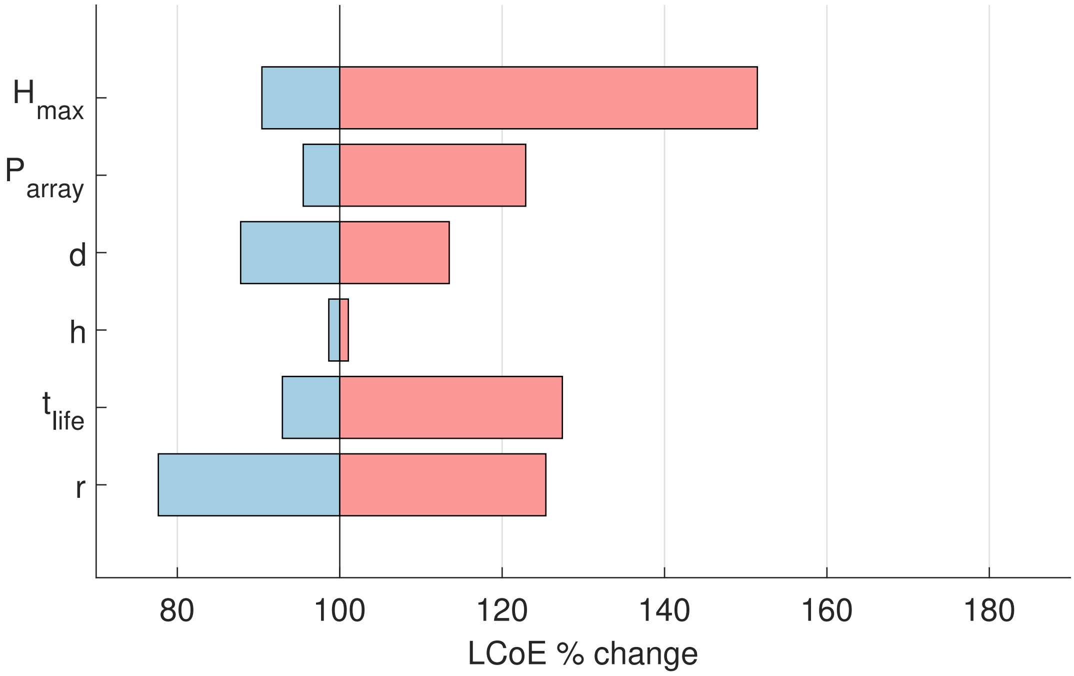

Figure 5.30: Change in surge-WEC LCoE for ±50 % parameter values given in table 5.12. The 100 % base case value is 0.22 £/kWh. Blue bar indicates best case LCoE reduction. Red bar indicates worst case LCoE increase.

One difference for the surge WEC is that, in relative terms, the sensitivity to discount rate is greater. A change in discount rate of 50 % changes LCoE by >20 %. This is because the AEP is much higher for the surge WEC and consequently, the truncation of future events has a larger impact[7]. Similarly, shortening the lifetime of the project means that AEP makes a lower contribution to LCoE whilst CapEx makes a higher contribution.

The discount rate is partly based on the cost of finance and the risk that a project could produce lower returns than expected (Hundleby, 2015). For wave energy, as a nascent technology, the discount rate is likely to be high in comparison to other technologies. However, these results show that, going forward, this is an important factor in achieving a low LCoE regardless of the technology.

Changing the value of distance to shore has a larger impact for the surge WEC than for the heave WEC. This is because of the increased energy production and consequent higher cable rating requirements and cost. It should be noted that, the base case relationship between depth and distance to shore gives a relatively shallow bathymetry gradient (see section 4.4 and appendix F) and that this was based on data for zone C only. It is likely that a general relationship between depth and distance to shore would be highly variable between the six zones and these results demonstrate the need for this variability to be included in future versions of the model.

For both types of WEC, the water depth is much less sensitive than distance to shore. In comparison to the relationship used to estimate distance, the relationship between depth and power level is more consistent except very near to shore. The change in water depth between the best and worse case is also roughly the uncertainty in the relationship that was estimated from the reference data (section 4.4).

[7]Truncation is an issue for any metric that uses discounting (see section 2.2)

5.4 Discussion

The second objective identified with the research question was to develop a techno-economic model that can be used at low TRL and that allows for a continuous parameter space to be explored. This chapter provided an overview of the methods that were used to try and meet that objective. The results showed how the input scenario could be scaled for site power level and WEC scale and how those parameters were mapped to LCoE for five different regional zones and two generic WEC types.

The LCoE of the base case heave WECs (0.89 £/kWh) was significantly improved (0.69 £/kWh) by optimising site power level and active width. However, this value is still significantly higher than other energy generating technologies (see table 1.1). On the other hand, a minimum LCoE value was achieved for the surge WEC (0.20 £/kWh) that could be considered acceptable for a nascent renewable energy technology but would still need to be improved to be considered cost-competitive.

Although the heave WEC has a poorer absorption efficiency, results in chapter 4 showed that this does not necessarily translate to a lower annual energy capture as this is also dependent on the distribution of sea state occurrence. Instead, the primary factor for the poor economic performance of the heave WEC is its poor volume efficiency. A large proportion of heave WEC cost was for the primary structure, which is driven by volume and scales with the active width to the power of three. A better volume efficiency could easily be achieved with a different geometry, where a higher proportion of the structure is involved in energy capture. The base case heave WEC had a diameter to length ratio of 1:1, using 1:0.5 instead provides a minimum LCoE of 0.52 £/kWh.

For the surge WEC, there are negative implications of higher energy capture that are not captured by the model. To some degree, the higher absorption efficiency was penalised by the higher costs, however, this also represents the transfer of much larger loads from the active surface to the PTO. This is a reliability and survivability problem, especially if the surface that experiences PTO forces is much smaller than the active surface (as is commonly the case for flap-type surge WECs). Practically, this would place limitations on scale and also dictate the type of PTO that is suitable. Further work is needed to investigate these practical limits and to include them in the model.

The LCoE results showed that there were optimums for WEC scale for both types of WEC. This was expected due to the inherent relationship between scale and absorption efficiency. For the heave WEC, the optimum scale remained relatively constant for increasing power level and across the different zones despite shifts in the predominant wave periods. In part, this was due to the balance of increased energy capture with the increased cost of the PTO and cabling. However, a wide bandwidth of good absorption efficiency is the most important factor in providing consistent economic returns in a number of locations. The results also show that the worst scale of WEC depends on the WEC type: very small surge WECs and very large heave WECs are the least economical.

Most of the literature on optimum scaling focuses on rated power (e.g. ARUP, 2018; de Andrés et al., 2016). The optimum rated power values were around 0.6 MW and 1.8 MW for the heave and surge WECs respectively. As discussed in section 5.2.1, a number of methods exist for estimating an appropriate rated power value based on other WEC dimensions and this can have a large impact on results. Using a rated power value that is based on Froude scaling (see section 5.1) results in larger optimums, 2 MW to 10 MW in (ARUP, 2018)[8], for example.

However, this approach neglects the impact of absorption efficiency and available resource on the annual average amount of power that is received by the PTO. In comparison, the approach used in the techno-economic model is to base rated power on a percentage of the energy that can be absorbed by the WEC across a year. Consequently, increases in active width result in a greatly reduced increase in rated power. The results highlight that absorption efficiency is the most important factor that limits WEC upscaling in terms of both the size of the wave absorber and the rated capacity.

[8]Based on the modelling of CapEx per MW

Also seen in the results were optimum values of site power level for both types of WEC in the range of 30 kW/m to 60 kW/m. The sensitivity to power level varies between the different zones but the balance between extra available energy and added costs suggests that there is not always a payoff in moving further offshore and in choosing higher energy sites. This range is also limiting in terms of the potential for providing cost-competitive LCoE.

In (ARUP, 2018), LCoE was modelled for a test site (33 kW/m), open ocean site (67 kW/m) and a maximum power level site (150 kW/m). No optimum was found and the corresponding LCoE values for the best case WEC configuration were 0.32 £/kWh, 0.15 £/kWh and 0.10 £/kWh respectively. However, only energy capture was scaled for the different power levels with expenditures for the 67 kW/m site kept constant.

In particular, improvements are needed for the reliability module to better model the number of O&M trips per year and consideration should be given to the relationship between failure rates and loads. Nonetheless, the sensitivity analysis conducted for these results suggests that any power level optimum is very sensitive to the capabilities of vessels and the cost of any delay time associated with waiting in port for an available weather window.

Older vessels typically operate in wave conditions up to $H_{\max} = 1.5\,\mathrm{m}$ but for newer vessels this can be as much as 3 m (O'Connor et al., 2013c). An increase in the maximum significant wave height from 2 m to 3 m increased the optimum site power levels by 10 kW/m to 20 kW/m in most cases. The results corresponds to Frost et al. (2018), who found that the lowest LCoE is achieved in the most sheltered locations with higher accessibility and that results are very sensitive to month of installation.

The sensitivity analysis also showed that LCoE is sensitive to the relationships used to model both depth and distance to shore from the site power level. In particular, cable costs are affected by the distance to shore estimate (see appendix F). As discussed, the relationships used for computing these results were representative of zone C and in reality there are significant differences between zones. Higher power levels may be possible closer to shore in places where the water is very deep, which is the case in zone F.

This also has implications for assessing WEC versatility. As discussed in section 4.5, surge type WECs are better suited to nearshore environments and historic examples have tended to be bottom fixed (Cameron et al., 2010). However, the surge WEC results show that an LCoE of below 0.3 £/kWh is possible even when limited to a site power level of 10 kW/m due to the high level of peak efficiency. On the other hand, the heave WEC performs worst in the lower energy sites. The interdependence between optimal WEC design and optimal site has led to some authors suggesting that certain WEC concepts should be marketed for targeted locations (or *vice versa*) (e.g. de Andrés et al., 2017a; O'Connor et al., 2013b).

It is important to note that the contribution of each cost centre to LCoE is also sensitive to the unit cost values that were used, given in appendix K. These were averages of values found in the literature but, in most cases, there were large discrepancies between sources.

As well as the lack of experience in the sector, uncertainty stems from the lack of consistency on how these values are used. For example, it's not always clear whether material costs include the cost of manufacture, raw material costs can have high inter-annual variability (Dalton et al., 2009) and labour cost can vary widely from country to country (Leal, 2008).

The aim of the research was to create a tool that could be used to identify areas of the parameter space that are worthy of further investigation and to rule out areas that are not. Therefore, the focus was on providing relative comparisons and establishing general trends, rather than on providing accurate absolute values of LCoE. A stochastic approach for modelling the variability in unit cost values is the subject of further work. This is needed to establish whether the uncertainty significantly alters the conclusions that can be drawn from the results.

5.5 Chapter Conclusions

This chapter outlines the development of performance, initial cost and reliability modules that are used to evaluate concept LCoE in the techno-economic model. The development of the modules focused on adapting methods for low-TRL assessment and for allowing a continuous parameter space to be explored. This was the second objective identified with the research question (see section 1.3).

