TECHNO-ECONOMIC ANALYSIS FRAMEWORK FOR WAVE ENERGY-TO-ELECTRICITY CONVERSION UNDER SOUTH AFRICAN CONDITIONS

A research report submitted to the Faculty of Engineering and Built Environment, University of Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the Masters of Science degree in Engineering

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Johannesburg 2018

DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

______________________, (Signature of Candidate)

10th day of September year 2018

ABSTRACT

This research report presents the research undertaken to develop a technical and economic analysis framework (Chapter 5) for Wave Energy Converters (WECs) in South Africa (SA) that can be used in the future for assessing and tracking developments of current and future technology designs. The study leading to the development of the framework is approached by understanding the wave energy resources, WECs, South African regulating policies, international practices and projects, and WEC analysis tools. The acquired information is used in case studies where two WECs of different design type are assessed for SA conditions. These WECs are assessed and compared using computational tools, which are themselves assessed and compared to verify their consistency and alignment of their outputs.

The framework to techno-economically analyse the future WECs' viability in SA was successfully developed, through knowledge acquired from literature review and case studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DEDICATION

I dedicate my research work to my loving mother, Phumzile MaDludla Biyela, whom I know her prayers are the foundation and guidance of my achievements.

To my sisters for unconditional love and the two late sisters who couldn't live to see me through this achievement.

To my late father "uCuphanisa" Biyela who couldn't live to raise me but his legacy continues.

I dedicate this research report to my beautiful daughter Melokuhle Biyela and future children.

Finally, to all my friends, it is worth mentioning Sifiso Mthiyane for providing me with unfailing support and continuous encouragement throughout.

This work is my humble sign of love for all of you!

ACKNOWLEDGEMENTS

I would like to thank my research supervisor Prof. Cronje for guiding me throughout the course of this research work. His office door was always open whenever I needed his advice. He encouraged and supported me to write conference papers which broaden my understanding of this subject.

I would also like to thank Christo Rautenbach of the CSIR for providing me with raw wave data measurements of the Slangkop site.

I extend my gratitude to Julia Chozas for developing and permitting me to use her Techno-Economic tool, and responding to my questions via emails regarding this tool. My gratitude also goes to the WECSim development team for inviting me to webinars to discuss and explain technical development of WECSim, and to the DTOcean team and sponsors for making the tool to be available free of charge.

I would also like to acknowledge the International Network on Offshore Renewable Energy (INORE) and fellow research members for accepting my application to attend the North American Symposium and share my research work via poster presentation. I thank Blue Energy Collaborative Scholarships (BECS) for offering me a grant to subsidise my travel fees to North America.

I would also like to thank Eskom for paying for my master’s degree studies and a special thanks to my colleague Kumaresan Cunden for proof reading and advising with formatting this research report.

Thank you.

LIST OF PUBLICATIONS

The list below shows the publications where the proposed scope and some results of this research work by the author are published and/or presented:

Journal Paper:

"Techno-Economic Analysis Framework for Wave Energy Conversion Schemes under South African Conditions: Modelling and Simulations" *World Academy of Science, Engineering and Technology.*

International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol: 10, No: 6, 2016.

https://waset.org/Publications/techno-economic-analysis-framework-for-wave-energy-conversion-schemes-under-south-african-conditions-modeling-and-simulations-/10004805

Conference Paper:

"A Proposal for Techno-Economic Analysis Framework for Wave Energy to Electricity Conversion Schemes under South African Conditions"

24th South African Universities Power Engineering Conference, Vereeniging 2016

"Techno-Economic Analysis Framework for Wave Energy Conversion Schemes under South African Conditions: Modelling and Simulations"

18th International Conference on Renewable Energy Resources and Applications, Paris 2016

Poster Presentation:

"Techno-Economic Analysis Framework for Wave Energy Conversion Schemes under South African Conditions Case Study"

2016 International Network on Offshore Renewable Energy (INORE) North American Symposium

CHAPTER 1

Introduction

Ocean wave energy can be summarised as a concentrated form of uneven solar energy [1] which interacts with the surface of the sea, causing the thermal rise in currents resulting in winds blowing across open water [2, 3]. The forces of the wind then generate the ocean wave energy.

Wave energy conversion to electricity is an emerging industry internationally, which could offer many benefits to South Africa (SA) if well researched and supported. But, the immaturity of these wave-harnessing technologies leads to large costs involved when deploying them. It should be noted that wave energy is excluded in the SA Integrated Resource Plan (IRP) 2010-30 due to immaturity of the technology and costs involved. The reliability, overall understanding and the lack of confidence in the technology is another contributing factor for renewable energy technologies being omitted in the IRP.

SA held its first workshop on Ocean Energy with a focus on ocean wave and ocean current energy in 2008 [4]. This workshop was hosted by the Centre for Renewable and Sustainable Energy Studies (CRSES). The South African National Energy Research Institute (SANERI), Eskom Research and Innovation Department (ERID), and private sector participated to establish a working relationship between government, national utility and the academic community to promote wave energy development in SA [4].

1.1 Reasons to Consider Wave Energy for Electricity

The research supported by a variety of literature has highlighted a number of significant benefits to utilise wave energy as compared to other forms of electricity generation. The following are some of these benefits of considering wave energy for electricity generation:

- Ocean waves offer the highest energy density amongst renewable energy resources [5].
- It is estimated that wave energy power devices can generate power up to 90 % of the time, as compared to approximately 20-30 % for wind and solar power devices [5-6].
- The energy supply is secure.
- Wave energy has the highest energy density among renewable energies [1].
- There are no carbon dioxide emissions.
- There is negligible land acquired.
- WECs built into harbour walls can have dual uses of protecting the harbour walls as well as generation of electricity [1].
- The deployment of Wave Energy Converters (WECs) can lead to economic growth and diversification of employment during construction and operation [1].

SA has numerous reasons to consider wave energy (not yet economically proven) to be included to its energy mix for electricity generation in future despite the reasons mentioned previously. It has sufficient wave energy resources due to its close proximity to the storm generation zone in the southern ocean. This is supported by measured wave data and literature [1-5]. This readily available wave energy resource spreads over 3000km of coastline and is in close proximity to populated coastal regions [2]. There is a capability in SA to venture into wave energy for electricity generation as there are well – established local engineering consultancies and port facilities to support a marine renewable sector [7]. Furthermore, wave energy may assist with local generation to coastal regions since the bulk of generation in the country is inland, resulting in long distance electrical power transmission lines to load centres. Long transmission lines pose risks to the reliability of the network and are costly to maintain.

Joubert [2] reported that some of the leading international developers of WEC technology in recent years have identified the potential for wave energy development in southern Africa with various projects planned for the southwest and southern coastline. The Scottish based Pelamis Wave Power Ltd has identified sites on the southern Cape coastline for deployment of their Pelamis attenuator WEC device (used in the case study in Chapter 4) after an initial resource assessment. It was also noted that Finavera Renewables has conducted a preliminary feasibility study for the deployment of the Aquabouy device along southwestern coastline of SA in 2006 [2]. So with all that mentioned, there is no direction towards evaluating and assessing WECs for local conditions. Hence, there is a strong motivation to fulfil the objectives of this research which are discussed in the following section.

1.2 Objective and Motivation of the Research

The research covered in this report reviewed work done by other authors, the initiatives, the developments and the tools available world-wide in the wave energy industry. It further looks at the work that has been done in SA regarding the renewable energy sector (discussed in Chapter 2). From the research it is evident that there is still a big gap in SA to initiate any development towards utilising wave energy into electricity generation.

This research is undertaken with the intention to close the identified gap by formulating and developing a framework for assessing, evaluating and selecting WECs for a selected site. The framework is intended to assist in making investment and strategic decisions to expedite ocean wave harvesting for electricity generation by analysing WECs for techno-economic performance in SA. This research also assesses the readiness of the two selected WEC technologies and their possible feasible applicability in SA.

The rest of this report discusses steps taken to learn and apply the knowledge into developing the framework, intended to close the identified gap. The framework discussed in Chapter 5 will guide a user in future with the steps to be taken to make a rational decision about a particular WEC, whether for investment, demonstration, pilot or alternative solution.

Furthermore, this research is motivated by the pressing need to integrate more renewable energy resources into the current energy portfolio. This is evident from the commitments made by SA with a number of organisations (UNFCCC (1997), Kyoto Protocol (2002), the Johannesburg Declaration (2002) and the Copenhagen Accord (2009) [7]) to reduce greenhouse gases by 34% by 2020 and to below 42% by 2025 [8]. Current electricity generation from renewable resources in the country are insufficient to reach the targets set through various agreements mentioned above. Hence it is important that the marine energy systems, specifically wave energy converters (WECs), are evaluated as part of the potential solution for meeting energy targets and reducing carbon emissions as necessitated. It is important to know if these technologies harvesting this energy are technically and economically feasible for the adoption in South Africa.

1.3 Research Methodology

Firstly, a comprehensive literature review was conducted to understand the wave energy industry with its development, and to determine the most suitable approach to perform a techno-economic study for marine energy technologies. Reference is made to a number of local and international literature, to determine the technologies and devices that are close to the commercialisation stage. This was done to select two technologies to be used for a comparison case study under South African conditions, the cost involved with wave energy converters and their associated levelised cost. From the literature review several tools to perform economic studies and technical modelling for different technologies were identified but only two of those were chosen for a case study in Chapter 4, for reasons outlined in Section 1.3.2.

Secondly, offshore electricity industry exposure was obtained through local and international conference networking sessions. The author presented papers that were well received by the peers and received constructive feedback from the audiences. The conferences also enabled the author to extract crucial information from other authors and presenters.

Thirdly, a symposium session that was held at the University of Maine in the United States of America (USA) added a lot of value in compiling this research report. The attendance to this symposium offered the author with the opportunity to network and to engage with international young researchers in offshore renewable energies as well as industry experts. Furthermore, the author learnt to use one of the commercial marine simulating tools and an offshore site visit in Cobscook Bay in north eastern coastline of USA, where a first commercial tidal wave energy project is deployed. The outcome of undertaking a self-funded journey to attend the symposium was worthwhile because of the opportunity to gather information from interactions such as networking and information sharing sessions, guest speaker's presentation, laboratory tour, and a sea site visit.

Lastly, a case study using all the information gathered is done to compare two WEC devices at a chosen location. The case studies are performed in different tools for either comparison or verification as discussed in Chapter 4 as well as the framework formulation thereof in Chapter 5.

Figure 1-1 elaborates the approach taken for a techno-economic analysis of a WEC using west coast sea conditions and all other South African energy regulations by applying a novel productivity and economic assessment of a wave energy project. It should be noted as cited previously that the success of this study is to be deemed as the framework and summarised in Chapter 5 to assist in deciding if a WEC (not limited to the WEC assessed in this report) is viable for South Africa and if so, which WEC assessed using this framework in future is most suitable.

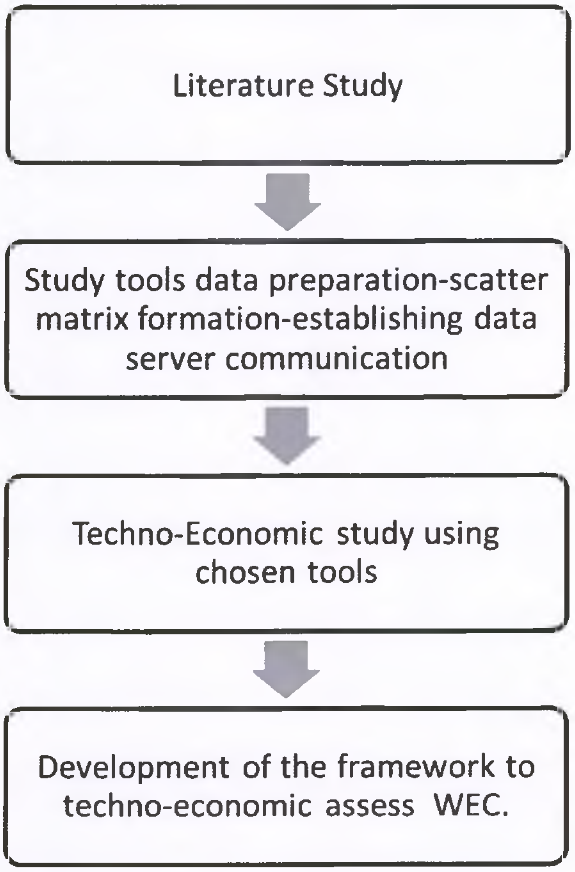

Figure 1-1: Research Flowchart

1.3.1 Site Location

The south-western coastline of the African continent according to Williams [9] is exposed to high energetic waves generated by eastwards moving, low pressure systems created in the south Indian and Atlantic oceans. High-density wave energy (40kW/m) reaches the south-western coastline of Africa as a result of the associated wind fields and cold fronts. A secondary source of wave energy generation on the south-eastern coast of Africa is the presence of tropical cyclones in the western Indian Ocean [2].

A wave energy site location study was conducted by the Council for Scientific and Industrial Research (CSIR) and documented in 2008 for Eskom [5]. The CSIR study was effectively a mapping exercise applying constraints mapping to eliminate areas where wave energy development would interfere with human or natural activities, and the results of this study are reported in references [5, 9].

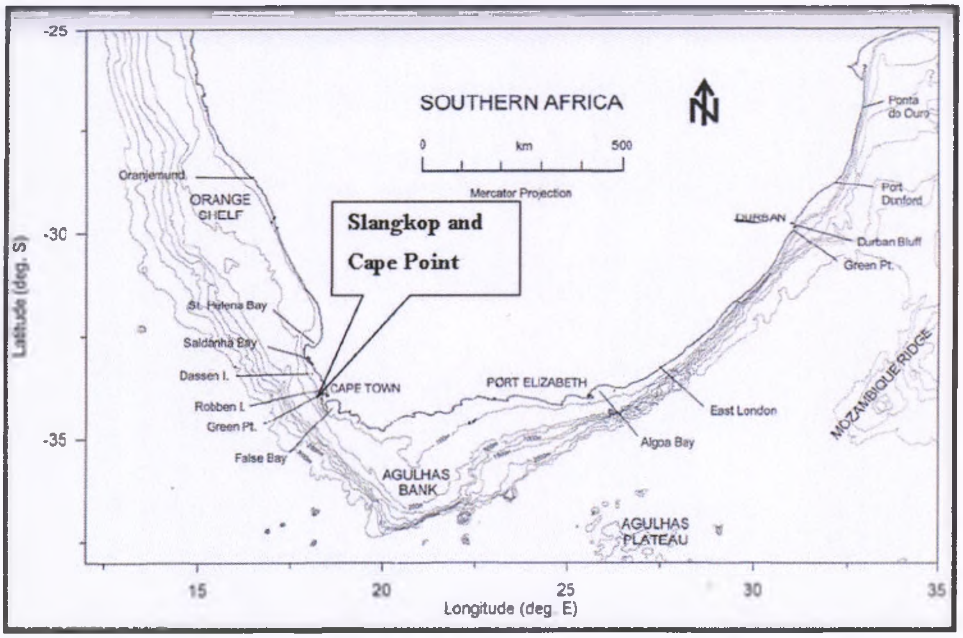

Figure 1-2: Scaled diagram showing Slangkop site location [6]

The wave power analysis of the measured wave data done in the study by Joubert [4] showed that the Slangkop and Cape Point sites have the highest wave power resources. The Cape Point mean annual average wave has approximately 40kW/m and closely contested by the Slangkop with its mean annual average of 39kW/h as tabulated and explained by Joubert [2]. For the SA techno-economic study the Slangkop site shown in Figure 1-2 is considered as the best site because it is one of the sites with high energy density plus it has reliable historical recorded sea-states data, hence it was chosen for the case study discussed in Chapter 4, the site sea wave data was requested by the author and provided by CSIR.

1.3.2 Computer Tools

This section discusses currently available computer tools to simulate WECs yielding technical and economic analysis. The computer tools used in the case study in Section 4.1 & 4.2 are discussed in details, and other tools that were identified but not used in the case study, are outlined in this section. These tools were chosen purely based on their free accessibility, technical capability to fulfil the intended tasks and authors understanding of each. The capabilities, limits and constraints of these tools are discussed in the following sections.

CoE Calculation Tool

In October 2011, the Danish Transmission Systems Operator Energinet.dk released a Microsoft Excel based open-access calculation tool to evaluate the Levelised Cost of Energy (LCoE) for WECs [10]. A consulting engineer J. Chozas together with Aalborg University and Energinet.dk developed the CoE-Calculation tool. The author has interacted with the tool developer Chozas [10], about using the tool and enquired on technical issues.

The CoE-calculation tool calculates the LCoE based on power production of a WEC at a particular location. Power production may be derived from laboratory testing, numerical modelling or from sea trials. The tool enables the economic evaluation of a deployment in a range of locations, while scaling WEC's features to the selected site [10]. Moreover, CoE-calculation tool provides good agreement between WEC's scales and locations. The following are the characteristics of the CoE-calculation tool [11]:

- It is an open-access economic calculation tool.
- It is based on well-known used software, Microsoft Excel.
- It includes default values for efficiencies, prices that can be overwritten.
- It is simple and transparent: it promotes the understanding of calculation steps and results.
- It focuses on power production values instead of an installed capacity.
- It evaluates the CoE / LCoE in a range of locations.
- It comprises the unique feature of scaling the WEC according to site locations.

The CoE-Calculation tool performs the assessment that comprises a combined productivity and costs assessment that performs quantification of the CapEx, OpEx and the productivity over the project lifetime as well as the financial calculator, which returns selected financial indicators. Inputs to this tool to assess a particular technology rely on the design specification, wave resource and market data. All input data such as: dimension, weight, minimum and maximum operative wave conditions, WEC rated power, conversion system efficiency, power production and prices, must be based on the same reference WEC device [11]. Two WEC devices are used for the case study using CoE-calculation tool, and they are briefly discussed in Section 2.4.1 and 2.4.2.

DTOcean

DTOcean development is coordinated by the University of Edinburgh and funded under the 7th Framework Programme for Research and Technology Development (FP7) with 6 million Euros over 36 months. There are 18 partners across 12 countries contributing to this platform, which include universities (Edinburgh, HRMC Cork, Exeter, Aalborg), utilities (Iberdrola, Vattenfall, DBE), the applied researchers (Tecnalia, Fraudhofer, WacEC, JRC, Sandia, MARINTEK, FEM), the supply chain (Prysmian, TTI, ITP) and the trade association (Ocean Energy Europe) [12]. This is the platform developed to accelerate the industrial development of ocean energy by providing shared access design tools for wave and tidal energy converter arrays.

The software automates the design of a feasible array of ocean energy converters for a relevant geographic location and technology type. The design process is set up in modular form with the following stages [13]:

- Hydrodynamic: designs the layout of the array configuration in a chosen region and calculates their power output.
- Electrical Sub-Systems: designs an electrical layout for the given converter locations and locates the electrical energy exported to shore.
- Mooring and Foundations: designs foundations and moorings required to secure the converters at their locations.
- Installation: designs the installation plans for the energy converter and the components required to satisfy the electrical sub-system, mooring and foundations designs.

- Operation and Maintenance: calculates the required maintenance actions and power losses resulting from operation of the converters over the lifetime of the array.

The outputs of DTOcean are the following:

- Economics: produces economic indicators for the design, in particular the LCoE.
- Reliability: assesses the reliability of the components in the design over the array lifetime.
- Environmental: assesses the environmental impact of each stage of the design.

Other Models

Several computer models currently exist globally in the form of interactive spreadsheets and software. These models were not explored in this study as they were considered to be beyond the scope of this study but they are briefly discussed in this section:

- NAVITAS is a commercially available economic analysis tool based on MS Excel, primarily developed by the authors of Hydraulics and Maritime Research Centre (HMRC) for economic analysis of marine devices [14].
- WEC-Sim an open source MATLAB tool for modelling and simulating WECs, provided to WEC design and research community by tool development team led by Sandia National Laboratory (in Appendix 1).
- The Carbon Trust model was first released in 2006; it divides cost into two large categories, CapEx and O&M costs. It uses the present-value method to

calculate the energy costs [15]. This model is currently outdated as the industry has evolved and it has been found to be inaccurate [15].

- NREL and RE Vision developed the Jobs and Economic Development Impact (JEDI) model. It has additional functionality of outputting the work, income, and economic activity that would result from a WEC array being used in a certain state. Other capabilities of this model include local revenues and equipment, supply chain impacts, and induced impacts. SNL with RE Vision created a spreadsheet that contains numerous cost factors involved in WEC array calculations as well as reporting many of the assumptions involved as part of the reference model project [15].

1.4 Identified Gap in Wave Energy to Electricity Research in SA

This chapter has introduced various available computer tools and model and assessed what international organisations are initiating, and exploring. Chapter 2 discusses common practices internationally and South African initiatives regarding renewable energy sector, in terms of legislation and regulations to energy mix. As mentioned in Section 1.2 it is clear that there is still a big gap in SA to initiate any development towards utilising wave energy into electricity generation. This research is addressing this fundamental step towards future adoption of wave energy technologies.

CHAPTER 2

Literature Review

This chapter discusses the development of the offshore wave energy industry and its technologies, by reviewing and extracting information from various literature. At this stage in the wave energy industry the developers are looking towards the cost reduction of generating electricity from ocean waves and connecting to the grid. The purpose of this chapter is to gather the available WEC technologies and their background, the active organisations in supporting wave energy industry and the research that has been done so far. It further discusses in detail the SA renewable policies as well as the tariff bidding process.

2.1 WEC Projects Progress

This section discusses some of the international wave energy projects undertaken in recent years, associated with UK institutions and other European as well as USA companies. The discussion focuses on technical organisations although there are a number of organisations that focus on promotion, economics, marketing and other aspects to expedite the introduction of the marine energy industry.

Europe is still the leading market in wave energy generation technologies and its applications, but other regions including United States of America are progressing relatively fast. Despite the world's interest in wave renewable energy South Africa is still left behind in participating in this electricity generation field. Hence, this research also focuses on some of the key issues contributing to this lack of interest. The following sections focus in Europe, and America roadmaps projects, more detailed roadmaps of more regions are covered by Sharp [15].

2.1.1 Europe's Involvement in Wave Energy

In Europe there are several groups concerned with analysing wave energy economics. In this section these groups are outlined. Firstly, the Carbon Trust, a group focusing on reducing carbon outputs in the UK and consequently promoting and aiding the development of energy. Also sources with low carbon emissions, such as marine [16]. The Carbon trust group is focusing on the economic survivability of marine hydrokinetic energy technologies and includes potential risks as part of their cost formulation.

The Strategic Initiative for Ocean Energy (SI Ocean) was a European Union funded project designed to create a plan that maximises the amount of ocean energy by 2020 [17-18]. The SI Ocean group conducted studies evaluating several aspects consisting of structure, prime mover, foundations, moorings, power take-off, installation, electrical connections, operations and maintenance [17].

European Union has recently funded a collaborative ongoing project by several European research institutes and few American organisations; together they developed a modelling package discussed in Section 1.4.2, called DTOcean. It is aimed at accelerating the development of marine energy by analysing WEC array/farm life cycle logistics and returning LCoE [19].

The EquiMar Project is the Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of performance, cost, and environmental impact. It is funded by the European Commission, for the collaborative research and development projects and involves a consortium of 23 partners and was planned to run for three years as from 15 April 2008. The aim of the EquiMar project is to deliver suitable protocols for the equitable evaluation of marine energy converters. These protocols will harmonise testing and evaluation procedures across the wide variety of devices. These protocols will be used to establish a base for future marine energy standards [17].

The commitment by United Kingdom (UK) to lower carbon emissions by 2050 [17] has inspired the UK Energy Research Centre and the Energy Technologies Institute to prioritise certain development wave energy programs.

- The first WEC devices to be deployed were 750kW Pelamis prototypes in and 2MW Archimedes Wave Swing prototypes in Portugal in 2004.
- Four years later, the first wave farm of 2.25MW was tested based on three Pelamis prototypes in 2008 in Portugal.
- In 2009, Aquamarine Power installed a 325kW Oyster WEC in Scotland, Orkney Island and later added the 800kW Oyster WEC in 2011.
- In 2011 a Danish company known as Dexawave commissioned 250kW 1:10 prototype plant in Denmark and Malta.

2.1.2 USA's Involvement in Wave Energy

The USA Department of Energy (DoE) oversees the federal support of Marine hydrokinetic (MHK) technologies. Under it there is a Wind and Water Power Technologies Office that is aimed at improving the performance, lower the costs and accelerate the deployment in innovative wind and water power technologies [17].

The Electricity Power Research Institute (EPRI) is a conglomerate of several individuals from different organisations working on offshore wave energy feasibility demonstration projects. The EPRI group has located several potential sites in the USA, from then EPRI used the Pelamis WEC as an input to run simulations for power, cost and environmental issues for proposed arrays at the sites [17]. According to Sharp [15], the simulations are preliminary and require many functional assumptions, but still provide a baseline for the subsequent research.

US National Laboratories are researching different costs aspect of MHK technologies. Sandia National Laboratories (SNL) has developed a tentative outline using Technology Readiness Level (TRL) discussed in Section 3.3.1. TRLs provide a consistent framework for discussing the advancement of different technologies towards connections [17].

2.1.3 Australia's Involvement in Wave Energy

Australia set a record of being the first country to connect an array of WECs to the national electricity grid generating electricity for more than 14 000 cumulative operating hours [18]. The Carnegie Wave Energy Project achieved this through support and funding from an Australian government organisation called Australian Renewable Energy Agency (ARENA). The array was made out of CETO5 WEC devices connected to three offshore wave power generators, to provide clean electricity and potable desalinated water to Australia's largest naval base on the Garden Island in Western Australia.

Currently the company is working on a project of their next generation of CETO units, CETO model 6 WEC to operate at higher wave heights and in increased wave power. The units are of larger size (1.5MW) to enable them to generate power at low cost.

2.1.4 Asia's Involvement in Wave Energy

China through the Guangzhou Institute of Energy Conversion, National Ocean Technology Centre, South China University of Technology, Sun Yat-sen University is showing a strong interest in wave energy by continuing support in new research, development, pilot testing and demonstration projects [20]. Two of the prominent projects are the 100kW onshore OWC plant in Shangwei and 100kW onshore pendulums WEC in Daguan Island since 2000 [20]. Other Asian countries showing interest are Japan (Mitsui) and Korea through Maritime and Ocean Energy Engineering Research Institute (KORDI) and Korea Maritime University respectively [20].

2.2 South African Energy Policy

There are a number of complex policies that have been conceptualised in South Africa by Department of Energy (DoE) over the past years to standardise and regulate trading of electricity whilst encouraging energy mix with the deployment of renewable energy technologies. The government regulates energy and electricity trading through the policies, and the constitution advocates the right to a healthy environment and sustainable supply of services including electricity. The Integrated Resource Plan (IRP) implemented in 2010 is one of the policies that have been put in place to develop a sustainable investment plan for electricity generation and transmission for the next 20 years. It was approved by the Inter-Ministerial Committee of Energy and enacted in May 2010 under the Electricity Regulation Act No.4 of 2006 [7]. The IRP is designed to provide direction for the expansion of the electricity supply over the period from 2010 to 2030 [21]. It indicates that renewable energy will be responsible for 42% of all new generation by 2030, contributing 9% to the future energy generation mix [7].

2.3 Renewable Feed-in Tariff

The South African government started exploring a Feed-In Tariff (FIT) that was higher than the market rate (FIT for coal powered power plants) in 2009 for renewable energy generation [22]. The incentive structure through FIT applied to renewable energy technologies was implemented under the Independent Power Producers Procurement Program (IPPPP), and it is known as the Renewable Energy Feed-in Tariff (REFIT) [23]. Wave, Tidal and Geothermal energy conversion technologies were excluded of REFIT phase I and II, because, these technologies were not commercially available at the time of publishing of REFIT phase I and II but hopefully with the framework from this study they will be considered in the next subsequent years annual REFIT reviews.

2.3.1 REIPPPP

The REFIT was later rejected in favour of the most effective policy instrument to date known as Renewable Energy Independent Power Producer Procurement Program (REIPPPP). REIPPP is a competitive bidding process that emerged in 2011 [23] and identified as a climate change flagship programme in the National Climate Change

Response white paper published in 2011 also, succeeding the REFIT policy that was never operationalized. Eskom was appointed to run the Renewable Energy Power Purchase Agency, as a single buyer office facilitated by National Energy Regulator of South Africa (NERSA) to award tenders to Independent Power Producers (IPPs). The bidders offered prices for 20 years in a Power Purchase Agreements (PPA) with Eskom.

Two additional agreements with the government underwrite Eskom's default risk, provided step-in rights to lenders in the case of default by the IPPs and ensure contractual obligations for delivery of up to 17 economic and social development obligations [23]. Table 2-1 tabulates these aforementioned economic development requirements.

The PPA signed under REIPPPP should fulfil the requirement obligating the communities surrounding the renewable energy plants to not less than 2.5% of the project total cost and it is mandatory for the developer to come up with ways to invest this, such as community trusts. Contractual evaluation is based on 70% on price and 30% on socio-economic factors.

The REIPPPP has to date enabled 34 wind power projects producing 3357MW, 45 PV projects producing 2292MW, seven concentrated solar projects producing 600MW and several much smaller biomass and hydro projects, totalling to 6327MW of power generated [23].

The 64 successful projects in the first three rounds involved over 100 different shareholder entities, 46 of these in more than one project [22]. The total of $19bn from banks, insurers, development banks, international utilities and foreign investors have all participated in this program. The signing of 49 Engineering, Procurement and

Construction (EPC) contracts benefited from these projects; the majority in more than one project either as primary or secondary contractor [22]. Prominent EPC contractors with three or more projects are listed in Table 2-2.

Table 2-1 Economic Development Requirement for Local Communities [23]

Element	Requirements	Description
Shareholding by local community	2.5% - 5% of project shareholding	The defined local community will have an ownership share in the project company. There are no explicit requirements on how these contributions should be exhausted, but would probably need to be developmental in nature.
Employment	12% - 20% of South African employees	This requirement requires that the South African employees in the project should come from the local community.
Enterprise development	0% - 0.6% project revenue	Enterprise development refers to contributions to black owned business with the specific objective of assisting or accelerating the development, sustainability and ultimate financial and operational independence of that enterprise.
Socio-economic development	1% - 1.5% of project revenue	These contributions should be directed towards activities that facilitate sustainable access to the economy for beneficiaries. These contributions can go towards a wide range of activities including rural development, the environment, infrastructure, enterprises, reconstruction of underdeveloped areas, development programmes for women or youth, education, health care as well as arts and culture and sports.

Table 2-2: Prominent EPC Contractors for SA Projects [22]

Company	Country
Vestas	Denmark
Acciona	Spain
Consolidated Power Projects	South Africa
Group Five Construction	South Africa
Murray and Roberts	South Africa
Abengoa	Spain
Iberdrola Engineering and Construction	Spain
Nordex Energy	German
Scatec	Norway
Suzlon	India
Temi Energia	Italy

2.4 WEC Classifications

WEC technologies can be sorted into six categories based on the type of wave motion from which the technologies produce energy. These classifications of the WEC technologies are according to European centres in Portugal and Britain, and examples are given for each extracted from [24].

Table 2-3: WEC Categories

Category	Technology	Description
Attenuator (pitching motion)	The Pelamis discussed in Section 2.4.1 (Ocean Power Delivery Ltd, UK) is the example of this class, it exposes a very small surface area to oncoming waves, a design strategy for survival in major storms.	A surface technology device that lies parallel to the direction of wave propagation and effectively rides over the waves. The water column acts a as a piston, compressing and decompressing a hydraulic fluid.
Point Absorber (heave and surge)	AquaBuoy (Finavera Renewables, Canada), Archimedes WaveSwing (AWS Ocean Energy, Scotland), CETO (Carnergie Corporation, Australia), FO3 (SEEWEC, Norway), Powerbuoy (OPT-Ocean Power Technologies, USA), Protean (Protean Power, Australia), Seadog (Independent Natural Resources, Minnesota), Wavebob (Wavebob Ltd, Ireland), Wavestar (Wave Star Energy, Denmark).	A floating structure that absorbs energy from all directions through movement of floats near or at the surface. Many different power take-off systems have been proposed from small water turbines through to linear motors.

Oscillating Surge (surge)	BioWave (BioPower Systems, Australia), Oyster (Aquamarine Power, Scotland), WaveRoller (AW-Energy, Finland).	This technology extracts the energy from the predominantly horizontal surge to water motion under waves in shallow to intermediate water depths. Most are mounted on pivots or hinges on the sea bottom, and a number of them pump high-pressure water to shore rather than generating power at sea.
Oscillating Surge (air pressure)	OE Buoy (Ocean Energy, Ireland), OWC LIMPET Plant (Voith Hydro Wavegen, Scotland), OWC Pico Plant (WEC, Portugal), Parabolic OWC with Deniss-Auld turbine (OceanLinx, Australia).	These technology devices extract energy from air movement induced by breaking large offshore waves, trapped in columns in front of breaking or above large waves. The trapped air is forced through low-pressure bi-directional turbines that generate electricity
Overtopping (breaking wave run-up)	Wave Dragon (Wave Dragon ApS, Denmark).	The forward momentum from a breaking wave will carry it at an elevation above sea level where it can be returned to the sea through conventional low-head turbines. The Wave Dragon overtopping device uses collector arms to concentrate the wave energy, which results in enormous forces on the device's stands during storms.
Submerged Pressure Differential (pressure)	SWC (Stellenbosch, South Africa).	The motion of the waves induces a pressure differential that can be used to pump fluids and generate electricity. This technology is typically bottom-mounted in a near-shore location.

It is reported that there are other WEC devices that have been proposed that are very conceptual or have unique designs and do not fall into the above mentioned categories. Although the wave technologies appear to have a theoretical basis, until they are tested at sea and have demonstrated that they can survive stormy conditions, they cannot be considered to be feasible candidates for inclusion in pilot studies.

2.4.1 The Pelamis

The first Pelamis array was installed in 2008 in Agucadoura wave farm in Portugal to make the world's first WEC operating in an array, following the first installation of one Pelamis prototype connected to into the electricity grid. The details of this project are reported in [14]. The first version of the Pelamis device, named P1, was an initial success that led to the development of the second generation WEC device, P2. It was reported [25] that the Pelamis P2 remained in Orkney where it was going through exploration for future development. The Scottish government funded the Wave Energy Scotland Company in 2014 as part of the Highlands and Islands Enterprise. Wave Energy Scotland acquired intellectual property and other assets of Pelamis Wave Power.

The Pelamis is categorised as an attenuator wave converter technology. The device uses the motion of the wave to generate electricity. It operates in water depths of greater than 50 m and it is typically installed between 2km to 10km from the shore. The machine is rated at 750kW with a target capacity factor of 25-40% depending on the conditions of the chosen project site. Each Pelamis device is 180 m long; with the tube diameter of approximately 4m. Approximately 60% of the device's body sits below the water's surface when installed at site. In total, approximately 1.68m of the device width is visible above water surface [26]. Figure 2-1 shows an image of the Pelamis in operation in Northern Portugal and the image below is a schematic showing up and down movements as the wave passes and the top view to illustrate the zigzag movement along the surface of the water.