The results demonstrate how the model can be used to compare different WEC types in different regions, site power levels and at different scales. The key messages from the results and discussion are as follows:

- ▷ Two types of WEC were modelled based on their representative absorption efficiency and geometry. The surge WEC has a higher peak efficiency and works best at shorter wave periods. The heave WEC has a lower peak efficiency but a wider bandwidth and works best at longer wave periods.
- ▷ The results demonstrated how active width and site power level could be continuously scaled by the model and mapped to LCoE. LCoE values of 0.69 £/kWh and 0.20 £/kWh for the heave and surge WECs respectively were achieved by optimising the site power level and active width. However, these values are still higher than is currently considered to be competitive.
- ▷ LCoE values can be improved further by using a better volume efficiency (where a higher proportion of the structure is involved in energy capture), improving performance above rated power and optimising rated power for the wave climate and absorption efficiency. However, further work is needed to explore limits regarding absorbed power, the transfer of loads to the PTO and the impact on reliability and survivability.
- ▷ The LCoE results showed that there were optimums for both WEC scale and site power level for both types of WEC and in each regional zone. For the heave WEC an optimum active width of 15 m stayed relatively constant with increasing power level and between zones. This was due to the balance of increased energy capture with

the increased cost and its wider bandwidth of absorption efficiency. For the surge WEC the optimum active width was between 25 m and 35 m.

- ▷ The results suggest that a 'one-size-fits-all' surge type WEC is less versatile than the corresponding heave WEC. Consideration also needs to be given to limits on depth and that different WEC types should potentially be marketed for different types of location.

- ▷ The optimum rated power values were around 0.6 MW and 1.8 MW for the heave and surge WECs respectively. These were lower than in a number of other studies due to the method chosen to select an appropriate rated power value based on the wave climate and the absorption efficiency of the WEC.

- ▷ The optimum values of site power level for both types of WEC were in the range of 30 kW/m to 60 kW/m depending on the zone of deployment. Although the techno-economic model is designed for low complexity, conceptual analysis, the results suggest that there is not always a payoff in moving further offshore and in choosing higher energy sites. This could be limiting in terms of the potential for providing cost-competitive LCoE.

- ▷ A sensitivity analysis showed that LCoE was most sensitive to the maximum significant wave height for vessel operation. Therefore, improvements are needed for the reliability module to more accurately model the number of O&M trips required per year for different technology types and wave climates.

The next chapter investigates three parameters that relate to WEC technology: material cost, PTO cost and conversion efficiency and their impact on the commercial attractiveness score. The technical achievability score is then used to assess improvements in these parameters and to provide an indication of the concepts worthy of further consideration.

6. Results and Discussion: Promising Scenarios

This chapter explores the final part of the concept generation and evaluation tool: evaluating the CA and TA scores and using thresholds to identify promising combinations of WEC concepts and deployment scenarios. This was the third objective identified with the research question and results are presented here to demonstrate how the method, as outlined in chapter 3, can be applied.

Results from two investigations are presented. The first investigation explores three parameters and their relationship with the CA and TA scores: material cost, PTO cost and PTO efficiency. Structural material and PTO technologies have previously been identified as having the potential for significant improvement in terms of reducing cost of energy (Carbon Trust, 2011) and they are also the focus of R&D funding programmes (WES, 2019). The scores were calculated for three different material types and four PTO types. Analysis of current R&D activity was used to assign the level of improvement potential for each technology type, which was then used in calculation of the TA score. The second investigation explores whether these technology types, in combination with other deployment and WEC parameters, can deliver a WEC that has the potential to be cost-competitive.

The remainder of this chapter is split as follows.

- ▷ Section 6.1 provides results for the different material types and section 6.2 provides results for the different PTO types. Each section starts with an overview of each technology, including current R&D activity.
- ▷ Section 6.3 then presents the results from the second investigation. For this, the concept generation and evaluation tools was used to evaluate and rank 432 combinations of WEC and deployment parameters. A short discussion is then provided on the functionality of the tool in terms of the aims and objectives identified with the research question.
- ▷ Finally, section 6.4 summarises the main conclusions of the chapter.

6.1 Material Technologies

The first technology improvement that was investigated was reduction in the unit cost of the primary material. This is used to calculate the cost of the WEC structure (see section 5.2). Three material types were considered: steel, composites (namely Glass Reinforced Plastic (GRP)) and reinforced concrete, which have all been/are all the focus of R&D activity within the wave energy sector. For example, Figure 6.1 provides the number of projects involved in the current WES materials programme that are developing each technology type. The 'other' category includes deformable materials and load bearing nets which are not considered here.

The current values of unit cost for each material type along with the other technical parameters used to calculate the CA and TA scores are given in section 6.1.1.

An overview of each of the three material types is provided here as context. Most of this information is based on a structural integrity study of the Pelamis WEC (Ocean Power Delivery, 2003)) and the landscaping study for the WEC materials funding call (WES, 2016a).

Steel is well established as the material of choice for offshore structures and has been widely researched. This means that there is now less scope for significant improvement, in comparison to more novel technologies. Disadvantages include fatigue of welded

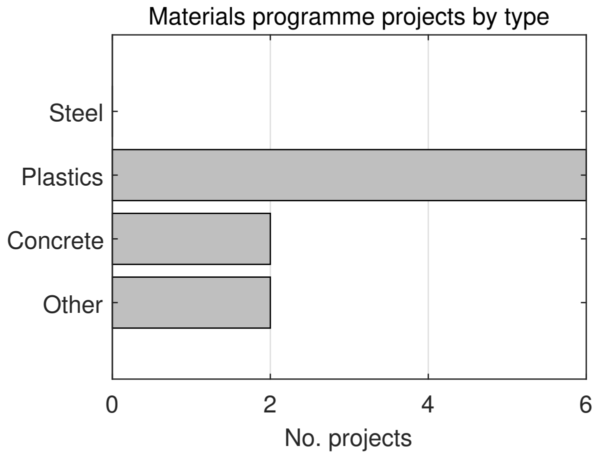

Figure 6.1: Number of WES materials programme projects for each type of technology. Refers to the material that is the main focus of each project. Concrete refers to reinforced concrete and plastics includes reinforced plastics. Source: WES (2019).

joints and the need for surface coatings to provide corrosion protection. Strict offshore standards relating to oil and gas exploitation means that cost of welding and corrosion protection can be high.

Possible cost-saving innovations include the use of adhesive bonding in place of welding, however, adhesive bonding is mostly untested for metals in the marine environment. Instead, it is likely that most cost reduction for steel structures would occur at a later stage of development through optimisation of the manufacturing process.

Composites such as GRP are already widely used in the marine environment for small ships such as pleasure craft and for larger military applications. More recently, composites are increasingly used for offshore wind turbine blades at very large scale. One of the stage 2 projects from the WES materials programme (fig. 6.1) is developing a polyester/E-Glass material for a heaving buoy WEC (CorPower, 2018b).

The main advantages of GRP is its strength, stiffness, light weight and corrosion resistance. In addition, the ability to use moulds for composite materials would place less restrictions on WEC geometry optimisation in comparison to welded steel, which cannot be used to make complex shapes (Garcia-Teruel et al., 2018).

However, it is mostly untested as a structural material for application to wave energy. The degradation of adhesive bonded joints is seen as a potential barrier to using composites as many modular WEC designs involve submerged sections or sections that operate in the splash zone (WES, 2016a). Most examples of adhesive bonding in the marine environment are in areas where the level of risk is not excessive (Rubino et al., 2020). Although standards exist for composites in shipbuilding applications (WES, 2016a), it is recommended to avoid adhesive joints in critical areas of direct contact with seawater or in areas where failure would compromise water tightness (DNV, 2017).

Reinforced concrete has been widely used in the construction industry and is a mature technology for which there is a wealth of experience. Examples of concrete use include some of the largest offshore structures that are used in the oil and gas industry. However, it is yet to be tested in the wave energy sector and its lack of tensile strength could be problematic for some WEC types with high bending loads (e.g. Attenuators - see section 1.1). Therefore, concrete is most compatible with more stationary WEC types such as OWC and overtopping devices (Arup, 2018).

The corrosion of steel reinforcements is also a major issue and large wall thicknesses are typically required to ensure durability. Many WEC concepts are designed to float at the the sea surface or 'splash zone' where they are particularly susceptible to corrosion. Large wall thicknesses could potentially be prohibitive for WEC design in terms of optimising geometry or structural mass. Ongoing R&D for the use of concrete in other sectors includes the development of high-strength concretes and non-ferrous replacements for steel reinforcements. However, projects in the WES materials programme focus on using traditional reinforced concrete in order to realise low unit cost (Arup, 2018).

6.1.1 Technical Parameters

Given in table 6.1 are the technical parameters used to evaluate the CA score for each material. The value of the other input parameters to the techno-economic model were for the base deployment scenario and base case heave WEC described in chapter 5. Table 6.1 also provides the improvement potential level of each material along with a justification.

The material volume parameters (see section 5.2.2) were calculated based on a structural integrity study of the cylinder shaped Pelamis WEC (Ocean Power Delivery, 2003). The analysis found that the mass of material required for a GRP structure was 0.19 times the amount of steel, whilst the mass of concrete required was 5.4 times the amount of steel. These values infer the different load bearing qualities and resistance to the operating environment of the three materials.

Table 6.1: Characteristics of each material type used to calculate CA and TA with justifications for the improvement potential level. The corresponding values of learning elasticity are provided in section 3.3.

Material	ϕ_{mat} [1]	ρ_{mat} [2] (kg/m^3)	Base c_{mat} [2] (£/kg)	Improvement Potential	Justification
Steel	0.030	7800	3.03	low	Steel is a mature technology that is the material of choice for the majority of offshore structures as well as for WECs. However, current focus is on other materials to deliver reductions in cost so a low improvement potential is assigned.
GRP	0.025	1850	9.11	high	GRP is an evolving technology that has recently become established as a structural material for offshore wind turbine blades. It is untested for wave energy but is the focus of substantial R&D. Therefore, a high improvement potential is assigned.
Concrete	0.190	2400	0.37	low	Reinforced concrete is a mature technology that has been used for offshore oil and gas structures. There is some active R&D within wave energy but with a focus on using traditional forms of reinforced concrete to enable lower unit cost. Therefore, a low improvement potential is assigned.

[1] Calculated based on a structural integrity study of the Pelamis WEC (Ocean Power Delivery, 2003) and at $H_{s_{50}} = 11\,\mathrm{m}$.
[2] Source: WES (2016a), Ocean Power Delivery (2003), Chozas et al. (2014), Carbon Trust (2016), Ramboll (2010), ARUP (2018), and Sandia (2014)

6.1.2 Improvements

The CA score of the heave WEC was calculated for each material and for decreasing values of unit material cost (c_{mat}). In fig. 6.2 the results for steel and GRP are presented. Despite a lower initial unit cost, the CA score for the steel WEC is significantly higher due to the greater amount of material required. This also means that the CA score decreases at a greater rate.

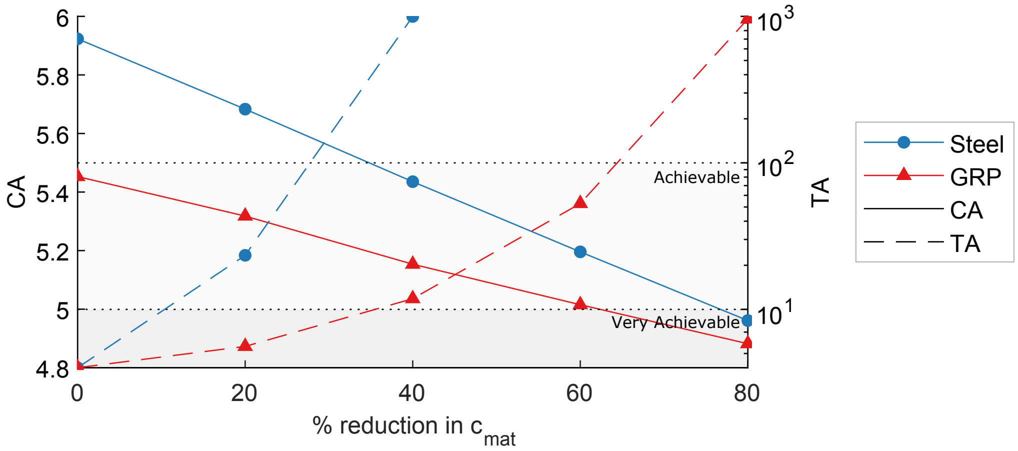

Figure 6.2: CA score and TA score versus percentage reduction in unit material cost for steel and GRP. Very achievable limit at TA = 10^1 and achievable limit at TA = 10^2.