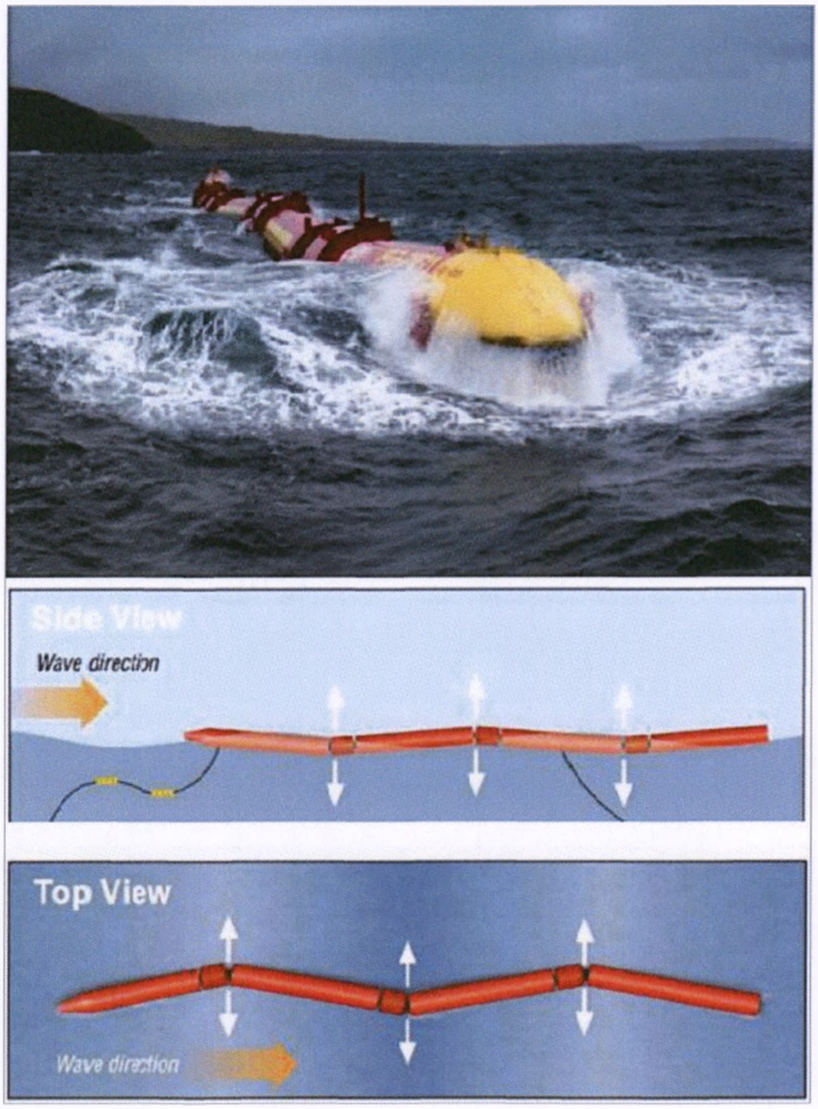

Figure 2-1: Pelamis WEC prototype in Northern Portugal and its schematic model [8]

The Pelamis is made up of five tubular sections linked by universal joints, which allow flexing in two planes. The device floats semi-submerged on the surface of the water and inherently swings perpendicular to the wave direction. As the wave passes down the length of the device, the tubular sections bend in the water, the movement is converted into electricity via hydraulic power take-off systems housed inside each joint of the devices tubes, and hydraulic power is transmitted to shore using standard subsea cables and substations.

Each Power Take-Off (PTO) unit at the joints of the device are identical, but operated independently from each other with redundancy of all main components. Hydraulic cylinders at the joints transmit hydraulic power that drives the PTO system. Hydraulics cylinders resist the wave-induced motion and pump fluid into high-pressure accumulators, allowing generation to be smooth and continuous. The hydraulic cylinders offer controlled resistance to allow generation to be maximised when waves are small, and the device response to be minimised in storms.

2.4.2 The Wavestar

The Wavestar technology shown in Figure 2-2 is characterised as a Point Absorber type wave converter and is being developed by a Denmark based company called Wave Star Energy, from a concept realised in the year 2000. It is said that the Wavestar has a potential of becoming one of the first fully commercially viable wave energy technologies [27]. The main body of the unit can be moved up and down its four pillars, which are fastened to the ocean floor in a depth of 7 to 30m of water. [8] The device is installed with structural bridges supporting the floats directed towards the dominant wave direction. The device has two rows of multiple floats, responsible for harnessing, the vertical vector of each wave passing underneath it [28]. The up and down movement of the floatation compartments driven by the passing waves power hydraulic pumps, which pressurises oil and pushes it into a common transmission system. The pressurised oil is eventually used to power a hydraulic motor that directly drives an electric generator.

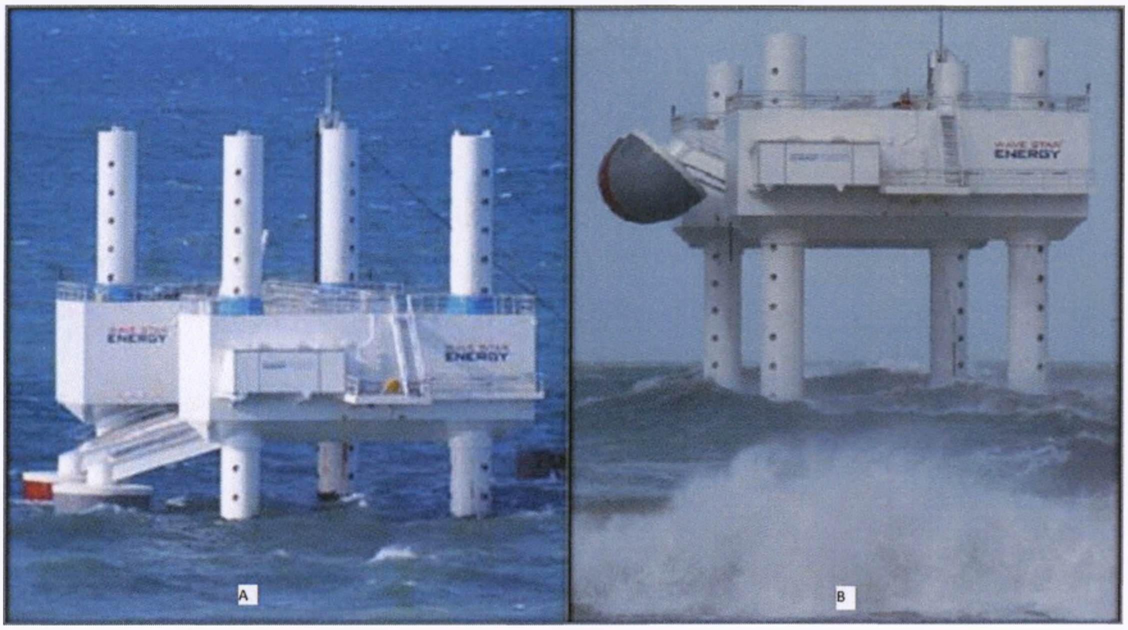

Figure 2-2 (A): Wavestar at Hanstholm [28], (B) storm protection mode [27]

In the event of storms and significant wave height exceeding the limits, the device engages its storm protection (Figure 2-2 (B)) mode by lifting its floats to a safe position known as the lockout position powered by large hydraulic cylinders. The storm protection mode is engaged by pulling out and lifting the floats one at the time then jacking up the device once all floats are pulled out. It takes a device less than one hour to lift itself to complete safe position as shown in Figure 2-2(B) [27]. For the full-scale devices, the floats hang approximately 20m above the ocean surfaces. The Wavestar is fitted with a sensor that measures the waves and ensures that the storm security system is automatically activated. The system can also be remotely operated [27].

CHAPTER 3

WEC Technology Assessment

This chapter highlights some of the key elements leading to the decision making of investing in the WEC technology. The economic viability of these technologies and main financial indicators are discussed followed by the technology levels. Technology readiness and performance levels discussed in Section 3.3 & 3.4 respectively, rate the technology in terms of readiness and performance, which consequently forms part of the technical analysis that is discussed towards the end of this chapter.

3.1 Annual Electricity Production

Annual electricity power production is a fraction of the wave power or energy flux due to conversion losses. Wave power is the rate at which energy is transmitted in the direction of propagation across a vertical plane perpendicular to the direction of wave front and extending down the entire depth. The wave power also referred to as the energy flux is given by Equation 3.1.

$$P = \frac{\rho g^2 T H^2{}_o}{32\pi} (W/m) \tag{3.1}$$

Where:

ρ : Seawater density (kg/m^3)

g : Gravitational acceleration (m/s^2)

T : Wave period (s)

H Wave height (m)

The CoE-Calculation tool discussed in Section 1.3.2 provides annual WEC production based on the device performance at the selected location (WEC power matrix and site wave measurements respectively), as well as on the device's availability, its own electricity consumption and extra production. The device availability takes into account the scheduled and the unforeseen maintenance by incorporating the probabilities obtained from statistics reliability studies. Its own consumption covers the annual energy consumption of the SCADA system, vital control and communication equipment, storm protection, etc. The extra electricity production is electricity generated by another power production source besides the device itself, i.e. production coming from the wind turbine incorporated into it.

Combining the annual energy production and cost assessment, the tool provides the economic value of the measured WEC. The cost assessment given by the financial indicators is briefly outlined in the following sections.

3.2 Economic Analysis of the WEC

Most economic studies of WECs adopt methodologies based on the Cost of Energy (CoE) approach. The CoE approach consists of determining the unit electricity production cost (currency per kWh). In the CoE study the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) of one particular WEC technology are assessed. In cost calculations, several estimates based on expert quotations, generally supplied by marine engineering consultants, are considered. The ratio between the costs associated with one WEC design and its predicted energy performance gives CoE. More recently, the CoE approach has been refined by several researchers, for instance, by applying discounting techniques to the future costs and energy production in order to obtain the Levelised Cost of Energy (LCoE) as a financial indicator. Net Present Value (NPV) is another financial indicator used alongside LCoE to assist in determining if the project is feasible or not.

3.2.1 Levelised Cost of Energy

Summing all lifetime costs of a device and dividing the total by the total lifetime energy output of the technology calculates the LCoE. LCoE allows the comparison of different technologies by calculating the price of electricity over the lifetime of the plant. The LCoE takes the interest rates into consideration and it accounts for inflations and other investment risks associated with the technology through the Discounted Rate (DR). This costing method allows renewable technologies to be compared amongst themselves as well as with traditional fossil fuel technologies accounting for their differing cost centres, intermittency, variability and efficiencies [10-11].

The economic feasibility of the WEC throughout the various development stages is assessed by the calculation of CoE. The CoE shows the cost of each unit of energy produced by a WEC throughout its lifetime and is calculated by Equation 3.2 below [11].

$$CoE = \frac{CapEx + \sum_{t=1}^{n} OpEx_t}{\sum_{t=1}^{n} WECproduction_t} \tag{3.2}$$

Where:

t : Period [years]

n : Number of years

Taking into account the variation in time of the money value, WEC costs in present value divided by electricity generation in present value; the LCoE is computed using Equation 3.3 [11].

$$LCoE = \frac{CapEx + \sum_{t=1}^{n} \frac{OpEx_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{WECproduction_t}{(1+r)^t}} \tag{3.3}$$

Where:

r : Interest rate (%)

3.2.2 Net Present Value

The Net Present Value (NPV) is the most common method of computing the net benefit of a project. NPV presents a value of the net cash inflows less the project's initial investment outlay discounting them back to present time, i.e. the sum of all years' discounted after-tax cash flows. When applying the discounted cash flow technique, cash inflows and outflows are converted for different years into a common value to recognize the time value money.

The NPV is obtained by adding all the discounted cash-flows over the lifetime as illustrated in Equation 3.4 for a project to be profitable, a strictly positive NPV at the end of the device life is a necessary condition [29].

$$NPV = \sum [\frac{FV_n}{(1+r)^n}] - i_o \tag{3.4}$$

Where:

NPV : Net Present Value [Currency]

FV : Future Value [currency]

i_o : Initial Investment [currency]

This method compares the benefit and cost of the project in relation with time. The NPV method is one of the dynamic approaches to calculating the present value of the money invested in the past or to be invested in the future with consideration of the interest rate and the length of time between the payment period and the present period [29].

3.2.3 Discounted Cash-flow Algorithm

This is the algorithm works out the value of a project at the present time based on the project's future income. Therefore the Discounted Cash-Flow (DCF) analysis projects the amount of money that will circulate within the company or the projects with respect to CapEx, OpEx, the revenue and a DR as illustrated in Equation 3.5 below [29].

$$DCF = \frac{\text{Re}v - OpEx - CapEx - Taxes}{(1+\frac{dr}{100})^t} \tag{3.5}$$

Where:

$\text{Re}v$: Revenue [currency]

Taxes : State/government taxes [currency]

3.3 Technology Readiness and Performance Level

The technology levels are often introduced in the technology assessment. There are two sets of levels and they are viewed as a two-dimensional representation of technology readiness and performance. Weber [30] forms a matrix visualisation as shown in Figure 3-1 that provides a useful means for the evaluation, comparison and discussion on different research technology development trajectories [30].

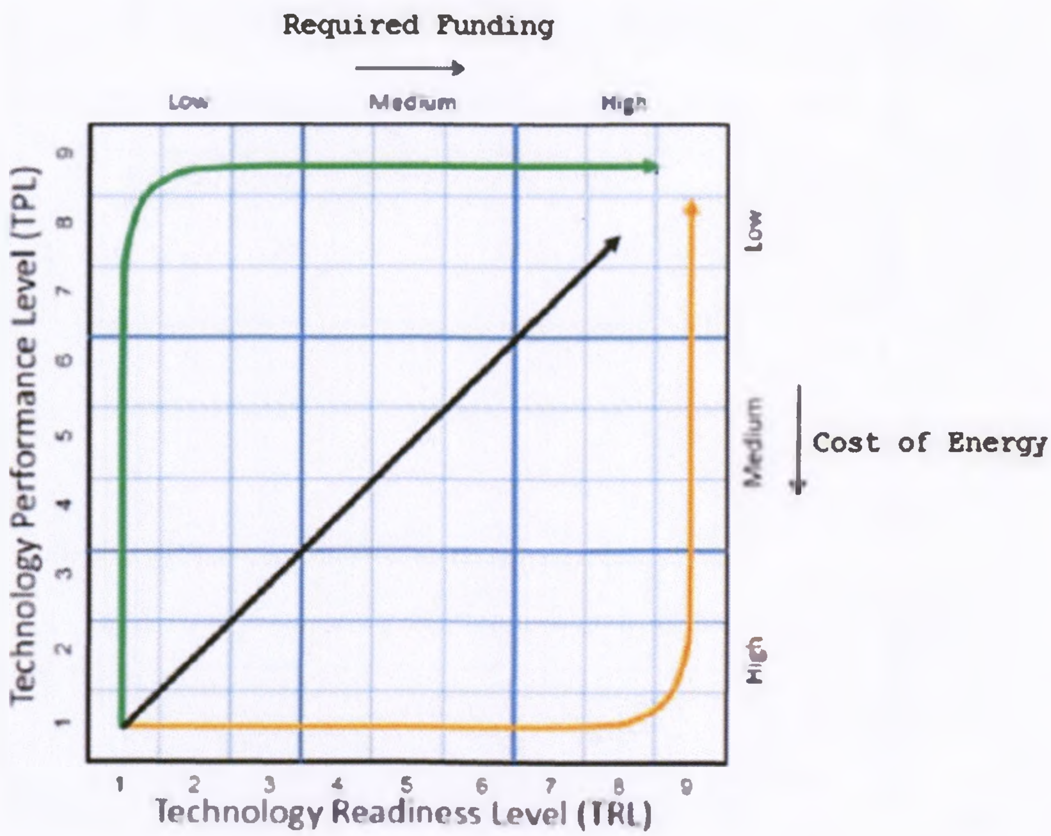

Figure 3-1: TRL and TPL trajectory [30]

The readiness before performance (yellow) trajectory represents technologies taking a risky and costly approach by omitting some of the basic WEC technology development protocols. This is because such technologies require several technology improvements at full technology readiness in terms of commercialisation. Weber [30] states that the technology development costs and durations would be unacceptably high at the high Technology Readiness Level (TRL) (discussed in Section 3.3.1) whereas the performance before readiness (green) is the trajectory representing rapidly developing technologies. This trajectory is often associated with WEC with significant changes and improvements to the technology fundamentals. This approach is affordable and practical at low TRL. The WEC development trajectory close to the green trajectory or above the black diagonal line in Figure 3-1 is recommended to get where both green and yellow trajectory converge (top right-hand corner), representing levels where the technology is technically and economically ready for commercialisation. This is where the technology is at its highest performance and readiness with developmental costs.

3.3.1 Technology Readiness Level

TRL is defined by how ready a technology is i.e. the commercial viability of the technology. Wave energy technology nowadays has evolved to a phase where different concepts are being tested at full-scale, pre-demonstration phase, and commercial demonstrations are being deployed.

Table 3-1: Technology Readiness Levels

TRL	L	Category Characteristics	TRL Characteristics
9	High	Technology is technically viable and competitive as a renewable energy form.	The technology in its final form, it is fully functional and is operating consistent with expectation.
8			Long-term, full-scale deployment of the technology in the open water. This deployment should exhibit all functionality of the technology. The technology should expect to encounter all operating conditions, as this stage should demonstrate readiness of the individual design for commercial deployment.
7			Short duration, full-scale prototype deployment in open water. This deployment will integrate all components at full-scale and should verify the expected operation.
6	Medium	Technology features some characteristics for potential technical viability under distinctive market and operational conditions. Technology or conceptual improvements may be required.	Testing has successfully demonstrated a technology's readiness to move to open water.
5			Specialised numerical models must have been developed. These specialised models should be representative of full-scale concerns. In addition, small to medium scale testing with goals related specialised conditions should occur.
4			Design phase focusing on developing the basic component models that are necessary to progress towards advanced concept designs. A medium scale concept verification test necessary to assess and refine the advanced concept design.
3 2 1	Low	Technology is not technically viable	Research is initiated in the form of an elementary numerical model and concept exploration. The concept exploration occurs both numerically and experimentally.

This section discusses the need to identify the techno-economic performance improvements at early stages of the WEC technology development process. Several research literature have discussed the development. TRLs for wave energy projects are used to provide a valuable metric of technology readiness and deliver useful guidance for the development process. TRL is essentially quantification into nine levels of the technology progress, originating in aviation, space, defence industries, and have in recent years been established in wave energy technology development [31]. The use of these TRLs has proven to be extremely valuable and applicable in assessing and quantifying WEC readiness, whether it is prototype demonstration at a particular scale or pre-commercial full-scale integrated system demonstration or a phased commercial utility project. Kelly [31] has defined the TRL as tabulated in Table 3-1.

3.3.2 Technology Performance Level

Technology Performance Level (TPL) is the feasibility rating of the technology, rated by how well the technology performs. These performance levels are tabulated and illustrated in Table 3-2. TPL is categorised into 9 levels quantifying both techno-economic functionality and lifecycle performance of the WEC system [30].

Table 3-2: Technology Performance Levels [30]

<table>
<tr><th rowspan="2">TPL</th><th></th><th>Category</th><th rowspan="2">TPL
Characteristics</th></tr>
<tr><th>L</th><th>Characteristics</th></tr>
<tr><td>9</td><td rowspan="3">High</td><td rowspan="3">Technology is economically viable and competitive as a renewable energy form.</td><td>Competitive with other energy source without special support mechanism</td></tr>
<tr><td>8</td><td>Competitive with other energy source given sustainable support mechanism</td></tr>
<tr><td>7</td><td>Competitive with other renewable energy sources given favourable support mechanism</td></tr>
<tr><td>6</td><td rowspan="3">Medium</td><td rowspan="3">Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technology or conceptual improvements may be required.</td><td>Majority of key performance characteristic & cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions.</td></tr>
<tr><td>5</td><td>In order to achieve economic viability under distinctive and favourable market and operational conditions some key technology implementation improvements are required.</td></tr>
<tr><td>4</td><td>In order to achieve economic viability under distinctive and favourable market and operational conditions some key technology implementation improvements are required.</td></tr>
<tr><td>3</td><td rowspan="3">Low</td><td rowspan="3">Technology is not economically viable</td><td>Minority of key performance characteristics & cost drivers do not satisfy potential economic viability.</td></tr>
<tr><td>2</td><td>Some of key performance characteristics & cost drivers do not satisfy potential economic viability.</td></tr>
<tr><td>1</td><td>Majority of key performance characteristics & cost drivers do not satisfy and present a barrier to potential economic viability.</td></tr>
</table>

3.4 Technical Analysis

The technical analysis covers the device design technical characteristics with the interaction with the ocean wave characteristics. The simulating packages enable us to study these hydrodynamic interactions and estimate the amount of energy that can be produced by each device. The wave characteristics are presented in the form of a scatter diagram, mapping out all probability of the possible sea states.

3.4.1 Wave Scatter Matrix

A wave Scatter matrix is a representation of frequency of occurrence of random wave conditions that occur at sea. Waves are three-dimensional in nature and different components travel in different directions which make their measurements to be difficult and thus spectra are made for uni-directional waves and corrected for three dimensions. Unprocessed measured data consists of a wave energy spectrum that is extracted using the Bretschneider spectrum, which has been found to be the best suitable function for deep sea long-fetch locations [32]. Bretscheider spectrum represents the water surface as the sum of sinusoidal waves with ranges of frequencies, amplitudes and directions. From the raw wave measurement time series, a spectral analysis is computed to obtain parameters per hour, which describe the sea-states. It indicates how often a sea-state with a particular significant wave height (Hs) and the peak wave period (Tp) occurs annually. The Slangkop wave measurements for every three hour represent a particular sea state by Hs and Tp. This information is important to WEC designers for optimal designs of WECs due to providing most important frequency occurrence of sea-states, and concurrent wave power of combinations of Hs and Tp values that is important in establishing efficiency in power extraction of WEC units. Comparing the dominant wave conditions and consequent available wave power resource to the performance curves of WEC units will predetermine the power extraction efficiency of WEC units [11]. In order to produce the wave energy matrix the following approach was taken:

- The raw data measured by the Waverider buoy transmitting date to Slangkop lighthouse, requested and obtained by the author from CSIR was exported to excel and Hs and Tp columns were extracted.
- The wave data is available in measurements of three-hour time stamps with significant wave heights, peak wave period, and peak wave direction for every day of the year 2014, was rearranged in wave heights ascending order on an excel spreadsheet.
- A frequency of sea-states occurrence was obtained by counting the number of a certain wave height that occurs at a specific wave period, this was conducted by the use of data sorting in excel spreadsheet.
- Wave periods and wave heights were divided into seventeen equal ranges or data bins to account for all possible wave periods and heights; this was done to account for all occurrences at the site represented by the raw data.
- The count of wave heights in a range at a certain wave period range was noted down in a matrix shown in Figure 3-2 as a frequency of occurrence of each sea-state, also illustrated in Appendix A.

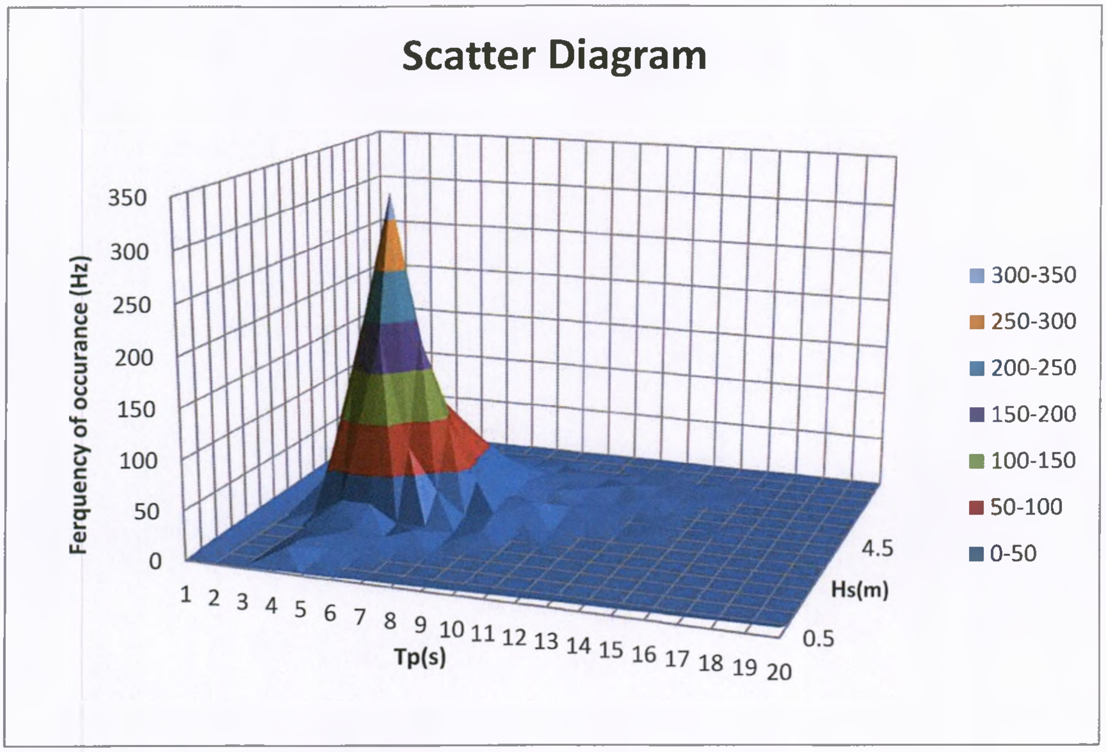

Figure 3-2: Slangkop scatter matrix diagram

One method is to present the power in a bivariate matrix; X and Y cells of the matrix would be Hs and energy period (Te) that depends on the energy density spectrum. The relationship between Te and Tp is linear, hence Te is derived from Tp, that is, Te = αTp. The Z direction would represent the power output from the WEC. This method does not include the sea direction.

CHAPTER 4

Economic Case Study

The case studies presented in this chapter are based on two computer tools with the use of data input from gathered data from the literature survey, simulations from other computer models, existing data from SA renewable projects and author's assumptions. The economic case study is based on a financial model that is subjected to established financial and governing policies at where the project is undertaken. This exercise is mainly academic as the reliability of the data and industry experience could not be verified at this stage. The approach to this study was to assess two WEC devices with dissimilar operating philosophies (to compare the performance of the different WECs based on different operating principles at Slangkop), which are in different categories that are the closest to the maturity stage, on one computer tool and then use another computer tool to verify and compare the results of the two computer tools.

4.1 CoE Calculation Tool Assessment

Comparing two WECs with the same site wave energy data using a CoE calculation tool resulted in the case study of economic analysis. These two devices were chosen because they have been tested in the sea at a prototype stage and they have a fair amount of published data. The input parameters to the CoE calculation tool for the Pelamis are tabulated in Table 4-1 and the Pelamis cost estimates were gathered from several literature publications referenced next to each cost estimate. The cost values are then adjusted to current currency value of 2014 (to match the year of data measurement) by applying indices of certainty as discussed and illustrated by Farrell [33]. The analysis is done based on 2014 wave data from Slangkop, the Discount Rate (DR) shown in Table 4-1 is assumed to be constant because NERSA stipulates a constant discount rate for all other renewable energy conversion technologies in the IPPP.

Table 4-1: Pelamis and Wavestar components' cost

Parameter	Pelamis 750 kW	Wavestar 600 kW
Power Conversion Module	€1,623,127 [28]	-
Steel per tonne	€6,000 [28]	-
Mooring	€552,165 [28]	-
Admin, Planning and Consenting	€5,682,925 [28]	-
Pre-Assembly and Transport	€35,228 [28]	-
Electrical Connections/Cables	€386,301 [28]	-
Total CapEx	€9,933,000 [28]	€24M [34]
Insurances	2% [11,34]	2% [13,34]
Discount Rate	12% [35]	12% [35]
Project Life Time	20 years	20 years

The second WEC assessed was the Wavestar and its parameters used for an economic analysis are also tabulated in Table 4-1, the analysis for both devices was only considering a single device (limited to this research scope) performance instead of multiple or arrays of each WEC technology.

CapEx-indicates the initial WEC's investment cost relating to:

- Development: engineering and management, planning and consenting
- Structure, including materials and components: materials, access system and platform and machine housing.
- Power Take-Off system (PTO), generator, power electronics, control and safety systems, etc.
- Mooring system.
- Installation: pre-assembly and transport, installation on site.
- Electrical connections.
- Others.

OpEx-represent Operational and Maintenance (O&M) costs, site lease and insurances, as cost per unit of energy produced. Annual OpEx comprises of:

- Operational and maintenance cost per year, assumed to be 6% of CapEx [36].
- Site lease and insurances; assumed to be 2% of CapEx [11, 34, 36].

For this analysis a Technology Readiness Level (TRL) of 7 was selected (based on the WEC advancement stages) for both the Pelamis and the Wavestar; this implies that the testing of these devices is at full-scale at test site, and the majority key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions [30, 37]. TRL 7 applies the uncertainty between -20% and 20% in calculations of this analysis by a CoE-Calculation tool.

4.1.1 Results and Discussion

The analysis done on a CoE-calculation tool for the Pelamis yielded the results represented by bar-chart in Figure 4-1 and 4-2. The results obtained by converting incident energy represented by the frequency of sea-states occurrences shown in Figure 3-2. In Figure 4-1 and 4-2 is the representation of the annual Pelamis power production over the lifetime computed by combining the power matrix and the wave measurements. The results illustrate that maximum annual power production of the device from wave of heights between 2m and 3m and periods between 6s and 9s. This is because the WEC devices are typically designed for resonant response, meaning that the natural period the WEC system matches incident wave period. The results indicate the performance of the WEC device (Pelamis 750kW) throughout its lifetime at Slangkop site. It can be noted that some wave heights represented by light blue bars in Figure 4-1 are not fully utilised for energy production, this is because their periods were not matching the WEC system natural period as explained previously.

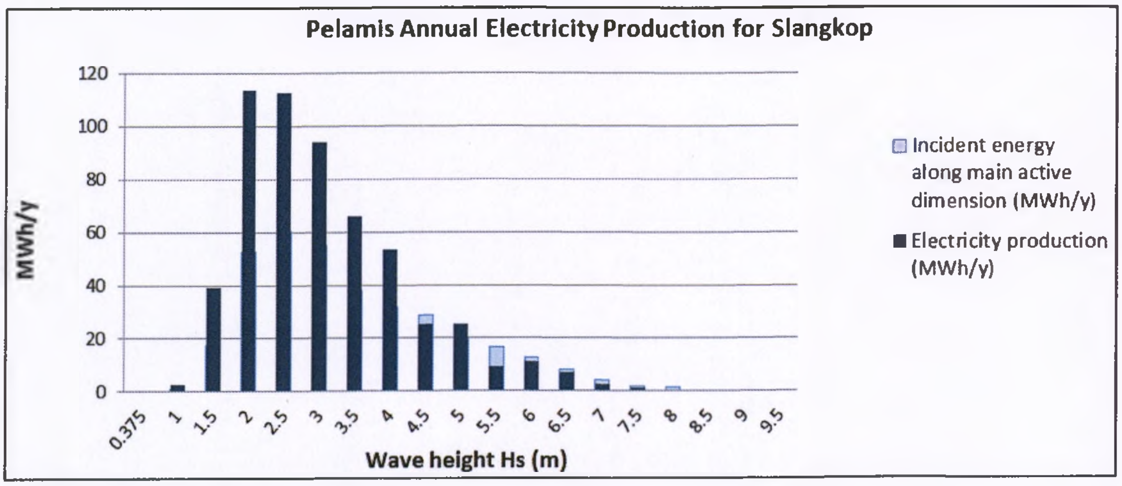

Figure 4-1: Pelamis-Wave heights

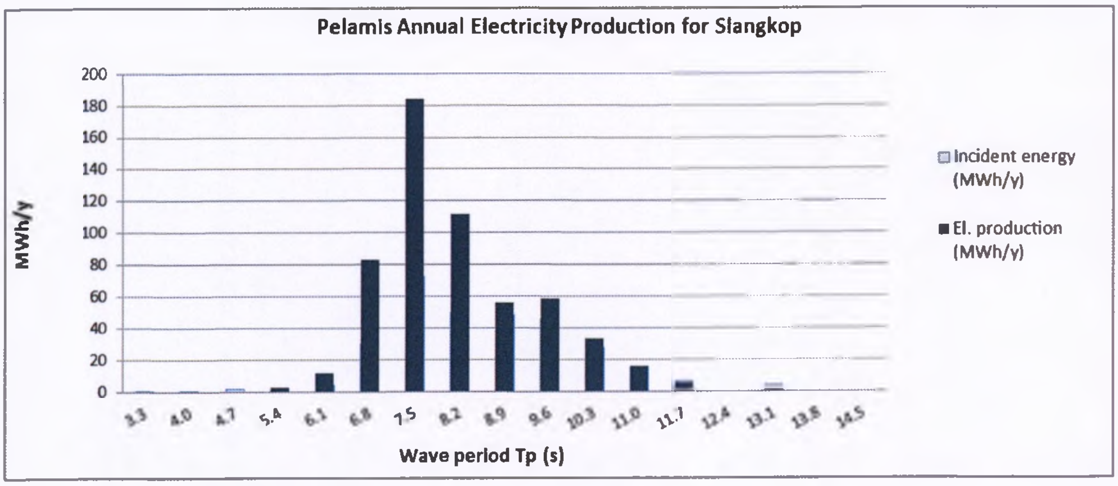

Figure 4-2: Pelamis-Wave periods

Likewise, for a Wavestar device 600kW, it is noted that the annual power production computed by combining the Wavestar power matrix and the Slangkop wave measured data was from the waves with heights up to 300MWh/y between 1.5m and 3m as shown in Figure 4-3. Figure 4-3 shows that there is significant wave power on waves with heights above 3m but not utilised for production of electricity, this is because a Wavestar engages a storm protection mode at higher wave heights to cease operation (Figure 2.2 (B)) to protect itself from being damaged high waves. Figure 4-4 shows that a bulk of electrical power produced is from the waves with peak period between 6.5s and 9s because this device's resonant response matches those wave periods.