On the other hand, GRP has a higher associated improvement potential owing to its immaturity for marine applications (relative to steel and concrete). Using the thresholds for technical achievability specified in section 3.3.3, suggests that a 64 % reduction in unit cost is achievable, equating to a reduction in CA score of 8 %, compared to values for steel of 27 % and 5 % respectively.

The results for all three materials are given in table 6.2. The lower unit cost of reinforced concrete provides the best CA score based on current values (4.98), however, the CA score of GRP is similar with an achievable improvement in unit cost (5.00). The results suggest that for current, 'status quo', steel WECs, a 16 % to 17 % reduction in LCoE could be achieved by switching to GRP or concrete. However, even with these reductions the CA score does not reach the cost-competitive threshold of CA = 1, showing that other improvements are required.

Other important considerations, which have not been taken into account, include 'installability' and 'manafacturability'. In Garcia-Teruel et al. (2018), composites were shown to provide a 35 % reduction in LCoE. However, this included a 3 % reduction in installation cost, which was modelled as proportional to the reduction in weight[1]. As discussed in section 5.1, first estimates of manufacturing costs for ship building also use a simple linear relationship based on weight and a design complexity factor. These relationships could easily be built into the techno-economic model, however, more data is required to accurately predict the magnitude of change in costs with weight.

Table 6.2: Current and improved (very achievable and achievable) CA scores for each material type with the percentage reduction in unit cost given in brackets.

CA score	Current	Very achievable	Achievable
Steel	5.92	5.78 (−12 %)	5.60 (−27 %)
GRP	5.46	5.20 (−36 %)	5.00 (−64 %)
Concrete	4.98	4.94 (−12 %)	4.89 (−27 %)

6.2 Power Take-Off Technologies

Reduction in unit PTO cost and increase in maximum conversion efficiency were the next technology improvements that were investigated. The former is used to calculate the total cost of the PTO from the site-appropriate power rating and the latter is used to calculate the amount of absorbed power that is passed on to the WEC cabling (see section 5.2).

Four types of PTO were considered that have all been/are all the focus of R&D activity within the sector: 'hydraulic', 'air', 'linear' and 'mechanical'. For example, fig. 6.3 provides the number of projects involved in the WES PTO programme (WES, 2019) that

[1] In addition, a much lower value of unit cost was used (1 £/kg), which is at odds with the literature reviewed here

are developing each technology type. The ‘other’ category includes dielectric elastomer and magnetic gear technologies that are very immature and are not considered here.

The current values of unit cost and maximum conversion efficiency for each PTO type along with the other technical parameters used to calculate the CA and TA scores are given in section 6.2.1.

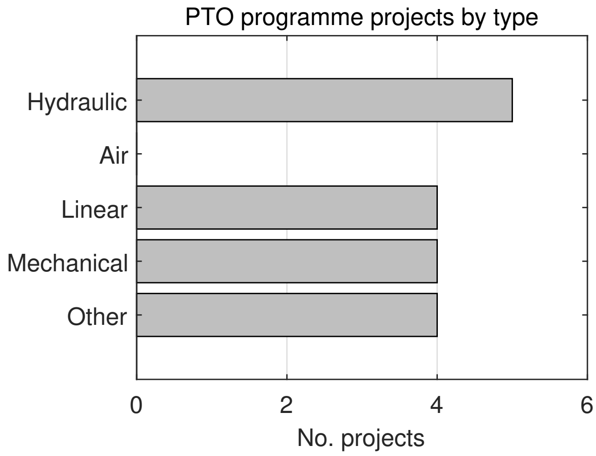

Figure 6.3: Number of WES PTO programme projects for each type of technology. Refers to the component that is the main focus of each project and includes hybrids. Source: WES (2019).

An overview of each of the four PTO types is provided here as context. Most of this information is based on a design and control study of the (failed) Wavestar device (Hansen, 2013) whilst the description of air turbines is based on a review study (Setoguchi et al., 2006).

Hydraulics have typically been employed in PTO systems as an intermediate component and means of transmission to a conventional rotatory electrical generator. They have the ability to absorb large forces and therefore, provide a useful interface between the wave action and the electrical generator. They are compatible with most oscillating-body WEC types, and were used in the Pelamis devices (Yemm et al., 2012).

Typical disadvantages of hydraulic systems are poor efficiency, including poor part-load performance and higher costs for more complex systems. However, they are the subject of active R&D; five entrants to the WES PTO programme (fig. 6.3) were for hydraulic

PTOs (or hybrids of). This includes a project, which is now at stage three testing, that uses digital displacement motors to improve part-load performance (Artemis Intelligent Power, 2017).

Air turbines are predominantly compatible with WEC types that manipulate a chamber of air such as OWC types or some submerged devices (Bombora Wave Power, 2020, e.g.). The turbine is driven by air flow induced by the oscillation of the seas surface in a semi-enclose chamber (see section 1.1). Therefore, a self-rectifying air turbine is typically required (can operate using a bi-directional air flow).

The simplest air turbine is the Wells type, which has previously been used in the Pico Plant in the Azores (WavEC, 2018) and the LIMPET device in Scotland (Alcorn et al., 2001). However, the Wells turbine creates high noise, has poor starting characteristics (a relatively high amount of energy needed to start or high cut-in airflow speed) and a narrow operating range. Other improved types of air turbine have been tested in prototype wave energy devices, however, these are more complex.

Linear electrical generators enable a direct coupling with the prime mover and remove the need for transmission components such as gears or components that convert linear motion to rotational. The large scale required to deal with the low frequency supply of wave energy can be a disadvantage. However, advances in permanent magnets and power electronics for use in direct-drive wind turbines have made the technology possible and mean that a sinusoidal and compliant waveform can be provided to the grid, although this comes with a higher cost.

Linear generators are potentially compatible with most oscillating-body WEC types but there are few examples of their use in ocean testing (an example is the Seabased WEC (Stålberg et al., 2008), whilst they were envisaged for the Waveswing (AWS, 2016)). They are the subject of active R&D and four entrants to the WES PTO programme (fig. 6.3) were for linear machines (three of which were direct drive). This includes a project for developing a modular machine that is simple to manufacture and construct and which is now at stage three testing (Project Neptune, 2017).

As with hydraulic systems, mechanical drive PTO use an extra mechanical system to turn the linear motion of an oscillating body into the rotational motion required to drive a conventional electrical generator. Therefore, they are compatible with a wide variety of WEC types. Mechanical components include gearboxes, pulleys, and flywheels, which are also used to increase velocity and smooth the power flow. Mechanical drive PTOs typically have high efficiency but the direct interface with the absorbed wave energy means that the components are subjected to many load cycles, resulting in reliability issues.

Four entrants to the WES PTO programme (fig. 6.3) were for mechanical drive machines. One of the projects uses pneumatics as an initial stage before the mechanical drive to control the resonance of a heaving buoy and to reduce the loading on the mechanical components (CorPower, 2018a). Other projects state that their motivation for developing a mechanical drive machine is to use 'off-the-shelf' components with proven high efficiency and established supply chains (e.g. Romax, 2017).

6.2.1 Technical Parameters

For each PTO type, table 6.3 provides the technical parameters, used to calculate the CA score, and the improvement potential level, used to calculate the TA score, along with a justification. As before, the value of the other input parameters to the techno-economic model were for the base deployment scenario and base case heave WEC described in chapter 5.

Table 6.3: Characteristics of each PTO type used to calculate CA and TA with justifications for the improvement potential level. The corresponding values of learning elasticity are provided in section 3.3.

PTO	η_{max} [1]	k [1]	Base c_{PTO} [2] (£/kW)	Improvement Potential	Justification
Hydraulic	0.80	1	1500	high	Novel hydraulic PTOs systems are an evolving technology that has featured in previous WECs but are the focus of substantial R&D. This includes novel innovations to address issues with efficiency and so a high improvement potential is assigned.
Air	0.60	0	1000	low	Wells turbines are a mature technology that has previously been used for wave energy, including full-scale ocean testing. However, these projects have now been discontinued and so a low improvement potential is assigned.
Linear	0.80	1	850	medium	Linear generators are an emerging technology that is mostly new to wave energy. They are the focus of active R&D including the initial testing of large-scale prototypes. Therefore, a medium learning potential is assigned.
Mechanical	0.85	2	1400	medium	Mechanical PTOs include emerging technology types as well as PTOs with 'off-the-shelf' components that are both the focus of active R&D. Therefore, a medium learning potential is assigned (with more information required to separate the two forms of the technology).

[1] Source: Hansen (2013) and Ricci et al. (2012)
[2] Source: Carbon Trust (2016), Sandia (2014), Ricci et al. (2012), Project Neptune (2017), and Artemis Intelligent Power (2017)

6.2.2 Improvements

The CA score of the heave WEC was calculated for each PTO type, for decreasing values of unit PTO cost (c_{PTO}) and for increasing values of conversion efficiency (η_{max}).

Figure 6.4 shows the CA score against reduction in PTO unit cost for the hydraulic and linear PTO types. The higher unit cost of the hydraulic PTO results in a higher initial CA score and a greater rate of decrease. At a 60 % reduction in unit PTO cost, the reduction in CA score is 8 % and 10 % for the hydraulic and linear PTOs respectively. This compares well with analysis presented in Pecher et al. (2017) that gives equivalent reductions in LCoE as between 8 % to 12 % for the Wavestar, Crestwing and LEANCON devices.

However, because of the difference in improvement potential, the feasibility thresholds are crossed at different points. For the hydraulic PTO, a 64 % reduction is achievable, which equates to a reduction in CA score of 7 %. For the linear PTO, these values are 50 % and 4 % respectively. This results in similar CA scores for the two technologies at the achievable threshold.

In fig. 6.5, the CA score is again shown for the hydraulic and linear PTO types, but this time is for improvement in conversion efficiency. As the same values of maximum conversion efficiency and part load performance are used for the two PTO types (table 6.3), the difference in CA score is due only to the difference in unit cost.

At a 10 % improvement in efficiency, the reduction in CA score is 10 % and 16 % for the hydraulic and linear PTOs respectively. This shows that efforts to improve efficiency provide a greater reduction in cost of energy and are more worthwhile than efforts to reduce cost. For comparison, the analysis presented in Pecher et al. (2017) shows that a 10 % improvement in efficiency produces a reduction in LCoE of 7 % to 21 % for the three devices.