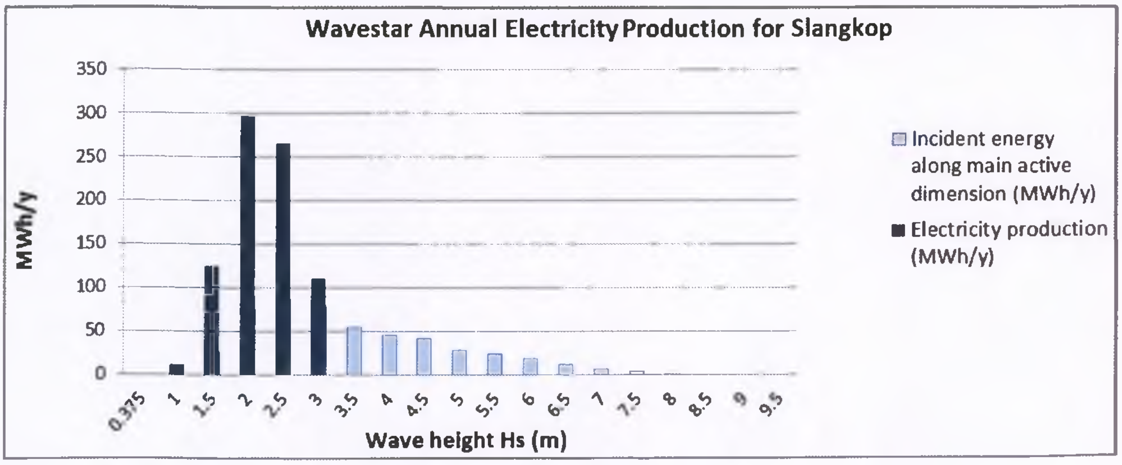

Figure 4-3: Wavestar-Wave heights

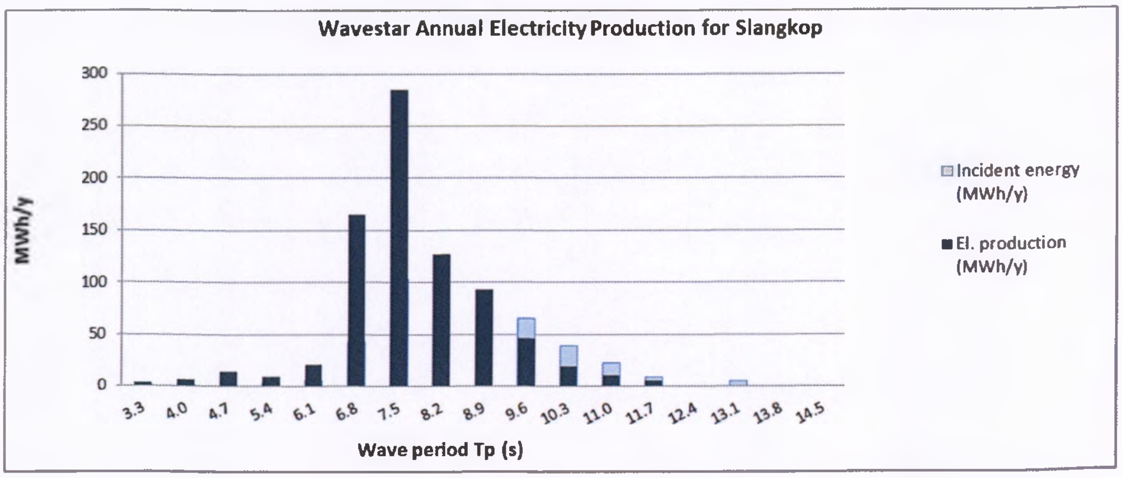

Figure 4-4: Wavestar-Wave periods

From the analysis it is seen that the Pelamis WEC's efficiency of converting wave power to electrical power is 53% (wave-to-wire efficiency is given by the annual electrical power production by the WEC divided by its dimensions and divided by the wave mean power), resulting in an average annual electricity production per wave front of 64kW that can also be represented as the annual electricity production of 563MWh/y at a 9% capacity factor (capacity factor is the ratio of the amount of energy produced to the rated output energy of a WEC, operating for 100% of the time). The low capacity factor indicate that the device is the WEC is overrated for the available resource or its natural period does not match the prevailing wave periods as discussed in Section 4.1.1. This is tabulated in Table 4-2, likewise for a Wavestar the efficiency is still 53% but the average annual electricity production is higher, giving 92kW equating to 808MWh/y annual electricity production at a high capacity factor of 15% also tabulated In Table 4-2.

It is deduced that both devices produce electricity from very few sea-states at the location but they are able to absorb more than 50% of incident waves when those favourable sea-states occur and the Wavestar absorbs more sea states than the Pelamis, resulting in more electrical power generated by it, more than that generated by the Pelamis. Important to note that the CoE-calculation tool coincidently calculated average wave-to-wire efficiency of both WECs to be 53%, this implies that both of these devices might be slightly overrated for Slangkop or not tuned to site wave periods or both.

Table 4-2: Pelamis and Wavestar technical results

Technical Outputs	Pelamis	Wavestar
Capacity factor	9%	15%
Annual electricity production	563 MWh/y	808 MWh/y
Average annual electricity production	64 kW	92 kW
Average wave-to-wire efficiency	53%	53%

The cost analysis results are shown in Figure 4-5 for the Pelamis and Figure 4-6 for the Wavestar. For the given cost assumptions tabulated in Table 4-1, feed-in tariff, predetermined discount rate and the TRL the CoE tool predicted a relatively high LCoE for both devices.

EUR	Development stage: Phase 4 / TRL 7		[-20 to 20%] uncertainty
FIT-User (€/MWh)	798.0	336.0	
Total CapEx	9.93 M€	**Annual OpEx**	794.61 k€/y
Payback period	Greater than project lifetime		
Discount rate	0%	4%	12.0%
LCOE (20 years, in €/MWh)	2293	2604	3368
NPV (20 years, in k€)	-22040.0	-18159.8	-14454.4

Figure 4-5: The Pelamis Economical results

EUR	Development stage: Phase 4 / TRL 7			[-20 to 20%] uncertainty	
FIT-User (€/MWh)	798.0	336.0			
Total CapEx	24.00	M€	**Annual OpEx**	2553.60	k€/y
Payback period	Greater than project lifetime				
Discount rate		0%	4%	12.0%	
LCOE (20 years, in €/MWh)		3862	4387	5672	
NPV (20 years, in k€)		-56970.5	-46404.0	-36313.6	

Figure 4-6: The Wavestar Economical results

Both the Pelamis and the Wavestar are development stage 4 and TRL 7; on a CoE-calculation tool this implies that there is an error margin of -20% to 20% of the results. The LCoE of €5672/MWh and €3368/MWh for the Pelamis and the Wavestar respectively, was obtained by using a REFIT of €336/MWh which is the highest granted REFIT in SA as the time, .DR of 12% (worst case scenario at the time and stipulated in the IRP for all included renewable energy technologies. A conservative WEC lifetime period 20 years (standardised in the IRP for all renewable energy devices and WECs have not yet been operated up to that period) was used in the calculation and the results show that the investment (indicated by negative NPV) will not be realised for this device lifetime. The recent published LCoE by the South African electricity utility, Eskom, for coal power station is R0.82c/kWh [38]. These results show that both WEC are still not economically viable at this stage, given that all the assumptions made in the study are correct. Negative NPVs were also obtained from several case studies for Europe such as

Belmutt test site in Ireland for both WECs at different power ratings [39]. The economic viability of these two WEC projects was computed on the basis of the net benefit NPV and the Payback period. The payback period is the length of time between the initial investment and recovery of the investment from the annual cash flow into the project. In both these project the payback period as seen in Figure 4-5 & 4-6 is longer than their lifetime which is 20 years.

4.2 DTOcean Assessment

The case study assessment performed on the DTOcean was only to focus on the hydrodynamics and economic assessment even though the software is capable of performing several assessments as briefly explained previously. The study is for only one device to compare or verify the CoE-Calculation tool results in Section 4.1. Any of the WECs used in Section 4.1 could have been used to compare and verify its performance given by both tools, however, the Pelamis was chosen due to it having more available data than the Wavestar. Moreover, the Pelamis is used for the assessment because the tool already has the database for this device model and parameters. The hydrodynamic module was prepared by creating Slangkop scatter matrix from the Slangkop wave measured data provided. In the following section the formulation of the scatter matrix using static probability of occurrence of sea state is illustrated.

4.2.1 User Inputs

WECSimulator is a DTOcean tool to simulate a WEC device within provided sea-states in a form of scatter matrix (shown in Figure 3-2). The tool evaluated the hydrodynamic properties of the WEC device in the local cylindrical coordinates system through its sub-module called Hydrodynamic, and extrapolate the hydrodynamic properties into the numerical model of the WEC power performance matrix inputted by the user (loaded into the DTOcean tool as MS Excel CSV files, and visualised on the DTOcean GUI as shown in Figure 4-7) of the device through a sub-module called Performance Fit. Performance Fit provides the ability of viewing, plotting and modifying parameters essential for the hydrodynamic interactions, and generates the hydrodynamic interaction file that is loaded to the DTOcean for WEC assessments.

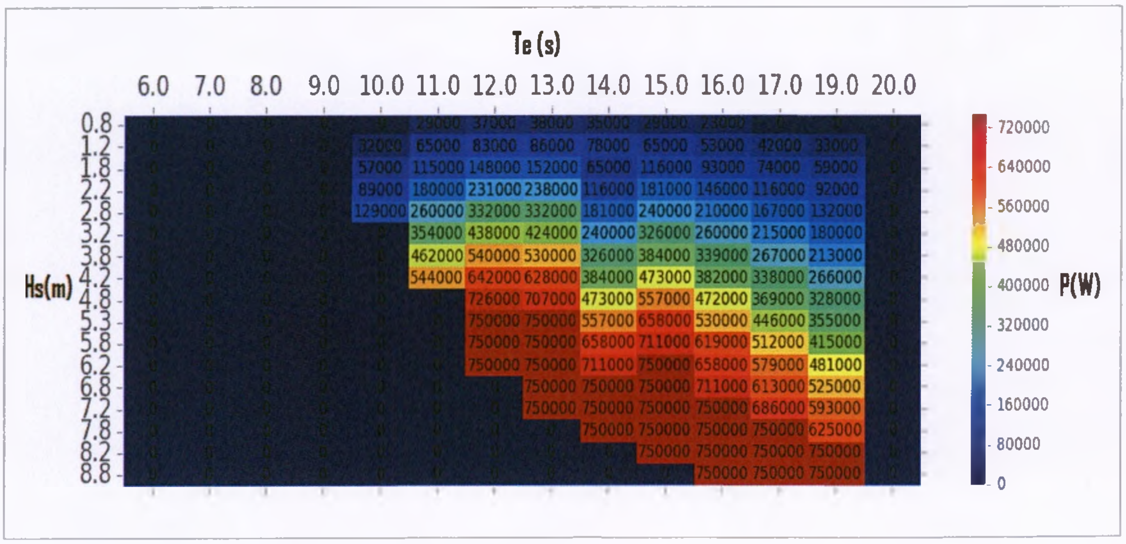

Figure 4-7: The Pelamis power matrix on DTOcean

Figure 4-7 shows the power matrix presentation of the Pelamis on the DTOcean WECsimulator, this matrix represent the rated power of the device given by its developer. It should be noted that maximum rated electrical power output of 750kW is achieved at energy periods above 11s and significant wave heights above 4.8m. The probability is the positive value lesser or equal to one, from Figure 4-8 it can be seen that the highest probability of occurrences is of those waves with heights around 2.2m and periods of 12s.

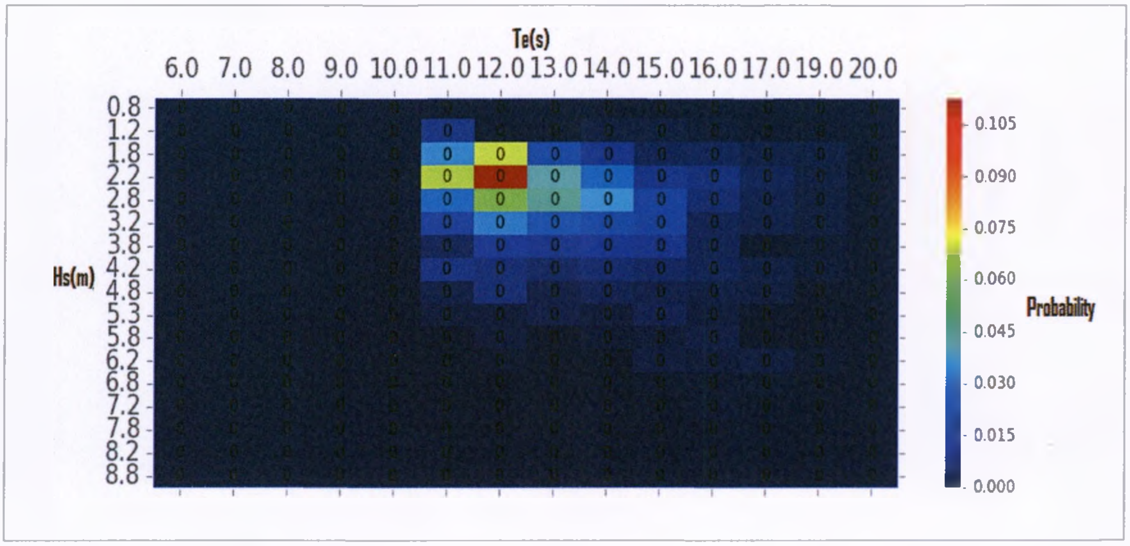

Figure 4-8: Slangkop probability scatter on DTOcean

The database used in this study was downloaded from the DTOcean website with essential parameters for the devices and its economics, environmental impacts, and reliability but filtered only for relevant study scope. A local database was created for DTOcean library and pre-set model conditions using database software called pgAdminIII shown in the Appendix C. Several scripts were written to enable connection so that DTOcean can access data from it and also to modify provided data. The modification of wave data provided to match sea-states of Slangkop shown in Figure 3-2 was done directly on the database by sorting MS Excel data to the format that can be uploaded by the database. The wave peak periods were converted to the wave energy period as explained in Section and the DTOcean only allows the visualisation of the data sorting discussed here as shown in Figure 4-9.

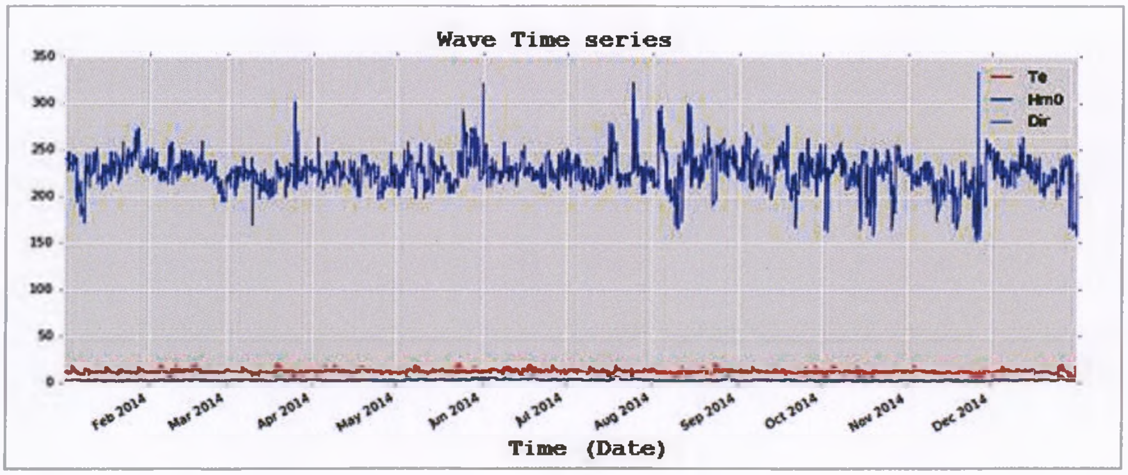

Figure 4-9: Slangkop time series diagram

The data represented by Figure 4-9 is for the year 2014, showing the wave direction (Dir) of the weighted average wave spectrum ranging between 150° and 340°, important to note that DTOcean denote Hs as Hm0. The weighted average wave spectrum is critical for some WEC that take into the account the direction of the incident waves (the Pelamis and the Wavestar are not direction dependent). The rest of the input data was modified directly on DTOcean to suit a particular device economics and SA conditions similar to the data used in the study in Section 4.1.

4.2.2 Results and Discussion

DTOcean economic assessments yielded LCoE over 20 years of 3.09€/kWh (3909 €/MWh) which closely matches the LCoE (3368€/MWh) of the Pelamis for the same DR obtained using the CoE-calculation tool, shown in Figure 4-6. Table 4-3 tabulates cost parameters for the Pelamis assessed for Slangkop site in SA. CapEx shown in Table 4-3 is broken down into components that contribute to the total project investment as shown in the pie-diagram in Figure 4-10.

Table 4-3: The Pelamis economic results on DTOcean

LCoE	3.09 €/kWh
CapEx	2905562 €
OpEx	15900000 €
Discounted CapEx	2905562 €
Discounted OpEx	66250 €
Discounted Energy	961084.73 kWh

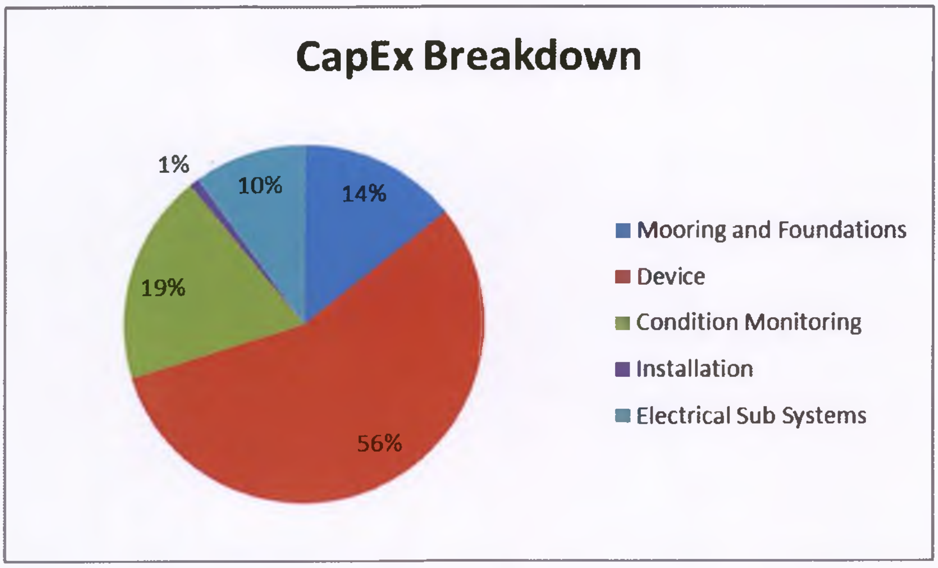

Figure 4-10: The Pelamis CapEx breakdown results on DTOcean

More than half of the CapEx is for device purchase and added to it is 19% of the CapEx for device's condition monitoring. That is, the system that remotely monitors the device health, maintenance schedule for the device and other operational issues. Third highest contributor is mooring and foundations, followed by electrical sub-systems. The installation costs are the least contributors to CapEx for the Pelamis. Figure 4-11 shows that the operational costs over the project lifetime are major expense over the project lifetime totalling to approximately 85% of the project cost in 20 years. These costs figures are based on literature gathered data, assumptions made by the author and in the literature, and the DTOcean built-in parameters.

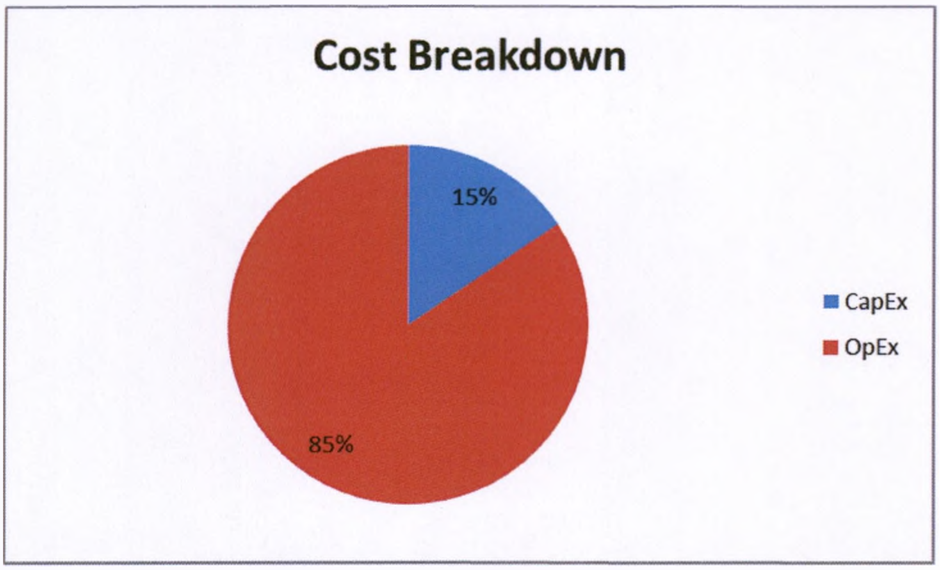

Figure 4-11: The Pelamis cost breakdown on DTOcean

Cost breakdown in Figure 4-11 above shows the percentage of CapEx and OpEx towards the total investment for the duration of its lifetime. OpEx is significantly larger than CapEx because it is the expenditure throughout the project lifetime whereas CapEx is a large once off upfront investment to the project. OpEx is supplemented by the returns through electricity production over the years.

CHAPTER 5

WEC techno-Economic Analysis Framework

In this chapter a framework to assess any WEC for techno-economic feasibility for deployment in SA is proposed, and outlined in a flowchart shown in Figure 5.1. The proposed framework is a combination of the steps taken and discussed in previous chapters of this research report. Each of the process, input, preparation and decision blocks in the logic of the flowchart is explained further in this chapter and the examples are made with reference to the case study discussed in Chapter 5 to illustrate the procedure being presented. This framework merely suggests the guidelines from the authors' experience from the research conducted and leading to the case study discussed in Chapter 5.

5.1 WEC Techno-Economic Flowchart stages

Choose a WEC

The process of assessing a WEC for techno-economic feasibility in SA conditions will always start with identifying potential sea-states and selection of the actual device of interest. It could be any available WEC in the market or at the development phase considered to be a candidate for deployment in SA. The flow chart shown in Figure 5-1 with its blocks explained in the following examples.

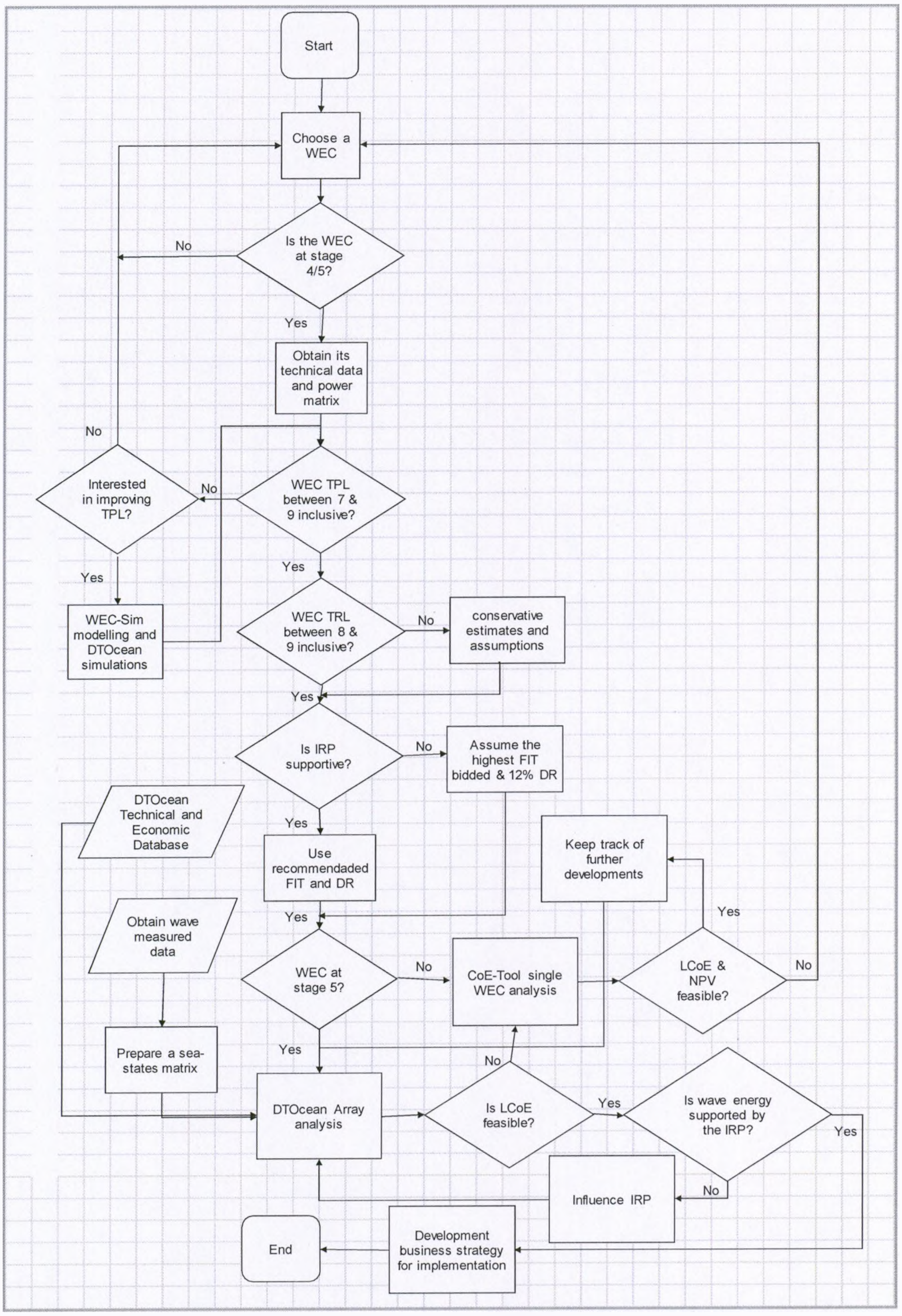

Figure 5-1: WEC assessment framework flowchart

Example: In the case study in Chapter 5, the Pelamis and the Wavestar were chosen because at the time they were at a more advance development stage and almost ready for commercialisation. It should be noted here that the assessment was limited only to two devices because the intention of this research was to develop a framework, this could have been achieved with one WEC assessment, however, one more WEC was assessed to verify the method and the calculations used in assessing the first WEC device.

Is the WEC at stage 4/5?

The following step after selecting a WEC is to assess the chosen WEC technology according to Table 5.1 to decide to which development stage is the WEC on. If the WEC is either at stage 4 or 5 the assessment continues otherwise another WEC has to be chosen.

Example: Referring to the case study in Chapter 5, both the Pelamis and the Wavestar were considered to be at stage 4; this is because both their prototypes have been tested at the open sea.

Obtain its technical data and power matrix.

Now that a user has established that the WEC is either at stage 4 or 5 and its technical data and power matrix have to be obtained, which are usually published for devices at higher stages of development or else the data can be requested from the developer.

Example: At this stage technical specifications and power production matrices of each device were extracted from various sources of literature, product technical reports and developers' websites.

WEC TPL between 7&9 inclusive?

A user has to evaluate the Technology Performance Level of the selected WEC as per Table 3.2. The TPL represents the economic potential of a WEC with its higher level corresponding to more competitive cost of energy [38]. Hence, higher levels of TPL should be reached at the lower levels of the TRL (Table 3.1) for a WEC implementation to be feasible. If TPL is lower than 7, a WEC may be re-simulated on WECSim and be verified on DTOcean Simulator for more optimisation or another WEC be selected.

Example: After analysing the collected data of both devices it was concluded that they are both at TPL 6, which does not satisfy the condition to continue with the assessment unless some improvement or modelling to obtain improved technical data is done. Since the WECs are not at s TPL between 7 and 9 inclusive, the author had to decide whether to improve TPL of the WECs for commercialisation or not, which could be done by modelling and simulating the WECs on WECSim. Then the WEC was modelled and simulated on a WECSim simulation tool as shown in Appendix 3 to highlight the concept of WECSim modelling and simulation, the improvement of the device for commercialisation was not part of the scope of this research work. Therefore, the decision to continue with the assessment as though both WEC are at TPL 7 or above was taken for the purpose of the academic exercise and development of the framework. It should be noted that for commercial deployment, a different WEC would have been selected or the current selected WEC be improved technically. To date there is no device identified to be at TPL 7 or above.

WEC TRL between 8&9 inclusive?

Having confirmed a WEC to be at TPL 7 or above, the user has to assess if the same WEC is at TRL 8 or 9 as tabulated in Table 3.1. TRL represents the technical maturity level of a technology. The TPL and TRL evaluation scales can be combined in the TRL-TPL matrix as shown in Figure 3.1. If the TRL is less than 8, a very conservative approach can be taken, as there will be higher uncertainties from the assumptions.

Example: The WECs used in the case study are deemed to be at technology readiness level 7. Hence the assessment can still be conducted for these devices with a cautious approach due to lack of reliable data. Conservative estimations from sources of literature were applied to assess both the Pelamis and the Wavestar in Chapter 5.

Is the IRP supportive?

The South African energy Integrated Resource Plan (IRP) currently, does not include wave energy as one of the renewable resources options. In the WEC assessment the IRP has to be checked if there is a latest plan that includes wave energy or not. If the IRP does not, the user may assume a highest REFIT (to date there hasn't been any applied REFIT for wave energy resources, literature shows that wave energy resources will most likely obtain the highest REFIT amongst Concentrated Solar Power (CSP), Solar and Wind) [21, 37] that was last awarded to other forms of renewable technologies and a latest published maximum DR for high-tech industries, 16.5% in May 2017 [39]. If it is supported a user should use the latest REFIT and DR that was awarded to a WEC implementation.

Example: When performing an economic model of the assessed WECs the IRP 2010-2030 was studied. This IRP has no inclusion of wave energy, wave current or tidal as a resource for electricity. Therefore there is no stated FIT or previously awarded FIT for wave energy, the author decided to use the same FIT that last awarded for CSP because it was the highest FIT awarded, wave energy is thought to acquire higher FIT. The DR chosen for both assessments was 12% because in the IRP document all other form of renewable energy were granted that DR.

Is the WEC at stage 5?

If a WEC is at stage 5 as illustrated in Table 5-1, then perform the techno-economic analysis on a DTOcean tool for an array of WECs. The user would need to determine the optimal number of devices to produce maximum or desired output power at minimal cost by simulations on DTOcean. If it is not at stage 5 a CoE-calculation tool may be used to perform a techno-analysis assessment for a single device. This is because there is not enough reliable data to use on DTOcean for a WEC array.

Example: It should be noted from Figure 5-1 and previous explanation that the WEC assessed could be in stage 4 or 5 and in the case study both devices are at stage 4.

This stage is where devices are being tested at full-scale and in open water but not in an array. The applicable tool to use in this case is a CoE-calculation tool because it is programmed to assess single devices, however, even though the DTOcean is intended for array operations the author, in Chapter 4, used it to verify the results from a CoE-calculation tool and gain confidence in both tools. The Pelamis was assessed in both assessment tools for verification as mentioned and illustration of this framework's purpose.

DTOcean Arrays analysis

Obtain measured wave data and formulate a sea-states matrix as outlined in Section 3.4.1 to input into a DTOcean or CoE-calculation tool. Import the relevant economic and technical data from the server database into DTOcean.

Example: For both assessment tools wave power matrices are needed. For the CoE-calculation tool a wave power matrix was developed as explained in Section 3.4.1 and Appendix A, and for DTOcean tool assessment the power matrix was prepared as explained in Section 4.2.1. The DTOcean tool has various algorithms that are computed using pre-loaded data from a created database server. For the case study a database file was downloaded from DTOcean sharing website, pgAdminIII and Python software were downloaded and installed on the computer. Scripts were modified or amended to enable exportation of data to pgAdminIII and to allow the communication of DTOcean and pgAdminIII, so that DTOcean can access the database when required (Appendix C). It can be seen in Figure 5-1 that DTOcean requires inputs from the Techno-Economic database server.

Table 5-1: Techno-economic development stages of WECs [38]

	Stage1 Concept model	Stage 2 Design model	Stage 3 Function model	Stage 4 WEC Prototype	Stage 5 Array demonstration
Scale	1:20 – 1:100	1:10 – 1:50	1:3 – 1:10	1:1 – 1:3	1:1
Location	Laboratory	Laboratory	Laboratory/benign site	Open seas	Open seas
Model / Prototype Characteristics	• Idealised setup • Load-adaptable PTO • Adaptable design variables	• Final design • Representative characteristics • Simulated PTO	• Full fabrication • True PTO and • Electrical generator	First fully operational device	Autonomous and operational WEC power plant
Waves	Representative power production and extreme sea states	Representative power production and extreme sea states	Pilot site waves	Operational and extreme sea states	Operational and extreme sea states
Experimental test objectives	Main: • Concept validation and optimisation • Power performance estimate • Assessing the impact of design variables and environmental parameters Possibly also: • PTO and mooring char. • Loads estimation • Movement estimation (RAO'S)	Main: • Power performance estimation • Mooring and structural loads • Sea keeping • PTO conditions • Assessing the impact of design and environmental variables Possibly also: • Detailed numerical calc. • Feasibility study	Providing experimental data and experience on: • Power performance • Wave-to-wire model, including control strategy • Mooring and structural loads • Survival and sea keeping • Marine environment	Real cost and power production data for projection for device sales: • CapEx • OpEx • Energy production And also • Wave-to-wire model • Structural and mooring forces • Lifecycle assessment	Real cost and power production data for projection for WEC array sales: • Array CapEx • Array OpEx • Array Energy production And also for WEC array • Wave-to-wire model • Structural and mooring forces • Lifecycle assessment

Is the LCoE feasible?

If the results obtained from DTOcean are satisfactory and feasible a user may continue to develop a business strategy to WECs implementation or compare the assessed WEC technology to other technologies converting other forms of renewable energies to electricity. If the IRP still does not consider wave energy in it, a user can use the study findings to motivate and influence the IRP and other relevant policies. If the results are not feasible a user should assess the WEC on a CoE-calculation tool and track further developmental improvements of the same WEC, if the results of the assessment are feasible, new data from the improvement can be used on a DTOcean assessment otherwise a user should choose another WEC.

Example: In the case study discussed in Chapter 5 the Pelamis WEC was assessed in both assessment tools. This was done for verification purposes to fulfil the academic exercise as mentioned previously, of which was applied in contrary to the procedure stipulated here. Since the Pelamis is at TPL 6 (refer to Table 3-2), it could have not been further assessed if the study was for business case for commercial deployment. On the final assessment the LCoE was found not to be feasible as compared to other forms of electricity generation on both assessments but DTOcean assessment was not done for the array operation. It has been concluded from the studies of computational modelling using algorithms that utilise analytic hydrodynamic models and arrays cost models, performed by other authors [15, 32] that with the optimal array operations the LCoE can be significantly reduced. On the CoE-calculation tool both LCoE and NPV financial indicators were relatively not feasible for both devices. The options would be to optimise the WEC interactions with the site sea-states, obtain more reliable data if it exists, track further development on these devices and reassess them or another WEC may be chosen.