However, as before, their are differences in the very achievable and achievable levels of improvement for each type. For the hydraulic PTO, an achievable improvement in

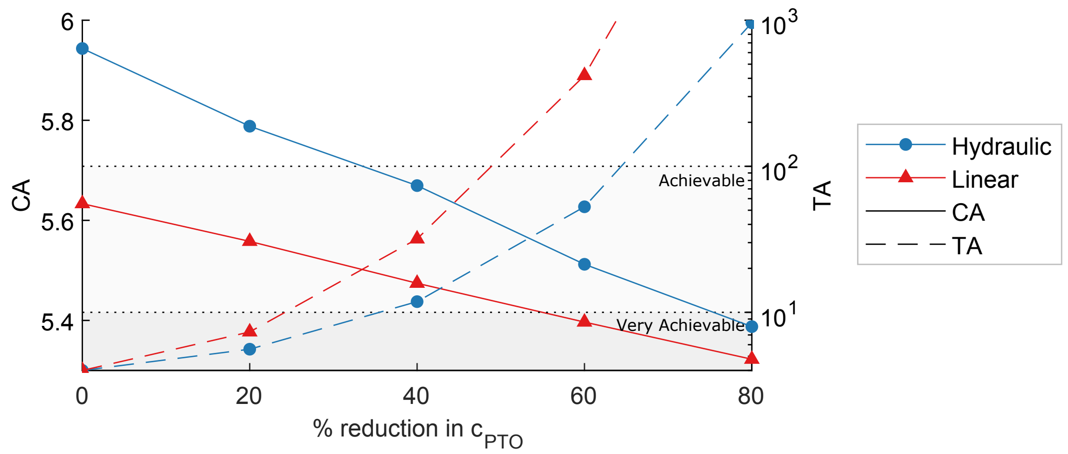

Figure 6.4: CA score and TA score versus percentage reduction in unit PTO cost for hydraulic and linear generator systems. Very achievable limit at TA = 10^1 and achievable limit at TA = 10^2.

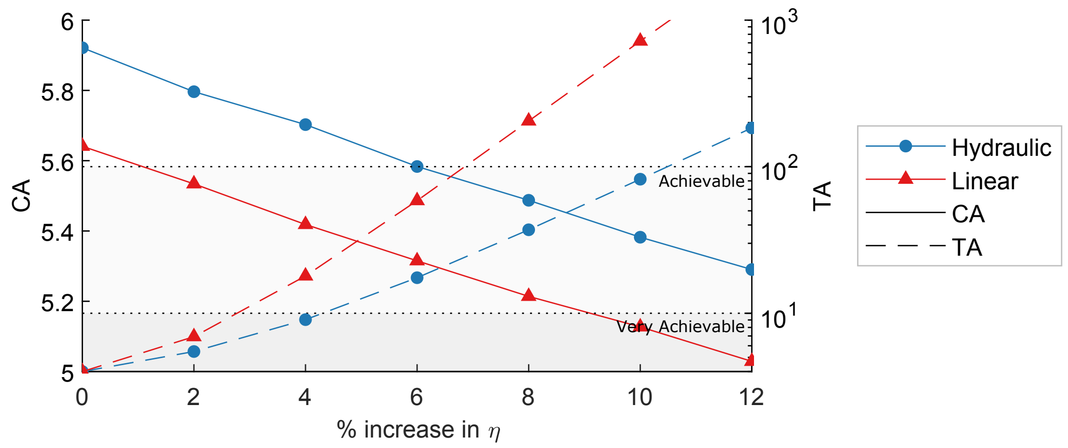

Figure 6.5: CA score and TA score versus percentage increase in maximum conversion efficiency for hydraulic and linear generator systems. Very achievable limit at TA = 10^1 and achievable limit at TA = 10^2.

efficiency can provide a reduction in the CA score of 9 %. Whereas, for the linear PTO, an achievable improvement in efficiency can provide a 6 % reduction in CA score.

The results for all four types are given in tables 6.4 and 6.5. The CA scores for the air turbine are much higher than for the other PTO types. As this is the only type of PTO applicable to OWC WECs it suggests that this combination is unlikely to be cost-competitive.

Table 6.4: Current and improved (very achievable and achievable) CA scores for each PTO type with the percentage reduction in unit cost given in brackets.

CA score	Current	Very achievable	Achievable
Hydraulic	5.92	5.68 (−36 %)	5.50 (−64 %)
Air	8.06	8.00 (−12 %)	7.88 (−27 %)
Linear	5.64	5.53 (−24 %)	5.44 (−50 %)
Mechanical	5.49	5.34 (−24 %)	5.18 (−50 %)

Table 6.5: Current and improved (very achievable and achievable) CA scores for each PTO type with the percentage increase in maximum conversion efficiency given in brackets.

CA score	Current	Very achievable	Achievable
Hydraulic	5.92	5.68 (4 %)	5.37 (10 %)
Air	8.06	7.94 (1 %)	7.80 (3 %)
Linear	5.64	5.48 (3 %)	5.28 (7 %)
Mechanical	5.49	5.32 (3 %)	5.12 (7 %)

Mechanical PTOs provide the best CA scores due to higher efficiency. However, an important consideration, which was not been modelled for these results, is the difference in reliability between each PTO type. For example, the number of components can have a large impact on reliability. In a study of WEC taxonomies (Tavner, 2017), failure rates were estimated for the Limpet device (air turbine) and the Pelamis device (hydraulics) that were based on number of components. A much lower failure rate was estimated for the Limpet device, which had more than half the number of components.

The type of components can also have a large impact. Analysis of wind turbines shows that mechanical gearbox failures result in the longest downtimes and most costly operations (Pecher et al., 2017). Therefore, direct-drive and hydraulic PTOs could provide a significant reduction in O&M costs over mechanical drive PTO types.

According to values given in Ricci et al. (2012), the ranking of the four PTO types in terms of O&M cost is (from lowest to highest cost): air, hydraulic, linear, mechanical, which is the opposite order to a ranking based on the CA scores given here. Therefore, further work is needed (along with reliable failure rate data), to understand whether reliability is more important than other PTO factors, such as efficiency and scale, in providing a lower cost of energy.

Nonetheless, to achieve the cost-competitive threshold of CA = 1, a combination of improvements would be required. The next set of results investigate these combinations to see what CA scores can be achieved.

6.3 Identifying Promising Scenarios

The results for improving current material and PTO technologies showed that individual improvements are not enough to achieve a cost-competitive WEC (CA = 1). The results in this section explore whether these technology types, in combination with different deployment scenarios, can deliver a cost-competitive WEC that is likely to succeed.

The concept generation and evaluation tool was used to evaluate input scenarios comprised of a subset of deployment and WEC parameters. Options for each parameter are provided in table 6.6, which gave 432 different combinations. For each combination three sets of values were used: current technology, very achievable improvement and achievable improvement. These values were calculated from the thresholds of the TA score and are given in tables 6.2, 6.4 and 6.5. Therefore, 1296 input scenarios were evaluated in total. In each case, and to provide a fairer comparison between results, the active width was optimised for minimal LCoE using an inbuilt Matlab solver. As before, the value of other inputs parameters were for the base case given in chapter 5.

Table 6.6: Subset of deployment and WEC parameters and the options for each parameter that were used to form input scenarios. In total there are 432 possible combinations.

Zone	$\bar{P}_{\text{site}}$ (kW/m)	WEC type	Primary material	PTO
A	20	Heave (H)	Steel (S)	Hydraulic (H)
B	50	Surge (S)	GRP (G)	Air (A)
C	80		Concrete (C)	Linear (L)
D				Mechanical (M)
E				
F				

Figure 6.6 shows the top 20 results for the heave WEC, based on an achievable level of improvement. It can be seen that zones B and F are omitted from these results, along with any lower energy (20 kW/m) sites. The best locations for the heave WEC are 50 kW/m sites in zone E and the optimum scale is around 20 m to 26 m across all the sites.

Figure 6.7 shows the top 20 results for the surge WEC, based on an achievable level of improvement. As with the results for the heave WEC, it can be seen that zones B and F are omitted, but conversely, higher energy (80 kW/m) sites are also omitted. For the surge WEC, the best locations are 20 kW/m sites in zones A and E and the optimum scale is 27 m to 41 m across all the sites.

The best CA scores for the heave WEC are 2.54 for current technology, 2.34 for very achievable levels improvement and 2.02 for achievable levels of improvement. This is for either a concrete structure and linear PTO combination or a concrete structure and mechanical PTO combination, depending on the level of improvement. Even with improvement, all of the heave WEC combinations give a CA score greater than double the target value (CA = 1), suggesting that a cost-competitive LCoE cannot be achieved.

This is primarily due to the poor absorption efficiency of the heave WEC. A useful area for further work could be to develop a method for manipulating the absorption efficiency curve, so that important parameters such as the peak efficiency and bandwidth of the curve can be improved. This could be realised through control of the WECs natural

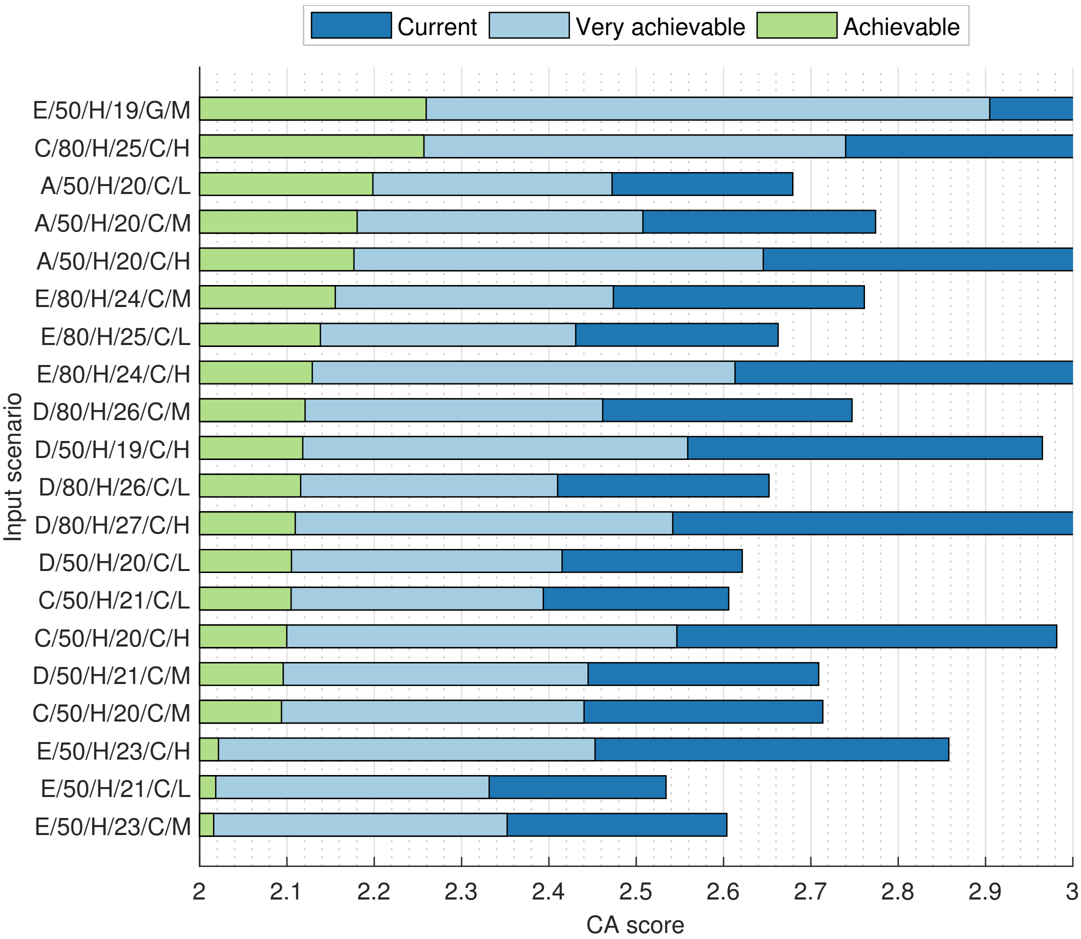

Figure 6.6: Top 20 CA scores for scenarios containing the heave WEC. The current, very achievable and achievable scores correspond to the TA thresholds given in section 3.3. Input scenario labels indicate: zone/$\bar{P}_{\text{site}}$/WEC/L_{a}/material/PTO and correspond to options given in table 6.6.