Develop a business strategy for implementation

At this stage a business case where comparison to other forms of renewable energy to electricity may be performed, is conducted and the implementation strategy can be initiated. This may be approached by following the assessment for commercial readiness developed by ARENA [40] known as Commercial Readiness Index (CRI) illustrated in Appendix D.

The business strategy for case study mentioned could not be developed as it was outside the scope of this research and the assessment results were not feasible or compelling enough to formulate an argument for a business case.

CHAPTER 6

Conclusions

A framework for the techno-economic analysis for wave energy conversion to electricity under SA conditions has been developed in this research. Should it occur that a decision has to be made about deploying a certain technology either commercially or for a demonstration phase, this developed techno-economic framework may be adopted by following the steps stipulated in the form of a flowchart discussed in Chapter 5 to assess any WEC and new technology design developments.

The in-depth knowledge of WECs, hydrodynamic interactions, SA wave energy conditions, renewable energy regulatory requirements and economics as well as financial calculations leading into techno-economic analysis were acquired. The case studies performed in Chapter 4 helped the author to utilise all the information gathered into decision making and adopted learnings from there into the development of the framework. The calculations in the case studies were based on some assumptions made by the author which were informed by the information acquired and the assumptions by other authors. The computer tools used have not yet been thoroughly scrutinised to be guaranteed accuracy and there is no other similar studies or guidelines in SA to benchmark against.

The computer tools used indicated that with the current SA conditions and assumptions made, it is not yet feasible to invest in both the Pelamis and the Wavestar

WECs in SA (Slangkop site). As discussed in Section 4.1.1 two financial indicators were used for the analysis:

- NPV produced a negative cash flow value, implying that the present value of the project's cash flow does not outweigh the investment i.e. there are no profit returns expected in the current investment setup.
- LCoE produced a relatively higher price as compared to those of coal fired power station.

The CoE-Calculation tool also indicated that the investment amount would not be paid back within the expected life period of the device. However, the Pelamis economic results are slightly better than those of the Wavestar. Both the LCoE-calculation tool and DTOcean are in agreement in terms of the results, that validates the calculation methods and inputs by the author. This analysis was done for two devices with the aim to verify consistency of the tools and also assess if any of the technologies performs better than the other.

6.1 Future Work

- More research focusing on modelling and optimising the WECs for the Slangkop site and other southern coastal sites with the aim to increase the capacity factor thus the annual production.
- Furthermore, the optimal number of devices and positioning in WECs array should be thorough researched to help reduce LCoE of the wave energy to electricity conversion.

- The study to investigate the possibility of importing only the raw materials into SA to establishing assembly plants locally for the deployment as compared to importing assembled products.
- Adopting a framework given in this research, a study to compare WECs to running peak demand supply generators such as the diesel generators, and or deploying more hydro-pump storages.

Lastly, the wave energy organisations and developers are optimistic that the costs of WEC technology deployment will significantly reduce over the years having gone through optimisation by design, testing, gaining operational experience and technology improvement (i.e. reaching a maturity stage) to competitive cost levels. The future work listed in this section will contribute towards overcoming the learning curve (design, testing, gaining operational experience and technology improvement), which also greatly contributes into high costs. Therefore, this developed framework is an essential tool to quickly analyse and assess future developments of and on WECs.

REFERENCES

[1] J. Du Plessis, "A Hydraulic Wave Energy Converter," Master's thesis, University of Stellenbosch, Matieland, South Africa, 2012.

[2] J.R. Joubert, D.E. Bosman," An Investigation of the Wave Energy Resource on the South African Coast, focusing on the spatial distribution of the South Western coast", Master's thesis, University of Stellenbosch, Matieland, South Africa, 2008.

[3] F. R. Spellman, R. M. Bieber, "The Science of Renewable Energy", Taylor & Francis Group, Boca Raton, 2012.

[4] J. R. Joubert, J. L. Niekerk "Recent Development in Wave Energy along the Coast of Southern Africa." 2010.

[5] W. Van Rooy, "Wave Power Technologies", Research Report, Eskom Research and Innovation Dept. Technology Strategy and Planning, 2013.

[6] K. L. Guiberteau, Y. Lui, J. Lee, T. A. Kozman, "Investigation of Developing Wave Energy Technology in the Gulf of Mexico," Distributed Generation and Alternative Energy Journal, vol. 27, pp 36-51, 2012.

[7] J. Frick. "Implementation Plan for the Stellenbosch Wave Energy Converter on the South-West Coast of South Africa." MSc. dissertation, University of Cape Town, South Africa, 2014.

[8] A. Eberhard, J. Kolker, J. Leigland, "South Africa's Renewable Energy IPP Procurement Program: Success Factors and lesson", PPIAF, Washington DC, 2014

[9] A. Williams, M. Nthontho, S. Chowdhury, S.P. Chowdhury, "Modelling South African Agulhas marine current profile data for electrical generation", Capetown, IEEE 2012, pp. 1-7.

[10] J. Fernandez-Chozas, J. P. Kofoed, N. E. Helstrup Jensen, "An Open-Access COE Calculation tool for Wave Energy Converters-the Danish approach", 2014.

[11] J. F. Chozas, J. P. Kofoed, and N. E. H. Jensen, "User guide-COE-calculation tool for wave energy converters ver. 1.6", Dept. of Civil Eng., Aalborg Univ. DCE Tech. Report; No. 161, 2014.

[12] DTOcean. (2015, Aug. 28). *An Overview and Progress Update* [Online]. Available: https://www.youtube.com/watch?v=KRnk2s8K56U.

[13] DTOcean, "DTOcean Technical Manual Release", October 2016.

[14] G. Dalton, R. Alcorn, T. Lewis, "Operational Expenditure Costs for Wave Energy Projects,"*3rd International Conference on Ocean Energy,* Bilbao, October 2010

[15]. C. J. Sharp, "Wave Energy Converter Array Optimization: Array Economic Analysis and Preliminary Results of a Genetic Algorithm Approach Introducing Cost Factors," MSc thesis, University of Oregon, Oregon, 2015.

[16] M. Goldberg and M. Previsic, "JEDI Marine and Hydrokinetic Model: User Reference Guide JEDI Marine and Hydrokinetic Model: User Reference Guide," 2011 [Online]. Available: http://www.nrel.gov/docs/fy11osti/50402.pdf

[17] SI Ocean, "Ocean Energy: State of the Art" [Online]. Available: http://siocean.eu/en/upload/docs/WP3/Technology Status Report_FV.pdf

[18] ARENA. (2016, March). Carnegie CETO 6 Technology [online]. Available: https://arena.gov.au/projects/carnegie-ceto-6-technology

[19] M. Leijon, H. Bernhoff, M. Berg, and O. Ågren, "Economic considerations of renewable electric energy production—especially development of wave energy," Renew. Energy, vol. 28, no. 8, pp. 1201–1209, Jul. 2003 [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S096014810200157X. [Accessed: 15Dec-2014]

[20] Wave Energy Technology Brief 4, International Renewable Energy Agency, June 2014.

[21] Department of Energy. "Draft 2012 Integrated Energy Planning report", June 2013.

[22] A. Eberhard, J. Kolker, J. Leigland, " South Africa's Renewable Energy IPP Procurement Program: Success Factors and Lessons" PPIAF, May 2014

[23] L. McDaid, Y. Abraham, P. Atkins, "Renewable Energy Independent Power Producer Procurement Programme Review 2014", Electricity Governance Initiative South Africa, 2014

[24] URS. "Final Wave Feasibility Report." City and Country of San Francisco, pg. 14, December 2009.

[25 S. De Chowdhury, J.R. Nader, A. M. Sanchez, A. Fleming, B. Winship, S. Illesinghe, A. Toffoli, A. Babanin, I. Penesis, R. Manasseh, "A Review of Hydrodynamic Investigations into Arrays of Ocean Wave Energy Converters" unpublished

[26] Wikipedia. (2016, Jun. 8). *Pelamis Wave Energy Converter,* [online] Available: https://en.wikipedia.org/wiki/Pelamis_Wave_Energy_Converter,

[27] M.M. Kramer, L. Marquis, P. Frigaard, "Performance Evaluation of the Wavestar Prototype" [unpublished]

[28] L. Marquis, M.M. Kramer, J.F. Chozas, N.E. Helstrup, " Introduction of Wavestar Wave Energy Converters at the Danish offshore wind power plant Horns Rev 2" 4th International Conference on Ocean Energy, 17 October, Dublin, 2012.

[29] J. Estrada," NPV and IRR," in *Understanding Finance.* A no-nonsense Companion to Financial Tools and Techniques. 2nd ed., Gosport, Hampshire, Prentice Hall, 2011, Pp. 261-276.

[30] J. Weber, "WEC Technology Readiness and Performance Matrix finding the best research technology development trajectory," 4th International Conference on Ocean Energy, Dublin, 2012.

[31] K. Ruehl, D. Bull, "Wave Energy Development Roadmap: Design to Commercialization", IEEE, 2012

[32] G. Dalton, R. Alcon and T. Lewis, "Case Study Feasibility Analysis of the Pelamis Wave Energy Convertors in Ireland, Portugal and North America," [unpublished]

[33] N. Farrell, C. Donoghue, K. Morrissey, Quantifying the uncertainty of wave energy conversion device cost for policy appraisal: an Irish case study, Working Paper 14-WP-SEMRU-02, 2014.

[34] M. O'Connor, T. Lewis, and G. Dalton, "Techno-Economic performance of Pelamis P1 and Wavestar at different rating and various locations in Europe", Unpublished.

[35] Y. Nitesh, G. Sandeep, "Pelamis wave energy converter, an efficient renewable energy system," unpublished.

[36] G. Dalton, R. Alcon and T. Lewis, "Operational expenditure costs for wave energy projects; O/M, insurance and site rent," 3rd International Conference on Ocean Energy, Biblao, 2010, pp. 1-14.

[37] MHK Technology Development Risk Management Framework-Draft (2015)

[38] Arthur Pecher, Jens Peter Kofoed, Handbook of Ocean Wave Energy, Ocean Engineering & Oceanography 7: Chapter 7

[39] South African Property Owners Association, *Research Cap & Discount Rate Report*. SA, SAPOA, 2017.

[40] Australian Renewable Energy Agency, *Commercial Readiness Index for Renewable Energy Sectors*. Australian Government, ARENA, 2014.

[41] Corporate Affairs Division. "[All Eskom Employees] Power alert 1 - Levelised Cost of Energy - response to EE Publishers article on 21 July 2016" Communication Email. (Jul. 21, 2016).

[42] G. J. Dalton, T. Lewis, and M. O'Connor, "Impact of inter-annual resource data variability on techno-economic performance of the WaveStar and Pelamis P1," 4th International Conference on Ocean Energy, Dublin, 2012. pp. 1-9.

[43] T. Thorpe, A. Clement, P. McCullen, A. Falcao, et al., "Wave Energy in Europe: Current Status and perspectives. Renewable and Sustainable Energy Reviews:," ETSU-R-72, vol. 6, no. 5, 2002, pp. 405–431.

[44] R. D. Murray, "Economic Wave Energy Resources Assessment Methodology & European Assessment," Master's thesis, University of Stratchclyde, Glasgow, Scotland, 2004.

[45] J. R. Joubert, J. L. van Niekerk, "South Africa Wave Energy Resource Data." A case study, Centre of Renewable and Sustainable Energy Studies, Stellenbosch, 2013.

[46] B. Drew, A. R. Plummer, M. N. Sahinkaya, "A Review of Wave Energy Converter Technology", University of Bath, UK, DOI: 10.1232/09576509JPE782

[47] M. Goldberg and M. Previsic, "JEDI Marine and Hydrokinetic Model: User Reference Guide JEDI Marine and Hydrokinetic Model: User Reference Guide," 2011 [Online]. Available: http://www.nrel.gov/docs/fy11osti/50402.pdf

[48] NREL, "JEDI Marine and Hydrokinetic Model -User Reference Model." National Renewable Energy Laboratory, 2010 [Online]. Available: http://www.nrel.gov/analysis/jedi/about_jedi_marine-hydro.html

[49] M. Previsic, R. Bedard, G. Hagerman, and O. Siddiqui, "System Level Design , Performance and Costs for San Francisco California Pelamis Offshore Wave Power Plant," 2004 [Online]. Available: http://oceanenergy.epri.com/attachments/wave/reports/006_San_Francisc o_Pelami s_Conceptual_Design_12-11-04.pdf

[50] M. Previsic, "Economic Methodology for the Evaluation of Emerging Renewable Technologies," 2011 [Online]. Available: http://energy.sandia.gov/wpcontent//gallery/uploads/Re-Vision-Economic-Methodology-for-the-Evaluation-ofEmerging-Renewable-Technologies-MP-11-9-11.pdf

[51] J. P. Koefed, N. E. H. Helstrup, and J. F. Chozas, "User guide – The COE Calculation Tool for Wave Energy Converters (Version1.6, April 2014)," 2014 [Online]. Available: http://vbn.aau.dk/files/197329237/User_guide_to_the_COE_Calculation_T ool_ver 1.6_April2014.pdf

[52] Aalborg University, "COE Calculation Tool for Wave Energy Converters." Aalborg University, 2014 [Online]. Available: http://vbn.aau.dk/en/publications/user-guide-coe-calculation-tool-for-wave-energy-converters(78b135d9-ea66-43f8-959fc799dc4df1a9).html

[53] K. Ruehl and D. Bull, "Wave Energy Development Roadmap: Design to commercialization," 2012 Ocean., pp. 1–10, Oct. 2012 [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6404795

APPENDIX A

Wave data

An average was taken for all wave heights corresponding to each particular wave period. Frequency of occurrence was obtained by the weighted count (counting the number of waves with equal periods and diving it by the total number of wave occurrences) of wave heights in a specified range divided by the total number of occurrence. The values in Table A.1 are used in the formation of the scatter matrix used in DTOcean tool. The significant heights were converted to zero-crossing wave period for the calculation of the wave power used in the LCoE-calculation tool. The calculated wave power matrix is shown in Figure A.1.

	Tz(s)															
Hs(m)	3.3	4.0	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.6	10.3	11.0	11.7	12.4	13.1	13.8
0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	0.0	0.0	0.0	0.0	8.0	36.0	25.0	1.0	4.0	5.0	2.0	0.0	0.0	0.0	0.0	0.0
1.50	14.0	12.0	9.0	6.0	23.0	135.0	198.0	60.0	29.0	12.0	14.0	8.0	7.0	0.0	1.0	0.0
2.00	4.0	7.0	13.0	8.0	23.0	188.0	327.0	123.0	82.0	28.0	24.0	14.0	6.0	0.0	1.0	0.0
2.50	0.0	2.0	9.0	2.0	5.0	76.0	182.0	121.0	100.0	53.0	19.0	12.0	5.0	0.0	1.0	0.0
3.00	0.0	0.0	3.0	11.0	6.0	33.0	96.0	71.0	67.0	54.0	13.0	7.0	5.0	0.0	0.0	0.0
3.50	0.0	0.0	1.0	1.0	3.0	10.0	38.0	35.0	36.0	34.0	12.0	6.0	2.0	0.0	0.0	0.0
4.00	0.0	0.0	0.0	1.0	8.0	16.0	22.0	16.0	21.0	16.0	12.0	2.0	3.0	0.0	0.0	0.0
4.50	0.0	0.0	0.0	0.0	0.0	9.0	21.0	9.0	14.0	11.0	9.0	7.0	0.0	0.0	1.0	0.0
5.00	0.0	0.0	0.0	0.0	1.0	3.0	5.0	10.0	5.0	11.0	5.0	4.0	0.0	0.0	0.0	0.0
5.50	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	3.0	6.0	9.0	1.0	1.0	0.0	1.0	0.0
6.00	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	7.0	3.0	2.0	2.0	0.0	1.0	0.0
6.50	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	1.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0
7.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	1.0	0.0	0.0	0.0
7.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
8.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
8.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure A.1: Wave power matrix

Table A.1: Sea-states occurrence frequency

Average Tp	Average Hs	Frequency of occurance
5.00	1.57	0.00069
5.20	1.50	0.00138
5.50	1.63	0.00415
5.80	1.75	0.00484
6.20	2.03	0.00242
6.60	2.21	0.00276
7.10	2.10	0.00276
7.60	2.14	0.00725
8.30	2.38	0.01036
9.00	2.15	0.02660
10.00	2.07	0.06356
10.50	2.06	0.11123
11.10	2.21	0.15302
11.70	2.34	0.16546
12.50	2.57	0.15579
13.30	2.72	0.12539
14.20	3.12	0.22073
15.30	3.26	0.04421
16.60	3.25	0.02314
18.10	2.92	0.01105
20.00	4.33	0.00242

APPENDIX B

WEC-Sim

The open-source reference models for marine energy conversions has been developed by the Reference Model project team, made up of members from Sandia National Laboratory, National Renewable Energy Laboratory, Pacific Northwest Laboratory and Oak Ridge National Laboratory with two consulting firms, Re-Vision Consulting and LLC & Cardinal Engineering, also with the University of Washington and Pennsylvania University. The aforementioned project is funded by the USA Department of Energy with the objective of collaborative research community that can play a role in speeding up the technology development and meets the rapidly evolving modelling needs. These reference models are used to develop a tool based on MATLAB and its simulation tools called WEC-Sim, an open-source simulation tool provided to WEC design and research community. It has the ability to model devices that comprise of rigid bodies and power take-off. WEC-Sim is a combination of the following toolboxes:

- WaveSim: code developed in MATLAB to generate simulated wave states using measured wave data and standard wave spectra.
- BEM: developed to determine hydrodynamic coefficient using boundary element simulation methods.
- HydroForce: developed in MATLAB to calculate time dependent hydrodynamic coefficient (from BEM module), viscous drag coefficients, relative device motion and the current sea state.