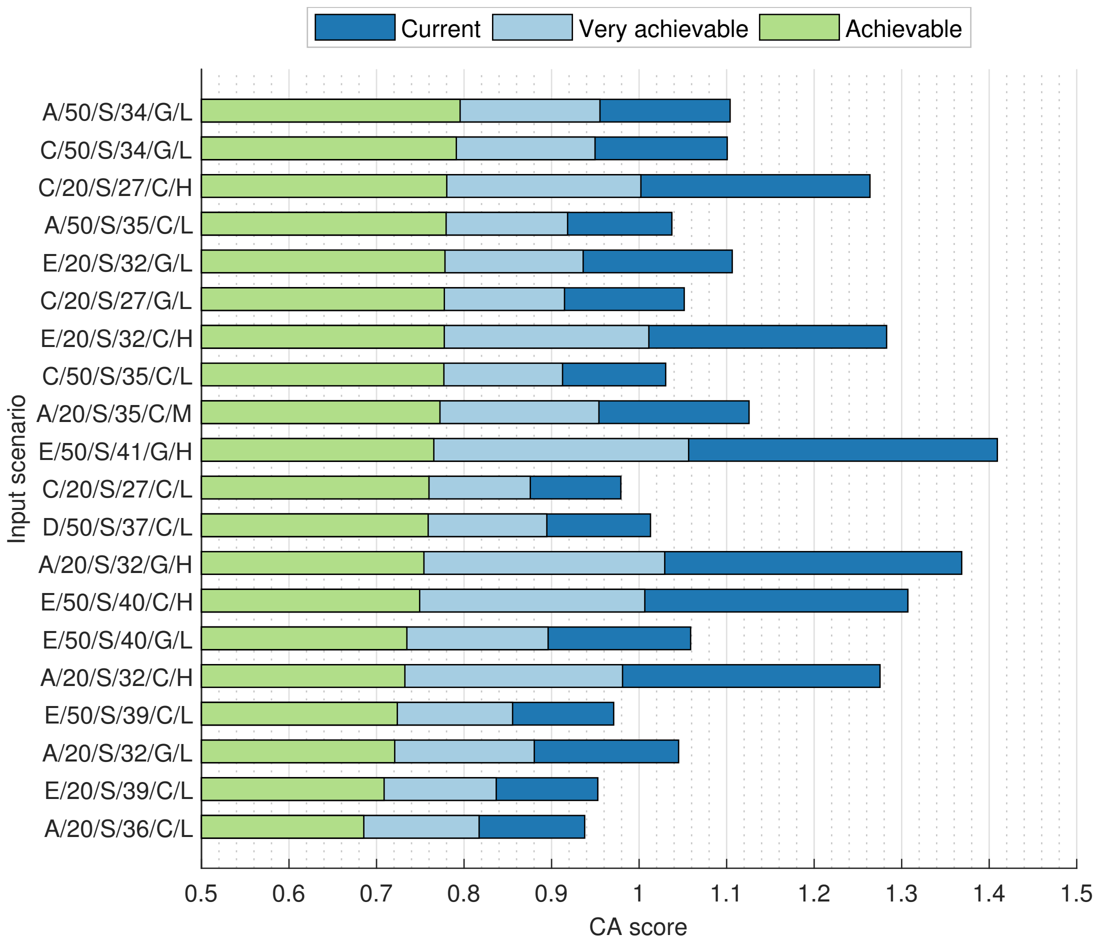

Figure 6.7: Top 20 CA scores for scenarios containing the surge WEC. The current, very achievable and achievable scores correspond to the TA thresholds given in section 3.3. Input scenario labels indicate: zone/$\bar{P}_{\text{site}}$/WEC/L_{a}/material/PTO and correspond to options given in table 6.6.

frequency and, as with the parameters investigated here, the technical achievability score could be applied to understand the potential for such improvement.

On the other hand, the best CA scores for the surge WEC are 0.94 for current technology, 0.82 for very achievable levels of improvement and 0.68 for achievable levels of improvement. In each case, this is for a combination of a concrete structure and linear PTO.

The results show that the selection of technologies which achieve the top CA scores is partly dictated by the ability of the WEC to absorb energy. For example, the heave WEC has a poor volume efficiency and the mass of the structure is high for the amount of energy captured. Therefore, concrete, which has lowest cost, appears in 18 of the top 20 combinations. Linear, mechanical and hydraulic PTO types appear six or seven times each, showing that if WEC absorption efficiency is poor then the choice of PTO technology is relatively arbitrary.

In contrast, for the surge WEC, which is able to absorb a greater amount of the available energy, the choice of PTO becomes more important. Linear PTOs appear in 13 of the top 20 combinations due to a lower unit cost and despite mechanical PTOs having a greater conversion efficiency. This is because the PTO power rating is dependent on the amount of energy absorbed by the WEC. Therefore, the higher the average absorption efficiency, the more important the PTO unit cost. The results also show that technologies that are unattractive based on their current cost and performance values, such as advanced hydraulic PTOs and composites such as GRP, could provide a competitive WEC should their high improvement potential be achieved.

6.3.1 Discussion

The third objective identified with the research question (see section 1.3), was to develop a scoring method for indicating likelihood of development success. These results show how the CA and TA score can be combined to indicate the attractiveness of current technology and the achievability of improvements required to reach the end development goal. However, as discussed in section 3.3, the TA score can only be used to indicate achievablility relative to other technologies at this stage and a method is required for selecting thresholds that is possible to validate.

The results suggest that two scenarios could already be cost competitive if they were developed. These are both for concrete structure/linear PTO WECs but in different locations and with different scales. However, as discussed in chapter 2, consideration is needed of the full set of factors that influence economic ability. More work is required to improve the modelling of key 'ilities', namely: reliability, installability and manufacturability, with regards to these technology types.

The research question focused on whether a structured innovation tool can be built for the wave energy sector. To answer that question the idea was to create a tool that can be used to scan the parameter space and identify any concepts that could achieve cost-competitiveness for a given location and available resource. Although the concept generation and evaluation tool achieves this to some degree, there is a need for further work (as discussed alongside the results presented in this thesis) for the tool to reliably identify concepts that are worthy of further development and consequently, for the tool to facilitate structured innovation.

6.4 Chapter Conclusions

The results presented in this chapter demonstrate how the CA and TA scores can be combined to indicate the attractiveness of current technology and the achievability of improvements required to reach the end development goal. This was the third objective identified with the research question.

The key messages from the results and discussion are as follows:

▷ The results for improving current material and PTO technologies showed that individual improvements are not enough to achieve a cost-competitive WEC. To explore the potential for combining improvements, the concept generation and evaluation tool was used to evaluate the CA scores of 432 input scenarios. The scenarios were a combination of the different technology types along with other WEC and deployment parameters.

- ▷ This included scenarios for the heave and surge WECs introduced in chapter 5. The results showed that the best locations for the heave WEC are 50 kW/m sites in zone E and the optimum scale is around 20 m to 26 m. For the surge WEC, the best locations are 20 kW/m sites in zones A and E and the optimum scale is 27 m to 41 m. Scenarios in zone B and F produced relatively poor results for both WECs and so are unlikely to be profitable for wave energy.

- ▷ The results showed that the question of which technologies should be considered for further development, is dependent on WEC type. The top CA scores for the heave WEC were mostly for concrete structures, whilst the best PTO type was less identifiable due to the poor absorption efficiency. The top results for the surge WEC were for either concrete or GRP structures and either linear or hydraulic PTOs.

- ▷ Finally, the results showed that technologies that are unattractive based on their current cost and performance values, could potentially provide a competitive WEC should their high improvement potential be achieved.

The results demonstrate how the concept generation and evaluation tool can be used to scan the parameter space and identifying promising concepts, which was the main aim for tool development (see section 1.3). However, further work is required to provide a fully functional structure innovation tool that can be used by developers or by a funding organisation. The next chapter summarises all the main conclusions included in this thesis and provides an overview of the proposed further work.

7. Conclusions and Further Work

This thesis outlines the steps taken to develop a concept generation and evaluation tool that can be used to facilitate structured innovation in the wave energy sector. An initial review of existing tools and metrics led to the conclusion that a techno-economic value based approach was the best way to identify promising concepts. In addition, it was decided that LCoE remains the most useful metric for evaluating concepts at this time, with the addition of a metric to indicate technology development risk. The proposed concept generation and evaluation tool can be used to scan the parameter space and identify promising concepts, this being the main aim of the research.

7.1 Summary of the Key Messages

The development of the tool was centred on three objectives which related to certain tool components. For each objective a set of results were produced to demonstrate how the corresponding component could be used. The key messages from these results can be summarised as follows:

- ▷ For the first research objective, a method was developed for providing flexible resource and site characteristics. The first set of results compared two different WEC types, heave and surge, in different regions and in high and low energy sites. The results showed significant differences between the different regions for the evolution of sea-state distribution with increasing power level.

- ▷ Consequently, there was a difference in the amount of energy captured by each WEC due to the difference in their absorption efficiency. In general, the surge WEC performed better in low energy sites and the heave WEC in high energy sites. However, this was not always consistent between the different regions and the results suggested that a deployment scenario may be profitable for one WEC type but not for another.
- ▷ In addition, there were significant differences in key cost drivers for varying site power levels, including the value of the extreme sea state and the length of the vessel delay duration. Potentially, these factors could have a large impact on lifetime expenditures and LCoE. Sensitivity analysis showed that LCoE was most sensitive to the maximum significant wave height for vessel operation.
- ▷ For the second research objective, a techno-economic model was developed that could be used to calculate concept LCoE. The second set of results compared the two WEC types in different regions, site power levels and at different scales. LCoE values of 0.69 £/kWh and 0.20 £/kWh were found for the heave and surge WECs respectively and were achieved by optimising power level and the principal WEC dimension. These LCoE values are higher than would be considered cost-competitive, showing that further technological improvements are required.
- ▷ The optimum scale of the heave WEC was around 15 m, which was relatively consistent with increasing power level and between regions. For the surge WEC the optimum active width was between 25 m and 35 m.
- ▷ The results also suggested that an optimal site power level, in the range of 30 kW/m to 60 kW/m, exists in each of the six regions that were analysed. It was found that this optimum was sensitive to the relationship with distance to shore and maximum significant wave height for vessel operation, in particular. Nonetheless, these results have implications for the deployment prospects of wave energy and show that it is important to consider design versatility when selecting the best concepts.
- ▷ The third objective was to develop a scoring method for indicating likelihood of development success. This was achieved by combining the two metrics: LCoE to represent 'commercial attractiveness' and a 'technical achievability' metric to indicate whether

technological improvements are realisable in a given development timeframe. For the final set of results, the scoring method was applied to 432 different combinations of deployment parameters and WEC parameters, including different types of structural material and PTO technologies.

- The results showed that certain structural material and PTO technologies are more likely to provide a cost-competitive WEC. The top scores, as based on values for current cost and performance, were for concrete structures and linear PTOs types. By taking into account an achievable level of improvement, the results showed that GRP structures and hydraulic PTOs, technologies with a high improvement potential, could also potentially provide a competitive WEC should that potential be realised.
- Finally, it was found that out of all the scenarios evaluated by the tool, those in zone B and F, representing the North Sea and Portuguese coast, were the least commercially attractive for both the surge and heave type WECs. This suggests that future wave energy deployment should avoid these areas unless the technology is very different from that modelled in this work.

7.2 Further Work

The following further work would improve the functionality of the tool so that it can be used by developers or by a funding organisation tasked with directing R&D.

- Further validation of the RERs: The results demonstrated how LCoE is very sensitive to the available resource and the weather window delay duration. A more complete uncertainty evaluation of the RER method would improve the understanding of concept versatility in terms of deployment location.
- Improved modelling of the 'ilities' in the techno-economic model, in particular:
    - Survivability: Inclusion of practical limits for the amount of absorbed energy that can be passed to the PTO subsystem.
    - Reliability: More detailed FMEA, including failure rates which are dependent on PTO type, and a method for calculating the cost of spare parts.

- ◇ Manufacturability: A simple expression for the cost of fabrication based on device scale and technology type, as is often used to estimate ship hull costs. The relationship between PTO type, rating and fabrication cost could also be investigated.
- ◇ Installability: A simple expression for the cost of installation based on device scale and the relationship with vessel type.

These improvement would improve the comparison of technology types and would help to remove unlikely combinations of parameters from the results. However, reliable historical examples are required to base these relationships on. The lack of such examples for wave energy would necessitate the use of examples from other similar sectors such as offshore wind and ship building.

- ▷ Develop a method for manipulating the absorption efficiency curve of the different WEC types. This could be used to replicate the effect of a control mechanism and would involve using parameters for peak efficiency, optimum wave frequency and bandwidth. The sensitivity of LCoE to these parameters could then be investigated.

- ▷ A stochastic approach for incorporating uncertainty: To account for the lack of reliable data, a stochastic method could be used to investigate the sensitivity of LCoE to the the variation in the available data. In particular, the uncertainty in unit cost values, failure rates and durations could be managed in this way. This would provide an understanding of whether uncertainty significantly alters the conclusions that can be made.

- ▷ Improvement and validation of the TA scoring method. The TA score was developed to constrain possible values of cost and efficiency in the tool and also to provide a quantitative measure of improvement achievability for different technology types. However, without an empirical method for selecting thresholds, the TA score can only be used to indicate this relative to other technologies. Further development of the score is needed, along with a method of validation.

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A. Role of Innovation Policy

Previous wave energy development was driven by a need to increase TRL in order to attract private investment. This also meant that IP was secured early in the process, resulting in a fixation on sub-optimal WEC concepts (Weber et al., 2015). Resultantly, important operational considerations were considered too late, limiting the possibility for design changes and leading to dead ends for design improvement. Analysis of the energy sector shows that allowing for feedback and design iterations is an important element for successful innovation (Gallagher et al., 2012).

Pre-Commercial Procurement (PCP) is an approach which is being implemented as part of the rethink on wave energy development. It is the procurement of R&D by government in order to stimulate innovation, allowing for a safer funding environment in which to test and experiment with design (Rigby, 2013). It also provides the freedom for developers to investigate areas of the design space that would otherwise present too much financial risk and uncertainty.

However, there is not a complete freedom and structured innovation approaches can be used to guide the development process. Important elements of PCP include the mapping of R&D needs, clear development structures, robust validation requirements and a search for technology transfer opportunities from other sectors (OECD, 2010).

For governments, the role of PCP is to achieve certain objectives through the development of new technology in cases where the market alone cannot provide a strong enough pull for their development. This might occur when there is a clear public demand for a new technology, in a market context which is typically slow to respond. The recognition of promising innovation through PCP then serves as a signal to private investors where best to direct their own capital.

In the energy sector, there is a clear need to provide low carbon energy generation but the competition is dominant and (typically) cheaper fossil fuels. Furthermore, the historic evolution of new technologies in the sector has been slow due to a high capital intensity and longevity of the existing systems (Wilson et al., 2014).

Recently however, the support and demand for renewables has sped up development and deployment, leading to significant and rapid learning-driven cost reduction (IRENA, 2017; ORE Catapult, 2016). To compete with other renewable technologies, an accelerated convergence in design is required for a transition to market-pull mechanisms and to limit the overall investment required for R&D (see MacGillivray et al., 2014).

The Organisation for Economic Co-operation and Development states that concerted approaches, such as PCP, are key to meeting current global challenges, will accelerate required technology development and bring innovative products to market(OECD, 2010).

B. Value Model Example

The following is an example of a simple value model for wave energy, as described in chapter 2. It is based on the example given in Eres et al. (2014) for the design of an aircraft. The model is made up of value functions which relate changes in parameter value to changes in design value.

The first step is to define design requirements and weight them according to their relative importance. For this example, five design requirements are defined: capture energy, survivability, low cost, reliability and deployability.

In fig. B.1, a binary scoring matrix is used to find the weighting of each requirement, where the rows and columns represent each requirement as indicated. The rows are compared against the columns: a one indicates that the row requirement is more important than the column requirement and a zero indicates that the row requirement is less important the column requirement. Scores for each requirement are calculated by counting the ones in the rows and the zeros in the columns and adding both together. This is then normalised to provide the weighting.

	Capture energy	Survivability	Low cost	Reliability	Deployability	Row score	Column score	Total score	Weighting
Capture energy		1	1	1	1	4	0	4	0.33
Survivability			0	1	1	2	0	2	0.20
Low cost				1	1	2	1	3	0.27
Reliability					1	1	0	1	0.13
Deployability						0	0	0	0.07
							Total:	10	1.00

Figure B.1: A binary scoring matrix is used to find the weighting of each of the five design requirements.

The second step is to create correlation and relationship matrices. The cells of the correlation matrix describes how strongly a design parameter is related to a design requirement. The cells of the relationship matrix describe the type of relationship (maximising, minimising and optimising (see chapter 2). The value of the correlation and the type of relationship describe the magnitude and shape of the corresponding value function.

Figure B.2 shows both matrices merged together as a single table. The columns represent each of the design requirements and the rows correspond to five design parameters: scale, material cost, material strength, capture width ratio (CWR) and mean time between failure (MTBF). Correlations between the parameters and requirements can be either 0.9, 0.6 or 0.3 to represent a strong, medium or weak relationship respectively. In this case, the relationships between the parameters and requirements are either maximising or minimising. Also included in the table is the neutral values for each design parameter. The model is design so that this set of values produces a total design value of 0.5.

		Capture Energy		Survivability		Low cost		Reliability		Deployability	
		Correlation	Relationship	Correlation	Relationship	Correlation	Relationship	Correlation	Relationship	Correlation	Relationship
WEC parameters	**Nominal values**										
Scale (m)	20	0.9	max	0.3	min	0.9	min			0.6	min
Material: Steel: Cost (£/kg)	3.03					0.9	min				
Material: Steel: Strength (MPa)	350			0.9	max	0.6	max				
Performance: CWR (%)	20	0.9	max			0.3	min	0.3	min		
Reliability: MTBF (days)	600							0.9	max		
	Sum of correlations	1.8		1.2		2.7		1.2		0.6	

Figure B.2: A table of correlation and relationships between design parameters and design requirements.

The third step is to calculate the individual design values. For a parameter value ρ, neutral value η and a simple maximising relationship, the design value is calculated using the formula:

$$f(\rho) = 1 - \frac{1}{2^{\frac{\rho}{\eta}}}$$

The equivalent formula for a simple minimising relationship is then:

$$f(\rho) = 1 - \frac{1}{2^{\frac{\eta}{\rho}}}$$

Figure B.3 gives an example set of parameter values which are different from the neutral values given in fig. B.2. Also in the table is a design value matrix where the value in each cell is the individual design value for the parameter corresponding to the row and the requirement corresponding to the column. If there is no relationship then the design value is zero.

Device			Parameter value	Capture Energy	Survivability	Low cost	Reliability	Deployability
				Design value				
Scale (m)			30	0.65	0.37	0.37	0.00	0.37
Material:	GRP	Cost (£/kg)	9.11	0.00	0.00	0.21	0.00	0.00
		Strength (MPa)	370	0.00	0.52	0.52	0.00	0.00
Performance: CWR (%)			50	0.82	0.00	0.24	0.24	0.00
Reliability: MTBF (days)			1000	0.00	0.00	0.00	0.69	0.00

	Capture Energy	Survivability	Low cost	Reliability	Deployability	
Weighting	0.36	0.20	0.28	0.12	0.04	
Sum of correlations	1.80	1.20	2.70	1.20	0.60	
Sum of values	1.32	0.58	0.90	0.69	0.22	**Total design value**
Satisfaction	0.26	0.10	0.09	0.07	0.01	**0.54**

Figure B.3: Design value matrix where the value in each cell is the individual design value for the corresponding parameter and requirement.

The final step is to calculate the total (or net) design value. First a satisfaction level is calculated for each requirement by finding the sum product of the individual design values and corresponding correlations to which the weighting is then applied. This is described by the following formula:

$$S_j = \frac{W_j}{C_j} \cdot \sum_{i=1}^{N} v_{i,j} \cdot c_{i,j}$$

Where:

▷ S_j is the satisfaction level for the requirement in column j,

▷ W_j is the weighting for the requirement in column j,

▷ C_j is the sum of the correlations for the requirement in column j,

▷ N is the number of parameters,

▷ $v_{i,j}$ is the design value for the parameter in row i and the requirement in column j,

▷ $c_{i,j}$ is the correlation for the parameter in row i and the requirement in column j.

The total design value is then simply the sum of the satisfaction levels. For the example given in fig. B.3, the total design value is 0.54. As this is greater than the neutral design value of 0.5, it shows that this particular combination of parameter values represents a net added value to the design.

C. Techno-economic Studies by Topic

Table C.1: Summary of literature investigating the wave energy parameter space in terms of financial returns. Grouped according to topic/main variable parameters.

Array scale	WEC scale	WEC type
Topper et al. (2019)	ARUP (2018)	de Andrés et al. (2017b)
ARUP (2018)	de Andrés et al. (2016)	Hutcheson et al. (2016)
Farrell et al. (2014)	Hutcheson et al. (2016)	O'Connor et al. (2013b)
Teillant et al. (2012)	O'Connor et al. (2013b)	Ricci et al. (2012)
Dalton et al. (2009)	Costello et al. (2012)	Dunnett et al. (2009)
	Ricci et al. (2012)	

Available resource	O&M parameters	Initial cost (or learning rate)
de Andrés et al. (2016)	Guanche et al. (2015)	Castro-Santos et al. (2015)
Castro-Santos et al. (2015)	Castro-Santos et al. (2015)	Guanche et al. (2014)
Guanche et al. (2014)	Teillant et al. (2012)	Farrell et al. (2014)
O'Connor et al. (2013b)	O'Connor et al. (2013a)	Teillant et al. (2012)
Dalton et al. (2009)		Allan et al. (2010)
Dunnett et al. (2009)		Dalton et al. (2009)

D. Experience Curves

Learning rates are used to represent cost reduction as a result of increased learning from experience and through economies of scale. Learning driven cost reduction is unlikely to occur across the installation period for a new project and instead bulk discount factors are used to represent a price discount for purchasing multiple WECs (Farrell et al., 2014). However, both are modelled as a function of cumulative deployment and so are calculated in the same way.