- Multi-Body Solver: developed in SimMechanics, a MATLAB toolbox, models WEC device from connected appropriate number of bodies, joints and connections, according to their physical layout. The multi-body six-degree-of-freedom system is then solved in the time domain by SimMechanics.
- PTO-Sim: developed in SIMULINK to enable time dependent electrical power predictions from the calculated mechanical power. PTO-Sim is broken into modules that allow for different PTO configurations.

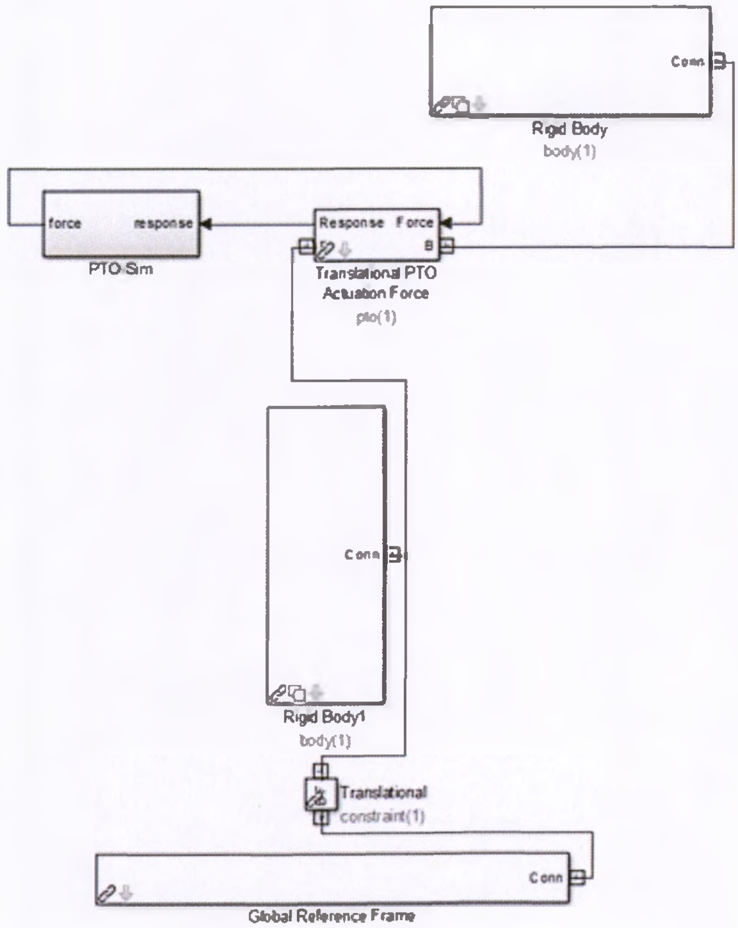

Figure B.1: Point-Absorber WEC Simulink model

Figure B.1 shows the simulation diagram on Simulink representing the point absorber WEC and its power take-off (PTO) is shown above. Its simulation output results are shown in Figure B.2-B.5. This was the work by the author to understand WEC modelling on WECsim and to simulate the results as it forms part of the optimisation process stipulated in the framework in Chapter 5.

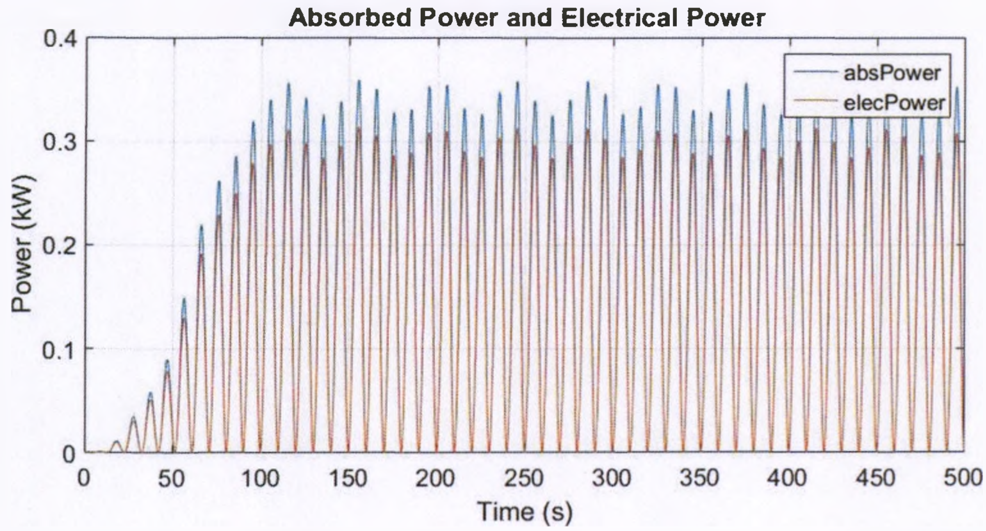

Figure B.2: WEC absorbed power and electrical power

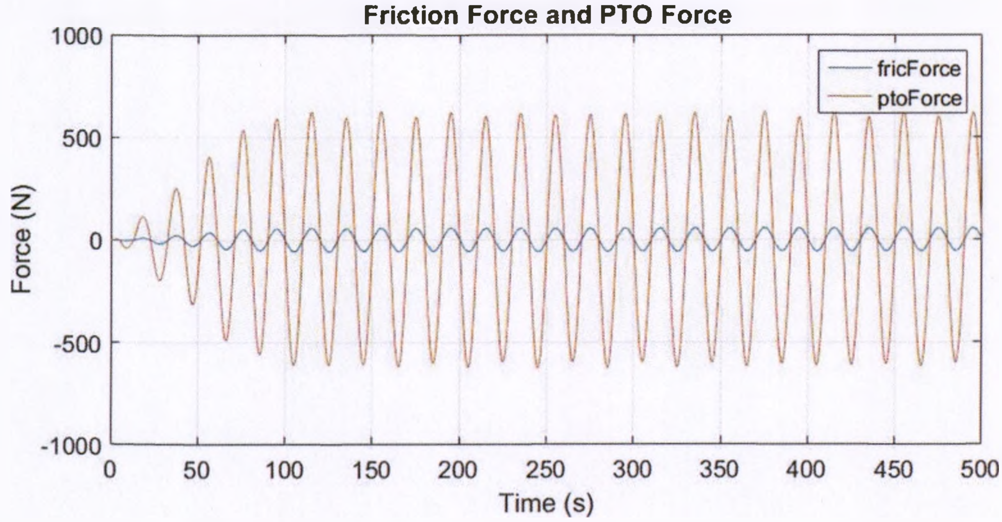

Figure B.3: WEC friction force and PTO force

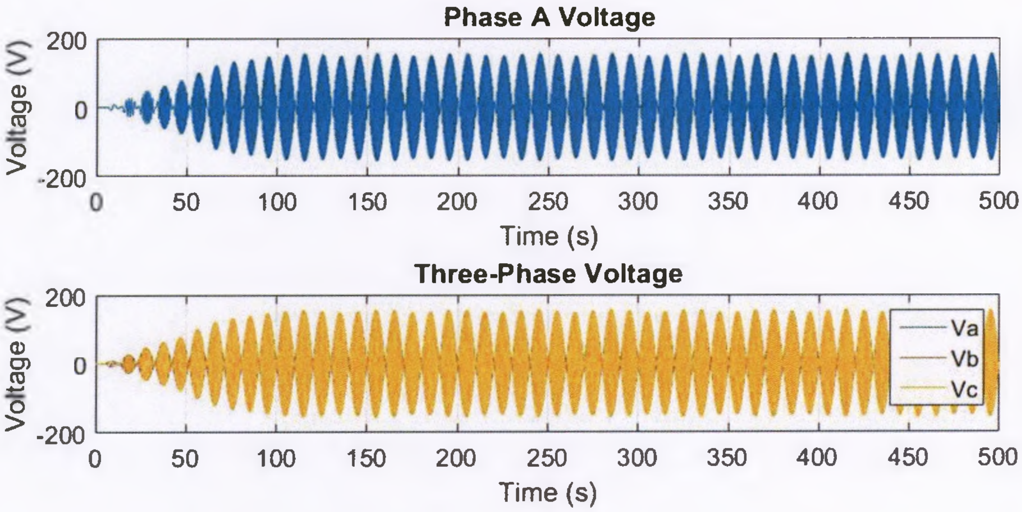

Figure B.4: WEC voltages

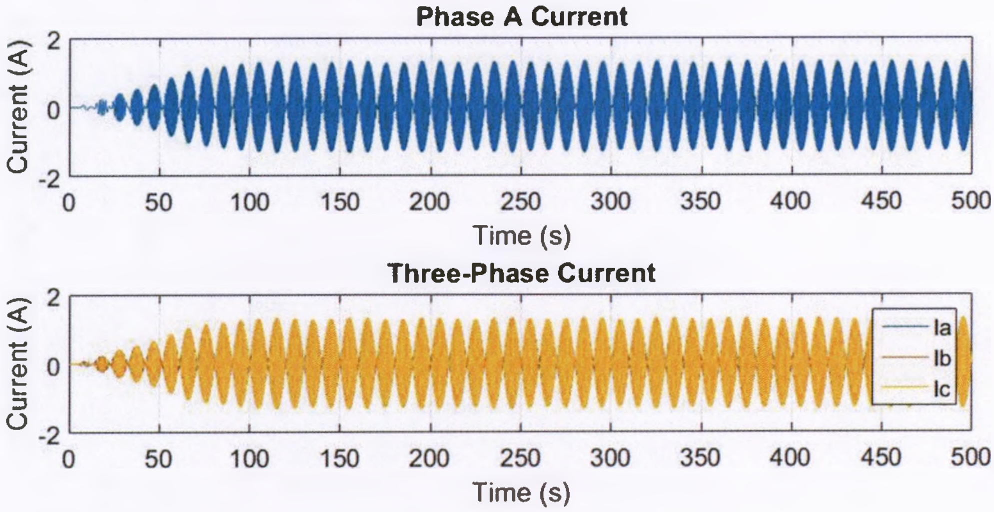

Figure B.5: WEC electrical currents

APPENDIX C

Database

The picture in Figure C.1 is a screenshot of a data server platform pgAdminIII. Challenges encountered by the author were to establish communication between DTOcean and this platform to access the data, to modify data within the server and process it.

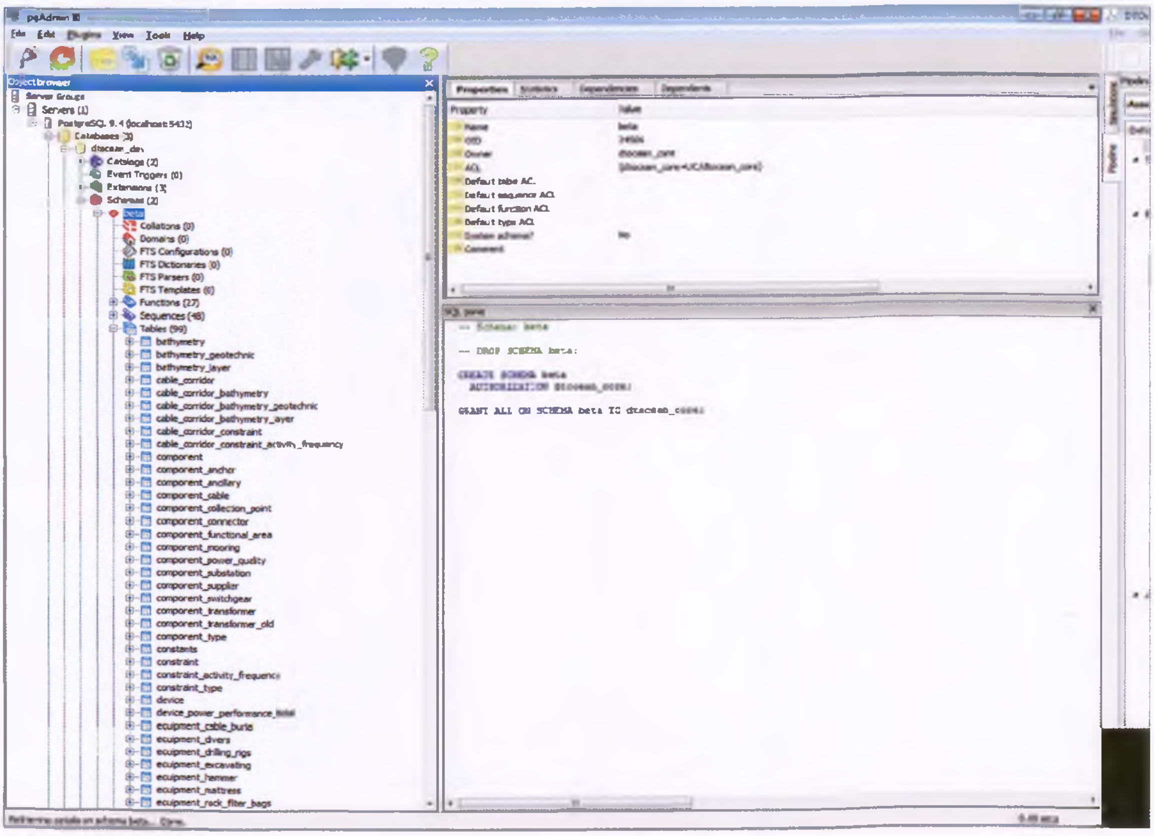

Figure C.1: pgAdminIII data server platform

APPENDIX D

Commercial Readiness Index

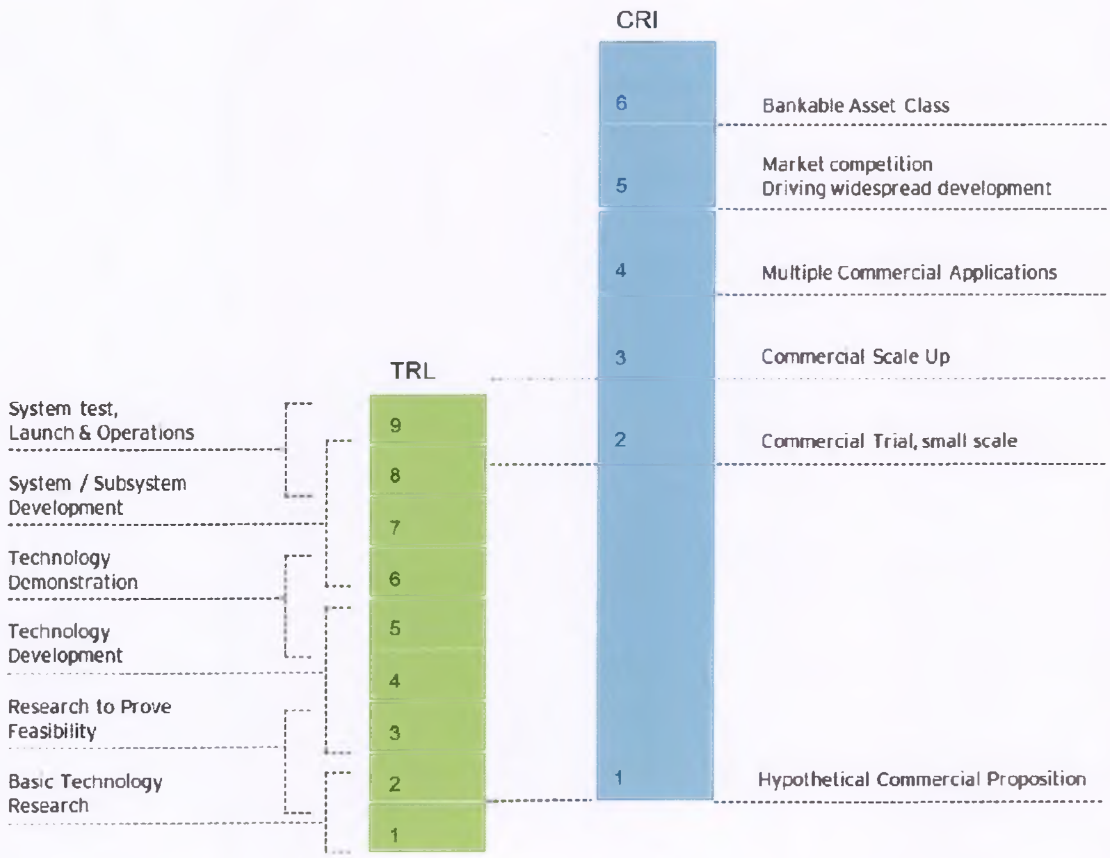

Figure D.1: The overlap of TRL and CRI

Indicators

The Indicators are used to reflect the commercialisation process of renewable energy. The CRI addresses a range of interlinked barriers in making progress towards widespread deployment.

Drawing on past experience, consulting with stakeholders and reviewing available literature, ARENA has identified the following Indicators as being sufficiently quantifiable to warrant inclusion. To improve a technology solution or an application's overall commercial readiness, we consider that it needs to progress along each of these dimensions. We would also expect that projects that are transitioning from measuring themselves in the TRL index to the CRI would aim to increase one or more of these Indicators. Table D.1 are the descriptive status levels from 1 to 6.

Table D.2: Commercial Readiness Levels

Status Summary Level	Description
6	**"Bankable" grade asset class** driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.
5	**Market competition driving widespread deployment** in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.
4	**Multiple commercial applications** becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
3	**Commercial scale up** occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.

2	**Commercial trials**: small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	**Hypothetical commercial proposition**: Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.