The cost reduction is calculated according to the formula for the experience curve:

$$C(x_t) = C(x_0) \cdot \left(\frac{x_t}{x_0}\right)^{-\alpha}$$

Where:

- ▷ x_0 is the total number of units at time $t = 0$,
- ▷ $C(x_0)$ is the cost of a unit at time $t = 0$,
- ▷ x_t is the total number of units at time t,
- ▷ $C(x_t)$ is the cost of a unit at time t
- ▷ and α is the learning elasticity (or bulk discount parameter).

The magnitude of α is determined from the learning rate (or bulk discount factor) using the formula:

$$\mathrm{LR} = 1 - 2^{-\alpha}$$

Therefore, the learning rate represents the % cost reduction with each doubling of the total number of units.

E. Resource Lookup Tables

RER-1: Power Level and Joint-PDF Parameters

Table E.1

Linear constants

Zone.	c_{α_1}	c_{α_2}	c_{β_1}	c_{β_2}
A	0.0253	1.95	0.00476	1.76
B	0.0458	1.26	0.00760	1.65
C	0.0277	1.69	0.00366	1.80
D	0.0331	1.36	0.00728	1.57
E	0.0344	1.35	-0.00225	2.09
F	0.0363	1.37	-0.01268	2.80

Mean values

Zone	a_1	a_2	a_3	b_1	b_2	b_3
A	0.919	1.041	0.162	0.0635	0.150	-0.0370
B	0.645	0.897	0.284	0.0769	0.176	-0.0417
C	0.740	1.185	0.182	0.0445	0.087	-0.0665
D	1.017	0.992	0.198	0.0432	0.112	-0.0686
E	0.923	1.127	0.181	0.0338	0.110	-0.0566
F	0.967	1.021	0.230	-0.0073	0.179	-0.0637

RER-2: Accessibility and Mean Delay Duration

Table E.2: RER-2 parameter lookup tables (eq. (4.13)). Top: summer periods (Apr-Sep). Bottom: winter periods (Oct-Mar).

Summer | c_{t_1}

$H_{\max} \backslash t_{\mathrm{ww}}$	12 h	24 h	36 h	48 h
1.0 m	6.10	6.31	6.47	6.70
1.5 m	5.13	5.22	5.38	5.74
2.0 m	4.66	4.62	4.62	4.73
2.5 m	5.07	4.98	4.96	4.88
3.0 m	6.13	5.96	5.90	5.77

Summer | c_{t_2}

$H_{\max} \backslash t_{\mathrm{ww}}$	12 h	24 h	36 h	48 h
1.0 m	1.83	2.86	3.54	4.13
1.5 m	1.44	2.41	3.08	3.72
2.0 m	1.10	1.99	2.57	3.08
2.5 m	1.19	2.05	2.62	3.00
3.0 m	1.79	2.60	3.13	3.48

Winter | c_{t_1}

$H_{\max} \backslash t_{\mathrm{ww}}$	12 h	24 h	36 h	48 h
1.0 m	6.90	6.97	6.61	6.48
1.5 m	6.74	6.74	6.75	6.37
2.0 m	6.05	6.17	6.49	6.50
2.5 m	6.01	6.11	6.27	6.54
3.0 m	6.75	6.83	6.93	7.03

Winter | c_{t_2}

$H_{\max} \backslash t_{\mathrm{ww}}$	12 h	24 h	36 h	48 h
1.0 m	3.45	4.44	5.00	5.48
1.5 m	3.69	4.65	5.30	5.62
2.0 m	3.52	4.53	5.35	5.85
2.5 m	3.59	4.58	5.31	5.95
3.0 m	4.16	5.13	5.81	6.35

F. Depth and Distance From Shore

Depth dependent factors that affect energy capture include the energy lost from the wave due to seabed friction and the type of wave (Pecher et al., 2017). Deep-water waves occur where the water depth is greater than half a wavelength and the energy in the wave is not in contact with the seabed. At shallower depths the friction from the seabed causes the particles in the bottom of the wave to slow down. This causes the wave to steepen and this changes the relative proportions of energy acting in each of the principle directions (see section 1.1).

Figure F.1 gives the power levels and water depths of the reference sites given in fig. 4.2 for depths below 200 m. This suggests that the relationship between water depth and site power level is relatively consistent when considered over large scale areas and discounting sudden changes in local bathymetry. The relationship, $\bar{P}_{\text{site}} = 0.39 \cdot h$, was used to estimate an appropriate water depth value (h) for calculating mooring costs in the initial cost module. According to the datapoints given in Figure F.1 this has an approximate uncertainty of ±15 kW/m in deeper water depths.

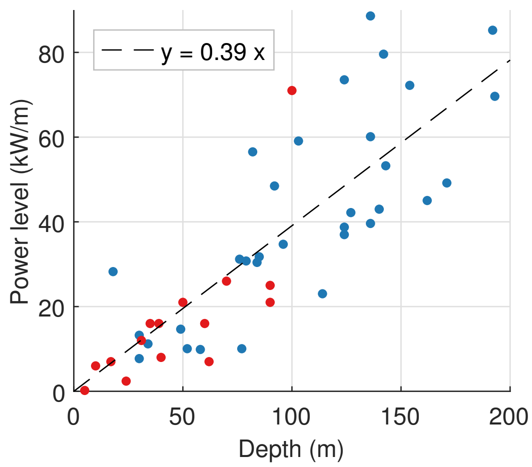

Figure F.1: Site power level versus water depth calculated for the reference sites given in fig. 4.2.

On the other hand, the relationship between water depth and distance to shore varies considerably depending on location. A general relationship of $h = d \cdot 4 \times 10^{-3}$ was used to estimate an appropriate distance from shore (d) for calculating cable costs and vessel travel times in the initial cost and reliability modules respectively. This gives a water depth of 100 m at 25 km from shore which is based on information provided online (INFOMAR, 2019) for zone C.

G. Analysis of a Cylinder Structure

For a cylindrical structure immersed in the ocean, the pressure acting on the outer walls is the sum of the hydrostatic pressure and hydrodynamic pressure calculated according to the formulas:

$$P_{\text{static}} = \rho \cdot g \cdot z$$

$$P_{\text{dynamic}} = \rho \cdot g \cdot h \cdot \exp\left(z \cdot \frac{2 \cdot \pi}{\lambda}\right) \cdot 2.5$$

Where:

- ▷ ρ is the density of sea water ($1025\,\text{kg/m}^3$),
- ▷ g is the acceleration due to gravity [m/s^2],
- ▷ z is the depth at which pressure is being calculated [m],
- ▷ h is the wave height [m],
- ▷ λ is the wavelength [m].

The 2.5 term represents the addition of the radiation and diffraction forces.

For a cylindrical shell of elastic material the buckling strength can be estimated using Glock's equation:

$$P_{\text{Glock}} = \frac{E}{1 - \nu^2} \cdot \left(\frac{l}{D}\right)^{2.2}$$

Where:

- ▷ E is the Young's modulus of the cylinder material [N/m^2],
- ▷ ν is the Poisson's ratio,
- ▷ l is the wall thickness [m],
- ▷ D is the cylinder diameter [m].

A minimum wall thickness can then be calculated by re-arranging Glocks equation and substituting for the pressure acting on the structure, multiplied by some safety factor (s_{f}), to give:

$$l_{\text{min}} = D \cdot \left(\frac{(P_{\text{static}} + P_{\text{dynamic}}) \cdot s_{\text{f}} \cdot (1 - \nu^2)}{E}\right)^{1/2.2}$$

For the design of steel plates for offshore applications a corrosion allowance is also added (DNV, 2016). This is calculated using the formula:

$$l_{\text{cor}} = v_{\text{cor}} \cdot (t_{\text{stru}} - t_{\text{coat}})$$

Where:

- ▷ v_{cor} is the corrosion rate [mm/a],
- ▷ t_{stru} is the design life of the structure [a],
- ▷ t_{coat} is the design life of the coating [a],

Figure G.1a and fig. G.1b shows wall thickness against H_{s} for different cylinder diameters and aspect ratios (diamter:length) respectively. The curves were computed using the formulas above, with values for steel given in table G.1. Values for wavelength were calculated using the corresponding wave periods for zone C (see chapter 4). A $v_{\text{cor}} = 0.3$ mm/a was used to represent non-tropical regions (DNV, 2016).

The total mass of the structure material can then be estimated by multiplying the wall thickness by the cylinder surface area and the density of steel given in table G.1.

Table G.1: Properties of structural steel.

E	200 GPa
ν	0.26
ρ_{steel}	7800 kg/m^3

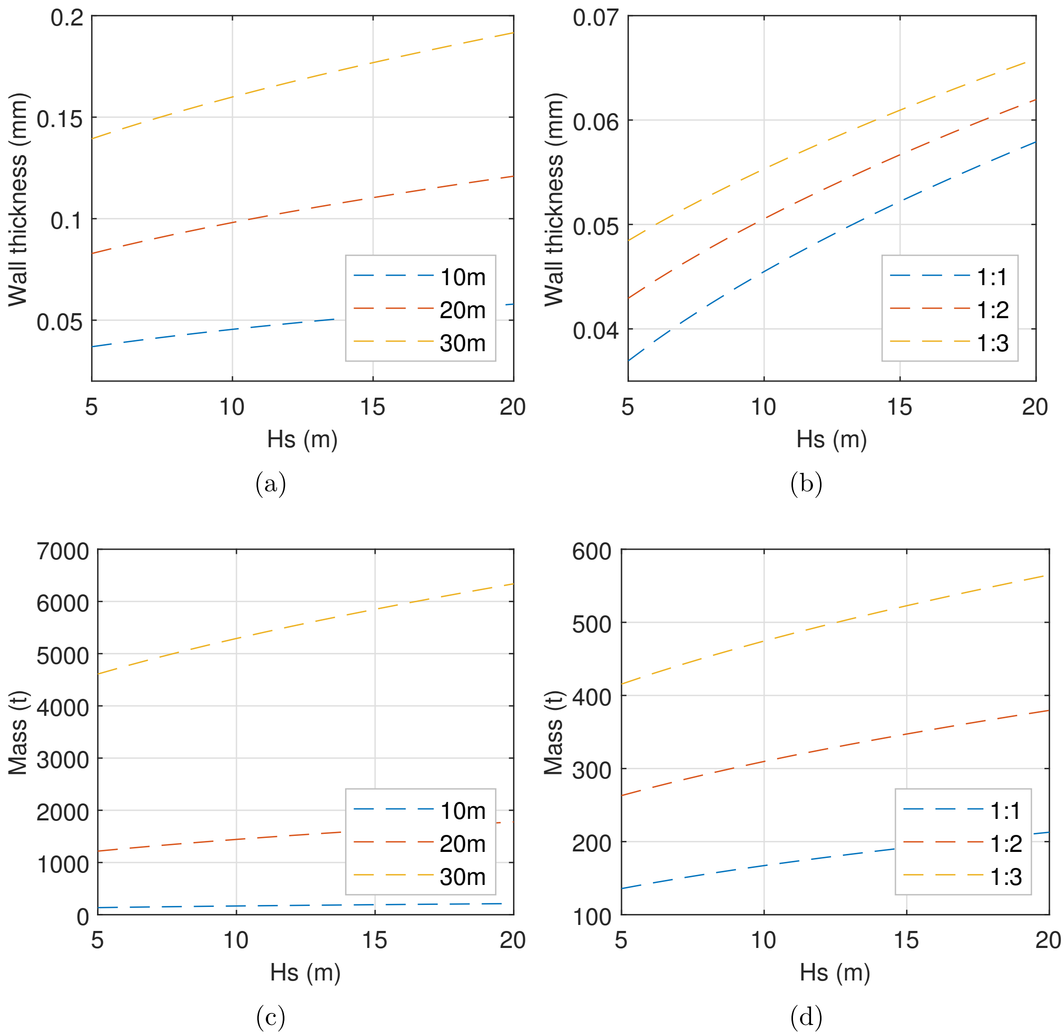

Figure G.1: Wall thickness and corresponding mass of material versus extreme H_s for:
a & c) varying cylinder diameters, aspect ratio = 1:2.
b & d) varying aspect ratios, diameter = 10 m.

H. Mooring Model

The mooring model uses three non-dimensionalised parameters, the horizontal force parameter a, the suspended scope parameter s_{mll}, and the tension parameter a_{mll}. These are defined by the formulas:

$$a(x) = \frac{F_{\mathrm{H}}}{w_{\mathrm{w}} \cdot l_{\mathrm{s}}(x)}$$

$$s_{\mathrm{mll}}(x) = \frac{l_{\mathrm{s}}(x)}{h}$$

$$a_{\mathrm{mll}}(x) = \frac{T^{\mathrm{mll}}}{w_{\mathrm{w}} \cdot l_{\mathrm{s}}(x)}$$

Where:

- ▷ w_{w} is the mooring weight in water per unit unstretched length [N m],
- ▷ h is the water depth [m],
- ▷ T^{mll} is the tension of the most loaded line [N],
- ▷ F_{H} is the horizontal force acting on the WEC [N].

Each of the three parameters is a function of non-dimensionalised offset calculated as $x = \mathrm{offset}/h$. This means that the model is scalable for both different water depths and mooring properties. Values for a, s_{mll} and a_{mll} were provided by the authors Touzón et al. (2018) for increments of $x = 0{:}0.5{:}101$. A lower offset limit might be desirable in deeper water. In this case, it was assumed F_{H} is acting in a direction centred between two mooring lines. The model is valid for mooring lines of a particular pretension.

Once the length of the mooring lines was obtained, their horizontal span was calculated using the equation for elastic catenary moorings (Pecher et al., 2017):

$$X = \frac{T_{\mathrm{H}}}{w_{\mathrm{w}}} \cdot \operatorname{arcsinh}\left(\frac{l_{\mathrm{s}} \cdot w_{\mathrm{w}}}{T_{\mathrm{H}}}\right) + \frac{w_{\mathrm{w}}}{K} \cdot l_{\mathrm{s}}$$

Where:

- ▷ T^{H} is the horizontal tension force [N],
- ▷ K is the axial stiffness [N].

For a typical steel mooring chain $K \approx 90000 \cdot D^2$, where D is the diameter in mm (Pecher et al., 2017). The mass of the mooring line per unit unstretched length is $\approx 0.02 * D^2$ (Astariz et al., 2015) and the value of w_{w} is found by adjusting the mooring weight according to the ratio of steel density (7800 kg/m^3) to sea water density (1025 kg/m^3).

I. Cable Model

Following the method outlined in Beels et al. (2011), the cable model selects a cable from standard CSA and voltage values for a 3-core submarine AC cable (table I.1) based on two criteria. Firstly, that the current (I) carried in each cable is smaller than the current carrying capacity of the cable such that:

$$I < \sqrt{I_{\mathrm{max}}^2 - (I_{\mathrm{c}} \cdot l)}$$

Where:

- ▷ I_{max} is the cable current rating (or ampacity) [A],
- ▷ I_{c} is the cable charging current [A/m],
- ▷ l is the cable length [m].

Values for I_{max} and I_{c} are given in table I.2 as given in Beels et al. (2011) and in Rebled-Lluch (2015). Extrapolation is used to find these values outside the range of CSAs provided. The current carried by the cables at rated power is calculated as:

$$I = \frac{P_{\mathrm{rated}}}{\sqrt{3} \cdot V}$$

Where:

- ▷ P_{rated} is the total rated power of the WECs connected to the cable [kW],
- ▷ V is the cable voltage rating [kV].

Secondly, that the cable provides the minimum reduction in LCoE as a result of its cost and loss of power due to resistance. To calculate this, the total power loss over the length of the cable is given by:

$$P_{\mathrm{loss}} = 3 \cdot \frac{\rho}{A} \cdot I^2 \cdot l$$

Where:

- ▷ A is the cross sectional area of the cable [m^2],
- ▷ ρ is the electrical resistivity ($=2.24 \times 10^{-8}\,\Omega\,\mathrm{m}$).

An indicative LCoE value is then calculated using the corresponding normalised cost value given in table I.1 and a value for AEP adjusted according to the formula:

$$\text{AEP} = (P_{\text{rated}} - P_{\text{loss}}) \cdot 8766 \cdot \delta$$

Where:

▷ δ is the capacity factor as calculated in eq. (5.3).

An average value for the efficiency of the cables is used to calculate AEP (eq. (3.1)). This is calculated by re-arranging the above equation to give:

$$\eta_{\text{cab}} = 1 - \frac{P_{\text{loss}}}{P_{\text{rated}}} \cdot \delta$$

Table I.1: Normalised installed cable costs from Sharkey (2013), based originally on work from Lundberg (2003).

CSA (mm^2)	10 kV	20 kV	33 kV	132 kV
35	0.79	0.82	-	-
50	0.81	0.85	0.88	-
70	0.85	0.89	0.94	-
95	1.00	1.05	1.11	-
120	1.05	1.11	1.18	-
150	1.10	1.17	1.25	-
185	1.25	1.34	1.43	-
240	1.35	1.46	1.58	-
300	1.65	1.80	1.97	-
400	1.80	1.99	2.21	2.79
500	2.00	2.25	2.53	3.25
630	2.25	2.55	2.89	3.75

Table I.2: Cable current carrying capacities (Beels et al., 2011; Rebled-Lluch, 2015)

CSA (mm^2)	I_{max} (A)	I_c (A/km)
95	300	0.9
120	340	1.0
150	375	1.0
185	420	1.1
240	480	1.2
300	530	1.3
400	590	1.5
500	655	1.6
630	715	1.8

J. Time to Failure Model

A time to failure model is used in the reliability module to determine the number of preventative (scheduled) and corrective (unscheduled) maintenance events for each year of operation. This is done for each input failure rate, where failure is used to describe any required trip to the WEC. The model is a simplified version to that outlined in Tecnalia (2017).

The failure rate (λ), typically in units of 1/a, is the inverse of the mean time between failures and the main assumption in the model is that maintenance is scheduled based on this characteristic.

The model starts at $t = 0$ and adds time steps, measured in unit of days until the specified project lifetime is reached. Each time step is for the time to failure plus the time for the maintenance operation.

The expected time to failure (t_{ex}) is calculated from the input failure rate. Preventative maintenance is scheduled prior to this, according to some tolerance (τ), such that time to scheduled maintenance is equal to $t_{\mathrm{ex}} \cdot \tau$ where $\tau < 1$. A default value of $\tau = 0.99$ was used for the results presented in this thesis.

At each time step an actual time to failure (t_{ac}) is selected at random from a Gaussian probability distribution centred at t_{ex} (fig. J.1).

The Gaussian distribution is given by:

$$\mathrm{PDF}\left(\Delta t_{\mathrm{ac}}\right) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left[-\frac{\left(\Delta t_{\mathrm{ac}} - t_{\mathrm{ex}}\right)^2}{2 \cdot \sigma^2}\right] \tag{J.1}$$

Where:

- ▷ σ is the standard deviation in t_{ex} [h].

If $t_{\mathrm{ac}} \geq t_{\mathrm{ex}} \cdot \tau$ then preventative maintenance is recorded, failure is avoided and the time step is calculated as:

$$\Delta t = t_{\mathrm{ex}} \cdot \tau + t_{\mathrm{so}} \tag{J.2}$$

If $t_{ac} < t_{ex} \cdot \tau$ then failure occurs, corrective maintenance is recorded and the time step is calculated as:

$$\Delta t = t_{ac} + t_{uo} \tag{J.3}$$

Values for σ are based on the maturity of the technology. Three levels are suggested in Tecnalia (2017) which are given in table J.1 as a percentage of t_{ex}.

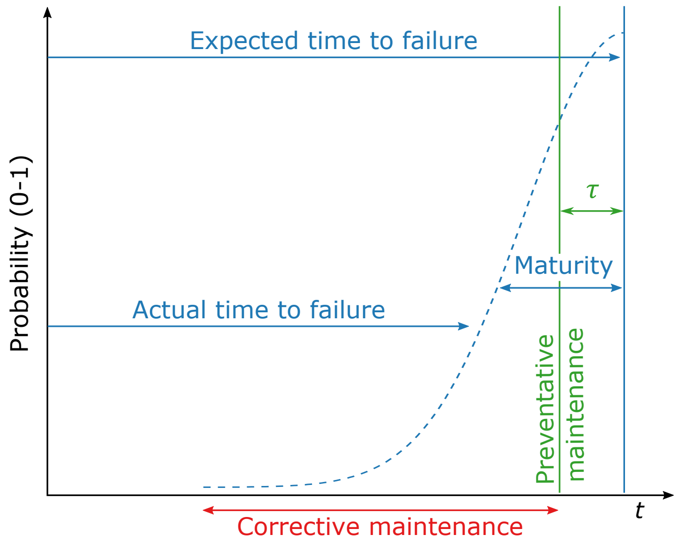

Figure J.1: The probability of failure occurrence is modelled as a Gaussian distribution dependent on the maturity of the subsystem.

Table J.1: Operational uncertainty based on maturity level as suggested in Tecnalia (2017).

Maturity Levels	σ (% t_{ex})
1	0.001
2	10
3	50

K. Base Cost Values

Table K.1: Average unit cost values found in the literature. σ is the standard deviation given as a %. Used as base values for the analysis presented in this thesis.

c_x	Type	Units	N. sources	Av. year	Av. value (£)	σ	Source
c_{mat}	steel	£/kg	5	2012	3.03	32 %	(Sandia, 2014; Ocean Power Delivery, 2003; Ramboll, 2010; Carbon Trust, 2016; ARUP, 2018)
c_{bal}	sand	£/kg	3	2009	0.07	3 %	(Ocean Power Delivery, 2003; Chozas et al., 2014; Ramboll, 2010)
c_{PTO}	hydraulic	£/kW	7	2012	1500	89 %	(Sandia, 2014; Chozas et al., 2014; Carbon Trust, 2016; Ramboll, 2010; Previsic, 2004; Ricci et al., 2012; ARUP, 2018)
c_{cab}	10 kV 95 mm^2	£/m	4	2013	140	31 %	(Sandia, 2014; Ramboll, 2010; Beels et al., 2011; ARUP, 2018)
c_{mor}	chain	£/kg	3	2014	1.65	59 %	(Sandia, 2014; Chozas et al., 2014; Astariz et al., 2015)
C_{mob}	O&M/install.	£	1/1	2017/2012	21.8 k/160 k[1]	-	(OPERA, 2016)/(Sandia, 2014)
c_{day}	O&M/install.	£/d	1/2	2017/2015	3 k/35 k	-	(OPERA, 2016)/(Sandia, 2014; ARUP, 2018)

[1] Converted to $£_{2019}$

[2] Mobilisation fee per whole array.